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Fausto Cavallaro *Editor*

Assessment and Simulation Tools for Sustainable Energy Systems

Theory and Applications

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To my Mother and Father

Preface

Energy and the supply of energy sources have played a central role in the development of modern society. The technological revolution of the last century would not have been achieved without the invention and rapid expansion of systems for electricity distribution.

Up until the energy crises of the 1970s and early 1980s, satisfying energy demand was basically a question of the availability of resources and the best technology on hand. The last 20–30 years, however, have seen a change in the way of interpreting the idea of availability and of energy supply.

The main factor that triggered this change is tied to the sharp rise in the price of energy caused by the first oil crisis in the 1970s. In the West, that era heralded the collapse of the myth of cheap, plentiful and easily available energy and raised in its place concerns about the imminent exhaustion of natural resources. At the same time, the worries linked to the environmental consequences deriving from an increasingly greater use of hydrocarbons led to the search for energy technologies that were environmentally compatible.

In recent years the concept of energy has been revised and a new model based on the principle of sustainability has become more and more pervasive. The idea of *sustainable energy* is founded on three main principles: *production* pertaining to technologies for generating energy particularly those using renewable sources, *use* which encompasses the different classes of energy efficiency and saving, and *environmental impact* in terms of pollution and the use of natural resources, which should be minimised. This broad-based model does not embrace merely energy production but also its utilization, both of which are inserted within a bigger and more complex picture, i.e. sustainable development. In order to tackle the problem of sustainable energy effectively, it requires that energy-related economic, technological and ecological issues are no longer approached separately but are dealt with as a single integrated concern.

In its recent report *Energy Technology Perspectives* (2012), the International Energy Agency (IEA) underlines that to achieve sustainability it is essential to make a determined effort to activate the development and propagation of technologies for the decarbonization of the energy system. Unfortunately, it is more than evident that current schemes for technological innovations are proceeding at a rather slow pace and presumably will not be able to guarantee any real change in the energy system in the short term, a key factor to meet environmental sustainability targets.

The IEA gives unequivocal warning of the unsustainability over the medium–long term of the current balance between economic growth, energy demand and environmental impact. Based on a scenario which does not include any additional measures or policies to tackle the energy issue, it forecasts that by 2050 emissions of pollutants will have doubled compared to the figures for 2009. The Agency also stresses that the majority of technologies that could play a leading role in the shift towards low-carbon energy systems are still progressing very slowly.

The European Union, conscious of the risks linked to climate change, has taken an active interest in the issues related to sustainable energy. Indeed, in late 2007, the European Commission launched the Strategic Energy Technology (SET) Plan to promote the development and deployment of low carbon technologies that are capable of demonstrating good cost/benefit ratios. The SET Plan highlights the key role that energy technologies have to play in order to meet the European targets for 2020 (and the longer term ones for 2050) to fight climate change.

In this context, the scientific procedure of *assessment* has a vital role in that it can supply the right tools to evaluate the actual situation and make realistic forecasts of the effects and outcomes of any actions undertaken. The results of an accurate and effective assessment are undoubtedly a valid aid and guide not only for decision makers as a whole, but also for entrepreneurs, managers, designers and scientists. In brief, for anyone who wishes to measure or simulate the propagation and effect of an action (i.e. a plan, a project, a research study, etc.).

This book aims to offer readers a review of the main methods and approaches that can be used for assessment and simulation in the field of sustainable energy systems. The volume is divided into three parts. The first is dedicated to the analysis of the theoretical foundations and applications of multicriteria decision making and contains the following chapters. Chapter 1 is dedicated to sustainability assessment of solar technologies based on linguistic information. In this chapter a modified multicriteria method (PROMETHEE) that uses fuzzy sets is proposed to handle linguistic information for the assessment and appraisal of solar energy technologies. Chapter 2 focuses on outranking approaches and the difficulties underlying choices in Multiple Criteria Decision Analysis (MCDA). In particular, the authors propose the RUBIS method and the RUBIS D3 web server to select photovoltaic plants for the insular grid on the French island of Corsica. In Chap. 3 the Analytical Network Process (ANP) is used in order to evaluate and select the main green energy alternatives for the country of Turkey. The conflicting criteria used in the evaluation process are classified using the Benefits, Opportunities, Costs and Risks (BOCR) framework. Chapter 4 deals with the study and evaluation of decision criteria that influence the location of solar photovoltaic and thermoelectric plants, in order to obtain their weights or importance coefficients to which Analytic Hierarchy Process (AHP) methodology is to be applied. In Chap. 5 a multi-attribute decision-making method combining cloud and utility theory is described in order to evaluate different locations for a wind farm in Northern Spain. Chapter 6 illustrates how geographical areas have diverse green energy resources and different levels of energy consumption. The aim of this chapter is to group geographic areas in such a way that energy demand in a geographic cluster matches the available green energy potential in the same cluster. In Chap. 7 a methodology based on a cumulative belief degree approach is suggested for the prioritization of energy sources. The approach enables the use of all types of evaluations, without the loss of any information. In Chap. 8 the ranking of different scenarios for wind farm configurations is computed and discussed. The TIMED approach and the methodological framework for robustness analysis are described. Finally, Chap. 9 focuses on the technological assessment of heat pump water heaters using a tool based on a hierarchical decision model.

The second part concentrates on the theory and practice of fuzzy inference, neural net and algorithm genetics and comprises the following chapters. Chapter 10 sets out a model providing a general mechanism to measure the sustainability of energy sectors. The model, based on the Sustainability Assessment by Fuzzy Evaluation (SAFE) approach, is applied to a large number of countries, ranked according to their sustainable energy development. Chapter 11 explains how Artificial Neural Networks (ANN) and Genetic Algorithms (GA) operate by presenting a number of problems regarding different applications of solar energy systems. Chapter 12 focuses on the theoretical background of ANN methodologies applicable to the field of wind speed and discusses the implementation issues in a region with complex terrain, namely Chania on the Greek island of Crete. In Chap. 13 a new approach is proposed to deal with the “allocation procedure” in Life Cycle Inventory (LCI). The approach used is based on GAs to resolve multi-output systems and it is applied to a case study related to a cogeneration process. The second part concludes with Chap. 14 which explains the design and implementation of the maximum power point (MPP) tracking algorithm for a photovoltaic module using fuzzy logic and genetic algorithm.

The third and final part of the volume is dedicated to simulation methods such as Monte Carlo analysis, Mathematical Programming (MP), Value Stream Mapping (VSM), Particle Smarm Optimization (PSO) and Discrete-Event Simulation (DES). Chapter 15 introduces the main simulation techniques for sustainable energy systems, i.e. Monte Carlo, Dynamic Systems (DS), DES and Agent Based Simulation (ABS). In Chap. 16 the authors propose a combination of Mathematical Programming and Monte Carlo simulation in order to deal with project portfolio optimization. A case study using real data from the Clean Development Mechanism (CDM) projects’ database is developed to illustrate the method. Chapter 17 offers a future-oriented Energy Value Stream Mapping approach designed to enhance energy efficiency in small- and medium-sized manufacturing companies. In Chap. 18 a simulation-based generic framework is described for the assessment of energy efficiency in Lean Manufacturing (LM) systems with the aim of contributing to theoretical and practical studies addressing both sustainable energy and performance in manufacturing systems. Finally, Chap. 19 focuses on the socio-effective value of bio-diesel production. An approach based on PSO and Self-Organizing Maps (SOMs) is implemented to obtain appropriate solutions of the model.

I hope that readers will find this volume a useful tool for energy assessment tasks. I also wish it to be a source of new ideas for further advancements in soft computing and simulation issues for sustainable energy.

Italy, December 2012 Fausto Cavallaro

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Contents

Part I Multi-Criteria Foundations and Applications

Part II Fuzzy Inference, Artificial Neural Net, Algorithm Genetics

Part III Simulation Models and Approaches

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Part I
Multi-Criteria Foundations and Applications

Chapter 1
Sustainability Assessment of Solar Technologies Based on Linguistic Information

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Abstract The leading role in the decision-making process is generally assigned to the decision maker who evaluates the various alternatives and ranks them. In some circumstances the decision is based on the use of different types of information often affected by uncertainty; thus the decision maker is not able to produce all the information necessary to make a strictly rational choice. In many cases the information can be expressed only by using linguistic labels, e.g. “very low”, “medium”, “high”, “fair”, “very high”, etc. It is not easy to precisely quantify the rating of each alternative and precision-based methods are often inadequate. Vagueness results when language is used, whether professional or not, to describe the observation or to measure the result of an experiment. This happens particularly when it is necessary to work with experts’ opinions which are translated into linguistic expressions. The use of fuzzy set theory has yielded very good results for modelling qualitative information because of their ability to handle the impreciseness that is common in rating alternatives. In this chapter a modified multi-criteria method (F-PROMETHEE) that uses fuzzy sets is proposed to handle linguistic information in comparing a set of solar energy technologies using only linguistic variables.

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1.1 Introduction

Targeting renewable sources entails making profound changes to the current organisation of the energy industry; to move towards a system that is increasingly more geographically scattered, technologically advanced and able to handle power generation and demand spread over a wide geographical area. The desired system would be one that: reduces the energy production chain, creates electricity and power directly from the sun and wind, and would gradually allow small users to become increasingly self-sufficient and thus become less dependent on large installations generating and distributing energy.

The challenge lies in getting environmental and energy objectives to converge and the overall success of future energy policy will depend on demonstrating that economic growth, an assured energy supply, and environmental protection are compatible goals. Although some technologies exploiting renewable energy sources (RES) have reached a certain maturity, there are numerous hurdles impeding their market penetration. It is fundamental to kick-start the launch of RES in order to accelerate and increase their market share. This strategy would favour the creation of economies of scale and consequently reduce costs.

Currently, the intense attention directed towards the environment has prioritised those RES that would have a minimal impact not only on the environment, but also on health and the quality of life. Therefore, this growing awareness of environmental issues has partially modified the traditional decision-making structure in the energy field. Indeed, the need to incorporate strictly qualitative considerations into energy planning has resulted in the adoption of multicriteria decision models.

Decision support systems based on multicriteria algorithms do not replace decision makers, rather they assist them in all the phases of the decision-making process by supplying useful information to reach decisions that are transparent with a clearly documented trail.

Broadly speaking, the decision is generated by a dynamic and interactive process involving the various players. Nevertheless, the leading role in the decision-making process is generally assigned to the decision maker who evaluates the various alternatives and ranks them.

In the decision-making process, decision makers often make great efforts to find the optimal solution. The activity linked to the search for a ‘best compromise’ solution requires a suitable assessment method and the various multicriteria methods available seem best suited to such a purpose. Buchanan et al. (1998), Henig and Buchanan (1996) have argued that good decisions will typically come from a good decision process and suggest that, where possible, the subjective and objective parts of the decision process should be separated. A decision problem can be conceived as comprising two components: a set of objectively defined alternatives and a set of subjectively defined criteria. The relationship between the alternatives and the criteria is described using attributes which describe, as objectively as possible, the features of the alternatives that are relevant to the decision problem. Each criterion attempts to reflect a decision maker’s preference with respect to a certain feature of the decision problem. These preferences, being specific to a decision maker, are subjective.

In many circumstances the decision is affected by uncertainty; thus the decision maker is not able to produce all the information necessary to make a strictly rational choice. In such circumstances it is said that the decision maker works under conditions of bounded rationality and the outcome of the decision will therefore depend on circumstances of which knowledge is imperfect (Simon 1957). In the majority of cases the problem of uncertainty in the evaluation process emerges when the assessor does not have a reasonably clear idea of what the consequences and effects of the decision taken will be. The comparison of the preferability of the various options is based on the probability of random or unknown circumstances occurring.

A first source of uncertainty comes from the variability of the data, due to the non-deterministic nature of social and natural phenomena. Another type of uncertainty is the imprecision that appears when observing or measuring the values of a variable, due to both the measuring instrument and the observer undertaking this task. Finally, vagueness results when language is used, whether professional or not, to describe the observation or to measure the result of an experiment. This happens particularly when it is necessary to work with experts' opinions which are translated into linguistic expressions.

The main objective of this study is to propose and to test the validity and effectiveness of a fuzzy multicriteria method called F-PROMETHEE to help the decision-making process to compare a set of solar energy technologies using only linguistic variables (e.g., "very low", "low", "rather low", "medium", "rather high", "high", "very high"). This chapter is organised as follows: Sect. 1.2 reviews the literature, Sect. 1.3 describes the main principles of fuzzy linguistic variables and the fuzzy PROMETHEE method, finally Sect. 1.4 is dedicated to the assessment of sustainable solar energy technologies using the proposed approach.

1.2 Linguistic Terms in Decision Making: Literature Review

The use of fuzzy set theory has yielded very good results for modelling qualitative information. Fuzziness measures to what extent something is found or to what degree a condition holds. The introduction of fuzzy logic therefore modifies considerably all the underlying principles of traditional logic. A non-dichotomic and approximate approach and the use of linguistic variables and rules in place of traditional mathematical models are the features of fuzzy systems that bring them closer to the way the human mind works. They are propounded mainly as a means by which to attempt a quantitative description of natural language.

Fuzzy logic resembles an approach that represents human thinking using empirical rules (sometimes approximate) derived from common sense or from experience, but hard to pin down in analytical terms. Fuzzy set theory was introduced by Lofti Zadeh 33 years ago with the publication of a paper that still now constitutes a milestone (Zadeh 1965). It is unlikely that Zadeh could ever have imagined what an impact this theory was to make on so many and so disparate fields, from control to modelling to the programming of calculators and decision support systems. Today, many control systems work using this logic and the number of applications in the field of decision-making systems is greatly increasing. Traditional mathematics is well-suited to modelling and finding solutions to crisp problems or problems in which vague parameters are stochastic. Vagueness includes phenomena that are inherently imprecise (Zadeh 1965; Bellman and Zadeh 1970). In many real situations it is more useful to model linguistic information using fuzzy set theory (Zadeh 1975a, b, c). As suggested by Martinez et al. (2010) different approaches and computational techniques have been proposed to deal with linguistic information. As regards linguistic computational models based on membership functions we can cite: Anagnostopoulos et al. (2008), Chang and Yeh (2002), Chen and Chen (2003), Degani and Bortolan (1988), Chen and Klein (1997), Chen and Tzeng (2004), Chiou et al. (2005), Martin and Klir (2006). Some very interesting papers on the computational model that uses type-2 fuzzy sets to model linguistic terms are the following: Mendel (2002), Turksen (2002), Dongrui and Mendel (2007). Linguistic symbolic computational models can be found in: Yager (1981a), Delgado et al. (1993), Xu (2004), Yager (1993). Finally, about the 2-tuple linguistic computational model the most interesting papers are: Herrera and Martìnez (2000, 2001), Wang and Hao (2006), Xu (2004), Martìnez (2007), Martìnez et al. (2006), Martìnez and Herrera (2012).

In recent years, many papers have been developed using linguistic terms for expressing ratings and weight importance within the energy assessment procedure. One important study that has contributed substantially to the advancement of knowledge on this topic is Doukas et al. (2009), which presents an approach to assess the sustainability of renewable energy options. The proposed method extends the numerical method TOPSIS in order to process linguistic terms in the form of 2-tuples thereby reducing the loss of information. Other studies are: García-Cascales and Lamata (2007) who proposed a multicriteria decision method where only linguistic information was available; García-Cascales et al. (2012) used the TOPSIS method to aggregate all the information combined with the use of fuzzy sets in order to model the use of linguistic labels in the process and Kahraman et al. (2012) who analysed the interactions between the criteria using Chouquet integral methodology to determine the best energy alternative in Turkey. The authors claim that the Chouquet integral is a suitable method to capture the vagueness and uncertainty of linguistic variables. Chen et al. (2012) presented a two-phase fuzzy decision-making method based on multigranular linguistic assessment seeking to overcome the drawbacks of ELECTRE and TOPSIS in dealing with decision problem. Yan et al. (2011) proposed a linguistic energy planning model with computation based exclusively on words considering the decision maker's preference information. Wu and Xu (2012) investigated multiple attribute decision-making (MADM) problems for evaluating investment in renewable distributed energy generation using triangular fuzzy linguistic information. Al-Yahyai et al. (2012) proposed an approach in which a linguistic quantifier's version of AHP-OWA aggregation function was used to classify lands based on their suitability for wind farm installation. Doukas et al. (2012) conducted a thorough investigation of the most appropriate RES technology which can be gradually introduced in the energy sector of Tajikistan. Adopted linguistic variables have been used in multi-dimensional methodology. Kabak and Ruan (2011) suggested a cumulative belief degree approach based on the belief structure. This is used to aggregate the incomplete expert evaluations that are represented with fuzzy linguistic terms. Kaya and Kahraman (2011) proposed a modified fuzzy TOPSIS methodology for the selection of the best energy technology alternative using linguistic terms. Ruan et al. (2010) developed a fuzzy multicriteria group decision software tool to analyse long-term scenarios for belgian energy policy in terms of linguistic variables. Van Der Heide and Triviño 2009, presented a method which is applied to automatically generate linguistic summaries of real-world time series data provided by a utility company. Abouelnaga et al. (2009) use the multiattribute utility theory (MAUT) to optimise the selection process of energy sources. Linguistic appraisal of all attributes was applied to MAUT. Finally, Doukas and Psarras (2009) presented a multiple criteria decision support model for appraising RES options using linguistic variables.

1.3 Use of Linguistic Variables Within Fuzzy PROMETHEE

1.3.1 Fuzzy Sets and Uncertainty: Basic Elements

Traditional mathematics is well-suited to modelling and finding solutions to crisp problems or problems in which vague parameters are stochastic. Vagueness includes phenomena that are inherently imprecise (Zimmermann 1983; Munda et al. 1994). The result of any decision-making model depends basically on the availability of information and, since the set of input data can take different forms, the assessment process should give due consideration to this potential lack of uniformity.

Generally the information used in decision-making models should be precise, certain, exhaustive and unequivocal. This is not possible in real life and often one is obliged to use data that do not possess these characteristics (Munda et al. 1994), particularly when dealing with problems concerning energy and the environment.

In many real-life situations the judgements formulated by a decision maker are often characterised by vagueness. In such cases the level of preference cannot be adequately defined by numerical figures. It is difficult for conventional quantification to express realistically situations that are complex or hard to define. The linguistic variable is extremely useful in such cases, namely to deal with situations that are not well-defined but need to be expressed quantitatively. Vagueness includes phenomena which are intrinsically vague such as “good labour relations”, “acceptable profits” and “high visual amenity”. For example “environmental impact” is a linguistic variable which can be evaluated as: very low, low, medium, high, very high, etc. Clearly, traditional mathematics is not adequate as a tool for modelling these kinds of phenomena, whereas the linguistic variable is useful in dealing with such situations (Zimmermann 1983). The phenomena are represented in words or sentences where each linguistic variable can be modelled by a fuzzy set (fuzzy-numbers). Linguistic terms are intuitively easier to use when decision makers wish to express the subjectivity and imprecision of their assessment. It is for this reason that fuzzy sets are becoming a popular approach to use in assessment procedures. The linguistic approach considers the variables which impinge on the problem being assessed by means of linguistic terms instead of numerical figures. Therefore, a term set is needed that defines the granularity of the uncertainty, which represents the level of distinction among different quantifications of uncertainty (Herrera et al. 2000).

Fuzzy sets, as devised by Zadeh, are based therefore on the simple notion of introducing the degree to which an item belongs to a set. Let us assume that symbol X means the universe of discourse, in classical set theory, given a subset A of X each element $x \in X$ satisfies the condition: either x belongs to A or does not belong to A. A function for belonging can be defined $\mu_A(x)$ which establishes the relationship between the elements x and the set A, and can have only two values, zero or one. The subset A is represented by a function $\mu_A : X \to \{0, 1\}$:

$$\mu_A(x) = \left\{ \begin{matrix} 1 & \text{if} & x \in A \\ 0 & \text{if} & x \notin A \end{matrix} \right\} \tag{1.1}$$

Fuzzy set theory extends classical theory by introducing the concept of the degree of *membership*. The theory acknowledges that an element can partially belong to a set, on the basis of a *membership function* as a real value in the interval [0,1]. For example, the statement “the air is fresh” creates partial conditions: the air can be 20 % fresh and at the same time 80 % not fresh (Kosko and Isaka 1993). A *fuzzy set* is a set of items in which there are no clear-cut boundaries between the items that belong or do not belong to it. A *fuzzy* set can be defined as a set of ordered pairs:

$$A = \{x, \mu_A(x)\}, \quad \forall x \in U \tag{1.2}$$

The map $\mu_A : X \to A$ defines the space M called the membership space, which is imagined as a closed interval [0, 1], where 0 and 1 represent, respectively, the lowest and greatest degree of membership. Thus, for $0 < \mu_A(x) < 1$, x belongs to A only up to a certain degree. The underlying assumption is that a *fuzzy set,* despite the vagueness of its boundaries, can be precisely defined by associating a number of between 0 and 1 to each element $x \in A$.

1.3.2 Fuzzy Numbers

Fuzzy numbers are useful tools when working with imprecise numerical figures, such as "about 8", "nearly 10" and "between 5 and 10". The use of fuzzy set theory allows them to be represented correctly, as fuzzy subsets of the set of real numbers. A fuzzy number is a convex and normalised fuzzy set defined on the set $\Re$ of real numbers. A triangular fuzzy number (TFN) is generally written as $A = (a, m, b)$. The concept of a triangular number can be demonstrated by an example; if asked to hypothesise what the CO_2 per kWh will be, we can reply "approximately 150 g/kWh". When an uncertain value has to be defined, a can be considered the smallest possible value, b as the largest possible value and m as the most plausible value. A TFN is defined via a triplet of the type $A = (a, m, b)$ where a and b are the lower and higher extremes of the figure while m is the element to which the highest degree of membership attaches (Fig. 1.1).

$$\mu A(x) = \begin{cases} \frac{x-a}{m-a}, & a \le x \le m \\ \frac{b-x}{b-m}, & m \le x \le b \\ 0, & \text{otherwise} \end{cases} \tag{1.3}$$

1.3.3 The PROMETHEE Method and Fuzzy Approach

The preference ranking organization method of enrichment evaluation (PROMETHEE) method was devised by Brans and Vincke (1985), Brans and Mareschal (1994, 1998), Brans et al. (1986). This technique is based on ranking and is well-suited to problems in which there are a finite number of actions to be assessed on the basis of a range of conflicting criteria.

Once the set of criteria and the alternatives have been selected then the payoff matrix is built. This matrix tabulates, for each criterion–alternative pair, the

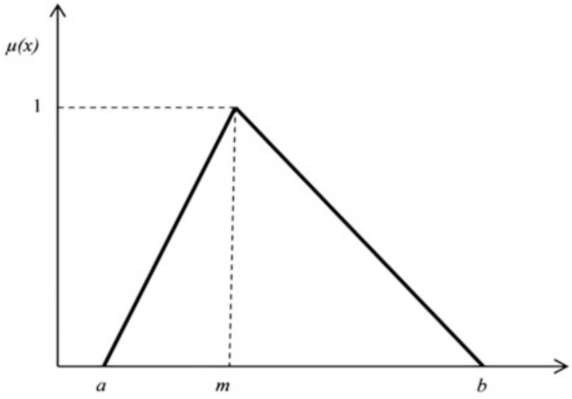

Fig. 1.1 A triangular fuzzy number

quantitative and qualitative measures of the effect produced by that alternative with respect to that criterion. The matrix may contain data measured on a cardinal or an ordinal scale. Each alternative $A_i = \{a_{i,1}, \ldots a_{i,j}, \ldots, a_{i,m}\}$ is composed of a group of evaluations a_{ij} representing the evaluation given to the alternative i with respect to the criteria j. For each criterion the decision maker can choose from a set of six different types of preference functions to model the decision maker's preferences. A preference function $P_k(d)$ is associated with each criterion and represents the difference between the value of the two alternatives, thus it can be expressed as follows (Brans and Mareschal 1998):

$$P_k(a_i, a_m) = P_k[d(a_i, a_m)] \tag{1.4}$$

$$P_k(c_k(a_i) - c_k(a_m)) = P_k(d) \in [0, 1] \tag{1.5}$$

The degree of preference of an alternative a_i in comparison to a_m is expressed by a number between 0 and 1 (from 0 indicating no preference or indifference up to 1 for an outright preference). Once the decision maker has described the preference function P_k ($k = 1, 2, 3, \ldots n$ represent the criteria) then a vector containing the weights of each criterion must be defined as $W^T = [w_1, \ldots, w_k]$. The weights π represent the relative importance of the criteria used for the assessment. In addition to weighting, the method involves setting thresholds that delineate the decision maker's preferences for each criterion and the critical thresholds are thus: the indifference threshold q_i and the preference threshold p_i (a more exhaustive description of the procedure can be found in the literature). The degrees of preference are used to estimate the index of preference Π calculated for each pair of actions a_i and a_m as the weighted average of preferences calculated for each criterion. The index Π is therefore defined as follows (Brans et al 1986):

$$\prod(a_i, a_m) = \frac{\sum_{k=1}^{K} w_k \cdot P_k(c_k(a_i) - c_k(a_m))}{\sum_{k=1}^{K} W_k} \tag{1.6}$$

The preference index Π (a_i, a_m) represents the strength of the decision maker's preference for action a_i over action a_m considering all criteria simultaneously and Π (a_m, a_i) how much a_m is preferred above a_i. Its value falls between 0 and 1.

Finally, we can consider how each alternative $a_i \in A$ is evaluated against $(n-1)$ another in A and thereby define the two following outranking flows (Brans et al. 1986; Brans and Mareschal 1994):

$$\Phi^+(a_i) = \frac{1}{n-1} \cdot \sum_{x \in A} \Pi(a_i, a_m) \tag{1.7}$$

This indicates a preference for action a_i above all others and shows how 'good' action a_i is (positive outranking flow).

$$\Phi^{-}(a_i) = \frac{1}{n-1} \cdot \sum_{x \in A} \Pi(a_m, a_i) \tag{1.8}$$

This indicates a preference for all the other actions compared with a_i and shows how weak action a_i is (negative outranking flow). According to PROMETHEE I a_i is superior to a_m if the leaving flow of a_i is greater than the leaving flow of a_m and the entering flow of a_i is smaller than the entering flow of a_m. (for further explanation see the method). PROMETHEE I method can provide a partial preorder of the alternatives, whereas the PROMETHEE II method can give the complete preorder by using a net flow, although it loses much of the information of preference relations. Under the PROMETHEE I method some actions remain incomparable, in this case a complete preorder is required that eliminates any incomparable items, then PROMETHEE II can give a complete ranking as follows (Brans and Mareschal 1994):

$$\Phi^{\text{net}}(a_i) = \Phi^{+}(a_i) - \Phi^{-}(a_i) \tag{1.9}$$

The net flow is the difference between the outflow and the inflow.

The fuzzy PROMETHEE method is preferable because crisp numbers are not adequate to express accurately the qualitative data used for the application analysed.

The first studies in the literature to develop an integration between PROMETHEE and fuzzy numbers were proposed by Le Teno and Mareschal (1998), Geldermann et al. (2000), Goumas and Lygerou (2000). Other interesting applications have been developed in recent years by Bilsel et al. (2006), Tuzkaya et al. (2010), Chou et al. (2007), Li and Li (2009), Giannopoulos and Founti (2010), Oberschmidt et al. (2010), Yuen and Ting (2012), Liu and Guan (2009), Halouani et al. (2009), Lee and To (2010), Yang et al. (2012), Shirinfar and Haleh (2011), Zhang et al. (2009), Moreira et al. (2009), Chen et al. (2011a, b).

In this chapter the performances of qualitative criteria are considered as linguistic variables and translated into fuzzy numbers. The semantics of the elements of the set of linguistic terms is provided by fuzzy numbers defined in the interval (0,1) and by the membership functions. We have used linear triangular membership functions as being fit to capture the vagueness of the linguistic assessments. The linguistic variables can be represented as positive TFNs as shown in Fig. 1.1.

According to Dubois and Prade (1978), the representation of a TFN can be presented in the form $x = (m,a,b)_{LR}$. If the variable x is equivalent to the value m, its membership function is $f(x) = 1$. Where its value is smaller than $(m-a)$ and larger than $(m + b)$, it does not belong to the set and $f(x) = 0$. If its value falls within the interval between $m-a < x<m + \text{b}$, its degree of membership is a number between 0 and 1. The letters L and R are used to refer to the left and right spreads of m. The following F-PROMETHEE equations are based on the representation of a TFN (m, a, b).

When a linear preference function, with preference p and indifference q threshold, is selected (type V), on introducing the fuzzy numbers the evaluation function becomes as follows (Goumas and Lygerou 2000):

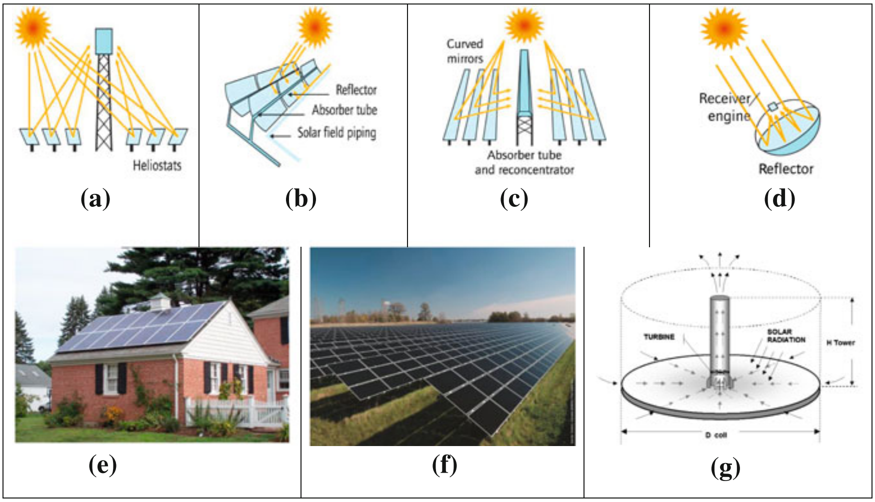

Fig. 1.2 Solar technologies. **a** Solar tower (SPT). *Source* OECD/IEA; **b** Parabolic solar trough (PST). *Source* OECD/IEA; **c** Compact linear Fresnel (CLFR) *Source* OECD/IEA; **d** Dish stirling (DS). *Source* OECD/IEA; **e** Photovoltaic in buildings (PVbuild). *Source* NREL; **f** Photovoltaic centralised (PVcentr). *Source* First solar; **g** Solar chimney (SC). *Source* Schlaich et al. 2005

$$P_k(a_i, a_m) = \left\{ \begin{array}{ll} 0 & \text{if } (n-c) \le q \\ \frac{(n,c,d)-q}{p-q} & \text{if } \; q \le n-c \; \text{ and } \; n+d \le p \\ 1 & \text{if } \; n+d \ge p \end{array} \right\} \qquad (1.10)$$

The calculations for the evaluation of alternatives described in the methodological procedure herein were carried out using fuzzy numbers (e.g., fuzzy difference $\tilde{d}$ is obtained using fuzzy subtraction), then the fuzzy algebraic operations developed by Dubois and Prade (1978) were used.

The decision parameters p and q, are considered as crisp numbers, due to the inherent risk of excessive fuzziness or approximation and the limited benefit of possible fuzzy modelling (Giannopoulos and Founti 2010; Dubois and Prade 1978). As in the case of criterion parameters, it was decided here to introduce the weighting factors also as crisp values.

Once calculations are complete, the fuzzy numbers obtained have to be compared. In the literature there are several techniques to compare two fuzzy numbers but defuzzification is a process commonly used to convert fuzzy numbers into appropriate crisp values. As suggested by Giannopoulos and Founti in the paper by Deng et al. (2000) the most popular defuzzification methods are reported here. Geldermann et al. (2000) applied one of the most popular methods for her analysis centre of area (COA) while Goumas and Lygerou (2000) and Le Téno and Marechal (1998) used the Yager index (Yager 1981b), which is the equivalent of the COA for triangular numbers (Giannopoulos and Founti 2010). The Yager index is the most transparent and "easy to use" defuzzification method. It calculates the weighted average of the fuzzy number that corresponds to the centre of the TFNs as:

$$F(m, a, b) = (3m - a + b)/3 \tag{1.11}$$

Thus, fuzzy numbers with a higher Yager index will be greater than the ones having a smaller Yager index. After converting the TFN (m, a, b) into a magnitude, the steps of the F-PROMETHEE become the same as those of the original PROMETHEE method.

1.4 Linguistic Terms for the Assessment of Sustainable Solar Energy Technologies

1.4.1 The Proposed Solar Energy Options

The empiric case presented here proposes a comparative evaluation between a series of alternative energy technologies using the above-described approach. The options are the following (see also Fig. 1.2) (Cavallaro 2009a; 2010)

1.4.1.1 Solar Power Tower

Solar power tower technology consists of a set of mirrors, called *heliostats*, which track the movement of the sun via electronically controlled electromechanical actuators, and which therefore reflect solar energy onto a receiver (heat exchanger) set at the top of a tower placed at the centre of the array of mirrors (see Fig. 1.2a). A heat transfer fluid circulates in the receiver (water, air or a mix of molten liquid sodium salts) which absorbs the heat captured and then sends it to a steam generator. The high temperature and high pressure steam produced feeds a turbine following a classic thermodynamic cycle. The system uses hundreds of heliostats and is suited to large-scale applications.

In Spain, the 11 MW PS10 solar power tower and 20 MW PS20 solar power tower are currently in operation. While the American Bright Source Energy Inc., which rose from the ashes of the Lux (the industry leader that built the well-known SEGS projects), has initiated the construction of various solar power tower projects in USA.

1.4.1.2 Parabolic Solar Trough

A parabolic trough power plant with heat storage is made up of three basic parts (Price and Kearney 1999; Herrmann et al. 2004; Reilly and Kolb 2001): (1) the solar field fitted with a circuit for heat transfer; (2) a system for storing heat; (3) a power block comprising a turbine, a generator and a cooling system (see Fig. 1.2b). This technology uses a curved mirror system to concentrate solar radiation onto a high thermal performance absorbent pipe laid along the focal line of the concentrators inside of which flows a fluid for heat transfer (OECD/IEA 2010). In such an installation, the solar field has a modular structure composed of linear parabolic collectors linked in series laid out in parallel rows up to several hundred metres in length. The fluid that carries the heat absorbed from the sun is generally a mineral oil and is pumped through receiver pipes to a power plant. Here, a heat exchanger converts the heat into steam which is then sent to a turbine to produce electricity. Parabolic troughs may also be used for desalination of seawater (Kalogirou 1998).

These devices first appeared in 1984 when the LUZ Company installed a 14 MW Solar energy power plant (SEGS I) in southern California. Currently in Europe, in the Marquesado valley in the province of Granada (Andalusia), Spain, there are two working power plants called AndaSol -1 and AndaSol -2, each station having a total power capacity of 49.9 MWe.

1.4.1.3 Compact Linear Fresnel Reflector systems

Linear Fresnel reflector concentrating systems are conceptually similar to linear parabolic trough systems with the advantage that they occupy less land and installation costs that are markedly lower due to less materials being needed to build them.

Linear Fresnel reflector systems are made up of a field of linear heliostats that reflect and concentrate solar radiation onto a receiver tube horizontally fixed above the mirrors (see Fig. 1.2c) (Xie et al. 2011). The heliostats are able to turn longitudinally in order to track the movement of the sun and constantly maintain the solar radiation reflected onto a receiver tube made of steel protected by glass (Xie et al. 2011). The systems built so far generate steam on-site reaching temperatures up to 270 °C and 40 bar, although prototypes have been developed producing steam of up to 400 °C.

Despite its great advantages, the average yield is lower than linear parabolic troughs due to the less efficient functioning of not only the collectors (temperature, shade, receiver tube not cavity insulated) but also that of the thermodynamic cycle. The lower costs nevertheless offset its lower efficiency. Several prototypes are still under trial and evaluation.

1.4.1.4 Dish Stirling

The dish concentrator reflects solar rays onto a concave receiver positioned at the focal point of the concentrator. Solar radiation is absorbed by the receiver which heats up a gas (helium or hydrogen) in the Stirling engine to a temperature of around 650 °C (Marketaki and Gekas 1999). The heat from the sun is converted into mechanical energy by the Stirling engine and this mechanical energy is subsequently converted into electricity by a generator directly connected to the engine. Optimal functioning requires that the concentrator is perfectly orientated towards the sun, therefore it is mounted on a two-axis tracking system that allows the concentrator to be aligned vertically and horizontally (see Fig. 1.2d).

In these systems the conversion of solar energy into electricity is particularly efficient with a net average annual yield rate ranging between 18 and 23 %, higher than any other solar energy system, and a record rate of 29 % has been attained for a brief time (Pitz-Paal et al. 2003). The most important feature of these systems is their modularity, allowing installations of any size or power to be built. The beauty of this technology is that its size can be adjusted to fit user needs: from a few kW, for use in remote sites or on islands, up to hundreds of kW for "distributed generation" uses connected to the electricity grid. Unfortunately, the high unit costs reflect the fact that these systems have not reached a high level of technological maturity.

1.4.1.5 Solar Chimney

The thermal solar chimney is a recently developed technology patented by "Schlaich Bergermann und Partner" which uses a large cylindrical tower that is able to exploit energy from the sun to produce electricity. The system comprises a *glass collector*, a *chimney* and *wind turbines*. It works on the basis of the following principle: a large mass of cold air enters freely underneath a large glass roof (glass collector) that is open around its periphery (see Fig. 1.2g) (Schlaich et al. 2005; Von Backstrom and Gannon 2004). Solar radiation heats this air until it reaches a temperature in excess of 35 °C, thus creating an artificial greenhouse.

The hot air tends naturally to move towards the centre of the collector where a cylindrical tower made of cement is located. This mass of hot air rises (hot air being less dense and thus lighter than cold) up the chimney tower, thereby supplying a natural convective force (Schlaich et al. 2005; Von Backstrom and Gannon 2004). This flow of air, which rises at a speed of 14–16 m/s, is captured by a set of wind turbines located at the chimney base which convert kinetic energy from the wind induced by solar heat into mechanical energy and then into electricity.

1.4.1.6 Photovoltaic

Photovoltaic (PV) stands out from other RES due to its simplicity and the modularity of its energy conversion system. In addition, it has virtually no environmental impact, emitting no pollution, heat or noise, and its lack of any mechanical moving parts subject to wear and tear makes it extremely easy to maintain. PV technology involves the direct conversion of solar radiation into electrical power and the entire process takes place within the PV device itself. The basic component of a PV plant is the PV cell.

Solar cells constitute an intermediate product of the PV industry and are often assembled together into a single unit called a PV module. This protects the solar cells within a strong and easy-to-handle casing.

To date, the most highly developed technology for the construction of these devices is one based on mono and polycrystalline silicon. An alternative production line is currently under development to produce thin-film cells, i.e. where the photosensitive material is reduced to a thickness of around one thousandth of a millimetre. The process of building thin-film modules is much simpler than that for crystalline silicon modules and requires far less material and energy. The cells capable of absorbing solar radiation that can be built are over 100 times smaller than those needed for crystalline silicon. There are currently a variety of processes and materials available to make thin-film cells but their relative costs and performance differ. The growth in the PV market certainly represents one of the long-term strategic objectives for future worldwide energy policy and poses a research challenge in the field of RES. In our analysis two different PV options will be considered: the first (PV_{centr}) refers to the installation of a centralised large PV power plant the other (PV_{build}) relates to small PV power plants installed on the roof-tops of buildings (see Fig. 1.2e, f).

1.4.2 Criteria Selected

The criteria are the tools that enable alternatives to be compared from a specific viewpoint. Undoubtedly, selecting criteria is the most delicate part in formulating the problem before the decision maker, and thus it requires the utmost care and attention. The number of criteria is heavily dependent on the availability of information and data. Here, 10 criteria were selected; five of these technical–economic and five socio-environmental (Cavallaro 2008, 2009b).

Economic and technical criteria.

These criteria refer to the costs that must be borne in order to realise the various projects included in each strategy and to guarantee the supply of energy. These factors are of special interest to State authorities.

- C_1: *Capital Investment costs.* This includes all costs relating to the purchase of mechanical equipment, technological installations, construction of roads and connections to the national grid, engineering services, drilling and other incidental construction work;
- C_2: *Financial risk.* This identifies the degree of financial risk attached to the technological options proposed;
- C_3: *Efficiency rate.* This is referred to the conversion efficiency of Solar energy into electricity;
- C_4: *State of knowledge of innovative technology.* Represents the degree of reliability of the technology adopted, as well as how widespread the technology is at both national and european levels;

- C_5: *Outlook for improvement*. This appraises the prospects of future improvements in the technologies analysed.

Environmental and social criteria

These criteria refer to protection of the environment and to the principle of *sustainability*:

- C_6: *Water usage*. This criterion refers to the water required for cooling and condensing process (as in any thermal power plant) and for the cleaning of the heliostats;
- C_7: *GHG/kWh*. This refers to the level of CO_2 emissions produced by the entire life cycle of the technologies (extraction and provision of raw materials, manufacture, transportation, assembly, generation and waste disposal) linked to 1 kWh produced;
- C_8: *Effect on the environment*. This criterion takes other impacts into account: the visual nuisance that may be created by the development of a project in a specific area or any noise disturbance and odours arising from the productive activity of plants, the potential risk to eco-systems caused by the production operations of the various projects included in the strategies;
- C_9: *Land use*. This criterion quantifies the area occupied by the plants and not available for possible alternative uses (i.e. agriculture or other commercial activities);
- C_{10}: *Social acceptability*. Expresses the degree of acceptance by the local population regarding the hypothetical realisation of the projects under review.

1.4.3 Computation Procedure and Results

Now that the basic principles of this methodology have been outlined, we can now proceed to apply it using the following procedure:

Step 1. First of all using the linguistic variables and a modified semantic scale of Bilsel et al. 2006 (see Table1.1 and Fig. 1.3), the decision maker is asked to compare alternatives considering each criterion in order to assess the performance of the technologies with regard to the set of criteria selected.

Table 1.1 Semantic scale

Linguistic terms	
Very low (VL)	$(0, 0, 0.15)_{LR}$
Low (L)	$(0.15, 0.15, 0.15)_{LR}$
Rather low (RL)	$(0.3, 0.15, 0.2)_{LR}$
Medium (M)	$(0.5, 0.2, 015)_{LR}$
Rather high (RH)	$(0.65, 0.15, 0.15)_{LR}$
High (H)	$(0.8, 0.15, 0.2)_{LR}$
Very high (VH)	$(1, 0.20, 0)_{LR}$

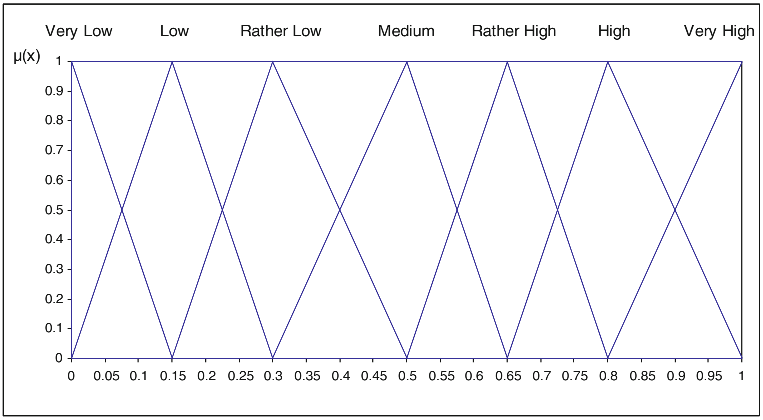

Fig. 1.3 Linguistic scale for performance assessment (Bilsel et al. 2006)

Table 1.2 The evaluation matrix (linguistic labels)

Technologies	Criteria									
	C_1 Min	C_2 Min	C_3 Max	C_4 Max	C_5 Max	C_6 Min	C_7 Min	C_8 Min	C_9 Min	C_{10} Max
Solar power tower (SPT)	H	M	H	RH	H	RH	L	M	RH	RL
Parabolic solar trough (PST)	H	RL	RH	RH	RH	H	L	M	H	RL
Compact linear Fresnel collector (CLFR)	RH	RH	M	M	VH	H	VL	RL	RL	M
Dish stirling (DS)	VH	VH	RH	L	L	RL	L	RL	RL	M
Photovoltaic on roof-tops of buildings (PV_{build})	RH	M	M	M	M	VL	M	L	L	RH
Photovoltaic centralised (PV_{centr})	M	L	M	RH	H	VL	M	M	H	M
Solar chimney (SC)	H	VH	RL	RL	M	RL	L	RH	VH	L

Step 2. In this phase we build the evaluation matrix (see Tables 1.2) which contains the options under consideration and the fuzzy values of the criteria selected. Normally, this matrix also contains the weights assigned to the various criteria, that is, the importance of each criterion in the evaluation process. How to attribute weights to the criteria remains one of the greatest weaknesses of this methodology. In fact, an arbitrary and subjective assignment of weights can greatly affect the outcome of the analysis. Nevertheless, some techniques do exist that allow weights to be measured more objectively, such as Shannon's based on entropy. In our case, after reflecting long and hard on this issue, we decided not to assign any weights to the parameters chosen. The generalised criterion with

Table 1.3 The fuzzy evaluation matrix (criteria 1–5)

Technologies	Criteria				
	C_1	C_2	C_3	C_4	C_5
(SPT)	(0.80, 0.15, 0.20)	(0.50, 0.20, 0.15)	(0.80, 0.15, 0.20)	(0.65, 0.15, 0.15)	(0.80, 0.15, 0.20)
(PST)	(0.80, 0.15, 0.20)	(0.30, 0.15, 0.20)	(0.65, 0.15, 0.15)	(0.65, 0.15, 0.15)	(0.65, 0.15, 0.15)
(CLFR)	(0.65, 0.15, 0.15)	(0.65, 0.15, 0.15)	(0.50, 0.20, 0.15)	(0.50, 0.20, 0.15)	(1.00, 0.20, 0.00)
(DS)	(1.00, 0.20, 0.00)	(1.00, 0.20, 0.00)	(0.65, 0.15, 0.15)	(0.15, 0.15, 0.15)	(0.15, 0.15, 0.15)
(PV_{build})	(0.65, 0.15, 0.15)	(0.50, 0.20, 0.15)	(0.50, 0.20, 0.15)	(0.50, 0.20, 0.15)	(0.50, 0.20, 0.15)
(PV_{centr})	(0.50, 0.20, 0.15)	(0.15, 0.15, 0.15)	(0.50, 0.20, 0.15)	(0.65, 0.15, 0.15)	(0.80, 0.15, 0.20)
(SC)	(1.00, 0.20, 0.00)	(1.00, 0.20, 0.00)	(0.30, 0.15, 0.20)	(0.30, 0.15, 0.15)	(0.50, 0.20, 0.15)

linear preference function was applied for all criteria. The indifference threshold q was considered equal to zero while the preference threshold p was set at 0.65. For p values lower than 0.60, the use of the fuzzy data would not be very useful for the assessment procedure (Tables 1.3, 1.4).

Step 3. Determination of deviations based on pairwise comparisons using Eqs. (1.4 and 1.5) and the basic operations with fuzzy numbers. The magnitude of (m, a, b) is then computed using the Yager index (1.11).

Step 4. Defining for all the alternatives a and b the preference index (0.65), representing the intensity of the decision maker's preference for alternative a_i over a_m considering all criteria.

Step 5. As for the PROMETHEE method, an overall global preference index is calculated using (1.6).

Step 6. Lastly, using (1.7) and (1.8) we obtain the leaving, the entering and net flows, which are also valid for the F-PROMETHEE (Tuzkaya et al. 2010). In relation to the hypotheses advanced, the parameters selected and the data used in the calculation, the complete ranking is obtained.

Having carried out all the calculations and applied the procedures of the methodology chosen, the final ranking of the alternatives emerging is shown in Fig. 1.4. Table 1.5 reports the scores for the leaving, entering, net-flow and ranking of technologies. The top-ranked option, i.e. the best performers, are options PV_{cent} and PV_{build}. The best options are therefore both PV systems probably due to economic criteria, not because PV costs less than other options in an absolute sense, but because the framework of incentives for PV technology is more stable and thus makes less impact in economic terms. Environmental criteria also favour PV as water consumption is virtually nil and other impacts are almost negligible.

Table 1.4 The fuzzy evaluation matrix (criteria 6–10)

Technologies	Criteria				
	C_6	C_7	C_8	C_9	C_{10}
(SPT)	(0.65, 0.15, 0.15)	(0.15, 0.15, 0.15)	(0.50, 0.20, 0.15)	(0.65, 0.15, 0.15)	(0.30, 0.15, 0.20)
(PST)	(0.80, 0.15, 0.20)	(0.15, 0.15, 0.15)	(0.50, 0.20, 0.15)	(0.80, 0.15, 0.20)	(0.30, 0.15, 0.20)
(CLFR)	(0.80, 0.15, 0.20)	(0.00, 0.00, 0.15)	(0.30, 0.15, 0.20)	(0.30, 0.15, 0.20)	(0.50, 0.20, 0.15)
(DS)	(0.30, 0.15, 0.20)	(0.15, 0.15, 0.15)	(0.30, 0.15, 0.20)	(0.30, 0.15, 0.20)	(0.50, 0.20, 0.15)
($\mathrm{PV}_{\mathrm{centr}}$)	(0.00, 0.00, 0.15)	(0.50, 0.20, 0.15)	(0.15, 0.15, 0.15)	(0.15, 0.15, 0.15)	(0.65, 0.15, 0.15)
($\mathrm{PV}_{\mathrm{build}}$)	(0.00, 0.00, 0.15)	(0.50, 0.20, 0.15)	(0.50, 0.20, 0.15)	(0.80, 0.15, 0.20)	(0.50, 0.20, 0.15)
(SC)	(0.30, 0.15, 0.20)	(0.15, 0.15, 0.15)	(0.65, 0.15, 0.15)	(1.00, 0.20, 0.00)	(0.15, 0.15, 0.15)

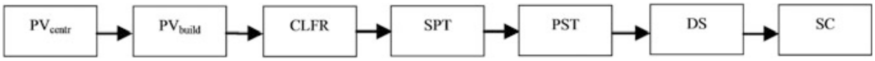

Fig. 1.4 Complete ranking (PROMETHEE II)

Table 1.5 Leaving, entering, net flow and rank of technologies

Solar technologies	Φ^{+}	Φ^{-}	Φ^{net}	Rank
(SPT)	1.22	1.03	0.188	4
(PST)	0.78	1.06	−0.282	5
(CLFR)	1.21	0.78	0.427	3
(DS)	1.00	1.33	−0.333	6
($\mathrm{PV}_{\mathrm{build}}$)	1.44	0.56	0.889	2
($\mathrm{PV}_{\mathrm{centr}}$)	1.78	0.56	1.051	1
(SC)	0.33	2.27	−1.940	7

Moreover, $\mathrm{PV}_{\mathrm{build}}$ occupies virtually no ground space as it is incorporated into preexisting buildings. The next ranking technology, i.e. CLFR, is well-placed due to its low cost and lower environment impact compared to other CSP technologies. The other technologies SPT, PST and DS are in fact penalised by their cost and their high water consumption used in the cooling systems and to wash the reflectors. The environmental impact linked to noise and visual intrusiveness is modest while they occupy a fairly large area of land due to the numerous parabolic reflectors and the heliostats. The lowest ranked option SC arises from its high capital cost, high financial risk and extensive land area occupied. Furthermore, this technology is not forecast to penetrate the market successfully in the short term.

1.5 Conclusion

Assessment procedures and energy planning may appear complex because of the number and diversity of the items to evaluate, the uncertainty of data and conflicts between interested parties. The decision-making process of an energy project is the closing link in the procedural chain of analysing and handling different types of information: environmental, technical, economic and social.

The judgements formulated by a decision maker are often characterised by vagueness, hence the level of preference cannot be adequately defined by numerical figures. The linguistic variable is extremely useful in such cases, namely to deal with situations that are not well-defined that need to be expressed quantitatively. Fuzzy sets are suitable for uncertain approximate reasoning and allow decision making with estimated values where information is incomplete or uncertain.

In order to deal with linguistic information in energy technologies assessment the F-PROMETHEE method is proposed here. The rating of each alternative is pronounced by decision makers in linguistic terms. These are represented by linear triangular membership functions so that they are fit to capture the vagueness of the linguistic assessments.

As this work demonstrates, the F-PROMETHEE method is able to provide a technical–scientific decision-making tool that can be efficiently integrated with linguistic information and can give valuable assistance to a decision maker for energy technologies assessment.

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Chapter 2
Photovoltaic Plants Selection on an Insular Grid Using Multicriteria Outranking Tools: Application in Corsica Island (France)

Pascal Oberti, Marc Muselli and Pierrick Haurant

Abstract Sustainable energy systems involve a multiplicity of stakes more or less conflicting. Multiple criteria decision analysis (MCDA) offers a broad methodological framework in which the ELECTRE-based outranking approach is suitable for searching good compromise solutions. Particularly, the RUBIS methodology offers new tools that we have used successfully for photovoltaic (PV) plants selection aid in Corsica island, a real case study from a research agreement between the University of Corsica and the Agriculture Chamber of the Haute-Corse department. This chapter will focus on the following points: outranking approaches and the choice problematic in MCDA, the RUBIS method and the RUBIS D3 web server, the insular power grid of Corsica and the studied case, the main results and their robustness, a comparison with the ELECTRE IS method.

2.1 Introduction

Sustainable energy systems are presented as alternative solutions to fossil fuels (Dinçer and Zamfirescu 2012), to provide better efficiency, better cost-effectiveness, better resources use, better design and analysis, better energy security, and better environment. This multiplicity of objectives requires scientific evaluation tools, testing the comparison of solutions in order to find good compromise, and multiple criteria decision analysis (MCDA) offers a broad methodological framework (Figueira et al. 2005a, b).

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Renewable and sustainable energy reviews highlight that MCDA methods are part of the assessment and Simulation tools. Notably, about alternative methodologies for analyzing off-grid electricity supply, Bhattacharyya (2012) identifies five main tools based on worksheet, optimization, multicriteria decision making, system-based participatory, and hybrid approaches to take advantage of strengths and weaknesses of these different tools. More particularly, MCDA deals with renewable and sustainable energy planning (Baños et al. 2011; Wang et al. 2009; Løken 2007; Pohekar and Ramachandran 2004). The main MCDA tools are AHP method and the families of outranking methods namely PROMETHEE and ELECTRE.

Numerous case studies with an insular context and renewable energy were processed using MCDA tools. For example, in Crete island (Greece), ELECTRE III method supported the Ranking of alternative strategies for energy supply ranging from high-level renewable energy production to continental interconnection (Georgopoulou et al. 1997). Furthermore, an appropriate mix of energy production means has been analyzed with PROMETHEE I and II methods (Tsoutsos et al. 2009), as in the Greek islands of Karpathos and Kassos with ELECTRE III (Papadopoulos and Karagiannidis 2008). In Sardinia (Italy), this method assisted in ranking the renewable energy technology best adapted (Beccali et al. 2003), and PROMETHEE I and II methods were implemented in Sicily (Cavallaro 2005). Moreover in the Eolian islands (Italy), the size of a wind farm with a photovoltaic plant was determined by combining NAIADE and PROMETHEE methods (Cavallaro and Ciraolo 2005). In Corsica island (France), participative location of a wind farm projects (Oberti and Paoli 2013) was implemented with ELECTRE III method, and photovoltaic plants selection (Haurant et al. 2011) has been computed with ELECTRE IS.

The aim of the research is to deal with a multicriteria choice problem under electrical and geographical constraints: it intends to select the best projects of PV plants among 16, developed by industries on farmlands and submitted to local decision-makers in Corsica island, while preserving the power grid stability (i.e., at most 30 % of intermittent renewable energies can be injected) and without spatial concentration of solar power parks (i.e., to avoid sudden declines in electric production due to climatic or technical factors). In MCDA, this problem refers to the choice problematic (Roy 1985, p. 57): … *to aid the decision maker by the choice of a subset that is as small as possible so that a single action can eventually be chosen. This subset contains best actions (optima) or, perhaps, satisfactory actions (satisficing solutions).*

Technically, the real case study has been solved in three main stages. Over a first phase was collected information to take into account the aforementioned constraints. To avoid spatial concentration of projects were located the points of connection to the power grid, and for each of them was defined the set of PV plants to be connected. Thus, the 16 alternatives were assigned to 4 different sets geographically distant. Also, to preserve the power grid stability was considered an additional power of maximum 46 MWp from the selected candidates. Over a second phase for each set of projects was computed the subset[1] of the best (or satisficing) PV plant. With this aim in view was applied the ELECTRE outranking framework, particularly the suitable ELECTRE IS and RUBIS methodologies (method and software). In this chapter the focus is on the RUBIS D3 web server, a tool used to solve the case. Over a final phase, the stability constraint was checked; the total power of the 4 selected projects should not exceed the above-cited threshold.

The key findings of this study are methodological. They arise from special features of the energy context and of the Sustainable development perspective. First, the installation constraints of intermittent renewable energies on the small power grid, such as in Corsica island (see Sect. 3.1), have taken part upstream (phase one) and downstream (phase three) of the multicriteria aggregation procedure. Thus, the decision problem must be well defined to integrate the MCDA method in the energy context. Second, the complexity of multicriteria evaluation in energy real case studies justifies a well-established methodology. Compensatory logic of the aggregation procedure and the robustness analysis of the results are significant issues for MCDA of sustainable energy systems. The ELECTRE outranking framework provides an operational research toolbox for a relevant selection of one best compromise solution; especially the RUBIS methodology based on the RUBIS method (Bisdorff et al. 2008) implemented in the RUBIS D3 web server to solve a choice problem. This non-compensatory approach, in the tradition of ELECTRE IS method, leads to the same robust selections of PV plant projects, with modern MCDA tools.

To study the subject of this chapter, two sections are developed. First of all, is presented an overview of the outranking approaches. The leading reasons to retain the RUBIS methodology are underlined, and the MCDA used tools are described commented. The second section focuses on the real case study and the results. Five subsections are considered. First, the insular power grid of Corsica is characterized, and second the research context is explained. In a third time the PV plants projects are listed, the family of evaluation criteria is presented and the performance table is presented. In sub-section four are produced the main results of the RUBIS outranking computations. Finally, a discussion concerns the robustness of the choice, a comparison with the ELECTRE IS method, and a possible solution to make explicit and improve the criterion about estimated net production of a PV plant.

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[1] Called kernel within the ELECTRE IS method and hyperkernel within the RUBIS method.

2.2 An Outranking-Based Approach of Multicriteria Selection: the RUBIS Framework

2.2.1 About Outranking Approaches

The overall purpose of outranking approaches is to aid in preference modeling computed on ordered pairs of solutions (called actions, alternatives or not) for the search of compromise, into processes with multiple criteria involving real decision maker(s). State of the art surveys on MCDA (Figueira et al. 2005a, b) have differentiated three classes of outranking approaches.

The first one is the family of ELECTRE methods (i.e., acronym stands for ELimination Et Choix Traduisant la REalité, designating ELimination and Choice Expressing the Reality), based on the pioneering work of Bernard Roy in the mid-1960s. The first method called ELECTRE I (electre one) becomes widely known and applied after its publication in Roy (1968). This tool for choosing the best solution(s) from a given finite set (or **choice problematic**), was devised to overcome the drawbacks of the classical weighted-sum based technique when applied to a concrete multiple criteria real-world problem. Thereafter, the contribution of outranking binary relation to preference modeling was highlighted by Roy (1974).

ELECTRE IS (electre one esse) appeared subsequently (Roy and Skalka 1984) as an extension of the previous method to take into account imperfect data with pseudo-criteria. Also, robustness analysis of the results was developed in Aït Younes et al. (2000). Let us note that ELECTRE IS remains the most rigorous tool for choice problematic within the ELECTRE family, and it inspired the RUBIS method used in this chapter. Meanwhile, other ELECTRE methods have emerged to deal with the ranking problematic (i.e., ranking solutions from the best to the worst), the most advanced tool being ELECTRE III (electre three) (Roy 1978; Roy et al. 1986), which inspired ELECTRE IV (electre four) (Roy and Hugonnard 1982) usable when relative criteria importance coefficients are not required. All these earlier researches were completed by a MCDA methodology established (Roy 1985) and a presentation of the outranking approach in ELECTRE methods (Roy 1991). More recently, ELECTRE TRI (electre tree) method (Yu 1992) was designed to deal with the sorting problematic (i.e., assigning each solution to one of the pre-defined and ordered categories) using boundary profiles. A comprehensive presentation of ELECTRE methods (among others) was collected by Vincke (1992) and (Roy and Bouyssou 1993).

A brief history of ELECTRE methods in given Figueira et al. (2005a, b), and methodological advances (Figueira et al. 2010) remain topical notably:

- About ELECTRE TRI-B method: pure-inference-based approaches for valuing model parameters from holistic judgments (i.e., alternative assignable to a category by the decision-maker) that should be combined with inference-robustness based approaches to derive some robust conclusion about assignments of solutions into categories; pseudo-robustness based approaches with Monte Carlo simulation for analyzing the stability of some parameters.

- New concepts for robustness measure of results obtained when using ELECTRE III and ELECTRE IV methods, but also new axiomatic analyses, evolutionary approaches, decision rules using dominance-based rough set approach.
- Improvements for modeling three different types of interaction among criteria and an outranking credibility index with reinforced preference thresholds and counter-veto thresholds.
- Recent ELECTRE-like methods: ELECTRE TRI-C generalized to ELECTRE TRI-NC where each category is defined by a set of reference characteristic actions; ELECTRE^{GMS} which consider all sets of parameter values compatible with the preference information provided by a decision-maker to give recommendation based on robust ordinal regression, with an adaptation for group decision making called ELECTRE^{GMS}-GROUP method; the RUBIS method in the tradition of ELECTRE IS, presented later in this chapter, introducing a bipolar outranking selection procedure to choose a single best solution.

Thus, over the four decades, a wide body of research in the field of ELECTRE family methods appeared mainly in Europe.

The second class of outranking approach is the family of PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) methods (Brans and Mareschal 2005), with the GAIA (Geometrical Analysis for Interactive Assistance) tool, also called PROMETHEE-GAIA methodology. In 1982 appeared the PROMETHEE I (partial ranking) and PROMETHEE II (complete ranking) methods published in Brans et al. (1986). The main novelty concerns a typology based on six criteria preference functions of the decision maker, particularly the Gaussian type. These PROMETHEE methods, very simple to understand, were completed by the GAIA visual interactive module (Mareschal and Brans 1988) which provided geometrical representations for sensitivity analysis of results.

Further extensions were produced, notably the PROMETHEE V procedure (Brans and Mareschal 1992), devoted to identify a subset of alternatives satisfying segmentation constraints, the PROMETHEE VI module (Brans and Mareschal 1995) which is a sensitivity tool to detect soft or hard decision problems to revolve, and finally a GDSS (Group Decision Support System) PROMETHEE procedure (Macharis et al. 1998) for providing decision aid to a group of decision makers and to visualize conflicts between them. For a comprehensive book on PROMETHEE-GAIA methodology, see Brans and Mareschal (2002).

The third class of approaches collects other outranking methods (Martel and Matarazzo 2005), more or less related to the principles of concordance or/and of discordance, with or without outranking binary relation, and dealing mostly with performance table of total preorders (one by criterion) on a finite solutions set (these are evaluated according to their ranks).

Outranking methods constitute one of the most fruitful approaches in MCDA. This leads to several software implementations of tools.[2] Let us note the Decision-Deck (D2) project,[3] providing a collaborative open source platform.

2.2.2 Why Implement the RUBIS Methodology?

In this plethora offer of outranking tools was first applied the ELECTRE IS method for analyzing the case study (Haurant et al. 2011), because it was necessary to deal with a multicriteria choice problem: select the best photovoltaic plant projects developed and submitted by industrial enterprises to local decision makers in Corsica island. Also, as outlined in the previous point, ELECTRE IS was the most rigorous method devoted to such problematic. Moreover, the ELECTRE I method could not be implemented because it considers only true criteria (i.e., criteria without imperfect data). Finally, the software implementation of ELECTRE IS was a great help to compute results and their robustness.

After delivering the final study report, new MCDA tools from the RUBIS methodology became available, which also deal with the choice problematic and pseudo-criteria (i.e., criteria with indifference and preference thresholds to consider imperfect data). Besides, this innovative framework includes the RUBIS method developed in the tradition of ELECTRE IS. Thus, it was scientifically interesting to compare the selections of photovoltaic plant projects resulting from these two outranking methods, with the same input data (i.e., performance table and parameter values). The robustness analyses of results (i.e., the best projects to be selected) were performed within each two MCDA tools and compared after.

Moreover, the new methodology provides a RUBIS MCDA-web service, for submitting a choice problem and requesting the single best solution in a finite set of alternatives. The benefits are substantial including open source software, no specific acquisition costs, an independence from the operating system (no problem of compatibilities), an easy access with a recent standard internet browser, the high quality of the output data well structured and presented, access to source code of the no black-box RUBIS method.

Furthermore, the real case study required to implement a non-compensatory aggregation method (i.e., no possibility of offsetting a disadvantage considered criterion by a sufficiently large advantage on one other criterion at least). RUBIS method allows to grant (or not) a veto power for each criterion, using veto thresholds. This possibility is useful in a sustainable development view, for searching potential compromise solutions, but also to penalize decision alternatives with value profiles which neglect certain dimensions of the problem.

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[2] http://www.inescc.pt/~ewgmcda/Software.html; http://www.lamsade.dauphine.fr/

[3] www.decision-deck.org

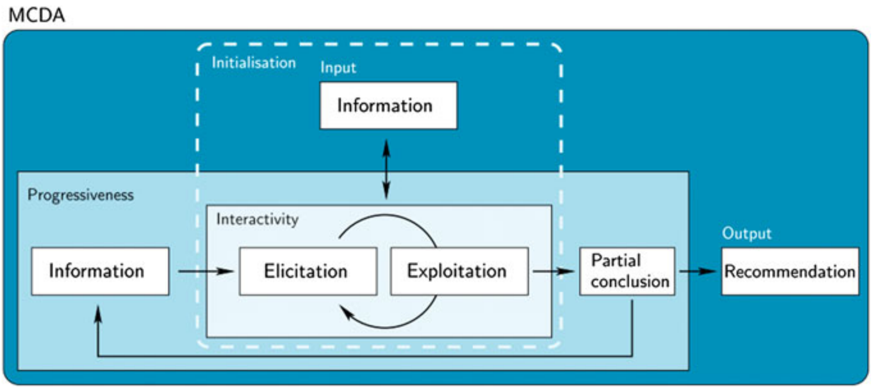

Fig. 2.1 General scheme of a progressive MCDA process (Meyer 2009)

Finally, let us note that the RUBIS methodology deals with a **progressive decision-aiding process** (Meyer 2009) (see Fig. 2.1), justified notably by prudence,[4] economic constraints,[5] and a constructive approach to the problem.[6] New foundations for a progressive choice decision aiding methodology were laid by Bisdorff et al. (2008), according to five pragmatic principles presented to the next point.

2.2.3 An Overview of the RUBIS MCDA Method

RUBIS (Bisdorff et al. 2008) is a new best choice method in the tradition of ELECTRE IS. This recent development is considered as a methodological contribution to the ELECTRE outranking approach of MCDA (Figueira et al. 2010).

RUBIS method focuses on the problem of selecting a single best decision alternative in a considered set of decision objects, on the basis of their performances (see example Tables 2.1 and 2.2) on a consistent (or coherent) family of criteria (Roy 1985). Methodologically, are performed pairwise comparisons of alternatives leading to a bipolar-valued outranking digraph, on which are determined the hyperkernels where is finally extracted the solution called RCR (RUBIS Choice Recommendation) in a progressive MCDA process (Meyer 2009). The main theoretical concepts and formulas of the method, and a few personal adjustments to expand the evaluation exercise[7] will be briefly outlined.

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[4] The ultimate recommendation does not necessarily have to be reached in one step.

[5] At a given moment, only limited financial or temporal resources may be available.

[6] Elicitation of decision maker's preferences and final recommendations are constructed via small steps.

[7] Each criterion and discrimination threshold (indifference, preference) can take their values out of $[0,1]$; each veto threshold (weak, strong) can take its values out of $[0,1] \cup \{2\}$. Each evaluation criterion can be to maximize or to minimize.

Table 2.1 The photovoltaic plant projects on farmlands in Haute-Corse

Sets of projects	Projects	Farmland sites	Villages	Powers (MWp)	Estimated net productions (GWh/yr)	Rented surfaces (ha)
Oletta	a_5	Malpergo	Rapale	10.26	12.82	40
	a_8	Griolo	Oletta	3.43	5.15	11.1
	a_{11}	Mignalojo	Oletta	3.55	5.32	14.3
Taglio	a_4	Querci	Penta di Casinca	11.06	16.5	41.5
	a_{10}	Citrinche	Venzolasca	4.5	5.85	12
Cervione	a_9	Farinaccio, Sandali	Linguizzetta	8.5	10.16	29.48
	a_{14}	Sbiri	Linguizzetta, Talonne	8	10.4	23
Ghisonaccia	a_1	Tozze	Aghione	11.64	17.5	36.68
	a_2	Alzolu	Prunelli di Fiumorbo	1.27	1.62	3.6
	a_3	Casa Calva	Prunelli di Fiumorbo	3.05	4.59	14.3
	a_6	Mortella	Ghisonaccia	3.89	5.179	11.5
	a_7	Maison Pieraggi	Pietroso	1.83	2.414	5.79
	a_{12}	Manalotte	Poggio di Nazza	4.5	5.85	17.43
	a_{13}	Chisacca	Serra di Fiumorbo	8	10.4	17
	a_{15}	Niellone	Prunelli di Fiumorbo	4.02	5.378	10.8
	a_{16}	Acqua di l'Asino, les Cigales	Ventiseri	10.65	14.995	30.21
Total	–	–	–	98.15	–	318.69

Table 2.2 The family of evaluation criteria (presented with RUBIS D3-web application)

Identifier	Name	Comment	Weight[a]	Scale			Thresholds		
				Direction	min	Max	Indifference	Preference	Veto
g_1	Estimated net production	GWh/yr	14.28 (12)	Max	0	17.50	0.00 + 0.10x	0.00 + 91.70x	20
g_2	Rent area unoccupied by the installation	%	19.05 (17)	Max	0	82.02	4.00	4.00	101
g_3	Study of the potential ecological degradation in the files	45-point scale	19.05 (17)	Max	0	30.00	2.00	10.00	20
g_4	Relevance of visual impact presentation in the files	10-point scale	19.05 (17)	Max	0	10.00	0.00	0.00	11
g_5	Observer-plant minimum distance	km	4.76 (4)	Max	0	1.00	0.15 + 0.35x	0.15 + 0.35x	1.1
g_6	Use conflicts risks	101-point scale	19.05 (17)	Max	0	101.00	3.00	13.00	43
g_7	Economic activity and financial benefits to inhabitants from RES facilities	15-point scale	4.76 (4)	Max	0	15.00	0.00	1.00	16
g_8	Financial income at the communal level	€/yr/inhab	(12.00)	Max	0	1033.06	0.00 + 0.21x	0.00 + 1.89x	1100

[a] In brackets are inserted the weight values when 8 criteria are considered

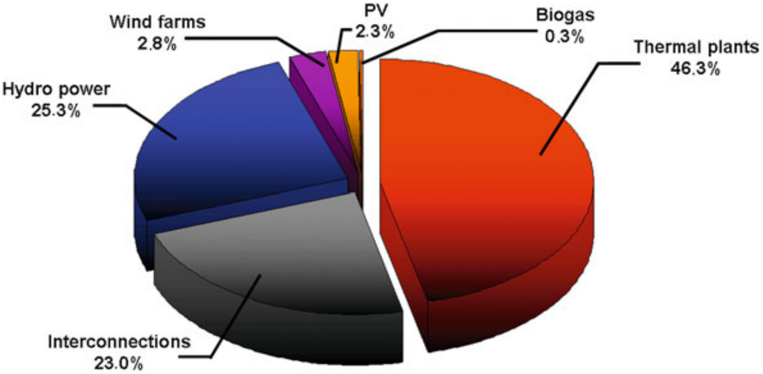

Fig. 2.2 Distribution of the power supply means in Corsica for June (EDF, 2011)

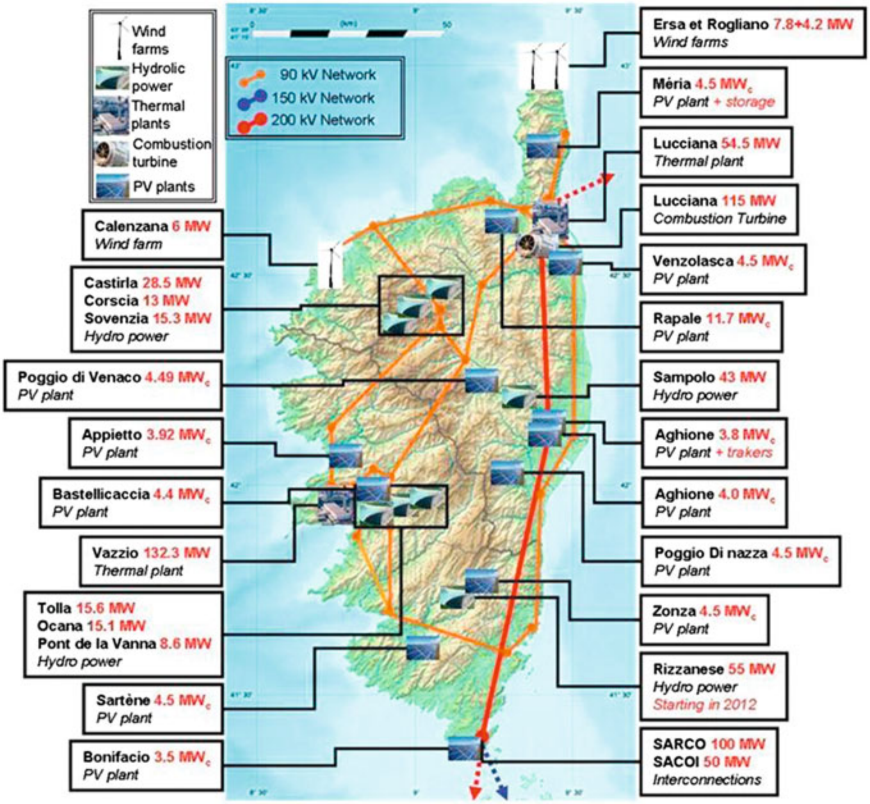

Fig. 2.3 Geographical dispersion of power supply means in Corsica

Let $X = \{x, y, \ldots, z\}$ be a finite set of $z \geq 2$ alternatives (or decision objects) evaluated on a finite family $F = \{g_1, \ldots, g_j, \ldots, g_p\}$ of $p \geq 2$ criteria. Each criterion g_j takes its values on an ordinal scale or on a weak interval scale (Bouyssou et al. 2006). For all ordered pairs of different elements x and y of X is tested the preferential statement "x is at least as good as y", or for short "x outranks y" that is the classical outranking situation xSy with $S \subseteq X \times X$ the binary relation of outranking. The founding principle of modeling S (Roy 1985) is to test if (concordance condition) a sufficient majority of criteria which supports xSy and if (non-veto condition) no criterion which raises a veto against it. RUBIS gives formal definition that allows to assign a valuation $\tilde{S}$ to each element of S in a so-called rational credibility scale $\mathcal{L} = [-1, 1]$. The more $\tilde{S}(x, y)$ is close to 1 (resp. -1), the more the assertion xSy is validated (resp. non-validated); the median value $\tilde{S}(x, y) = 0$ means this assertion remains undetermined.

Let $g_j(x)$ and $g_j(y)$ be the evaluations (or performance) of two alternatives x and y of X on criterion g_j, and $\Delta_j(x, y)$ the difference of the two values such that:

$$\Delta_j(x, y) = \begin{cases} g_j(x) - g_j(y), & \text{if } g_j \text{ is to be maximized} \\ g_j(y) - g_j(x), & \text{if } g_j \text{ is to be minimized} \end{cases} \tag{2.1}$$

To each preference scale of a criterion is associated thresholds (variable or constant), to determine whether the difference $\Delta_j(x, y)$ is significant (preference and veto thresholds) or not (indifference threshold). Threshold functions are supposed to verify the standard non-decreasing monotonicity condition (Roy and Bouyssou 1993, p. 56). Also, more formally $v_j(g_j(x)) \geq wv_j(g_j(x)) \geq p_j(g_j(x)) \geq q_j(g_j(x)) \geq 0$, with $q_j(g_j(x))$ the indifference threshold, $p_j(g_j(x))$ the preference threshold, $wv_j(g_j(x))$ the weak (or potential) veto threshold, and $v_j(g_j)$ the strong veto threshold. Thus, for each criterion it is possible to:

- define $q_j(g_j(x))$ as the largest difference of values compatible with a situation of indifference (no preference) between alternatives x and y;
- define $p_j(g_j(x))$ as the smallest difference of values from witch a situation of a preference for x or to y is clearly established;
- grant or not a veto power, and determine if it can alone reject or not the preferential statement xSy.

If an actor of the evaluation process deems necessary the absence of compensation effects (a good performance of an action in one criterion does not hide a poor performance in another), then at least one criterion $g_{j'}$ will have a positive veto threshold (weak or/and strong) value greater than the preference threshold value but also smaller than $\text{Max}\{g_{j'}(i); \forall i \in X\} - \text{Min}\{g_{j'}(i); \forall i \in X\}$ or than the magnitude of the criterion scale. In contrast, if all actors agree this compensation between performances, none of the criteria will have different values of preference and veto thresholds $(v_j(g_j(x)) = wv_j(g_j(x)) = p_j(g_j(x)))$. In these two ways, it is possible to set the compensatory logic of the MCDA method.

Several elicitation techniques can be used to assign values to such thresholds (Figueira et al. 2005a, b).

Let w_j from $[0, 1]$ be the relative weight of the criterion g_j. All weights of criteria are normalized, such that $\sum_{j=1}^{p} w_j = 1$, and can be computed with the revised Simos' procedure (Figueira and Roy 2002) implemented in the SRF software.

In order to formalize the concordance and non-veto conditions of an outranking situation xSy, are defined the following functions:

- the criterion concordance index $C_j : X \times X \to \{-1, 0, 1\}$ such that

$$C_j(x,y) = \begin{cases} 1 & \text{if } \Delta_j(x,y) > \; - q_j(g_j(x)) \\ -1 & \text{if } \Delta_j(x,y) \leq - p_j(g_j(x)) \\ 0 & \text{otherwise} \end{cases} \tag{2.2}$$

$C_j(x, y) = 1$ (resp. -1) denote that the criterion g_j agree or is concordant with (resp. disagree or is discordant with) the preferential statement xSy. $C_j(x, y) = 0$ in case it cannot be determined whether xSy or not.

- the global (multicriteria) concordance index $\tilde{C} : X \times X \to [-1, 1]$, such that:

$$\tilde{C}(x,y) = \sum_{j \in F} w_j \cdot C_j(x,y) \tag{2.3}$$

$\tilde{C}(x, y)$ aggregates all weighted criterion concordance indexes (i.e., solely balance rational significance weights) and indicates the concordance degree of the criteria family F with the preferential statement xSy.

- the criterion veto index $V_j : X \times X \to \{-1, 0, 1\}$, such that:

$$V_j(x,y) = \begin{cases} 1 & \text{if } \Delta_j(x,y) \leq \; - v_j(g_j(x)) \\ -1 & \text{if } \Delta_j(x,y) > \; - wv_j(g_j(x)) \\ 0 & \text{otherwise} \end{cases} \tag{2.4}$$

$V_j(x, y) = 1$ reflects a veto situation observed on the criterion g_j when the difference $\Delta_j(x, y)$ gives a strong disadvantage of x over y. $V_j(x, y) = -1$ when no veto appears. $V_j(x, y) = 0$ is an undetermined response to xSy.

- the negated criterion-based veto index, $-V_j(x, y)$, such that $-V_j(x, y) = -1$ (resp. 1) when a (resp. no) criterion veto is observed.

Thus, the global (multicriteria) outranking index $\tilde{S} : X \times X \to \mathcal{L} = [-1, 1]$, is as follows:

$$\tilde{S}(x,y) = \min\{\tilde{C}(x,y), -V_1(x,y), \ldots, -V_p(x,y)\} \quad (2.5)$$

The min operator translates the conjunction between the global concordance index and all the negated criterion-based veto indexes, according to the founding principle of an outranking situation (Roy 1985). Analogously to the ELECTRE methods, $\tilde{S}$ is a function representing the **credibility of the validation or non-validation of an outranking situation** for each ordered pair of alternatives. More particularly in the RUBIS framework, "$\tilde{S}$ is called the bipolar-valued characterization of the outranking relation S, or for short, the ***bipolar-valued outranking relation***" (Bisdorff et al. 2008, p. 147) or also "***bipolar outranking index***" (Figueira et al. 2010). The maximum value $\tilde{S}(x,y) = 1$ is obtained in the case of unanimous concordance (all criteria are agree with xSy, i.e., $C_j(x,y) = 1, \forall g_j \in F$). The minimum value $\tilde{S}(x,y) = -1$ is reached either in the case of unanimous negative concordance ($C_j(x,y) = -1, \forall g_j \in F$), or when exists a strong veto situation on at least one criterion ($\exists g_j \in F : V_j(x,y) = 1$). The median value $\tilde{S}(x,y) = 0$ represents a case of indeterminateness: either the arguments in favor of xSy are compensated by those against it or a positive global concordance in favor of this outranking is outbalanced by a weak (potential) veto situation ($\exists g_j \in F : V_j(x,y) = 0$). The other cases of values occur when a sufficient majority of criteria or criteria coalition of positive significance (i.e., gathering more than 50 % of the global criteria significance weights) is more favorable than unfavorable to xSy ($\tilde{S}(x,y) \in [0,1]$) or vice versa ($\tilde{S}(x,y) \in [-1,0]$). For example, computed values (in percentages) from our real case study are collected in Table 2.3 and rounded in Tables 2.4, 2.5.

The semantics linked to $\tilde{S}$ are such that for any two alternatives x and y of X:

- $\tilde{S}(x,y) = -1$ means that xSy is clearly non-validated (cases of unanimous negative concordance or of strong veto situation for one criterion at least);
- $\tilde{S}(x,y) < 0$ means that xSy is more non-validated than validated, for a sufficient majority of criteria;

Table 2.3 Performance table restricted to the Ghisonaccia set of projects (presented with RUBIS D3-web application)

Alternative	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8
a_1	17.50	68.70	9.00	6.00	0.20	52.00	2.00	1033.06
a_{12}	5.85	82.02	27.00	4.00	0.50	89.00	7.00	388.89
a_{13}	10.40	70.00	26.00	4.00	0.05	77.00	6.00	453.02
a_{15}	5.38	67.20	22.00	6.00	0.30	32.00	7.00	-
a_{16}	14.99	66.08	26.00	10.00	0.05	30.00	7.00	152.84
a_2	1.62	63.89	20.00	2.00	0.30	55.00	4.00	8.38
a_3	4.58	60.14	29.00	6.00	0.10	48.00	2.00	30.93
a_6	5.18	75.13	8.00	0.00	1.00	33.00	4.00	42.88
a_7	2.41	76.34	8.00	0.00	0.10	43.00	2.00	249.10

Table 2.4 Pairwise outranking significance degrees in the range −100.00 to 100.00 (without the optional criterion g8)

$\tilde{S}(x,y)$	a_1	a_{12}	a_{13}	a_{15}	a_{16}	a_2	a_3	a_6	a_7
a_1	0.00	−23.82	14.28	14.28	14.28	52.38	0.00	42.86	61.90
a_{12}	47.62	0.00	47.62	100.00	100.00	100.00	61.90	100.00	100.00
a_{13}	47.62	−14.29	0.00	100.00	100.00	100.00	42.85	100.00	61.90
a_{15}	9.52	0.00	0.00	0.00	28.57	61.90	4.75	52.38	42.85
a_{16}	47.62	0.00	0.00	100.00	0.00	61.90	42.85	52.38	23.80
a_2	9.52	−57.15	−57.15	38.10	19.05	0.00	28.57	38.10	47.62
a_3	0.00	−9.52	0.00	0.00	0.00	71.43	0.00	100.00	100.00
a_6	9.52	−100.00	−100.00	14.28	0.00	−14.30	−100.00	0.00	42.85
a_7	28.57	−100.00	−38.10	0.00	0.00	−4.77	−100.00	28.58	0.00

Table 2.5 Scale of condorcet robustness degrees

Unanimously concordant	3
Ordinal majority concordant	2
Cardinal majority concordant	1
Balanced concordance and discordance, or weak veto	0
Simple majority discordant	−1
Ordinal majority discordant	−2
Unanimously discordant, or veto	−3

- $\tilde{S}(x,y) = 0$ means that xSy is undetermined (neither the validation, nor the invalidation may be assumed) at this stage of the decision-aiding process;
- $\tilde{S}(x,y) > 0$ means that xSy is more validated than non-validated, for a sufficient majority of criteria;
- $\tilde{S}(x,y) = 1$ means that xSy is clearly validated (case of unanimous concordance: all criteria are agree with xSy).

For example in Table 2.3, are denoted that:

- $\tilde{S}(a_6, a_{12}) = -100\,\%$, i.e., the outranking statement "PV project a_6 outranks PV project a_{12}" is clearly non-validated;
- $\tilde{S}(a_1, a_{12}) = -23.82\%$, i.e., the outranking statement "PV project a_1 outranks PV project a_{12}" is more non-validated than validated;
- $\tilde{S}(a_1, a_3) = \tilde{S}(a_3, a_1) = 0\,\%$, i.e., the outranking statements a_1Sa_3 and a_3Sa_1 are undetermined at this stage of the decision-aiding process;
- $\tilde{S}(a_1, a_{13}) = 14.28\,\%$, i.e., the outranking statement "PV project a_1 outranks PV project a_{13}" more validated than non-validated;
- $\tilde{S}(a_{12}, a_{15}) = 100\,\%$, i.e., the outranking statement "PV project a_{12} outranks PV project a_{15}" is clearly validated;

To give an abstract representation of the outranking situations supported by a criteria coalition of positive significance (i.e., gathering more than 50 % of the global criteria significance weights), is used the concept of **bipolar-valued crisp outranking digraph** which is the ordered pair $\tilde{G}(X, \tilde{S})$ comprising the set X of alternatives associated to $\tilde{S}$ such that $\tilde{S}(x, y) > 0$ (i.e., in the graph, an black arc or arrow is directed from x to y). In this way, the **crisp outranking binary relation** S is a strict 0-cut relation modeled as follows: $xSy \Leftrightarrow \tilde{S}(x, y) > 0$.

An illustration of the bi-polar crisp outranking digraph is given in Fig. 2.4. Lets us note that are added in this digraph the indeterminate outranking situations ($\tilde{S}(x, y) = 0$), identifiable by empty arrows heads, because the credibility degree 0 represents a temporary delay in characterizing the validation or non-validation of the outranking statement. Thus, *In the framework of progressive decision aiding, this feature allows us to easily cope with currently undetermined preferential situations that may eventually become determined to a certain degree, either as validated or non-validated, in a later stage of the decision aiding process.* Bisdorff et al. (2008, p. 145). A purpose of the progressiveness is to resolve undetermined cases.

To compute the **best choice recommendation** (**BCR**) in bipolar-valued digraphs, mathematical and algorithmic results were obtained in Bisdorff et al. (2006). RUBIS choice recommendation (RCR) verifies five following pragmatic principles funding the progressive MCDA:

1. *Non-retainment for well-motivated reasons*: each non-retained alternative is eliminated without missing any potentially best alternative;
2. *Minimal size*: the number of alternatives retained in a BCR set is as small as possible;
3. *Efficient and informative refinement*: at each step of the progressive decision aiding is delivered a stable refinement of the previous BCR;
4. *Effective recommendation*: a BCR does not correspond simultaneously to a best as well as a worst choice recommendation;
5. *Maximal credibility*: the BCR is as credible as possible with respect to the preferential knowledge available in the current stage of the decision-aiding process.

A formal translation of these principles is given in Bisdorff et al. (2008) and leads to a new graph theory-related object, the **maximally determined strict outranking hyperkernel**, which is considered as an appropriate RCR (i.e., solution) in a progressive MCDA context. For example, from our real case study, only the PV project a_{12} is selected (see Fig. 2.4 the yellow alternative in the outranking digraph).

The RCR algorithm, thoroughly presented and discussed by the authors, is implemented in the Python programming language within the digraphs Python solver module accessible via the RUBIS MCDA-web service presented hereafter.

2.2.4 The RUBIS D3 Web Server

RUBIS method is available in the Decision-Deck (D2) software package (Bisdorff 2008). The D2 project,[8] started in early 2006, provides a collaborative open source software platform pertaining to the field of MCDA. Typical end-users of D2 are MCDA researchers, MCDA consultants or practitioners, and teachers in academicals institutions. The platform architecture includes a distributed web server (D3) at the University of Luxembourg, serving implemented MCDA methods such as RUBIS.

The D3-Web application allows to submit an online XML encoded RUBIS problem description (XMCDA input data file) and to visualize the RUBIS solver's response and the solution (output data file) in a recent Internet browser session. XMCDA is a data standard[9] which allows representing MCDA data elements in XML according to a clearly defined grammar. To validate an input data file, see the current XML schema approved[10] by the specifications committee of the D2 project. The main steps for using the RUBIS D3 web server and solving a choice problem are the following:

1. Go to the webpage http://ernst-schroeder.uni.lu/d3/.
2. Enter login and password provided.
3. Online submission of a problem description file (XML encoded data for RUBIS):
    - 3.1 Click on "Remote".
    - 3.2 Click on the "My Jobs" icon.
    - 3.3 Click on the "Add…" button.
    - 3.4 Select the XML file (input data).
    - 3.5 Upload this XML file on the server by clicking the green arrow.
4. Save a new job:
    - 4.1 Click on the "Register new job" icon.
    - 4.2 Fill in the form "Method properties":
        - 4.2.1 Give a problem description.
        - 4.2.2 Select the uploaded XML file (if it not appears, click on "Refresh the list" button).
        - 4.2.3 Select the MCDA Method "Rubis Choice XMCDA-2.0".
        - 4.2.4 Select service to use.
        - 4.2.5 Submit the form (success if appears "Job successfully saved").

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[8] www.decision-deck.org

[9] http://www.decision-deck.org/xmcda/index.html

[10] http://www.decision-deck.org/xmcda/current.html

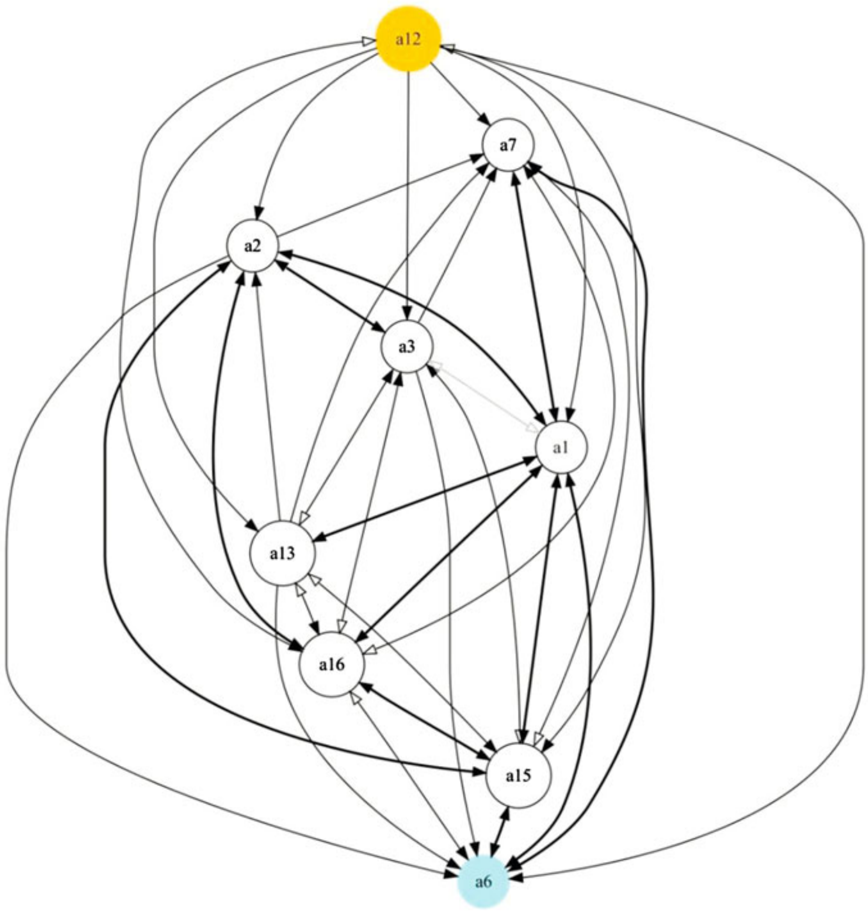

Fig. 2.4 Significantly concordant outranking graph (Ghisonaccia set of projects)

5. Interact with remote service:
    - 1.1 In the list of jobs, click right on the saved job and on “Submit problem” (success if appears “Remote invocation succeeded”).
    - 1.2 Click on the “Refresh” button: the saved job status is changed from “pending” to “waiting” (i.e., the problem has been submitted).
    - 1.3 In the list of jobs, click right on the saved job and on “Request solution” (success if appears “Remote invocation succeeded”).
    - 1.4 Click on the “Refresh” button: the saved job status is changed from “waiting” to “solved” (i.e., the problem has been successfully solved).

6. Visualization of the RUBIS solver's response in a standard internet browser session: click right on the saved job and on “view solution”, then select the desired output format (Raw XML or HTML).

To compute a robustness analysis of the results, the selected MCDA method should be “Robust Rubis XMCDA-2.0.0 Choice Loew” in step 4.2.3.

Let us present the real case study and implement it on the RUBIS D3 web server.

2.3 Real Case Study in Corsica and Results of the PV Plants Selection Procedure

The study was requested by the Agriculture Chamber of the Haute-Corse department (CDA2B, http://www.chambragri2b.fr/), which is an advisory and professional actor for agricultural interests with public authorities. This stakeholder wanted an informed opinion about PV plant projects which would affect farmland, economic, ecological, and social issues, under electrical and geographical constraints. Let us present before the electric network of the island.

2.3.1 The Insular Power Grid of Corsica

The electricity supply in Corsica is constrained by insularity, particularly a small electrical grid which is weakly interconnected to continental sources. Also, the demand fluctuates considerably with the tourist pressure especially during summer. The distributions of electricity generation means in Corsica are presented in Figs. 2.2 and 2.3. The total amount of production in Corsica represents about 651 MW (EDF 2011). The thermal power plants and the energy imported are the main production sources (respectively, 46.3 and 23 %), while other technologies are used for periods of peak demand. The electricity is transported by two power lines (200 kV primary net and 90 kV high voltage).

About thermal power plants:

- the fuel plant of Bastia-Lucciana supplies 132.3 MW thanks to 7 diesel engines of 18.9 MW;
- the plant of Ajaccio-Vazzio produces 54.5 MW with 5 engines of 10.9 MW;
- a 40 MW turbine and 3 turbines of 25 MW were installed in Lucciana and started in November 2008. They are used for peak demands.

Furthermore, 23 % of the total power is imported from Italy (Tuscany and Sardinia) through two submarine transmission lines. The line SACOI (line Sardinia—Corsica—Italy, connecting Tuscany, Elba, and Sardinia via Corsica) provides a maximal power of 50 MW in 200 kV direct current, while the line SARCO (line between Sardinia and Corsica) supplies 100 MW of alternative current (EDF 2011).

Renewable energies represent 30.6 % of the means, 25.3 % are waterpower stations (Fig. 2.2) cumulating 139.1 MW (EDF 2011) and installed in different valleys (Prunelli, Golo, and Fium'Orbo) (Fig. 2.3). There are many micro-hydro plants around the island whose production is fatal for the grid. Also, in spite of a significant exploitable wind potential, valued at 433 MW for a wind speed above 7 m/s at 10 m over the ground (Notton et al. 2005), only 18 MW are generated by three farms in the territories of Balagne and Cap Corse:

- the Ersa Wind farm is composed with 13 wind turbines of 600 kW, representing 7.8 MW and produces 20 GWh per year;
- the wind park of Rogliano, with 7 wind generators of 600 kW, represents 4.2 MW and produces 10 GWh per year;
- the Calenzana wind farm supplies 6 MW with 10 turbines of 600 kW and produces 15 GWh per year.

The wind generated power accounts for only 2.8 % of the electric production in Corsica. Finally, PV power represents not even 2.3 % of the total production (Fig. 2.2) despite a workable capacity of 1400 TEP. In May 2011, Corsica had only 15 MWp of grid connected PV (EDF 2011). Also new PV plants have emerged (Fig. 2.3) and the power achieved in July 2012 is 58.31 MWp.

Let us note that a power constraint for intermittent renewable energies is established with the modified ministerial decree of April 23, 2008: all production means of at least 3 kVA could be disconnected to the Corsica grid by its administrator once 30 % of the injected total power is delivered by such resources. This threshold should be achieved in 2012 (EDF 2011). Despite of this, plant projects are still studied and developed. Another solution to avoid intermittence is to couple energy storage with wind and solar power generation. Two examples are the PV plant with a storage unit located in Meria (Fig. 2.3) and the R&D Platform MYRTE located in Ajaccio that combines a PV array and a storage system based on hydrogen (Thibault et al. 2012). Also the national electricity supplier "Electricité de France" (EDF) foresees that smart grids will constitute an alternative for integrating massively intermittent renewable energies into an insular grid, and the experimental project called Millener was officially launched in Corsica during 2011.

2.3.2 Context of the Study

This real case study (Haurant et al. 2011) was the subject of a research agreement achieved between University of Corsica Pasquale Paoli (UCPP), the Agriculture Chamber of the Haute-Corse department (CDA2B) and the French National Center

Table 2.6 Outranking and condorcet robustness degrees between PV projects

	a_1	a_{12}	a_{13}	a_{15}	a_{16}	a_2	a_3	a_6	a_7
a_1	0 (0)	−23 (−2)	14 (2)	14 (2)	14 (2)	52 (2)	0 (−3)	42 (2)	61 (2)
a_{12}	47 (2)	0 (0)	47 (2)	100 (2)	100 (2)	100 (3)	61 (2)	100 (2)	100 (3)
a_{13}	47 (2)	−14 (−2)	0 (0)	100 (2)	100 (2)	100 (3)	42 (2)	100 (2)	61 (2)
a_{15}	9 (2)	0 (−3)	0 (−3)	0 (0)	28 (2)	61 (2)	4 (1)	52 (2)	42 (2)
a_{16}	47 (2)	0 (−3)	0 (−3)	100 (3)	0 (0)	61 (2)	42 (2)	52 (2)	23 (2)
a_2	9 (2)	−57 (−2)	−57 (−2)	38 (2)	19 (2)	0 (0)	28 (2)	38 (2)	47 (2)
a_3	0 (0)	−9 (−2)	0 (0)	0 (0)	0 (0)	71 (2)	0 (0)	100 (2)	100 (2)
a_6	9 (2)	−100 (−3)	−100 (−3)	14 (2)	0 (0)	−14 (−1)	−100 (−3)	0 (0)	42 (2)
a_7	28 (2)	−100 (−3)	−38 (−2)	0 (0)	0 (0)	−4 (−2)	−100 (−3)	28 (2)	0 (0)

for Scientific Research (CNRS). The aim was to aid this public institution in formulating a recommendation about the selection among 16 photovoltaic plant projects on farmlands, developed and submitted by industries to local decision makers. The actors' preoccupations and constraints listed hereafter were considered:

- The use conflict risks, particularly because the planned installations could potentially use up to 318.69 ha of cultivated grounds.
- The Social acceptability: had to be studied negative and positive impacts, both visual and financial, due to such installations on local populations.
- The ecological impacts: their definitions, the compensatory actions, the demonstration of equivalence between impacts and compensatory actions, the artificiality of farmland.
- The economic and financial impacts at regional and local levels: activity for Corsica-based firms, employment, financial aid to local inhabitants for renewable energy systems facilities, additional fiscal income per capita for the municipality.
- At most 30 % of intermittent renewable energies can be injected into the Corsica power grid in order to preserve its stability (see the aforementioned decree). This ratio corresponded to an additional power of maximum 46 MWp (Assemblée de Corse 2009a, b) but the studied PV plant projects represented a total of 98.15 MWp, which justifies a selection.
- No geographic concentration of PV plants is requested, to avoid sudden declines in production due to climatic or technical factors.

These last two constraints implied that the number of selected photovoltaic plant projects should be as small as possible. This type of intended outcome corresponds to the choice problematic in MCDA (Roy 1985). Thus, the 16 candidate projects (see Table 2.6) were assigned to 4 sets[11] each defined by the common point of connection to the power grid, and **the selections of a single best**

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[11] Namely: Oletta, Taglio, Cervione and Ghisonaccia.

project were separately computed on each set of alternatives. In other terms, among the 16 alternatives, only 4 will be selected with the RUBIS and ELECTRE IS methods under the above constraints. Also, in this way maximum 41.46 MWp could be achieved.

Finally, let us note that project evaluations were based on data files.

2.3.3 PV Plant Projects, Criteria Family and Performance Table

The 16 projects, divided into 4 sets separately analyzed to find a single best solution for each of them are characterized in Table 2.6. All of them satisfied three preselecting constraints, about guarantee of plant dismantling, farmland out of ecological classifications (Natura 2000, wetlands) and area's topography (slopes must not exceed 10 %).

A family of 8 criteria to be maximized (Table 2.1) has been constructed to evaluate each alternative project (Table 2.2). The criteria family was worked out in dialog with the two actors (CDA2B, UCPP), directly involved in the decision aid process: the Stakeholder CDA2B requesting the study, the researchers of the UCPP specialized in multicriteria analysis of renewable energies and Sustainable development. Criteria were chosen to take into account the preoccupations of these actors about the consequence of the PV plant projects. More particularly, the risk of conflicts between farmland uses and PV plant projects, specific stake of the CDA2B, was considered with the criteria g_2 and g_6. Let us note that g_6 also considers tourist and archeological interests. In contrast, all other criteria translate common preoccupations of CDA2B and UCPP, based on energy production (g_1), ecological degradation (g_3), social issues (g_4, g_5), economic and financial effects (g_7, g_8). Let us also note that criterion g_8 was optional because based on very uncertain information (i.e., keeping or not of professional tax in France) or too different data (i.e., professional tax amounts vary considerably between files for similar projects). Also, only criteria g_3 and g_6 have veto powers (i.e., each veto value is lower than the magnitude of the criterion scale), according to the sensitive preoccupations which are associated. A fuller description is given in Haurant et al. (2011). Moreover, no distinction is done between weak veto thresholds and strong veto thresholds.

Based on these evaluations (performance, weights and thresholds on criteria), the RUBIS methodology can be implemented to aid in selecting the best alternative PV plant project.

2.3.4 Main Results of RUBIS Outranking Computations

As presented in Haurant et al. (2011), detailed results are given for the PV plant projects which composed the set called Ghisonaccia, because it is the main case (9 alternatives, 48.85 MWp and 490.7 ha concerned). The selection is mainly based without the optional criterion g8. Its consideration is discussed later. Also, for the three over sets of projects, finals results (i.e., robust RUBIS choice recommendations) are stated in the discussion. The reader can compute all the cases using the RUBIS D3 web server, as presented above. Here are the main results.

About Fig. 2.4, let us recall that from an alternative x to an alternative y: a black arrow (or arc) is directed if "x outranks y" ($\tilde{S}(x, y) > 0$). For example, a_{12} outranks all over projects. Also, an empty arrow head indicates an indeterminate outranking situation ($\tilde{S}(x, y) = 0$) at this stage of the decision-aiding process. It is the case for the ordered pair $(a_3,\ a_{13})$, or even between a_3 and a_1. Moreover, a thick arrow means an indifference situation between these two alternatives, because x outranks y and y outranks x ($\tilde{S}(x, y) > 0$ and $\tilde{S}(y, x) > 0$). For example are indifferent a_6 and a_7, a_7 and a_1, a_6 and a_1. Finally, the case with a black arrow from x to y and no arrow from y to x means a preference situation of x over y. For example, a_{12} is preferred to a_7, a_2, a_3, a_{13}, a_1 and a_6.

The RCR algorithm implementation leads to the result that **project a_{12} is selected as the best choice: it is the RUBIS choice recommendation** (yellow alternative in the outranking digraph). It is a good compromise of criteria. Intuitively (see Tables 2.1 and 2.2), this result can be found by reading performance (taking into account the thresholds) in the descending order of criteria weight. Indeed, on the most important (g_2, g_3, g_4 and g_6), the project a_{12} is the best (or is indifferent to the best) except for g_4 where the alternative obtains the median rank. For the criteria of second-rank importance (g_1 or optionally g_8), a_{12} gets a rank higher than median. Considering the least important criteria (g_5 and g_7), project a_{12} is the best or the second.

Let us note that the RUBIS D3 web server also delivers the non-retained alternatives, called potentially bad choices, outranked by at least one alternative of the choice recommendation translating the aforementioned principle of non-retainment for well motivated reasons. Therefore, **project a_6 is the worst bad choice** (blue alternative in the previous outranking digraph), then a_7, and finally $\{a_1,\ a_3\}$.

2.3.5 *Discussion*

Hereafter are discussed the following points: robustness analysis of the preceding results, introduction of the optional criterion g_8, RUBIS final recommendations with a comparison to the ELECTRE IS method, and the estimated net production (criterion g_1).

Regarding the uncertainty of the input data, it was necessary to assess the robustness of the results (i.e., best choice, indeed bad choice). It can be easily computed within the RUBIS D3 web server which provides a tool called "Robust Rubis XMCDA-2.0.0 Choice Loew" for implementing a Condorcet robustness of a RUBIS Best Choice Recommendation [and also robustness of the bad choice(s)].

The assessment scale shown in Table 2.4 is applied to each outranking significance degree (see Table 2.5). Pairwise outranking significance degrees are in the range $[-100, 100]$ and Condorcet robustness degrees are shown in brackets. Thus, is obtained the Robustly Concordant Outranking Graph (Fig. 2.5).

Thus, it allows resolving the indeterminate outranking situations associated to lowest Condorcet robustness degree (-3). From the Significantly Concordant Outranking Graph (Fig. 2.4) are removed 5 empty arrow heads concerning the following ordered pairs of alternatives: (a_{16}, a_{12}), (a_{15}, a_{12}), (a_1, a_3), (a_{16}, a_{13}), (a_{15}, a_{13}). Therefore, at this new stage of the decision-aiding process providing the Robustly Concordant Outranking Graph (Fig. 2.5), **the robust RUBIS choice recommendation is still the project** a_{12}. Let us note that project a_6 remains a robust bad choice. It is also the case of projects a_7 and $\{a_1, a_3\}$, which is an additional results that can be obtained with the RUBIS D3 web server.

Moreover, by introducing the optional criterion g_8 into RUBIS computations, a new robust bad choice appears: the project a_{15}. Thus, in considering the full criteria family, 5 of 9 alternatives would be rejected and the robust good choice remains the project a_{12}.

Consequently, taking into account the results and their robustness, the RUBIS final recommendation is the PV plant project a_{12}. It was also the obtained conclusion by implementing the ELECTRE IS method (Haurant et al. 2011).

Considering now the four sets of projects (see Table 2.6; see Table 8 in Haurant et al. 2011), separately analyzed to compute on each the single best solution, the selected PV plants were finally a_{11}, a_4, a_{14}, and a_{12}. They are all robust best choices recommended with the two outranking methods. This final selection covers 96.2 ha (on 318.69 ha concerned) of farmlands in Haute-Corse and represents a total power of 27.1 MWp (on 98.15 MWp submitted by industries to local decision makers). As expected at the point 3.2, the regional limit of 46 MWp additional is not exceeded and no geographic concentration of PV plants is obtained (Haurant et al. 2010). The actor CDA2B requesting the study was satisfied with the clarifications made by the outranking multicriteria selection aid of projects, well taking into account his preoccupations. In contrast at a regional level, during the real decision making process led by the Assembly of Corsica, let us lay the stress on the fact that only the Stakeholder ODARC (Agricultural and Rural Development Office of Corsica) has expressed his opinion on value of agricultural land.

More broadly, are to be considered some elements of **discussion about the ELECTRE-based methods for the choice problematic**. In the progressive search for a single best alternative, the outranking kernel(s) of an outranking digraph are taken as BCRs within the methods ELECTRE I and ELECTRE IS. Nevertheless, as shown by Bisdorff et al. (2008), the kernel may be too restrictive in certain cases and either no recommendation may be performed, or obvious BCRs may be left out. To overcome this problem, the authors have defined the concept of outranking hyperkernel which can always be found in any bipolar-valued outranking digraph. Thus, with the RUBIS method, the authors introduced new operational instruments which contribute to enrich the set of multicriteria decision-aiding tools for the

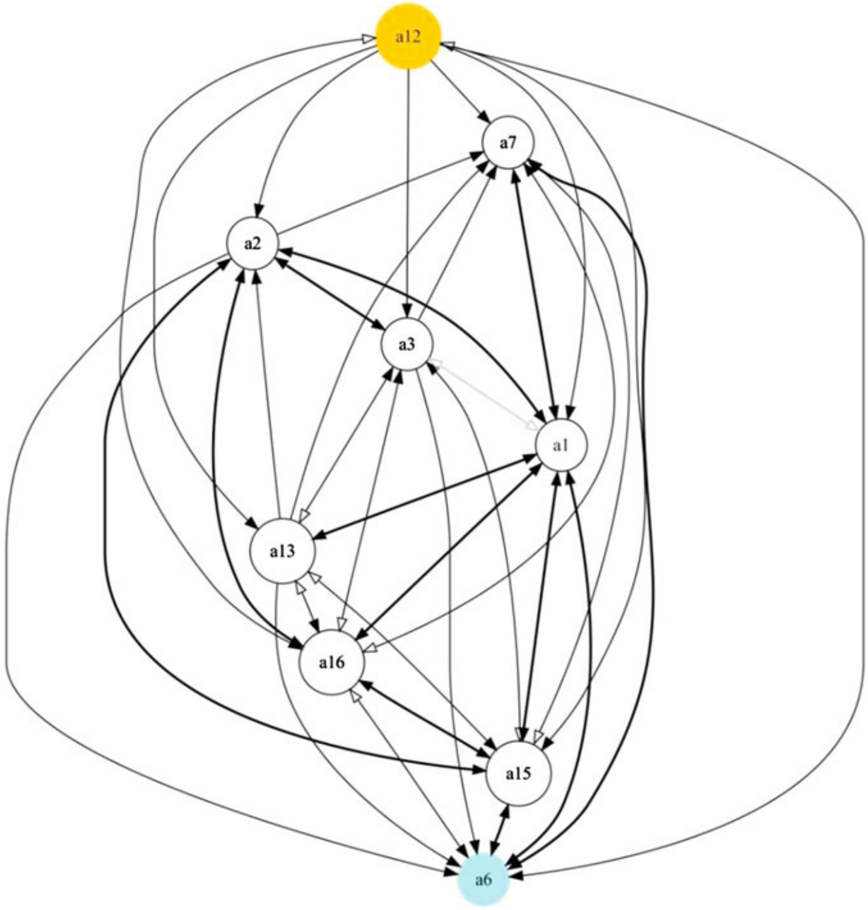

Fig. 2.5 Robustly concordant outranking graph (Ghisonaccia set of projects)

choice problematic. Also, the method appears intelligible, because the bipolar valuation of the outranking relation is solely based on sums and differences of weights of individual criteria. Similarly, the steps of the RCR algorithm seem clear. However, the analyst must be computer-aided both with the methods RUBIS and ELECTRE IS, because the complexity of calculus (digraphs processing and Robustness analysis of the results) increases in real cases studies. Let us note the advantage of RUBIS to be implemented in a solver web service at the University of Luxembourg, thereby removing the constraint of incompatibility due to a change of operating system. In addition, the RUBIS method delivers enriched conclusions such as the bad choice alternative(s). In contrast, ELECTRE IS method offers the possibility to parameter the so-called sufficient majority of criteria to test an outranking statement. In the RUBIS method is considered a strict

0-cut outranking relation, corresponding to more than 50 % of the global criteria significance weights. A more general crisp relation could be considered, to apply other values of majority.

Finally, as pointed upstream, the evaluations of PV plant projects were based on data files provided by industries to local decision makers. The estimated net production, given by the criterion g_1, was directly extracted. The lack of detail on the calculations has left us sceptical. Consequently, have been defined threshold values to avoid cases of strict preference between projects. Also, the actor CDA2B requesting the study has given a median rank of importance to this criterion. Thus, its role was somewhat restricted. Recently and after submission of the study report, we have developed a mapping of solar potential in Corsica (Haurant et al. 2012), based on sub-pixel disintegration method, reducing the errors of radiation estimates and improving the spatial resolution. This advance would reassess projects on this criterion.

2.4 Conclusion

Was successfully implemented the RUBIS methodology confirming the results previously obtained with the ELECTRE IS method for aiding to select photovoltaic plants on farmlands in the Haute-Corse department of the island (Haurant et al. 2011). Moreover, let us assert that the basic ELECTRE I method is still applied especially to support an investor in choosing the best alternative to develop a small photovoltaic park, in the Greek PV market (Siskos and Houridis 2011). All these operational researches dealing with the choice problematic are performed within the ELECTRE outranking-based approach and they implement robustness analysis of the results (i.e., the best solution(s) to be selected). The complexity of MCDA in energy real case studies justifies well-established scientific methods and a computer-aided analyst. This combination is possible within the RUBIS methodology, as outlined in this chapter. In summary, it offers an operational research toolbox, coherent, modern, and transparent, to deal with the choice problematic in MCDA. The main three innovative tools are a new graph theory-related object (i.e., the maximally determined strict outranking hyperkernel), the outranking method RUBIS in the tradition of ELECTRE IS and the RUBIS D3 web server for computing and solving a choice problem with Cordorcet robustness analysis of the results.

In contrast, at a regional level (i.e., the Haute-Corse and Corse-du-Sud departments), the Assembly of Corsica has carried out its own multicriteria evaluation (Assemblée de Corse 2009a, b) of all the 74 proposed PV plant projects (on farmlands or not) with a simplistic framework (weighted arithmetic mean strongly compensatory, no rigorous tool for weighting the 39 qualitative criteria, no robustness analysis of the recommendations). Sustainable energy systems in Corsica island must be evaluated in a more formalized framework for a relevant multicriteria selection.

More broadly, assessment and simulation tools in MCDA must meet a variety of methodological challenges, including in particular the four following: coupling with GIS (Oberti and Bollinger 2013) notably for site selection (Defne et al. 2011) (Van Haaren and Fthenakis 2011) focusing on the compensatory logic of the data aggregation and on the robustness of mapping results; participatory approach (Oberti and Paoli 2013) to sustainable energy futures (Kowalski et al. 2009); dealing with the sorting problematic such as the outranking ELECTRE TRI-based methods notably implemented to biogas plants (Madlener et al. 2009) and energy efficiency (Neves et al. 2008); and finally delivering new MCDA- web application such as the Decision Deck collaborative open source software platform (www.decision-deck.org).

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Chapter 3
Assessment of Green Energy Alternatives Using Fuzzy ANP

Başar Öztayşi, Seda Uğurlu and Cengiz Kahraman

Abstract Sustainability has gained tremendous importance and has been an important issue both for policy makers and practitioners. Realizing that the resources on the earth are limited, green energy (GE) alternatives have flourished and started to replace the conventional energy alternatives. Energy planning using different energy alternatives, for the long term becomes a vital decision. In this study, fuzzy multi criteria decision- making methodology, fuzzy analytic network process (FANP) are utilized for the ranking GE alternatives. The ANP is a multi criteria decision-making (MCDM) technique which enables feedback and replaces hierarchies of relationships with networks of relationships. In ANP technique, not only does the importance of the criteria determine the importance of the alternatives, as in a hierarchy, but also the importance of the alternatives may have impact on the importance of the criteria. Fuzzy ANP allows measuring qualitative factors by using fuzzy numbers instead of crisp numbers in order to make decisions easier and obtain more realistic results. A case study is presented for the assessment of GE alternatives in Turkey with respect to various perspectives such as; technical, economical, and environmental. According to the outcome of the BO/CR method, hydropower has the highest priority which is followed by geothermal and biomass energy sources. Though the hydropower is not the best alternative from Benefits and Opportunities viewpoint, because of low costs and risks it comes into view to be the best alternative for Turkey.

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3.1 Introduction

Economic development is aligned together with energy use, which is one of the main inputs as well as a consequence. High economic development, increased population of the world, and rapid technological advances have increased the demand for energy globally. Over many years, the main resource for energy has been fossil fuels. However, fossil fuels such as petroleum, natural gas are estimated to be exhausted in a near future with the increasing need of energy. Another issue with the excess consumption of the fossil fuels is their irreversible hazards on the ecological environment as well as human health.

Realizing that the resources on the earth are limited, sustainability has gained tremendous importance and has been an important issue both for policy makers and practitioners. Sustainability is described as the long-term maintenance of responsibility, which has environmental, economic, and social dimensions, and encompasses the concept of responsible management of resource use. As sustainable sources of energy gained importance, green energy (GE) alternatives have flourished and started to replace the conventional energy alternatives.

Sustainable energy is the sustainable provision of energy that meets the needs of the present without compromising the ability of future generations to meet their needs. Together with goal of sustainability, specifically GE includes natural energetic processes that can be harnessed with little pollution. Technologies that promote GE include renewable energy sources (RES) such as geothermal power, wind power, small-scale hydropower, solar energy, biomass power, tidal power, and wave power. On the other side, fossil fuels are non-renewable resources because it takes millions of years to form, and reserves are being depleted much faster than new ones are being made. The production and use of fossil fuels raise environmental concerns. Even so, fossil fuels had a great importance for many years because they can be burned, producing significant amounts of energy per unit weight.

The complex relations of the energy issue with the ecological environment, socio-economical environment, and energy production technologies reveal a multifaceted assessment problem. Besides, evaluation of energy issues is a complex problem due to conflicting objectives and a large number of stakeholders with different aims and preferences. This complexity of the problem leads to apply multi criteria decision making (MCDM) as a methodology used to resolve the emerging conflicts by summing up the performances of each criterion weighted with their importance.

On the other side, energy planning generally involves many sources of uncertainty and a long time frame. The source of uncertainty exists mainly due to external factors closely related to energy issues as well as unknown future conditions need to be considered because of the long time frame of planning. Thus, judgments of decision makers are prone to a high degree of uncertainty rising from the nature of energy issues. Under these conditions, it is relatively difficult for the decision makers to provide exact numerical values for the criteria or attributes.

Besides, ambiguity often exist among decision makers' judgments with respect to the criteria that they evaluate. Fuzzy logic which resembles human thoughts is effectively used in many areas in order to model these types of uncertainty. Fuzzy logic uses fuzzy set theory to deal with imprecise information by using membership functions. In fuzzy set theory, an element of a fuzzy set naturally belongs to the set with a membership value from the interval [0, 1].

In this study, we employ analytical network process (ANP) in order to evaluate and select the primary GE alternatives for the case of Turkey. The network structure of ANP is particularly suitable to incorporate the multi criteria evaluation of different GE alternatives by aggregating views and preferences of multiple participants. The conflicting criteria used in the evaluation process have been classified through the use of benefits, opportunities, costs, and risks (BOCR) framework which help to systematically consider the multifaceted nature of energy planning.

The chapter is organized as follows: the next section gives a brief summary about GE alternatives and their assessment. Literature review on multi criteria decision approaches about energy alternative is given in Sect. 3.3. Section 3.4 contains the fuzzy multi attribute approach that is used in this study. A numerical energy alternatives assessment application is supplied in Sect. 3.5. Finally, the results of the study are discussed and suggestions about future studies are given in conclusion section.

3.2 Assessment of Green Energy Alternatives

Prior to the presentation of the evaluation framework for selecting the primary GE alternatives of Turkey, we will discuss the GE alternatives with their present use and potential both globally and locally in Turkey. Then, we will identify the advantages and disadvantages of GE alternatives in the following subsections.

3.2.1 GE Alternatives

Together with goal of sustainability, GE is characterized by the natural energetic processes that can be harnessed with little pollution. Technologies that promote GE consists of RES such as hydropower, geothermal power, wind power, solar energy, biomass power (small-scale hydropower, tidal power, and wave power).

3.2.1.1 Hydropower

Hydro energy is obtained by allowing water to fall on a turbine to turn a shaft. Electricity is produced from the kinetic energy of falling water. The water in rivers and streams can be captured and turned into hydroelectric power, also called hydropower. Hydropower is inexpensive, and like many other RES, it does not produce air pollution (Erdogdu 2011). Hydropower is a source of energy with long viability, low operation, and maintenance cost. Moreover, it promotes energy safety, independence, and price stability (Yuksel and Kaygusuz 2011).

Hydropower is certainly the largest and most mature application of RES. In 2007, the electricity output of hydropower installations was 3,078 terawatt-hours (TWh), which covered, approximately, 15.5 % of the world's entire electricity demand.

3.2.1.2 Geothermal Power

Geothermal energy sources include both low-temperature ground source heating and deep thermal wells to exact high temperatures for electricity generation (Harmon and Cowan 2009). It is widely accessible globally and realized as an important RES which allows direct and indirect use. The common direct use is residential and thermal facility heating whereas indirect use of geothermal resources is generally for electrical power generation.

3.2.1.3 Wind Power

Wind was one of the first energy sources to be harnessed by early civilizations. Ever since, it has furnished an abundant resource and one of the least expensive methods of power generation. Wind power has been used to propel sailboats and sail ships, to provide mechanical power for grinding grain in windmills, and for pumping water (Angelis-Dimakis et al. 2011).

Since then, Wind energy in electricity generation has developed and spread widely. The development in wind energy technology, despite the uncertain nature of the wind energy source, has made it one of the most promising alternative to conventional energy systems in recent years (Castronuovo et al. 2007). As a result of this development, total installed capacity of the world reached to 120.791 MW in 2008 (Baris and Kucukali 2012).

3.2.1.4 Solar Energy

Solar power uses heat energy from the sun both to generate electricity and to distribute heat for industrial and residential use. Today, the most common technologies for utilizing solar energy are photovoltaic (PV) and solar thermal systems. PV systems use specific wavelengths of light to produce electricity directly. The advantage is they are small, simple, with no moving parts but presently it offers the most expensive forms of power generation (Harmon and Cowan 2009).

One of the main influencing factors for an economically feasible performance of solar energy systems (besides of installation costs, operation costs, and lifetime of system components) is the availability of solar energy on ground surface that can be converted into heat or electricity. Therefore, precise solar irradiation data are of utmost importance for successful planning and operation of solar energy systems. Solar irradiation means the amount of energy that reaches a unit area over a stated time interval, expressed as $\mathrm{Wh/m^2}$ (Angelis-Dimakis et al. 2011).

3.2.1.5 Biomass Power

Biomass is defined as the biodegradable fraction of products, wastes and residues from agriculture, forestry, and related industries, as well as the biodegradable fraction of industrial and municipal wastes. Moreover, biomass can be grown on purpose in dedicated energy crops (Angelis-Dimakis et al. 2011). Residual biomasses derive from:

- the agricultural sector, both in the form of crop residues and of animal waste;
- the forestry sector, from forests' thinning and maintenance;
- the industrial sector of wood manufacture and food industries;
- the waste sector, in the form of residues of parks maintenance and of municipal biodegradable wastes.

Biomass energy is derived mainly by burning plants or products made from them. Combustible renewables and waste (CRW) are traditional biomass energy obtained from burning garbage. Advanced biomass involves the creation of more sophisticated fuels, such as ethanol or biodiesel, which can be used in automobiles or for power generation (Harmon and Cowan 2009).

3.3 Literature Review

Assessment of energy alternatives and related policies has been the subject of researches that use different MCDM techniques. Table 3.1 represents a classification of these researches according their approach (crisp or fuzzy) and the methods used.

Among the crisp approaches the mostly used methods are PROMETHEE, ELECTRE, and AHP/ANP. The other MCDM methods used in the assessment of energy alternatives are TOPSIS, VIKOR, MAUT, and DEA.

PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) is an outranking method based on the pairwise comparison of different options against the criteria defined by the decision maker. Using PROMETHEE, Madlener et al. (2007) compared five renewable energy scenarios considering Austria in the year 2020. In their comprehensive study, Terrados et al. (2009) proposed a hybrid methodology using SWOT analysis, Delphi, and PROMETHEE for renewable energy planning for Jae'n Province.Region. The researchers used SWOT analysis to define 28 potential renewable energy strategy,

Table 3.1 Linguistic scales for weight matrix (Hsieh et al. 2004)

Approach	Methods used	References
Crisp	PROMETHEE	Madlener et al. (2007), Terrados et al. (2009), Tsoutsos et al. (2009)
	Electre	Catalina et al. (2011), Georgopoulou et al. (1997), Papadopoulos and Karagiannidis (2008)
	TOPSIS	Streimikiene et al. (2012)
	VIKOR	San Cristóbal (2011a)
	MAUT	Loken et al. (2009)
	AHP	Shen et al. (2011), Wang et al. (2010), Yi et al. (2011) Zangeneh et al. (2009)
	ANP	Dağdeviren and Ergün (2008), Erdoğmuş et al. (2006), Köne and Büke (2007), Ulutaş (2005)
	DEA	San Cristóbal (2011b)
Fuzzy	Fuzzy AHP	Heo et al. (2010), Kahraman et al. (2009), Shen et al. (2010), Talinlia et al. (2010)
	Fuzzy TOPSIS	Boran et al. (2011), Kaya and Kahraman (2011)
	Fuzzy VIKOR	Kaya and Kahraman (2010)
	Fuzzy AD	Kahraman et al. (2009)

then expert opinions are collected via Delphi technique, and PROMETHEE is utilized to select among the alternative actions. Tsoutsos et al. (2009) exploits the PROMETHEE for the sustainable energy planning on the island of Crete in Greece. A set of energy planning alternatives are determined and assessed against economic, technical, social, and environmental criteria.

ELECTRE, developed by Benayoun at late 1960s, is classified as an outranking method in MCDM (Triantaphyllou 2000). In the ELECTRE method concordance and discordance indexes are defined as measurements of satisfaction and dissatisfaction that a decision maker chooses one alternative over the other. These indexes are then used to analyze the outranking relations among the alternatives. Georgopouloe et al. (1997) use ELECTRE III to assess the renewable energy options for energy planning for a Greek Island. Using ELECTRE, Catalina et al. (2011) evaluate and choose the optimal multi source renewable energy alternatives. The same method is also used in the study of (Papadopoulos and Karagiannidis 2008) which assesses different scenarios for using RES for the purpose of electricity generation.

Analytical hierarch process (AHP) and analytic network process (ANP) are the other most commonly used techniques used in assessment of energy alternatives. The AHP, developed by Saaty (1980), structures a decision problem as a hierarchical, containing an overall goal, a group of alternatives, and of a group of criteria. The method is based on the use of pairwise comparisons. Pairwise comparisons are carried out by asking how more valuable an alternative A is to criterion C than another alternative B. These pairwise comparisons are later used to calculate the weights of the alternatives. The ANP is an generalization of AHP and developed by Saaty to deal with dependence and feedback among alternatives and criteria. Shen et. al (2011) assess the renewable energy portfolio using AHP, Wang et al. (2010) build a model to evaluate the energy alternatives for China, Yi et al. (2011) propose a benefits, opportunities, cost, and risks (BOCR) model with AHP. As will be discussed in the forthcoming sections, BOCR is a way of modeling decision problems from different perspectives. The ANP can also be used with BOCR approach, (Ulutaş 2005) determine the appropriate energy policy for Turkey (Dağdeviren and Ergün 2008) build a model to prioritize energy policies, (Erdoğmuş et al. 2006) used the model to evaluate alternative fuels for residential heating in Turkey.

Fuzzy approaches to the problem are relatively limited in number. Fuzzy versions of methodologies such as Fuzzy AHP, Fuzzy TOPSIS, Fuzzy VIKOR, and Fuzzy Axiomatic design are used. Heo et al. propose a model with five criteria and 17 factors to assess the renewable energy dissemination programs. Shen et al. (2010), propose a model to reveal the suitable RES for the purposes of meeting the 3E policy goals which are to pertain to energy, the environment, and the economy. Talinli et al. (2010) build a model using Fuzzy AHP for a comparative analysis of three different energy production process scenarios for Turkey. Kahraman et al. (2009) utilize fuzzy AHP with fuzzy Axiomatic Design to make selection among the RES. In the study, Fuzzy AHP is used to prioritize the criteria and fuzzy AD is used to evaluate the alternatives under objective or subjective criteria with respect to the functional requirements obtained from experts.

Fuzzy TOPSIS enables fuzzy values to be used in the decision problem. Boran et al. (2011) evaluate the renewable energy technologies for electricity generation in Turkey, using intuitionistic fuzzy TOPSIS. PV, hydro, wind, and geothermal energy have been evaluated for long-term renewable technologies for Turkey.

Kaya and Kahraman (2011) propose a modified fuzzy TOPSIS methodology for energy planning decisions by taking into account technical, economic, environmental, and social attributes. They also incorporate fuzzy AHP to determine the weights of the selection criteria. Kaya and Kahraman (2010) propose using AHP and VIKOR together under fuzziness. They apply the model in order to determine the best renewable energy alternative and energy production sites for Istanbul.

The literature review presents that renewable energy assessment problem is a MCDM problem that can be handled with crisp and fuzzy However, there is an absence in using Fuzzy ANP on the area, thus in this study Fuzzy ANP with BOCR approach is used as a case study. The details about the fuzzy multi attribute approach are given briefly in the following section.

3.4 A Fuzzy Multi Attribute Approach

3.4.1 Fuzzy Set Theory

The fuzzy set theory was designed by Zadeh (1965) to deal with real-world uncertainties. In the classical set theory, an element either belongs or does not belong to a set. However, in fuzzy sets each element has degree of membership for a fuzzy set that can get values in the interval [0, 1]. This membership degree is described with a membership function. In classical crisp modeling, the imprecise parameters have to be represented with crisp values, however, using fuzzy representations empowers the process and the results are expected to be more credible (Kahraman et al. 2006). Using membership functions, fuzzy sets can mathematically represent uncertainty and vagueness, thus provide an important problem modeling and solution technique.

Fuzzy sets are represented with a tilde "$\sim$" above the set symbol; a fuzzy set M is represented as $\tilde{M}$ and the membership functions for the fuzzy set is shown as $\mu(x|\tilde{M})$. The term fuzzy number is used to handle imprecise numerical quantities such as "close to 10", "about 7". A fuzzy number may be represented in discrete or continuous forms. One of the commonly used continuous forms is the triangular fuzzy number (TFN). A TFN is denoted simply as (m_1, m_2, m_3). The parameters m_1, m_2, and m_3, respectively, denote the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event. A TFN $\tilde{M}$ is shown in Fig. 3.1.

The linear representation of membership function can be given as:

$$\mu\left(x|\tilde{M}\right) = \begin{cases} 0, & x < m_1 \\ \frac{x-m_1}{m_2-m_1}, & m_1 \le x \le m_2 \\ \frac{m_3-x}{m_3-m_2}, & m_2 \le x \le m_3 \\ 0, & x > m_3 \end{cases} \tag{3.1}$$

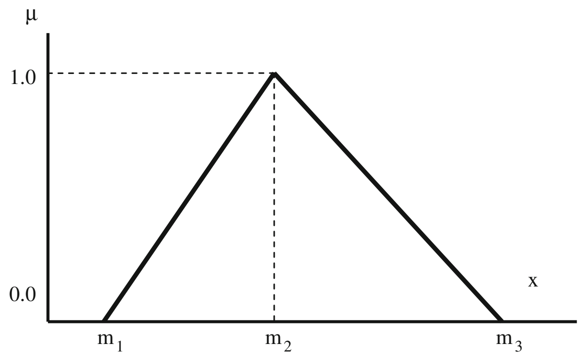

Fig. 3.1 A triangular fuzzy number, MI

Mathematical operations are needed to use the fuzzy numbers in real-world problems. (Chen et al. 1992) give the fuzzy operations for TFNs M (m_1, m_2, m_3) and N (n_1, n_2, n_3) as follows:

$$\text{Addition:}\, M(+)N = (m_1 + n_1, m_2 + n_2, m_3 + n_3)$$

$$\text{Subtraction:}\, M(-)N = (m_1 - n_1, m_2 - n_2, m_3 - n_3)$$

$$\text{Multiplication:}\, A(.)N \cong (m_1 n_1, m_2 n_2, m_3 n_3) \text{ if } M > 0 \text{ and } N > 0$$

$$\text{Division:}\, A(:)N \cong \left(m_1/n_1, m_2/n_2, m_{3/}n_3\right) \text{ if } M > 0 \text{ and } N > 0$$

3.4.2 Fuzzy Analytic Network Process

In many real-world decision-making cases interaction and dependence exist among the decision elements from different levels. ANP is a methodology developed by Saaty (1980) as an alternative to deal with such interactions. Hierarchies and network have different structures (Fig. 3.2), a hierarchy is consist of a goal, levels of elements, and connections between elements, however, a network is composed of element clusters which can influence each other.

The influence between the elements of a network can be classified into two groups: outer and inner. Inner influence specifies the influence of elements in a group on each other. Outer influence is the influence of elements in a cluster on elements in another cluster with respect to a control criterion.

ANP methodology is based on pairwise comparisons of decision elements. In the pairwise comparisons, the decision maker is asked to evaluate the two element with respect to the common property using the smaller element as the unit and estimate the larger element as a multiple of that unit (Saaty and Özdemir 2005). In the original crisp method, each scale is associated with a corresponding crisp

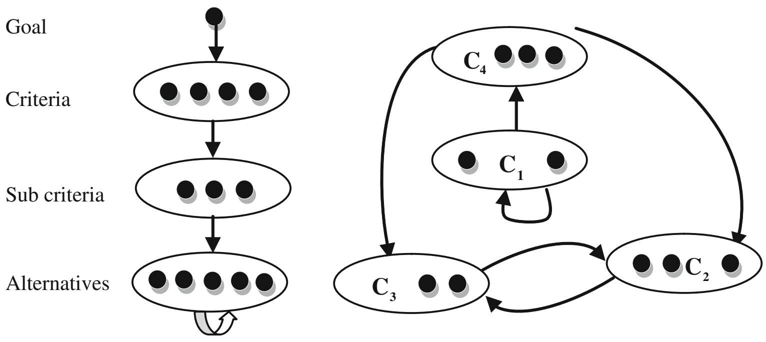

Fig. 3.2 Hierarch and network structures

Table 3.2 Linguistic scales for weight matrix (Hsieh et al. 2004)

Linguistic scales	Scale of fuzzy number	
(1,1,3)	Equally important	(Eq)
(1,3,5)	Weakly important	(Wk)
(3,5,7)	Essentially important	(Es)
(5,7,9)	Very strongly important	(Vs)
(7,9,9)	Absolutely important	(Ab)

number, however, in the fuzzy case linguistic scales can be used and each judgment is represented as a TFN (Table 3.2).

As the pairwise comparison matrix is formed, the next step is to determine the relative importance/priorities of each decision element. There are different methods proposed for Fuzzy ANP in the literature (Buckley 1985; Chang 1996). Using one of these methods, the priorities can be calculated from the pairwise comparison matrix that is composed of linguistic judgments. Table 3.3 presents a sample pairwise comparison matrix, the fuzzy weights calculated using Buckley's method and the defuzzified weights.

In the ANP methodology, matrix is used to represent the flow of influence between decision elements. Each cell in a supermatrix represents the influence priority of the element on the left side of the matrix and on the element at the top of the matrix with respect to a particular control criterion. Zero is assigned to the considered cell if there is no influence between the elements. A supermatrix is shown in formula 3.2 with an example of one of its general entry matrices. Formula 3.3 shows the detail of a component in a supermatrix.

$$\mathrm{W} = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \ldots & C_N \\ e_{11}e_{12}\ldots e_{1n_1} & e_{11}e_{12}\ldots e_{2n_2} & \ldots & e_{N1}e_{N2}\ldots e_{Nn_N} \end{array} \\ \begin{array}{cc} & e_{11} \\ C_1 & \ldots \\ & e_{1n_1} \\ & e_{21} \\ C_2 & \ldots \\ & e_{2n_2} \\ & e_{11} \\ C_1 & \ldots \\ & e_{1n_1} \end{array} & \left[\begin{array}{cccc} W_{11} & W_{12} & \ldots & W_{1N} \\ W_{21} & W_{22} & \ldots & W_{2N} \\ & & \ldots & \\ W_{N1} & W_{N2} & \ldots & W_{NN} \end{array}\right] \end{array} \tag{3.2}$$

Table 3.3 Sample pairwise comparisons, fuzzy and crisp weights

	C1	C2	C3	C4	Fuzzy weights	Crisp weights
C1	Eq	Vs	Ab	Ab	1.56, 1.88, 2.17	0.429
C2	1/Vs	Eq	Es	Wk	0.79, 0.93, 1.18	0.224
C3	1/Ab	1/Es	Eq	Wk	0.63, 0.71, 0.93	0.175
C4	1/Ab	1/Wk	1/Wk	Eq	0.62, 0.79, 0.84	0.172

$$W_{ij} = \begin{bmatrix} W_{i1}^{(j1)} & W_{i1}^{(j1)} & \cdots & W_{i1}^{(jn_j)} \\ W_{i2}^{(j1)} & W_{i2}^{(j2)} & \cdots & W_{i2}^{(jn_j)} \\ \vdots & \vdots & \ddots & \vdots \\ W_{in_1}^{(j1)} & W_{in_1}^{(j2)} & \cdots & W_{in_1}^{(jn_j)} \end{bmatrix} \tag{3.3}$$

The supermatrix is raised to its powers to capture the transmission of influence along all possible paths of the supermatrix. Each power of the matrix captures all transitivities of an order that is equal to that power. For the final results, the steady state priorities are investigated from the limit of the supermatrix. The limit supermatrix is computed according to whether it is irreducible or it is reducible with one being a simple or a multiple root and whether the system is cyclic or not. There are two possible outcomes, each column of the limit matrix can be equal or not. If each column is identical, each one gives the relative priorities of the elements from which the priorities of the elements in each cluster are normalized to one. In the second, the limit cycles in blocks and the different limits are summed and averaged and again normalized to one for each cluster. The limit priorities are put in the idealized form because the control criteria do not depends on the alternatives (Saaty and Özdemir 2005).

3.4.3 BOCR Approach

In decision making, there are criteria that are opposite in direction to other criteria, such as criteria in benefits (B) versus those in costs (C), and criteria in opportunities (O) versus those in risks (R). Saaty (2001) presented BOCR model to analyze a decision problem from four different perspectives and synthesize the priorities of alternatives by combining the priorities of alternatives under these perspectives. Under the BOCR concept, four different subnetworks are structured and pairwise comparison questions ask which alternative is most beneficial, has the best opportunity, which one is riskiest and costliest according to the structured networks. The weights of alternatives are determined first according to the weights of criteria for each network. Later, the weights of the alternatives under *B*, *O*, *C,* and *R* are combined to get a single outcome for each alternative. There are five ways to combine the scores of each alternative under *B*, *O*, *C,* and *R*. The relative priority, *P*, for each alternative can be calculated using the formulas given below where *B*, *O*, *C,* and *R* represent, respectively, the synthesized results of alternatives and *b*, *o*, *c,* and *r* are, respectively, normalized weights of merit *B*, *O*, *C,* and *R*.

1. Additive:

$$P = bB + oO + c\left[(1/C)_{\text{Normalized}}\right] + r[1/R_{\text{Normalized}}] \tag{3.4}$$

2. Probabilistic additive:

$$P = bB + oO + c[1 - C] + r(1 - R) \tag{3.5}$$

3. Subtractive:

$$P = bB + oO - cC - rR \tag{3.6}$$

4. Multiplicative priority powers:

$$P = B^b O^o \left[(1/C)_{\text{Normalized}}\right]^c \left[(1/R)_{\text{Normalized}}\right]^r \tag{3.7}$$

5. Multiplicative:

$$P = BO/CR \tag{3.8}$$

The steps that should be followed when applying BOCR approach with ANP application as follows (Saaty and Özdemir 2005):

Step 1: Description of the decision problem.

Step 2: Determine the control criteria and subcriteria in the four control hierarchies.

Step 3: For each control criterion or sub-criterion, determine the clusters of the general feedback system with their elements and connect the according to their outer and inner dependence influences. An arrow is drawn from a cluster to any cluster whose elements influence it.

Step 4: For each control criterion, construct the supermatrix.

Step 5: Perform paired comparisons on the elements within the clusters themselves according to their influence on each element in another cluster they are connected to (outer dependence) or o elements in their own cluster (inner dependence).

Step 6: Perform paired comparisons on the clusters as they influence each cluster to which they are connected with respect to the given control criterion.

Step 7: Compute the limit priorities of the stochastic supermatrix.

Step 8: Synthesize the limiting priorities by weighting each idealized limit vector.

3.5 Assessment of Energy Alternatives Using Fuzzy ANP

In this section, a numerical is given using BOCR approach and Fuzzy ANP. Initially, the current and potential situation of the GE alternatives in Turkey is given and then the assessment model is described and the results are discussed.

3.5.1 GE Alternatives in Turkey

Hydropower Energy: Turkey takes place in the first 15 largest hydropower producing countries with a capacity of 35,851 GWh and a percentage of 1.2 by 2007. Turkey's theoretical hydroelectric potential is 1 % of that of the world and 16 % of Europe. The gross theoretical viable hydroelectric potential in Turkey is 433 billion kWh and the technically viable potential is 216 billion kWh. The economically viable potential, however, is 140 billion kWh (Yuksel and Kaygusuz 2011). Among RES in Turkey, hydropower has the highest share with 93.8 % in terms of installed capacity. Turkey has been divided into 26 river basins; however, 97 % of its economically feasible hydropower potential is distributed into 14 river basins.

As of 2009, 172 hydropower plants have been put into operation, 148 are under construction, and a further 1,418 are at various planning stages. Hydropower plants in operation have an installed capacity of 13,700 MW with an annual average generation of 48,000 GWh. Only 34 % of the economically utilizable hydro potential has been developed in Turkey (Erdogdu 2011).

Geothermal Energy: Turkey has a significant geothermal potential owing to its geographical location along Alpine–Himalaya belt. A total of 172 regions having geothermal energy potential have been explored in Turkey. Among them, the most important geothermal systems of Turkey are located in the major grabens of the Menderes Metamorphic Massif, while those that are associated with local volcanism are more common in the central and eastern parts of the country (Yuksel and Kaygusuz 2011).

Turkey's geothermal power potential corresponds to one-eighth of the world's total geothermal potential (Balat 2004). There may exist about 2,000 MW of geothermal energy usable for electrical power generation and about 31,500 MWt for geothermal heating purposes (Yuksel and Kaygusuz 2011). The installed capacity in Turkey currently being used in residential and thermal facility heating is 635 MWt while an installed capacity of 192 MWt is being used for green house heating. Moreover, an installed capacity of 402 MWt is being used for thermal tourism purpose. Hence, the total direct use of geothermal energy in the country is 1,229 MWt (Baris and Kucukali 2012). In recent years, the search for new geothermal sites and projections for new installations have been emphasized in the Turkish governmental plans and the total direct use planned for 2013 is significantly high compared to actual values in 2005 (Baris and Kucukali 2012).

Wind energy: Turkey has one of the richest wind energy potentials among European countries. Turkey's total technical potential for wind power is estimated to be around 114.173 MW. Turkey's total economically feasible potential for wind power is estimated to be 20.000 MW (EIE 2009; MENR 2008). The most attractive regions for wind energy utilization are the Marmara, Aegean, and Black Sea regions possessing, respectively, 38.5, 23, and 12.5 % of the total wind power potential of the country.

Although Turkey has much higher technical wind power potential than other European countries, only a very small percentage of this potential is used when compared to those countries (Baris and Kucukali 2012). As for Turkey's situation related to wind energy utilization, it can be seen that Turkey is rather unsuccessful in using its potentials (Erdem 2010). This is mainly due to the lack of incentive policies which are provided by the governments of EU countries for promoting the utilization of RES. An initiative toward encouraging the utilization of RES in Turkey has been the Renewable Energy Law in Turkey. By the enacting of this law in 2005, the capacity of wind power has started to increase significantly. A total of 93 wind projects with a total installed capacity of 3,363 MW have been licensed after the enactment of the law (Baris and Kucukali 2012).

Solar energy: The climate and geographical location of Turkey highlight the solar energy as an important RES with the yearly average solar radiation 3.6 kWh/m^2-day and the total yearly radiation period being, approximately, 2,640 h in Turkey. The solar energy potential of Turkey is calculated as 380 billion kWh/year. Average solar energy potential of Turkey and corresponding insolation durations on monthly basis (Baris and Kucukali 2012).

In spite of this high potential, solar energy is not now widely used, except for flat-plate solar collectors which turn solar energy into thermal energy. They are only used for domestic hot Water generation, mostly in the sunny coastal regions (Angelis-Dimakis et al. 2011). In 2006, country has about total 7.0 million m^2 solar collectors and it is predicted that total energy production is about 0.390 Mtoe in 2006 (Yuksel and Kaygusuz 2011).

Currently, Turkey does not have an organized commercial and domestic PV program. Taking the high rates of solar irradiation rates and wide area of the land, PV applications are suitable for the energy generation. However, the PV generation application is insignificant and currently, the total PV generation capacity in Turkey is 3 MWp. PV energy is used for signaling purposes and in rural areas such as the watch towers of the Ministry of Environment and Forestry, light houses and lighting of highways (Erdem 2010).

Biomass Energy: Biomass is the major source of energy in rural Turkey since it is available locally and allows widespread production of energy at reasonable costs. The annual biomass potential of Turkey is approximately 32 Mtoe. Among OECD countries, Turkey takes the fourth place from the top in the estimated total energy potential from crop residues with 9.5 Mtoe (Erdem 2010).

Biogas production potential of Turkey is estimated to be 1.5–2 Mtoe. However, the current production capacity is limited with two small operating producers and one new licensed facility. Around 85 % of the total biogas potential is from dung gas, and the remainder is from landfill gas. The dung gas potential is obtained from 50 % sheep, 43 % cattle, and 7 % poultry (Erdem 2010).

Biodiesel production is also limited in Turkey by one bioethanol manufacturer with a total production capacity of 30.000 m^3/year. However, it is projected that the number of producers will increase because there are many production companies waiting for the production licenses to be granted by energy market regulatory authority (EMRA).

3.5.2 The BOCR Model

The BOCR model designed for the assessment of GE alternatives is shown in Table 3.3. For the construction of the BOCR model, first an extended literature review is accomplished and the potential clusters and potential criteria for each network are determined. In the second phase, the determined alternative cluster listed to a group of experts and the ones that the group is agreed on are selected. In the third phase, the alternative criteria are evaluated and with the view of the experts the criteria are picked. In the final BOCR model, each network has the alternatives and participants clusters. Benefits network, however, includes economical, environmental political, technical, and social criteria clusters. The criteria used in the model are also listed in Table 3.4

The steps listed in the previous subsection are followed for the assessment of the GE alternatives but only representative calculations are given. Based on the subnetwork shown in Fig. 3.3 and the criteria listed in Table 3.3, pairwise comparisons are done on the elements within the clusters themselves according to outer and inner dependencies. Buckley's (1985) fuzzy calculations are used to calculate the priorities from the pairwise comparisons. Table 3.5 represents the supermatrix constructed with the eigenvectors of the pairwise comparison matrix.

As the supermatrix is formed, the cluster matrix is constructed. The clusters themselves are compared to establish their importance and use it to weight the corresponding blocks of the supermatrix to make it column stochastic. The clusters that effects target cluster are pairwise compared for the importance of their impact

Table 3.4 Criteria used in the BOCR model

Economical (C1)	*Opportunity criteria* (C6)
• Low and stable energy prices (C11)	• Potential for commercialization (C61)
• Economic life time of the investment (C12)	• Local economic development (C62)
• Incentives and subsidies (C13)	• Low carbon economy integration (C63)
Environmental (C2)	*Cost criteria* (C7)
• Reductions in emission to air (C21)	• Investment cost (C71)
• Environmental sustainability (C22)	• Operating cost (C72)
	• Maintenance cost (C73)
	• Distribution and transmission cost (C74)
	• Grid cost (C75)
	• Social cost (C76)
Technical–Technological (C3)	*Risk criteria* (C8)
• Maturity of the technology (C31)	• Availability (C81)
• Reliability of the technology and operation (C32)	• Social risk (C82)
• Simplicity of construction and installation (C33)	• Environmental risk (C83)
• Technical know-how of local actors (C34)	• Human health risks (C84)
• High learning rate (C35)	• Safety risks (explosion, firing, etc.) (C85)
Social (C4)	*Alternatives* (A1)
• Increase in employment rate (C41)	• Solar (A11)
• Public acceptance (C42)	• Wind (A12)
• Regional benefits (C43)	• Biomass (A13)
• Social sustainability (C44)	• Hydropower (A14)
	• Geothermal (A15)
Political (C5)	*Participants* (P1)
• Security for energy supply (C51)	• Policy Makers (P11)
• Foreign dependency (energy import/export) (C52)	• Suppliers (P12)
• Morality effect (C53)	• Consumers (P13)
• Political acceptance (C54)	• Local Stakeholders (P14)
• Interboarder impacts (C55)	

on it with respect to opportunities control criterion. Table 3.6 represents the cluster matrix for opportunities subnetwork.

The next step is to construct the weighted supermatrix. Weighted supermatrix is obtained by multiplying each entry in a block of the component at the top of the supermatrix by the priority of influence of the component on the left from the cluster matrix shown in Table 3.6. For example, the value 0.251 is used to multiply the nine entries in the block (Opp. Criteria–Opp. Criteria) in the unweighted supermatrix. The weighted supermatrix for the opportunities subnetwork is shown in Table 3.7.

After the weighted supermatrix is constructed, the limit priorities of the supermatrix are calculated. The weighted supermatrix is raised to its powers till the limit supermatrix is reached. Table 3.8 represents the limit supermatrix for opportunities subnetwork.

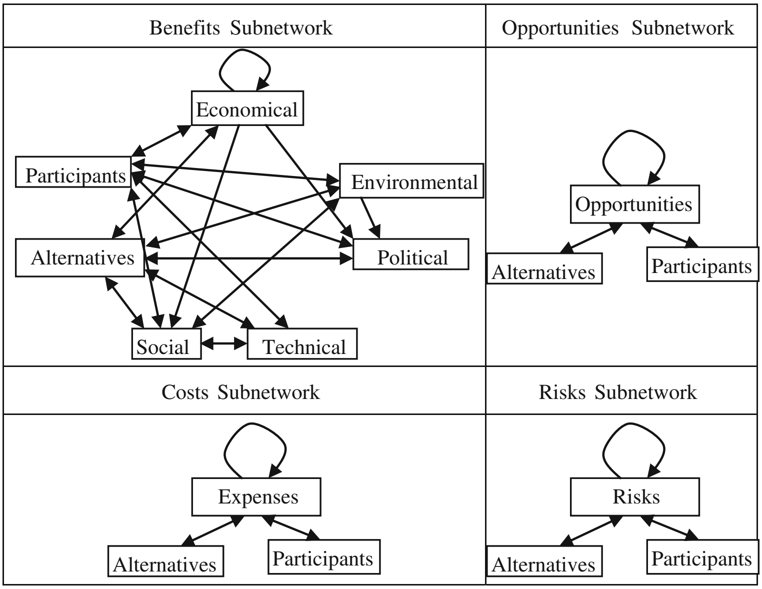

Fig. 3.3 BOCR model for green energy assessment

The values from the limit matrix represent the limit priorities of the decision elements. The values for each alternative can be normalized or idealized for further synthesis. According to the results represented in Table 3.9, biomass has the highest priority in the opportunities subnetwork, followed by geothermal and hydropower.

To complete the BOCR process, the above-mentioned processes are repeated for other control criteria (benefits, costs, risks). The limit priorities of these subnetworks are listed in Table 3.10. For the final synthesis the multiplicative method (Formula 3.7) is used to combine the scores of each alternative under B, O, C, and R. The alternative with the highest outcome score appear to be the best alternative.

3.6 Discussion and Results

In the BOCR application made for Turkey, five different GE alternatives are evaluated from four perspectives. The results show that Biomass energy is ranked as the best GE from the benefits perspective. Solar energy is determined as the source of energy which has the lowest benefits. Just like the benefits, from the opportunities perspective the best alternative is the biomass which is followed by geothermal energy. When compared with the other alternatives solar and wind energy does not provide enough opportunities. When the alternatives are evaluated according to their costs, solar leads the group and is followed by biomass and wind

Table 3.5 The unweighted supermatrix for opportunities subnetwork

	Opp. Criteria			Alternatives					Participants			
	C61	C62	C63	A11	A12	A13	A14	A15	P11	P12	P13	P14
C61	0.000	1.000	1.000	0.333	0.262	0.369	0.251	0.333	0.369	1.000	0.000	0.250
C62	0.000	0.000	0.000	0.333	0.369	0.262	0.251	0.333	0.369	0.000	0.500	0.750
C63	1.000	0.000	0.000	0.333	0.369	0.369	0.498	0.333	0.262	0.000	0.500	0.000
A11	0.144	0.144	0.200	0.000	0.250	0.250	0.250	0.250	0.234	0.118	0.200	0.247
A12	0.144	0.144	0.200	0.250	0.000	0.250	0.250	0.250	0.170	0.226	0.200	0.169
A13	0.284	0.284	0.200	0.250	0.250	0.000	0.250	0.250	0.234	0.226	0.200	0.247
A14	0.144	0.144	0.200	0.250	0.250	0.250	0.000	0.250	0.234	0.312	0.200	0.169
A15	0.284	0.284	0.200	0.250	0.250	0.250	0.250	0.000	0.129	0.118	0.200	0.169
P11	0.287	0.338	0.333	0.000	0.000	0.000	0.292	0.000	0.000	0.262	0.750	0.250
P12	0.425	0.000	0.000	0.662	0.750	0.500	0.369	0.500	0.333	0.000	0.250	0.750
P13	0.000	0.000	0.333	0.000	0.000	0.000	0.000	0.000	0.333	0.389	0.000	0.000
P14	0.287	0.662	0.333	0.338	0.250	0.500	0.369	0.500	0.333	0.369	0.000	0.000

Table 3.6 The cluster matrix

	Opp. criteria	Alternatives	Participants
Opp. criteria	0.251	0.251	0.333
Alternatives	0.498	0.251	0.333
Participants	0.251	0.498	0.333

Table 3.7 Weighted supermatrix for opportunities criteria

	Opp. Criteria			Alternatives					Participants			
	C61	C62	C63	A11	A12	A13	A14	A15	P11	P12	P13	P14
C61	0.000	0.251	0.251	0.084	0.066	0.093	0.062	0.084	0.123	0.331	0.000	0.083
C62	0.000	0.000	0.000	0.084	0.093	0.066	0.062	0.084	0.123	0.000	0.167	0.250
C63	0.251	0.000	0.000	0.084	0.093	0.093	0.123	0.084	0.087	0.000	0.167	0.000
A11	0.072	0.072	0.100	0.000	0.063	0.063	0.062	0.063	0.078	0.039	0.067	0.082
A12	0.072	0.072	0.100	0.063	0.000	0.063	0.062	0.063	0.057	0.075	0.067	0.056
A13	0.141	0.141	0.100	0.063	0.063	0.000	0.062	0.063	0.078	0.075	0.067	0.082
A14	0.072	0.072	0.100	0.063	0.063	0.063	0.000	0.063	0.078	0.103	0.067	0.056
A15	0.141	0.141	0.100	0.063	0.063	0.063	0.062	0.000	0.043	0.039	0.067	0.056
P11	0.072	0.085	0.084	0.000	0.000	0.000	0.143	0.000	0.000	0.087	0.250	0.083
P12	0.107	0.000	0.000	0.330	0.374	0.249	0.181	0.249	0.111	0.000	0.083	0.250
P13	0.000	0.000	0.084	0.000	0.000	0.000	0.000	0.000	0.111	0.129	0.000	0.000
P14	0.072	0.166	0.084	0.168	0.125	0.249	0.181	0.249	0.111	0.122	0.000	0.000

Table 3.8 Limit matrix for opportunities criteria

	Opp. Criteria			Alternatives					Participants			
	C61	C62	C63	A11	A12	A13	A14	A15	P11	P12	P13	P14
C61	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132
C62	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071
C63	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078
A11	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063
A12	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064	0.064
A13	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082
A14	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069
A15	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072
P11	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063
P12	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150
P13	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
P14	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123

energy. From the risks perspective the most risky GE alternative is found as biomass and geothermal, wind carry risk when compared to others.

Table 3.9 Alternative values from the limit matrix

	Values from limit matrix	Normalized values	Idealized values
Biomass	0.0817	0.233	1.000
Geothermal	0.0715	0.204	0.876
Hydropower	0.0694	0.198	0.850
Wind	0.0641	0.183	0.785
Solar	0.0633	0.180	0.775

Table 3.10 Limit priorities for BOCR and the synthesized outcome

	Benefits	Opportunities	Costs	Risks	Outcome *BO*/*CR*
Solar	0.157	0.180	0.251	0.181	0.625
Wind	0.176	0.183	0.204	0.214	0.789
Biomass	0.242	0.234	0.217	0.222	1.134
Hydropower	0.198	0.198	0.152	0.161	1.612
Geothermal	0.227	0.205	0.176	0.222	1.149

When the alternatives are evaluated one by one from the mentioned perspectives, Solar energy is found as an expensive investment with low levels of benefits, opportunities, and risks. Wind on the other hand, is a risky investment that needs a medium level of investment, and generates below medium benefits. Biomass, is the best alternative from benefits and opportunities perspective, however, the costs are high and it is has the highest level of risk. Hydropower has a medium level of benefits and offers a medium level of opportunities but the cost and the risks are in the lowest level. Geothermal energy generates high level of benefits and also provides opportunities; however, it is the most risk alternative when compared with the others.

According to the aggregated outcome of the *BO*/*CR* method, hydropower has the highest priority which is followed by geothermal and biomass energy sources. Although the benefits score of biomass is higher than all others when considering the high risk and costs, biomass is moved to third place. Although the hydropower is not the best alternative from Benefits and Opportunities perspectives, because of low costs and risks it appears to be the best alternative for Turkey.

3.7 Conclusion

Energy is one of the scarce sources that will be tremendously needed. Preferring RES for this need seems to be a solution to this problem. Hydropower, geothermal, wind, solar, and biomass are among the GE alternatives of the future.

The evaluation criteria and the energy alternatives have a network structure since they have internal and external dependencies. ANP is an excellent method to handle this structure. The considered network in this chapter is composed of four subnetworks which are Benefits, Opportunities, Costs, and Risk.

The evaluation process has been realized under fuzzy environment since humans prefer linguistic expressions rather than numerical ones in this process. Linguistic expressions have been converted to corresponding numerical values using the fuzzy set theory.

The application made for Turkey shows that the hydropower energy alternative is the most suitable one. Hydropower is the energy alternative with minimum risk and minimum cost but not the best from benefits and opportunities perspective. The synthesis gave the hydropower the first rank. The following alternatives are geothermal, biomass, wind, and solar, respectively.

For further research, we suggest the other synthesis approaches such as additive, probabilistic additive, subtractive, and multiplicative priority powers to be used and the results obtained by these approaches to be compared with the results in this chapter.

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Chapter 4
Decision Criteria for Optimal Location of Solar Plants: Photovoltaic and Thermoelectric

J. Miguel Sánchez-Lozano, M. Socorro García-Cascales and M. Teresa Lamata

Abstract This chapter deals with the study and evaluation of decision criteria that should be considered for the optimal location of solar photovoltaic plants and solar thermal plants with high temperature and which are to be connected to the electricity distribution network. Criteria and subcriteria to be regarded will be of different nature, since environmental, geomorphologic, location, and strictly climatic criteria will all be considered, some of which are dependent on the technology being installed. Thus, we consider as possible alternatives the optimal locations and we will begin with a set of criteria, which must be evaluated for each of the possible alternatives for such a purpose, and includes both quantitative as well as qualitative information. As vaguely implied linguistic variables and numeric values have to be employed due to this disparity in the nature of the information, we will model the weights of the criteria by triangular fuzzy numbers. In order to reflect this and to carry out the extraction of knowledge a survey based on the fuzzy AHP methodology will be elaborated and sent to experts. In this way it will be possible to obtain the weights of the considered criteria for further evaluation of the alternatives.

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4.1 Introduction

At the end of the nineteenth century it began to be suspected that there were natural changes in the climatic conditions of the planet earth and the greenhouse effect was identified (Arrhenius 1896). The scientific community, through the Intergovernmental Panel on Climate Change (IPCC), alerted the world about the threat posed by this discovery and the effects it could have on climate change (Working Group I-II-III 1990a, b, c).

In response to the report by the IPCC, the United Nations set as a main goal to stabilize concentrations of greenhouse gases in the atmosphere (United Nations 1992). However, it was not until the development of the Kyoto Protocol (United Nations 1997) that they managed to limit net emissions of greenhouse gases from major developed countries. To achieve the objectives, a series of policies and measures were established, among which the increased use of renewable energies (RE) was highlighted.

Among the various issues to consider in carrying out the implementation of an installation of RE, its location must be highlighted since the investment required to undertake any installation is of such magnitude that a minimal error of planning can cause serious damage both economically and environmentally.

Nowadays, the decision criteria that are taken into account by an RE promoter seeking to establish an electricity generating plant in order to pour that power into the distribution grid are scarce and even at times null. Choosing a proper location is essential and for this type of generation plants the availability of land is not the most important factor. On occasions, plants of this type have been started to develop in areas that for various reasons (environmental, technical, etc.) their subsequent implementation has proved unfeasible. In such cases, if the area for its location had been discussed in a certain degree of depth and detail, it could have been claimed that the said area did not fulfill all the requirements for the development and implementation of an RE plant.

As the starting point in the search for a location for solar plants a number of restrictive criteria should be taken into account (Van Haaren and Fthenakis 2011). These permit to limit the area of study to those sites that fulfill the rules and guidelines in force, such as the compliance distance to existing infrastructure (road and rail networks); separation of the areas that involve risk of flooding (channels and watercourses); remoteness of guard bands of protected areas (high value landscape, archaeological, paleontological, etc.) Current regulations permit to define what are the restrictive criteria to be considered when implementing any infrastructure—not just for RE plants but also for any other area or sector (private building, construction, agriculture, etc.)

Although restrictive criteria allow to delimit the study area, it is necessary to consider another set of criteria that will influence the decision of selecting optimal sites (Charabi and Gastli 2011). The choice of such criteria is directly related to the type of infrastructure to be installed, i.e., they do not follow any rules in force but are factors that have a certain weight depending on the type of infrastructure to be made. Moreover, it is essential to distinguish among the various RE plants, those in which by their very nature require their location to be previously defined, from those other plants in which it is essential to carry out an assessment of all the criteria involved in the decision to place them in a great location.

It is possible to establish an RE classification based on the location of its facilities, and thus two groups can be distinguished: the first group would consist of those RE plants requiring a particular and clearly defined situation. Their location is mainly due to specific characteristics of the environment, with one or more criteria having a much greater importance than the rest. That group would include the RE such as biomass, biogas, biofuels, geothermal, energy from the seas and oceans and hydropower. The second group would be formed by those RE plants in which choosing the correct location is also a key issue, and this subject presents a greater uncertainly as a result of the criteria involved in the decision. There is not one single criterion or more criteria whose weight is so superior to the others so as to permit discarding the rest and not taking them into account. Among the RE plants of this second group, the solar photovoltaic and high temperature solar thermal (thermoelectric) plants stand out above the rest, and they will therefore be the RE plants to be analyzed in this chapter.

When the correct location for a solar photovoltaic or solar thermal plant is selected, there are a number of criteria which, depending on the type of installation, will have a greater or lesser importance. Thus, the crossing of criteria between these two technologies offers many variants and carrying out a thorough analysis can be of considerable interest.

Therefore, this chapter deals with the study and evaluation of decision criteria that influence the location of solar photovoltaic and thermoelectric plants, in order to obtain their weights or important coefficients. These take into account the information provided by experts and will be developed under the following headings and the methodology applied.

4.2 Decision Criteria for the Optimal Location of Solar Power Plants

In this chapter the criteria that must be taken into account when implementing solar photovoltaic and solar thermal energy plants will be discussed, these are diverse and thematic relating to the environment, and geomorphology, climatology or location. Such thematics allow to classify the criteria in a criteria tree (shown in Fig. 4.1).

Each of the above criteria is briefly described:

- C_1: *Agrological capacity* (*Classes*): Suitability of land for agricultural development, if a zone has excellent agrological capacity, it will not be ideal to host the facility, and vice versa.

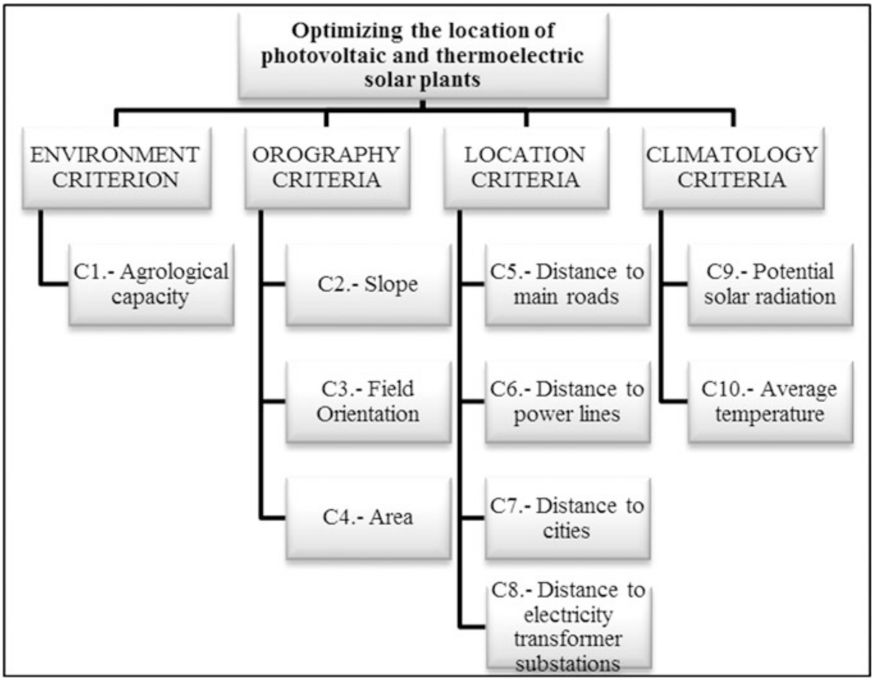

Fig. 4.1 Criteria tree for optimizing the location of solar photovoltaic and thermoelectric plants

- C_2: *Slope* (*%*): Land slope, the higher percentage of having a surface inclination, the worse aptitude to hold a solar plant.
- C_3: *Field Orientation* (*Cardinal points*): Position or direction of the ground to a cardinal point.
- C_4: *Area* (m^2): surface contained within a perimeter of land that can accommodate an RE plant.
- C_5: *Distance to main roads* (m): Space or interval between the nearest road and the different possible sites.
- C_6: *Distance to power lines* (m): Space or interval between the nearest power line and the different possible sites.
- C_7: *Distance to cities* (m): Space or interval between cities (cities or towns) and the different possible sites.
- C_8: *Distance to electricity transformer substations* (m): Space or interval between transformer substations of electric power and the different possible sites.
- C_9: *Potential solar radiation* (kJ m^2/day): This corresponds to the amount of solar energy a ground surface receives over a period of time (day).
- C_{10}: *Average temperature* (°C): Average temperatures measured on the ground in the course of one year.

4.3 Methodology

To solve the location problem, a multicriteria decision method MCDM (Chen and Hwang 1992; Hwang and Yoon 1981; Keeney and Raiffa 1976; Luce and Raiffa 1957) can be used to choose the best alternative A_i, $i = 1,2,\ldots,n$ with $n \geq 2$ a number of criteria C_j, $j = 1,2,\ldots,m$ with $m \geq 2$ are considered, and experts E_k, $k = 1,2,\ldots,r$ with $r \geq 2$; considering that both n and r are finite.

Specifically, an MCDM called Analytic Hierarchy Process (AHP) will be applied, which is detailed below.

The AHP method

The AHP method was proposed by Saaty in (Saaty 1980) and it is based on the idea that a decision making problem with multiple criteria can be solved by the ranking of the proposed problems, i.e., it consists of an alternative selection method based on a number of criteria which are often in conflict.

The main feature of the AHP method is that the decision problem is modeled using a hierarchy whose apex is the main objective of the problem, and the possible alternatives to evaluate are situated at the base, the intermediate levels correspond to the criteria/subcriteria based on which a decision is made (Fig. 4.2).

At each level of the hierarchy, comparisons are carried out between pairs of elements of that level, based on the importance or contribution of each element of the upper level to which they are linked.

The target in the case under study is the optimal location of sites for solar photovoltaic and thermoelectric plants, and specifically in determining the weight or coefficient of importance of the intermediate levels of the hierarchy, i.e., the criteria that influence the decision (see Fig. 4.1).

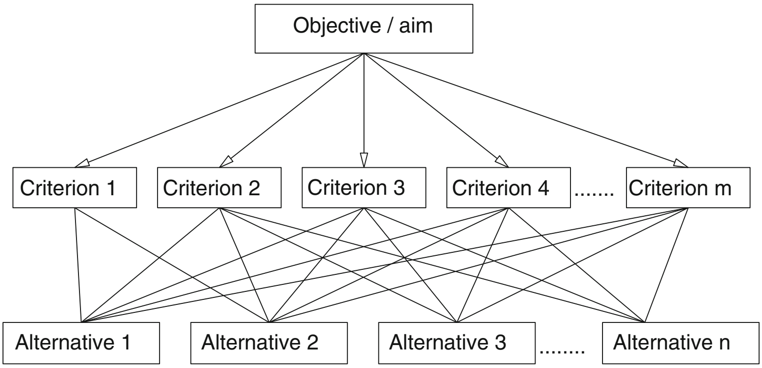

Fig. 4.2 AHP Hierarchy process

4.4 Survey of Experts

To carry out the extraction of knowledge from the experts a pseudo-delphi technique will be used in which the members involved in the decision are independent of each other, i.e., they do not interact in the moment of extraction of knowledge. For that purpose, a questionnaire similar to that made by García-Cascales et al. (2012) was developed, which was given to experts with the aim of reducing uncertainly and imprecision of the proposed problem.

The group of experts involved in the decision process for photovoltaic solar plants was composed of a doctor engineer (expert E_1) specialized in solar photovoltaic technology; a doctor in physics (expert E_2) with more than 10 years experience in solar photovoltaic technology; and a promoter of RE plants (Expert E_3) with more than 5 years of experience in the industry.

The group of experts involved in the decision process of thermoelectric solar plants consisted of three doctor engineers (experts E_1, E_2, *and* E_3) and a doctor in physics (expert E_4) with more than 10 years experience in the RE sector, all of them specialized in solar photovoltaic and thermoelectric technologies.

The survey is divided into two parts:

1. The decision problem is explained indicating what the goal to achieve is (optimal location of sites of solar photovoltaic and thermoelectric); the methodology used; and the criteria that influence the decision making process. Thus, the basic elements of the decision problem are described through a hierarchical structure, as shown in the criteria tree (see Fig. 4.1).
2. It is based on the hierarchical structure described and its purpose is to gather data to obtain the weight or coefficient of importance of criteria.

The survey consists of a block of 3 questions:

- Q1: Do you believe that the ten criteria considered have the same weight?

If the answer is yes, $w_i = w_{j=1/n} \times \sqrt{i,j}$ it will not be necessary to apply any MCDM to obtain the weights of the criteria as these will have the same value. Otherwise, i.e., if experts consider that not all the criteria have equal importance, the second question in the survey will be posed:

- Q2: List the criteria in descending importance.

According to the experts, the order of importance of the criteria for the two types of RE plants for analysis is shown in Table 4.1.

Once the orders of importance provided by each of the experts have been obtained, then the third question will be asked:

- Q3: Compare the criterion considered as having the greatest order of importance with respect to that considered second and successively, using the following tags, (II), (M+), (+I), (Mu + I), (Ex + I) according to the meanings in Table 4.2.

Table 4.1 Order of importance of the criteria for each of the experts

Solar photovoltaic energy	
E_1	$C_8 > C_6 > C_4 > C_{10} > C_2 > C_3 > C_9 > C_5 > C_7 > C_1$
E_2	$C_7 > C_2 = C_3 > C_5 = C_{10} > C_6 = C_8 > C_1 = C_4 > C_9$
E_3	$C_9 > C_6 > C_4 > C_2 > C_8 > C_5 > C_{10} > C_3 > C_7 > C_1$
Solar thermoelectric energy	
E_1	$C_9 > C_3 > C_2 > C_{10} > C_4 > C_6 > C_8 > C_7 > C_5 > C_1$
E_2	$C_8 > C_6 > C_2 > C_4 > C_3 > C_9 > C_{10} > C_5 > C_7 > C1$
E_3	$C_4 > C_1 > C_6 > C_8 > C_5 > C_9 > C_2 > C_3 > C_7 > C_{10}$
E_4	$C_5 = C_7 = C_{10} > C_1 = C_2 > C_4 = C_6 = C_8 > C_3 = C_9$

Table 4.2 Scale of valuation in the pair-wise comparison process (Saaty 1980)

Labels	Verbal judgments of preferences between criterion *i* and criterion *j*	Triangular fuzzy scale and reciprocals
(II)	C_i and C_j are equally important	(1,1,1)/(1,1,1)
(M + I)	C_i is slightly more/less important than C_j	(2,3,4)/(1/4,1/3,1/2)
(+I)	C_i is strongly more/less important than C_j	(4,5,6)/(1/6,1/5,1/4)
(Mu + I)	C_i is very strongly more/less important than C_j	(6,7,8)/(1/8,1/7,1/6)
(Ex + I)	C_i is extremely more/less important than C_j	(8,9,9)/(1/9,1/9,1/8)

4.4.1 Configuration Data

The information provided by the experts is qualitative in character or is very vague since it has been obtained through linguistic terms This means that the data obtained should be set and modeled so that further handling is feasible and easy.

Among the various options for representing information and because, on the one hand the data is grouped perfectly, and on the other, handling is simple and effective, fuzzy numbers will be chosen to represent information (Delgado et al. 1992; Herrera et al. 2009). In the particular case study, the data provided shall be represented by triangular fuzzy numbers (Zadeh 1965; Klir and Yuan 1995; Dubois and Prade 1980).

4.4.2 Calculating the Weights of the Criteria

The weights of the criteria will be determined by pair-wise comparison among criteria. As a result of the data collection process used, a total of $(n-1)$ comparisons will be required. Tags that have been used and their meanings are shown in Table 4.2.

The process will run pair-wise comparison between criteria for the case of photovoltaic solar sites and for expert 1 as an example; the value pairs are shown in Fig. 4.3.

$$\begin{array}{c|cccccccccc} & C_8 & C_6 & C_4 & C_{10} & C_2 & C_3 & C_9 & C_5 & C_7 & C_1 \\ \hline C_8 & (\mathrm{II}) & (\mathrm{M+I}) & (\mathrm{+I}) & (\mathrm{+I}) & (\mathrm{Mu+I}) & (\mathrm{Mu+I}) & (\mathrm{Mu+I}) & (\mathrm{Ex+I}) & (\mathrm{Ex+I}) & (\mathrm{Ex+I}) \end{array}$$

Fig. 4.3 Values given by *E₁* for location of solar photovoltaic plants

Triangular fuzzy numbers expressed according to Table 4.2 prove to be as shown in Fig. 4.4.

According to Garcia-Cascales and Lamata (2011) and by expression (4.1) the weights for the example shown will be obtained (see Fig. 4.5).

The above matrix was obtained by performing a normalizing operation using the following expression:

$$\left(w_{c_{ia}}, w_{c_{ib}}, w_{c_{ic}}\right) = \left[\frac{c_{ia}}{\sum_{i=1}^{n} c_{ic}}, \frac{c_{ib}}{\sum_{i=1}^{n} c_{ib}}, \frac{c_{ic}}{\sum_{i=1}^{n} c_{ia}}\right] \tag{4.1}$$

4.5 Result of the Weights of the Criteria

Analogously to the procedure developed to obtain the weights of the criteria for expert E_1 in the location problem for solar photovoltaic installations, it will be extended to the other experts in this decision problem (Table 4.3) and for the location problem of solar thermoelectric plants (Table 4.4).

$$\begin{array}{c|cccccccccc} & C_8 & C_6 & C_4 & C_{10} & C_2 & C_3 & C_9 & C_5 & C_7 & C_1 \\ \hline C_8 & (1,1,1) & (2,3,4) & (4,5,6) & (4,5,6) & (6,7,8) & (6,7,8) & (6,7,8) & (8,9,9) & (8,9,9) & (8,9,9) \end{array}$$

Fig. 4.4 Matrix of decision making for *E₁* for location of solar photovoltaic plants

Fig. 4.5 Weight criteria *E₁* for location of solar photovoltaic plants

$$\begin{array}{c|c} & C_8 \\ \hline C_8 & (1,1,1) \\ C_6 & (1/4, 1/3, 1/2) \\ C_4 & (1/6, 1/5, 1/4) \\ C_{10} & (1/6, 1/5, 1/4) \\ C_2 & (1/8, 1/7, 1/6) \\ C_3 & (1/8, 1/7, 1/6) \\ C_9 & (1/8, 1/7, 1/6) \\ C_5 & (1/9, 1/9, 1/8) \\ C_7 & (1/9, 1/9, 1/8) \\ C_1 & (1/9, 1/9, 1/8) \\ \hline & (2.292, 2.495, 2.875) \end{array} = \begin{bmatrix} (0.348, 0.401, 0.436) \\ (0.087, 0.134, 0.218) \\ (0.058, 0.080, 0.109) \\ (0.058, 0.080, 0.109) \\ (0.043, 0.057, 0.073) \\ (0.043, 0.057, 0.073) \\ (0.043, 0.057, 0.073) \\ (0.039, 0.045, 0.055) \\ (0.039, 0.045, 0.055) \\ (0.039, 0.045, 0.055) \end{bmatrix}$$

Table 4.3 Weights of the criteria for location of solar photovoltaic plants

	Expert 1			Expert 2			Expert 3		
C_1	[0.039,	0.045,	0.055]	[0.050,	0.054,	0.062]	[0.026,	0.027,	0.032]
C_2	[0.043,	0.057,	0.073]	[0.057,	0.069,	0.082]	[0.039,	0.049,	0.063]
C_3	[0.043,	0.057,	0.073]	[0.057,	0.069,	0.082]	[0.026,	0.027,	0.032]
C_4	[0.058,	0.080,	0.109]	[0.050,	0.054,	0.062]	[0.235,	0.247,	0.254]
C_5	[0.039,	0.045,	0.055]	[0.050,	0.054,	0.062]	[0.039,	0.049,	0.063]
C_6	[0.087,	0.134,	0.218]	[0.050,	0.054,	0.062]	[0.235,	0.247,	0.254]
C_7	[0.039,	0.045,	0.055]	[0.453,	0.485,	0.493]	[0.026,	0.027,	0.032]
C_8	[0.348,	0.401,	0.436]	[0.050,	0.054,	0.062]	[0.039,	0.049,	0.063]
C_9	[0.043,	0.057,	0.073]	[0.050,	0.054,	0.062]	[0.235,	0.247,	0.254]
C_{10}	[0.058,	0.080,	0.109]	[0.050,	0.054,	0.062]	[0.026,	0.027,	0.032]

In order to unify the weights of the obtained criteria a homogeneous aggregation will be carried out, i.e., all experts are equally important in the decision, as a measure of aggregation the arithmetic average will be used (expression 4.2).

$$(\bar{X}_{ia}, \bar{X}_{ib}, \bar{X}_{ic}) = \left[\frac{\sum_{i=1}^{n} X_{ia}}{n}, \frac{\sum_{i=1}^{n} X_{ib}}{n}, \frac{\sum_{i=1}^{n} X_{ic}}{n} \right] \tag{4.2}$$

By the homogeneous aggregations indicated, the weights of the criteria will be obtained, taking into account the entire decision making group, therefore, the values obtained for the problem location of solar photovoltaic plants are those indicated in Table 4.5.

The results shown in Table 4.5 are represented graphically in Fig. 4.6.

Analyzing both Table 4.5 and Fig. 4.6 it is shown that the three best criteria for the location problem for solar plants are the distance to power lines (C_6); distance to electricity transformer substations (C_8); and distance to cities (C_7), with the latter being the highest rated. By contrast the criteria that less influence the decision, that is to say, those with the lowest values, correspond to the criterion of agrological capacity (C_1) and to the criterion of distance to main roads (C_5).

Proceeding analogously to the decision problem of solar thermoelectric plants, the values of the weights of the criteria will be obtained (Table 4.6).

The results shown in Table 4.6 are represented graphically in Fig. 4.7.

Analyzing in this case Table 4.6 and Fig. 4.7 it is shown that the three best criteria for the location problem for solar thermoelectric plants are potential solar radiation (C_9); distance to electricity transformer substations (C_8); and distance to main roads (C_5), with the latter being the highest rated. By contrast the criteria that have less influence in the decision in this case are distance to cities (C_7); and field orientation (C_3).

Table 4.4 Weights of the criteria for location of solar thermoelectric plants

	Expert 1			Expert 2			Expert 3			Expert 4		
C_1	[0.029,	0.036,	0.047]	[0.036,	0.042,	0.053]	[0.233,	0.272,	0.298]	[0.056,	0.068,	0.082]
C_2	[0.066,	0.109,	0.188]	[0.080,	0.127,	0.211]	[0.029,	0.039,	0.050]	[0.049,	0.053,	0.061]
C_3	[0.066,	0.109,	0.188]	[0.040,	0.054,	0.070]	[0.029,	0.039,	0.050]	[0.049,	0.053,	0.061]
C_4	[0.044,	0.065,	0.094]	[0.053,	0.076,	0.105]	[0.233,	0.272,	0.298]	[0.049,	0.053,	0.061]
C_5	[0.033,	0.047,	0.063]	[0.036,	0.042,	0.053]	[0.058,	0.091,	0.149]	[0.444,	0.477,	0.490]
C_6	[0.044,	0.065,	0.094]	[0.080,	0.127,	0.211]	[0.058,	0.091,	0.149]	[0.049,	0.053,	0.061]
C_7	[0.044,	0.065,	0.094]	[0.036,	0.042,	0.053]	[0.029,	0.039,	0.050]	[0.056,	0.068,	0.082]
C_8	[0.044,	0.065,	0.094]	[0.320,	0.380,	0.421]	[0.058,	0.091,	0.149]	[0.049,	0.053,	0.061]
C_9	[0.264,	0.327,	0.377]	[0.040,	0.054,	0.070]	[0.029,	0.039,	0.050]	[0.049,	0.053,	0.061]
C_{10}	[0.066,	0.109,	0.188]	[0.040,	0.054,	0.070]	[0.026,	0.030,	0.037]	[0.056,	0.068,	0.082]

Table 4.5 Weight vector by homogeneous aggregation and arithmetic average for the location problem for solar installations

Criteria	Weight vector		
C_1	0.0384	0.0419	0.0493
C_2	0.0464	0.0586	0.0728
C_3	0.0421	0.0513	0.0622
C_4	0.1145	0.1271	0.1414
C_5	0.0427	0.0493	0.0599
C_6	0.1242	0.1449	0.1778
C_7	0.1725	0.1855	0.1931
C_8	0.1458	0.1680	0.1871
C_9	0.1097	0.1195	0.1293
C_{10}	0.0448	0.0538	0.0675

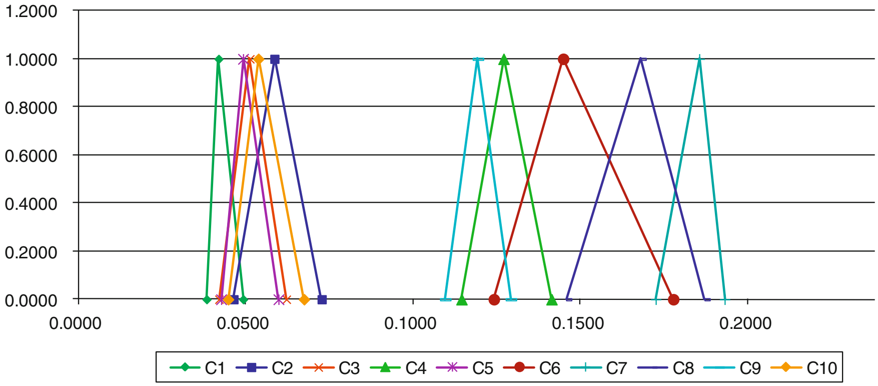

Fig. 4.6 Location criteria of solar photovoltaic plants (homogeneous aggregation)

Table 4.6 Weight vector by homogeneous aggregation and arithmetic average for the location problem of solar thermoelectric plants

Criteria	Weight vector		
C_1	0.0884	0.1046	0.1197
C_2	0.0561	0.0819	0.1275
C_3	0.0461	0.0638	0.0924
C_4	0.0949	0.1165	0.1396
C_5	0.1428	0.1642	0.1885
C_6	0.0579	0.0840	0.1287
C_7	0.0410	0.0537	0.0695
C_8	0.1179	0.1474	0.1813
C_9	0.0956	0.1184	0.1395
C_{10}	0.0468	0.0655	0.0944

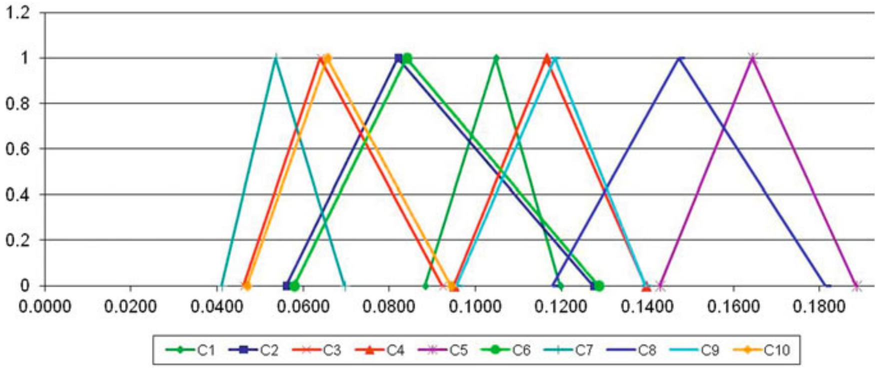

Fig. 4.7 Location criteria for solar thermoelectric plants (homogeneous aggregation)

4.6 Conclusions

Comparing the results for both RE technologies, it is noted that although, according to the experts, the decision criteria that influence the location of these installations are identical, they do not affect the decision equally.

The highest rated criterion for solar photovoltaic plants corresponds to distance to cities (C_7), while this criterion for the case of solar thermoelectric plants is the one with the worst rating.

For the case of solar thermoelectric plants the highest rated criterion corresponds to distance to main roads (C_5), while this same criterion for the case of solar photovoltaic is one of the worst rated. Among the various reasons cited for this notable difference is the emphasis placed on the physical characteristics of these types of plants. For example, the equipment systems and components required to implement a solar thermoelectric plant are such that it is essential to have infrastructure networks such as roads sufficiently close to the implantation site. In the case of photovoltaic plants this is not a great advantage because their equipment systems are smaller and more manageable.

It is also interesting to highlight that there are a number of criteria whose importance is similar for both technologies: these are potential solar radiation (C_9); distance to electricity transformer substations (C_8); and area (C_4).

The current study has shown that a number of criteria must be taken into account when selecting the best location for a solar photovoltaic or thermoelectric plant. Moreover, such criteria do not equally influence the decision making, so it is very important to know beforehand the weights of these criteria for each technology when implementing such facilities.

Extending the analysis to other technologies (wind energy, biomass, etc.), selecting a set of sites to study and supplementing it with other techniques for decision support, are all pending issues that could well be framed as future research.

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Chapter 5
A Multi-Attribute Model for Wind Farm Location Combining Cloud and Utility Theories

José Ramón San Cristóbal

Abstract Nowadays sustainable development is a major focus of national and international economic, social, and environmental agendas, so that a good quality of life can be enjoyed by current and future generations. The problem of climate change has caused great concerns at all levels, from the general public to national governments and international agencies. Renewable energies can be an important remedy to many environmental problems that the world faces today. In this context, some new governmental policies have been adopted to encourage the introduction of renewable energies. But the energy planning scenario has completely changed over the past two decades from and almost exclusively concern with cost minimization of supply-side options to the need of explicitly multiple and conflicting objectives. Different and numerous groups of actors, such as institutions and administration authorities, potential investors, environmental groups, get involved in the process of fossil fuel energy substitution by renewable energies. This complex environment indicates the multi-criteria character of the problem. In this chapter multi-attribute decision-making method combining cloud and utility theory is proposed in order to evaluate different locations for a wind farm in the north of Spain. Whereas utility theory allows us to use different utility curves describing different attitudes toward risk, cloud theory provides a model that facilitates transformation of uncertainty contained in both quantitative and qualitative concepts to a uniform presentation in a numerical domain. Six locations are candidate to place the wind farm according to their topography, infrastructure, land use, safety, and number of days with wind speed >=70 km/h. The results show that the location with the highest number of days with wind speed >=70 km/h and the best land use attribute is the best place to locate the wind farm for both a risk aversion decision-maker and a risk-seeking decision-maker.

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5.1 Introduction

Mitigation of climate change, in order to reach the targets set by the Kyoto Protocol, requires significant reductions of greenhouse gas emissions and, consequently, the adequate policy formulation for fossil fuel energy substitution by renewable energy (RE) sources. In the selection of a RE project a multitude of technical, financial, environmental, legal, social and political objectives, and/or constraints, some of which are not even quantifiable, some of which are conflicting, must be taken into account. In addition, different groups of decision-makers become involved in the process, each group bringing along different criteria and points of view.

The policy formulation for fossil fuels energy substitution by RE demand the use of analytical tools that describe and evaluate the problem in its social, environmental, economic, and technological dimension. The complexity of energy planning and energy projects makes multi-criteria analysis a valuable tool in the decision-making process. Multi Criteria analysis, often called multi criteria decision-making (MCDM) or multi criteria decision aid methods (MCDA), is a branch of a general class of Operations Research models which deal with the process of making decisions in the presence of multiple objectives. MCDM methods have been widely used in RE projects in areas such as wind farm projects, geothermal projects, hydro-site selection, etc. Multi objective decision-making, Decision Support Systems, Multi-attribute decision-making [Analytical hierarchy process (AHP), PROMETHEE, ELECTRE, Multi-attribute utility theory], and Fuzzy programming have been the main MCDM methods applied to RE projects (1–16).

In this chapter, a multi-attribute decision-making method combining cloud and utility theories for wind farm location is proposed. The chapter is organized as follows. In the next section the cloud theory is presented. Next, in order to evaluate six locations in the north of Spain, an application section is shown. Finally, there is a concluding section with the main results of the chapter.

5.2 Cloud Theory

Cloud theory provides a model that facilitates transformation of uncertainty contained in both quantitative and qualitative concepts to a uniform presentation in a numerical domain. The cloud theory proposed by Li and Du (2005), Li and Meng (1995) and Li et al. (1998), combines both fuzzy theory and probability together for establishing a model transforming qualitative terms described in a natural language to distributions patterns of quantitative values. However, the uniform transforming function used in cloud theory may not be the best choice to evaluate problems with multiple attributes that exhibit different behaviors in problem domain. Following Dyer et al. (1992), Fisburn (1970) and Jiménez et al. (2003) the concepts of handling information transformation in utility theory are more

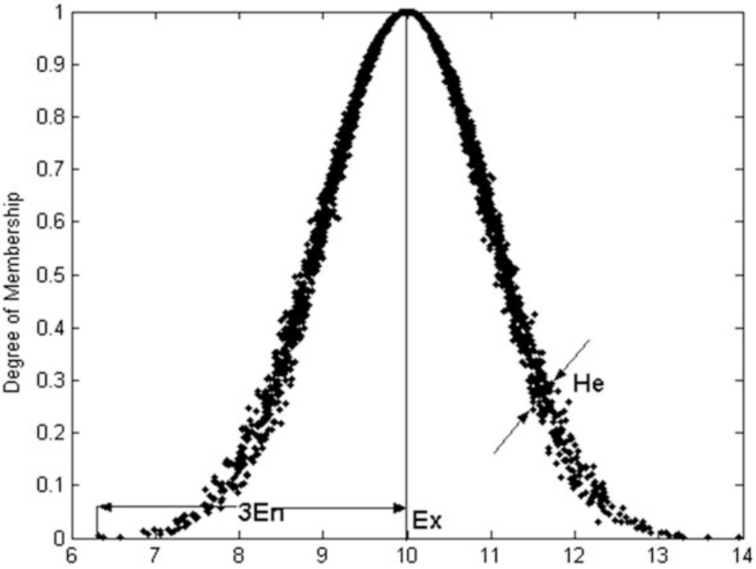

Fig. 5.1 Cloud model

appropriate to multi-attribute evaluation problems. The basic concepts of cloud theory can be outlined as follows Liao and Guo (2012).

Suppose that L is the language value of domain u and mapping $M_L(x) : u \rightarrow [0, 1]$, $\forall x \in u, x$, then the distribution of $M_L(x)$ is called the membership cloud of L, or cloud in short, and each projection is called a cloud drop in the distribution. If distribution of $M_L(x)$ is normal, it becomes a normal cloud model illustrated in Fig. 5.1. The normal cloud model is determined by the following three parameters: Expectation (Ex), Entropy (En), and Hyper Entropy (He). Ex determines the center of the cloud. En determines the range of the cloud and about 99.74 % cloud drops fall within the range between Ex − 3En and Ex + 3En. He determines the dispersion of cloud drops: The larger the He the more dispersive the cloud drops.

The methodology incorporating cloud and utility theories consists of the following steps (Liao and Guo 2012): (1) selecting evaluation attributes and structure; (2) substantiating attributes; (3) determining utility and cloud models for attributes; (4) computing cloud characters of individual attributes; (5) calculating the weighted evaluation results; and (6) analyzing evaluation results.

- Step 1. *Selecting evaluation attributes and structure*. The method starts from selecting relevant attributes used as the input to a multi-attribute evaluation problem. Since an attribute may be comprised of more than one level of multiple factors, selected attributes can form a hierarchical structure representing all relevant factors necessary to the evaluation.
- Step 2. *Substantiating attributes*. Quantitative and qualitative data are commonly used in evaluation problems. For quantitative attributes, their

substantiation can be done through direct utilization or recalculation of statistical data of business operation for the concerned company. Results of customer survey and/or experts' assessments on operational aspects of the company can be used to substantiate qualitative attributes. This is usually done through some kind of linguistic system, for example, a spectrum of bad, average, or some kind of score system.

- Step 3. *Determining utility and cloud models for attributes.* Different quantitative attributes may have values with different scales and units. In order to make them comparable with each other, it is necessary to transform values of these quantitative attributes to a unique numerical scale. This can be done by using concepts in the utility theory: a utility function $U(x_i)$ being designed for each quantitative attribute $X_i : \{x_i\}$ according to its characters. In this way, all values of different quantitative attributes can be transferred to a new domain of the same scale, usually between 0 and 1. For qualitative attributes, their linguistic values or scores can be regarded as cloud drops defined in a utility domain between 0 and 1, and thus a cloud model can be designed in this utility domain to transfer the linguistic values or scores of qualitative attributes into the same numerical domain shared by other transferred quantitative attributes.
- Step 4. *Computing cloud characters of individual attributes.* Since individual attributes, either quantitative or qualitative, have been transferred into the same numerical domain, through either utility models or cloud models, cloud characters of individual attributes in the new numerical domain can be calculated according to the cloud theory as follows:

$$\mathrm{Ex}_i = {(u_i(x_1) + u_i(x_2) + \cdots u_i(x_t))}/_{t} \tag{5.1}$$

And

$$\mathrm{En}_i = \sqrt{\frac{1}{t}\sum_{j=1}^{t}(u_i(x_i) - \mathrm{Ex}_i)^2} \tag{5.2}$$

where t is the total number of utility values of the ith attribute. For qualitative attributes, according to cloud theory, expectation and entropy of the ith attribute can be determined as follows:

$$\mathrm{Ex}_i = {\left(\mathrm{Ex}_1\mathrm{En}_1 + \cdots + \mathrm{Ex}_j\mathrm{En}_j + \cdots + \mathrm{Ex}_t\mathrm{En}_t\right)}/{\left(\mathrm{En}_1 + \cdots + \mathrm{En}_j + \cdots + \mathrm{En}_t\right)} \tag{5.3}$$

And

$$\mathrm{En}_i = \sqrt{\frac{\mathrm{En}_1^4 + \cdots + \mathrm{En}_j^4 + \cdots \mathrm{En}_t^4}{\left(\mathrm{En}_1 + \cdots + \mathrm{En}_j + \cdots + \mathrm{En}_t\right)^2}} \tag{5.4}$$

where Ex_j and En_j are the expectation and entropy of transferred values from the linguistic values or scores given by the *j*th expert to the *i*th attribute.

- Step 5. *Calculating the weighted evaluation results*. Based on expectation and entropy values for individual attributes obtained by Eqs. (5.1–5.4), expectation and entropy for either the entire multi-attribute evaluation can be calculated using the following equation recursively from the lowest level to the highest level in a hierarchical structure:

$$\mathrm{Ex} = \sum_{i=1}^{m} w_i \mathrm{Ex}_i \tag{5.5}$$

$$\mathrm{En} = \sqrt{\sum_{i=1}^{m} w_i^2 \mathrm{En}_i^2} \tag{5.6}$$

where w is the weight of each attribute and m is the total number of attributes at the same level in the evaluation structure.

- Step 6. *Analyzing evaluation results*. Expectation and entropy calculated from Eqs. (5.5) and (5.6) can be used as quantitative measures to the multi-attribute evaluation problem. Ex provides the solution to the problem whereas En measures quality of this solution. The smaller the entropy is the more credible the solution is. This information on quality of the solution cannot be provided by other traditional evaluation methods. A coefficient of relative dispersion of a solution can be defined as:

$$\mathrm{Rd} = \frac{\mathrm{En}}{\mathrm{Ex}} \tag{5.7}$$

A small *Rd* indicates a credible solution to the evaluation problem. A solution in the numerical domain can also be converted to its corresponding linguistic term through inversion of its cloud model.

5.3 Application

The aim of this section is to determine the most convenient location for a wind farm in the north of Spain. Six locations are candidate to place the wind farm: Cabo Vilán, Estaca de Bares, Fisterra, Cabo Busto, Cabrales, Taramundi. Selecting evaluation attributes is the first step in this process, to this end four qualitative criteria will be used: topography (*T*), infrastructure (*I*), land use (*LU*), and safety (*S*). As a quantitative criterion, the number of days with wind speed >=70 km/h collected in the locations during April, May, and June 2012 (AEMET 2012), shown in Table 5.1, will be used for analytical purposes.

Table 5.1 Days with wind speed >=70 km h (year 2012)

Month	Cabo Vilán	Estaca de Bares	Fisterra	Cabo Busto	Cabrales	Taramundi
April	10	50	13	44	6	12
May	7	21	9	1	8	5
June	6	28	9	16	7	6

To assess weights to individual attributes according to their relevance importance in evaluation several methods can be used. In this application, the AHP developed by Saaty (2000) is used. Since it is not within the scope of this chapter to show the AHP methodology and the method has been extensively used in the literature, the reader is referred to Aras et al. (2004) and San Cristóbal (2011) for details on AHP. Based on experts assessments, weights assigned to individual attributes are the following: topography (0.25); infrastructure (0.25); land use (0.10); safety (0.15); and days with wind speed >=70 km/h (0.25).

In step 2, values assigned to the four qualitative attributes are collected from six independent experts based on the following linguistic set: Extremely Bad, Very Bad, Bad, Inferior, Average, Acceptable, Good, Very Good, Excellent. These data are shown in Table 5.2.

Determining utility and cloud models for attributes is the third step. For the qualitative attributes a composite normal cloud model is developed to transform the linguistic terms of assessment from individual experts into the same numerical domain u [0,1] for comparability with other quantitative attributes. The model is shown in Fig. 5.1 and the Range, Expectation, and Entropy are detailed in Table 5.3.

5.3.1 Utility Theory

Based on the characters of the quantitative criterion, the utility functions showing the decision-maker's preferences are constructed by the method suggested by Keeney and Raiffa (1976). The first step involves the identification of the best and the worst outcomes for the criterion days with wind speed >=70 km/h. The decision-maker is free to set these utility values at any level provided that the best outcome has the higher value. The usual method is to assign the worst outcome a utility value of zero and the best outcome a utility value of unity. This establishes the range of utility values to from 0 to 1 between the worst and the best possible outcomes. The worst outcome (Cabo Busto, 1 day in May) is assigned a utility value of zero and the best outcome (Estaca de Bares, 50 days in April) a utility value of unity. The utility of the intermediate values is then determined by offering the decision-maker a choice between two lotteries. For example, to determine the utility value of 21, the decision-maker is offered the following options shown in Fig. 5.2.

Table 5.2 Values for qualitative attributesattributes

Expert	Cabo Vilán	Estaca de Bares	Fisterra	Cabo Busto	Cabrales	Taramundi
Topography (*T*)						
1	Very good	Acceptable	Average	Good	Excellent	Bad
2	Good	Average	Inferior	Acceptable	Good	Inferior
3	Acceptable	Good	Average	Good	Acceptable	Acceptable
4	Excellent	Average	Acceptable	Average	Very good	Average
5	Good	Acceptable	Inferior	Acceptable	Good	Bad
6	Very good	Good	Average	Acceptable	Very good	Acceptable
Infrastructure (*I*)						
1	Average	Acceptable	Very good	Inferior	Inferior	Good
2	Inferior	Good	Good	Inferior	Acceptable	Average
3	Inferior	Acceptable	Good	Acceptable	Good	Inferior
4	Acceptable	Very good	Excellent	Average	Average	Average
5	Inferior	Good	Good	Bad	Acceptable	Acceptable
6	Average	Excellent	Very good	Acceptable	Good	Inferior
Land use (*LU*)						
1	Inferior	Very good	Average	Good	Inferior	Acceptable
2	Acceptable	Good	Inferior	Average	Inferior	Good
3	Good	Good	Inferior	Inferior	Acceptable	Acceptable
4	Average	Excellent	Acceptable	Average	Average	Very good
5	Acceptable	Good	Inferior	Acceptable	Bad	Good
6	Good	Very good	Average	Inferior	Acceptable	Excellent
Safety (*S*)						
1	Inferior	Average	Acceptable	Very good	Good	Inferior
2	Inferior	Inferior	Good	Good	Average	Acceptable
3	Acceptable	Inferior	Acceptable	Good	Inferior	Good
4	Average	Acceptable	Very good	Excellent	Average	Average
5	Bad	Inferior	Good	Good	Acceptable	Acceptable
6	Acceptable	Average	Excellent	Very good	Inferior	Good

Table 5.3 Range, expectation and entropy for linguistic terms (Liao and Guo 2012)

Linguistic variable	Distance range	Expectation	Entropy
Extremely bad	(0.00, 0.15]	0.00	0.0500
Very bad	[0.05, 0.25]	0.15	0.0333
Bad	[0.15, 0.35]	0.25	0.0333
Inferior	[0.25, 0.45]	0.35	0.0333
Average	[0.35, 0.65]	0.50	0.0500
Acceptable	[0.55, 0.75]	0.65	0.0333
Good	[0.65, 0.85]	0.75	0.0333
Very good	[0.75, 0.95]	0.85	0.0333
Excellent	[0.85, 1.00]	1.00	0.5000

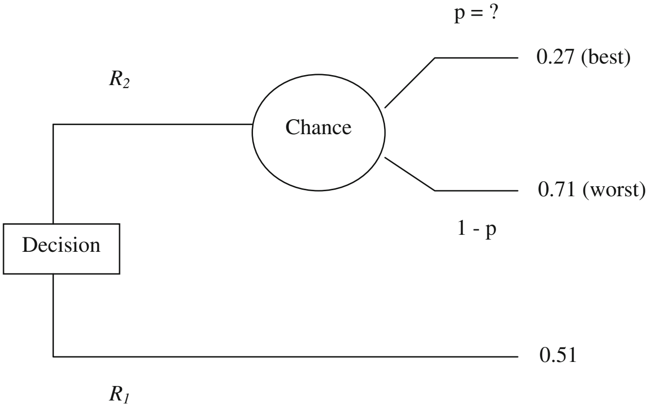

Fig. 5.2 Routes to assign utility values

1. Certain option: go to route R_1 for a certain attribute of 21 with a probability $p = 1$.
2. Risk option: go to route R_2 for either a best attribute of 50 with a probability p or a worst attribute of 1 with a probability $1 - p$.

What utility value should the decision-maker assign to a certain attribute of 21? For the decision-maker to make good decision and choose from the two routes, the utility value of 21 must be assessed and compared with the expected utility of the risk option. To do this, the decision-maker determines a relative preference for the certain attribute of 21 by finding the probability p for the best outcome, to which the decision-maker is indifferent, between the certain route R_1 for the certain attribute of 21 and the gamble route R_2 for the two possible outcomes of 50 and 1 day with wind speed >=70 km/h. Let us assume that there is a probability of 0.3 for getting the best outcome and a probability of 0.7 of getting the worst outcome from the route R_2. Which route would the decision-maker prefer in this case? Since $p = 0.3$ the chance of getting the best outcome from route R_2 (50) is very small, or the chance of getting the worst outcome (1) is very high ($1 - p = 0.7$), so in this case a risk-aversion decision-maker will not gamble in order to avoid running the risk of choosing that location with the lowest number of days with wind speed >=70 km/h to place the wind farm. He prefers to choose route R_1 with a 21 certain attribute. However, a risk-seeking decision-maker will gamble even though the chance of getting the best outcome from route R_2 and choose the highest number of days, is very small ($p = 0.3$).

Now, let us assume that there is a probability of 0.9 for getting the best attribute and a probability 0.1 for getting the worst case from route R_2. Since $p = 0.9$, in this case there is a high chance of getting the best outcome (50), so a risk-aversion decision-maker will gamble and choose route R_2, trying to choose the location with the best number of days with wind speed >=70 km/h. Now, let us take a probability of 0.45 of getting the best outcome and a probability of 0.55 of getting the worst outcome from route R_2. Which route does the decision-maker now prefer? Putting $p = 0.45$ makes the thing difficult to choose for the decision-maker but a risk neutral decision-maker will go for the certain outcome route R_1. Doing some more of these trials and errors, the decision-maker considers that a probability of 0.5 will make him indifferent between the two routes R_1 and R_2. According to utility theory, by choosing the probability that makes him indifferent between the two routes, the decision-maker has assigned a utility value for the certain outcome of 21. It is known from the principles of probabilities that the expected value of any random variable in the space will equal the sum of probability of each variable times its score. In this case, the expected utility for the route R_2 which includes two variables or two outcomes (the best outcome with $u = 1$ and the worst outcome with $u = 0$) will be:

$$\begin{aligned} & p(\text{utility of best outcome}) + (1 - p)(\text{utility of worst outcome}) \\ & = 0.5 * u(50) + (1 - 0.5) * u(1) = 0.5 \end{aligned}$$

Since the decision-maker is indifferent between an attribute of 21 for certain and this gamble, the alternatives must have the same utility value, that is $u(21) = 0.5$. The same procedure is used for the rest of criteria.

Before transferring these data into a uniform numerical domain using utility curves, the data corresponding to the criterion days with wind speed >=70 km/h must be normalized. Since the maximum value is desirable for this criterion the intermediate utility values are obtained by normalizing the evaluation matrix as follows:

$$u_j = \frac{A_j - A_{\min}}{A_{\max} - A_{\min}} \tag{5.8}$$

where A_j, $A_{\max}$, and $A_{\min}$ represent the score, the maximum and the minimum scores assigned to the jth ratio, respectively.

In step 4, cloud characters of individual attributes are calculated. For the quantitative attribute two different types of utility curves have been used each one describing different decision-maker's attitude toward risk. These curves are shown in Fig. 5.3, a concave function exhibiting risk-averse behavior and a convex function exhibiting risk-seeking behavior. Table 5.4 shows the expectation and entropy for the quantitative attribute using Eqs. (5.1) and (5.2), and concave and convex utility functions. Table 5.5 shows the cloud characters using Eqs. (5.3) and (5.4). The following calculations explain the process for Cabo Vilan and a Risk-aversion decision-maker:

Normalized value for Cabo Vilan of days with wind speed >=70 km h:

$$\frac{10 - 1}{50 - 1} = 0.184(\text{April});\ \frac{7 - 1}{50 - 1} = 0.122(\text{May}),\ \frac{6 - 1}{50 - 1} = 0.102(\text{June})$$

Risk-aversion value:

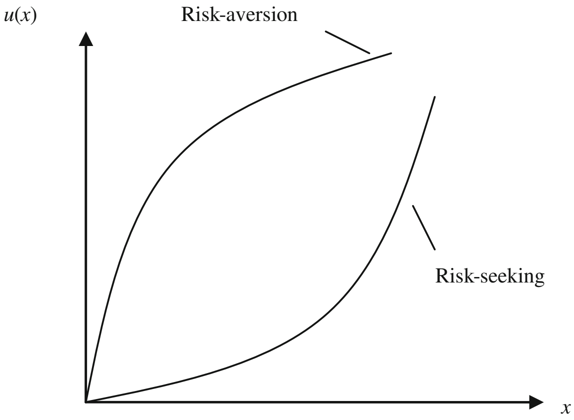

Fig. 5.3 Utility curves

Table 5.4 Expectation and entropy for the Quantitative attribute

Cabo Vilán		Estaca de Bares		Fisterra		Cabo Busto		Cabrales		Taramundi	
Ex	En	Ex	En	Ex	En	Ex	En	Ex	En	Ex	En
Risk aversión $u(x) = -1.42x^2 + 2.1x + 0.249$											
0.507	0.059	0.948	0.057	0.595	0.059	0.669	0.312	0.484	0.029	0.503	0.104
Risk seeking $u(x) = 1.20x^2 - 0.43x + 0.05$											
0.016	0.003	0.361	0.332	0.014	0.003	0.228	0.265	0.016	0.002	0.019	0.003

$$-1.42(0.184)^2 + 2.1(0.184) + 0.249 = 0.587 \text{ (April)}$$
$$-1.42(0.122)^2 + 2.1(0.122) + 0.249 = 0.485 \text{ (May)}$$
$$-1.42(0.102)^2 + 2.1(0.102) + 0.249 = 0.449 \text{ (June)}$$

Expectation:

$$\frac{0.587 + 0.485 + 0.449}{3} = 0.507$$

Entropy:

$$\sqrt{\frac{1}{3}\left((0.587 - 0.507)^2 + (0.485 - 0.507)^2 + (0.449 - 0.507)^2\right)} = 0.059$$

5.3.2 Results

Based on expectation and entropy values for individual attributes obtained in step 4, expectation and entropy for the entire multi-attribute problem are calculated

Table 5.5 Expectation and entropy for qualitative attributesattributes

Attributes	Cabo Vilán		Estaca de Bares		Fisterra		Cabo Busto		Cabrales		Taramundi	
	Ex	En	Ex	En	Ex	En	Ex	En	Ex	En	Ex	En
Topography	0.823	0.016	0.614	0.018	0.480	0.019	0.646	0.016	0.823	0.016	0.446	0.016
Infrastructure	0.457	0.018	0.792	0.016	0.838	0.016	0.462	0.016	0.600	0.016	0.514	0.018
Land use	0.600	0.016	0.838	0.016	0.457	0.018	0.514	0.018	0.462	0.016	0.792	0.016
Safety	0.462	0.016	0.457	0.018	0.792	0.016	0.838	0.016	0.514	0.018	0.600	0.016

Table 5.6 Expectation, entropy and coefficient of relative dispersion

	Risk aversion				Risk seeking		
	Ex	En	Rd		Ex	En	Rd
Estaca de Bares	0.741	0.016	0.022	Estaca de Bares	0.594	0.083	0.140
Fisterra	0.643	0.016	0.025	Cabo Busto	0.511	0.067	0.131
Cabo Busto	0.621	0.078	0.126	Fisterra	0.498	0.007	0.014
Cabrales	0.600	0.01	0.017	Cabrales	0.483	0.007	0.014
Cabo Vilán	0.576	0.016	0.028	Cabo Vilán	0.453	0.007	0.015
Taramundi	0.535	0.027	0.050	Taramundi	0.414	0.007	0.017

using Eqs. (5.5) and (5.6). These data are used as quantitative measures in order to analyze the evaluation results in the final step.

Table 5.6 shows the expectation, entropy and the coefficient Rd. The results are very similar in both cases, except for the second and third place. At the lower level of the table, we can see the worst rated locations. Those locations that, due to their attributes, are not the best places to locate the wind farm. This is the case, for example, of Cabo Vilán and Taramundi. At the top of the table, the best rated location for both a risk aversion decision-maker and a risk-seeking decision-maker is Estaca de Bares. This is the location with the highest number of days with wind speed >=70 km/h and the best land use attribute and, therefore, the best place to locate the wind farm.

5.4 Conclusions

In the selection of a RE project a multitude of technical, financial, environmental, legal, social and political objectives, and/or constraints, some of which are not even quantifiable, some of which are conflicting, must be taken into account. In this chapter a multi-attribute decision-making method combining cloud and utility theory is proposed in order to evaluate different locations for a wind farm in the north of Spain. Whereas utility theory allows us to use different utility curves describing different decision maker's attitudes toward risk, cloud theory provides a model that facilitates transformation of uncertainty contained in both quantitative and qualitative concepts to a uniform presentation in a numerical domain.

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Chapter 6
Territorial Design for Matching Green Energy Supply and Energy Consumption: The Case of Turkey

Seda Uğurlu, Başar Öztayşi and Cengiz Kahraman

Abstract Green energy (GE) refers to energy sources that have no undesired consequences such as carbon emissions from fossil fuels or hazardous waste from nuclear energy. Alternative energy sources are renewable and are thought to be "free" energy sources. These include biomass energy, wind energy, solar energy, geothermal energy, and hydroelectric energy sources. GE supply is viewed as an option for satisfying the increased energy demand with the prospect of carbon accountability. However, geographical areas have diverse GE resources and different levels of energy consumptions. Territory design is defined as the problem of grouping geographic areas into larger geographic clusters called territories in such a way that the grouping is acceptable according to the planning criteria. The aim of this study is to group geographic areas in such a way that energy requirement in a geographic cluster matches the available GE potential in the same cluster. In this way, investments may be supported through region specific policies.

6.1 Introduction

Energy has always played an important role in human and economic development. Today, modern society uses more and more energy for industry, services, homes, and transport. Without the heat and electricity from fuel combustion, economic

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activity would be limited (IEA 2005). However, neither oil nor any of the other fossil fuels, such as coal and natural gas, are unlimited resources. Because of the extensive use in various industrial and nonindustrial sectors, fossil fuels have caused some major human health and human welfare problems. As a result of global energy dependency, environmental factors such as greenhouse gas emissions and human health problems, green energy (GE) sources have gained tremendous attention. Midilli et al. (2006) identify the reasons why GE technologies can be the key factor in sustainable development as follows: GE (1) provide a more environmentally benign and more sustainable future, (2) increase energy security, (3) facilitate or necessitate the development of new and clean technologies, (4) reduce air, water and soil pollution and the loss of forests, (5) reduce energy-related illnesses and deaths, and (6) reduce or stop conflicts among countries regarding energy reserves.

Energy supply system is the chain of systems and activities required to ensure supply of energy. The supply system is made up of the supply sector, the energy transforming sector and the energy consuming sector. The supply involves indigenous production, imports or exports of fuel, and changes in stock levels. Transformation converts different forms of energies for ease of use by consumers. Transformation processes normally involve a significant amount of losses. Transportation and transmission of energy also involve losses. The final users utilize various forms of energies to meet the needs of cooling, heating, lighting, and motive power. For the sustainability of the current quality of life the balance between supply and consumption is very important. Before 1970s, the demand side of the balance was treated as an uncontrollable variable and the energy planners were trying to constitute the balance with aligning the supply side. However, after the price increases in 1970s, the planners started to focus on the demand side of the system. Today, governments and policy makers' primary aim in energy planning efforts is to align all the energy supply chainso as to meet the excess energy demand in an optimal way considering the environmental issues.

Over the last few years, investment in GE technologies has steadily increased and reached to 12.9 % of global primary energy supply in 2008 (IPCC 2012). While solar and wind energy showed a significant growth that are still only covering a small fraction of global energy supply. Bio-energy is leading the Renewable energy sources by around 80 % share among the renewable energies. As a result of the new investments in clean energy, the total investments have reached to 260 billion in 2011 from 54 billion dollars in 2004 with a constant increase (BNEF 2012). While governments were leading the GE investments a decade ago, today private investments have become the largest source of the capital for new projects. This growth is the result of two factors: the new energy policies have created new market opportunities that encourage private sector investments, and on the one hand technology improvement has led to increased reliability and declining costs (Wüstenhagen and Menichetti 2012). For instance, average project cost for wind energy has decreased from 3,500$ in 1985 to around 1,500$ in 2004 (Wiser and Bolinger 2007), and the average price of grid-connected solar photovoltaic (PV) systems has decreased around 30 % just in the year of 2009 (IEA 2010). These two types of energy investments have shown dramatic growth during the past 10 years. As a result of the regulations about the carbon emissions, investment in renewable energy is supposed to show further growth.

In the literature, there are various studies related with energy planning. In this study, we classify and present these studies into six groups: (1) Optimization model (OMs) try to find the best solution given a set of constraints. Energy flow optimization, energy source OMs can be given as examples, (2) Multi criteria decision-making (MCDM) techniques are used to select best alternative among the, alternative policies or energy sources, (3) Forecasting models are used to get insight about future demand and supply levels. The findings of these results can be used for future planning, (4) Integrated energy planning which aims to optimize overall energy system using both commercial and renewable energy sources (5) Energy planning models focus on environmental issues as the environmental factors gain importance and regulations are being developed, environmental constraints have become a part of energy planning models, and (6) Decentralized energy planning (DEP), apart from the traditional centralized energy planning (CEP) perspective, DEP considers various available resources and demand in the appropriate planning level such as villages, blocks, or districts.

Territory design is defined as the problem of grouping small geographic areas such as counties, zip codes, or company trading areas, into larger geographic clusters called territories. The territories are generated according to relevant planning criteria which can be economically motivated (e.g., average sales potentials, workload, or number of customers), or have a demographic background (e.g., number of inhabitants, and voting population). In territorial design problems, spatial restrictions such as contiguity and compactness can be demanded (Kalcsics 2005). In the field of energy planning, territorial design approach can help identifying the regions or districts that will be the focus of decentralized planning efforts. To that end, the planning criteria should be related to energy planning issues, such as energy production capacity and consumption.

In this study, we present a case study for using territorial design approach to a new GE planning problem. The aim of the model is to determine the GE planning territories in Turkey to make the energy consumption and the GE potential equal for each territory. In this manner, the chapter is organized as follows. In Sect. 6.2, energy planning literature and factors used in energy planning are introduced in details. Section 6.3 describes territorial design and provides a brief literature review about previous studies. Section 6.4 contains a territorial design application for the case of Turkey and finally further steps are discussed in conclusion.

6.2 Energy Planning

The core aim of energy planning is balancing the consumption and the supply of energy. The two criteria in balancing are the relative magnitudes and spatio–temporal characteristics of supply and demand. Demand increase, high costs of energy, and the environmental pressure fossil fuels cause, have necessitated many countries to search for new energy sources such as GE alternatives as well as new strategies. Among these strategies, one of the promising trend is to decentralize energy resource management. Decentralization of the energy can give relief from large-scale decisions and decrease the losses in transmission and distribution which forms 7 % of the total cost of energy system typically in a centralized energy model (Hutchingson 2011). In some countries such as Turkey, the losses in the transmission and distribution phases count up to almost 18 % (EPDK 2010). Coordinating energy use locally with decentralized energy systems, seen as the future of the energy systems, would eliminate a large portion of such inefficiencies and present flexibility for energy planning.

In order to balance demand and supply, energy planners need to forecast the demand which is distributed both spatially and temporally. At the same time, the supply of energy is planned based on different energy resources considering the potential and limitations posed by them.

6.2.1 Consumption and Demand Forecasting

Energy planners need to forecast the spatial and temporal consumption of energy in order to adjust the energy supply. For this aim, demand forecasting is used to predict the electricity demands for the succeeding energy generation period. Demand forecasting of energy is classified into two groups based on the time scales: short–medium term and long-term forecasts.

Short–medium term forecasts mainly focus on identifying the variation of energy demand on a daily, weekly, and seasonal scale. The high and low level of energy consumption in a day commonly corresponds to business hours and common daily routines such as meal times. Seasonal peaks in demand also occur, for instance due to widespread use of air conditioning in hot weather (Ogston et al. 2007).

On the other side, long-term forecasts for a year or several years are used to predict the total magnitude of energy demand in order to plan maintenance and evaluate the necessity for additional capacity. The spatial distribution of energy demand is needed to be considered in demand forecasting, since it is not possible to store the energy and it is needed to be dispatched to the right place when it is required.

Traditional systems which are mainly characterized by centralized generation capacity and the associated infrastructure such as transmission facilities require long planning and construction times. Thus, accuracy in long term forecasting becomes crucial. However, decentralized energy systems in which, customer loads and small generators located close to load centers offer adaptive and flexible systems where quick response to changes in demand level can be achieved efficiently. Decentralized systems can give relief from large-scale decisions where long-term forecasting is over-emphasized due to long-term planning/construction periods of large-scale facilities and high investment costs. Decentralized systems can also assist constrained electricity distribution networks during summer and winter demand peaks and decrease the transmission and distribution costs (Born 2001).

Techniques for demand forecasting include statistical methods (Ozveren et al. 1997) such as time series (NEMMCO Operating Procedures 2000), profile classification (Shrestha and Lie 1993), and artificial intelligence techniques such as neural networks (Born 2001; Bitzer et al. 1997; Kermanshahi et al. 1997).

6.2.2 Supply and Renewable Energy Potentials

The main energy supply in the last century mainly depended on reserves of fossil fuels and uranium which are generally named as conventional energy resources. However, it is important to know the extent of available reserves of the conventional energy resources and the limitations posed on them due to environmental damage and territorial unbalance caused by the centralized energy model (Yüksel and Kaygusuz 2011). In view of these inconveniences, it seems obvious that we must transform the current energy systems by integrating new resources and modifying the way we use them. It is necessary to make compatible socioeconomic development with a sustainable energy model that could generate local wealth and do not damage the environment. The key issue is to address the current energy model toward a more balanced and decentralized system based on the exploitation of GE resources (Terrados et al. 2009).

All the options we name as GE resources (hydroelectric, PV power plants, wind, solar thermal and PV roofs, biomass, geothermal, etc.,) enjoy the advantage of being sustainable and to alter only marginally the carbon balance of the planet's atmosphere, because the production, use, and decommissioning of conversion facilities involve some emission that is normally small in comparison to those involved in the production of the same energy by conventional energy resources (Angelis-Dimakis et al. 2011).

On the other hand, complexity of energy production (heat and/or power) from GE sources has to be considered. Renewable energy forms such as the solar, wind, or hydro energy are characterized by being spatially distributed. As well, such GE forms differing from fossil fuels cannot be stored easily in order to balance the temporal differences between supply and demand of energy. So the exploitation of these sources of energy is somehow more complex. Their spatial distribution also means that their exploitation is closely linked to the characteristics of the local environment, and in turn it may have environmental impacts distributed on a wider area (Angelis-Dimakis et al. 2011).

The main practice in evaluating the potential of GE forms, wind, and solar energy is analyzing data from meteorological measurement stations. However, there exist a limited number of meteorological measurement stations within a geographical area. Thus, in order to determine the potentials in the whole territory, prediction methods are used to estimate the wind and solar promise in other locations where no measurement stations are available. Most commonly, geographical modeling and interpolation methods are used to predict the GE potential in the whole territory which is investigated. An example of such an interpolation method, named as kriging, is based on least-square linear regression algorithms. Kriging is used to estimate values of a variable at locations where data are not available based on the spatial pattern of the available data (Dagdougui et al. 2011; Alsamamra et al. 2009). Ordinary kriging is the only technique that takes into account two sources of information regarding the attributes, variables, and distance between points (Saito et al. 2005). The technique is widely used to find the linear unbiased estimation of a second-order stationary random field with an unknown constant mean as in Eq. (6.1) (Chen et al. 2012):

$$\hat{Z}(x_0) = \sum_{\mathrm{i}=1}^{n} \boldsymbol{\lambda}_{\mathrm{i}} Z(x_{\mathrm{i}}) \tag{6.1}$$

where $\hat{Z}(x_0)$ is the kriging estimation at the location x_0, $Z(x_i)$ is the sampled values at x_i and λ_i is the weighting factor related to $Z(x_i)$. The spatial correlation between the data, which is obtained by a variogram, determines the weighting factors used in the estimation. The variogram for a specified lag distance is defined as the average squared difference between the values of each pair of locations which are separated approximately by the specified lag distance. The best lag distance for revealing the spatial correlation is found by calculating experimental variograms. As a result, variogram values are plotted with respect to different lag distances and an appropriate lag distance is selected.

The estimates $\hat{Z}(x_0)$ are calculated as linear combinations of the n location values with the weights λ_i as coefficients. The estimation error (residual) is defined as in Eq. (6.2).

$$R(x_0) = \hat{Z}(x_0) - Z(x_0) = \sum_{\mathrm{i}=1}^{n} \boldsymbol{\lambda}_{\mathrm{i}} Z(x_{\mathrm{i}}) - Z(x_0) \tag{6.2}$$

where $Z(x_0)$ is the true value of the regionalized variable at the spatial location x_0 and $R(x_0)$ is the estimation error (residual). In an unbiased estimator, the expected value of the residual must be 0.

6.2.3 Literature Review on Energy Planning

Both the growth in population and increased per capita energy consumption, which is one of the indices of improved quality of life, the total demand for energy has multiplied. As a consequent of the increased demand, the supply cannot easily fulfill the energy demand by traditional energy technology using a few local resources. Under these circumstances, the energy-planning attempts to find a set of sources, strategies, and conversion technologies so as to meet the excess energy demand in an optimal way.

Energy planning consists of the supply side and the demand-side management activities. Before the rising of the energy prices in the 1970s, the focus of energy planning was on the supply side that is, the demand was treated as an uncontrollable data and the objective of the studies was to find resources and satisfy the demand. After 1970s the researchers, professionals, and governments started to focus on demand side. CRA (2005) defines energy demand management as "systematic utility and government activities designed to change the amount and/or timing of customer's use of energy". Demand management consists of the planning, implementing, and monitoring activities of energy utilization that are designed to encourage consumers to modify their level and pattern of energy usage. Energy demand management includes various categories of activities such as: load management, energy conservation, fuel substitution and load building.

Load management aims to plan the size or timing of the demand. Energy conservation focuses on technical efficiency improvements for reducing the demand. Fuel substitution aims to substitute one fuel by another in order to modify the demand. And finally, load building implies developing load for strategic purposes which could help manage the system better.

Energy planning activities can be handled at centralized or decentralized level. CEP activities are generally commercial energy oriented which is focused on fossil fuels and centralized electricity. CEP has resulted in inequities between different parts of the population and environmental degradation. For example, large proportions of the rural population and urban poor depend on low-quality energy sources and inefficient devices, leading to low quality of life. DEP focuses on efficient utilization of the resources. The regional planning perspective considers various available resources and demand in a region. In this regard, villages, blocks, or districts are accepted as the appropriate planning level. The planners have various forms of mediation to overcome energy shortage:

- energy conservation through promotion and use of energy efficient tools;
- supply expansions through energy plantations and;
- utilizing renewable sources of energy.

In the literature, there are several efforts to formulate and implement energy planning activities. In this study, we provide a brief overview of the various types of energy planning models, namely, optimization, forecasting, integrated energy planning, environmental planning, and decentralized planning models.

OM are used to define the best solution in a given circumstance. OM has an objective function that is to be maximized according to the given alternatives and the assessed constraints. Scott et al. (2012) classify optimization into two groups, optimization with many alternatives and optimization with few alternatives. Some leading examples of optimization with many alternatives can be given as follows: Cormio et al. (2003) build an optimization model using linear programming (LP) methodology based on the energy flow optimization model. The objective of the model is to support planning policies for promoting the use of renewable energy sources with respect to the environmental constraints.

Drozdz (2003) proposes an optimization model for a geothermal energy source. The objective of the model is to maximize the net power of the source, based on the theoretical water well of different quality parameters. Ayoub et al. (2009) present an optimization model so as to design and evaluate an integrated system of bioenergy production supply chains using evolutionary algorithms.

MCDM techniques are used for optimization problems with few alternatives. Commonly used MCDM techniques include, PROMETHEE, ELECTRE, TOPSIS, VIKOR, MAUT, AHP, and ANP. Besides the classical crisp approach, fuzzy approaches are also used with these techniques. In these kind of studies, the energy alternatives or the energy planning strategies are generally evaluated and prioritized (Papadopoulos and Karagiannidis 2008; Shen et al. 2011; Tsoutsos et al. 2009). A brief literature review about MCDM in GE researches is given in Chap. 3.

Forecasting Models: energy forecasting models aim to estimate energy demand or supply using different variables such as population, income, price, growth rate, and natural sources. Forecasting models are used for both conventional and renewable energy supply. Persaud and Kumar (2001) propose an oil and gas supply model so as to present the projections of supply and demand to the year 2020 for Canada. Weisser (2003) determines the wind energy potential of Grenada based on historic hourly wind velocity. Poggi et al. (2003) utilize an autoregressive time series model for forecasting and simulating wind speed in Corsica. Forecasting models are also used to model the future energy demand. Amarawickrama and Hunt (2008) use time series to forecast the energy demand for Sri Lanka. Similar to this, Bianco et al. (2009) build a model to forecast electricity consumption in Italy using linear regression models. Energy prices have also been estimated using forecasting models. Amjady and Keynia (2008) propose a day ahead price model that is a combination of a wavelet transform and a hybrid forecast method using neural network and evolutionary algorithms. Shafie-khah et al. (2011) propose a hybrid method to estimate the day-ahead prices in electricity market using Auto-Regressive Integrated Moving Average models and Radial basis function Neural Networks.

Integrated Energy Planning is another type of energy planning research area seeking to integrated energy planning. In this field, researchers try to develop integrated energy models using both commercial and renewable energy sources. Lin and Huang (2010) propose a stochastic energy systems planning model for supporting the decisions of energy systems planning considering greenhouse gases emission management at a municipal level. Sadeghi and Hosseini (2008) propose an integrated energy planning model for the transportation sector using Energy Flow Optimization Model-Environment model. Arnesano et al. (2012) apply portfolio theory to energy planning. The model is applied to Italia and the analyses are done for various scenarios. Frei et al. (2003) propose a dynamic top–down and bottom–up merging energy policy model in order to present new developments in the field of the consistent evaluation of sustainability assessment indicators.

Environmental Planning Models: The environmental planning models deal with both local environmental factors such as land degradation, loss of forests, indoor air pollution, and global environmental factors (e.g., greenhouse gas emissions and loss of biodiversity). Matthews (2001) evaluates the energy and carbon budgets of the biofuel production systems of wood fuel coppice. Choi and Ang (2001) build a time-series analysis model for energy-related carbon emissions and their relationships with energy consumption in Korea. Giatrakos et al. (2009) propose a model for sustainable planning which aims to fulfill the electric needs of the island by replacing the conventional energy sources with renewable ones.

Decentralized Energy Models (DEP): DEP models refer to regional energy planning and assist policy makers in evaluating energy policies and energy plans. In these models, various scenarios like, base case scenario, high-energy intensity, and transformation, state-growth scenarios can be built to get insight about future patterns and assess the expected impacts of energy policies. DEP models that focus on subnational levels are villages, clusters of villages, blocks, and districts. These kinds of models require a bottom-up approach using disaggregated data when compared to the models that have a national or global focus. Silva Herran and Nakata (2012) propose an optimization energy model for designing decentralized energy systems using biomass for rural electrification in developing countries with a case study in Colombia. Hiremath et al. (2010) build a model using goal-programming method in order to analyze the DEP through bottom-up approach.

The model is also applied for Tumkur district in India. Weber et al. (2006) propose a decentralized system combining a solid–oxide fuel cell (SOFC) with an absorption chiller-heater (ACH). The CO_2-emissions and costs are calculated for an office building in Tokyo and showed that the fully decentralized SOFC-based energy system could result in a potential CO_2 reduction of over 30 % at an estimated cost increase of about 70 % compared to the conventional system.

The literature review shows that DEP is healthier when compared to centralize planning. Since DEP can focus on different levels varying from regional to village level, identifying the focus level has a great importance. In this study, a model is proposed to identify the planning regions, based on their energy supply and renewable energy potential. The territorial design approach methodology and a case study in Turkey are presented in the following sections.

6.3 Territory Design

The aim of territory design which has also been named as "districting" is to group small geographical areas into larger area clusters with respect to a planning criterion. Some of the most common applications of territory design are political districting, design of the sales territories, design of territories for schools, waste collection or emergency services, and electrical power districting. In the political districting problem, the objective of the design is to form final areas such that each area has approximately the same number of voters, i.e., areas of similar size.

Another common application in business is designing the sales territories in order to subdivide the market area into regions of responsibility in terms of sales potentials or workload, or which reduce travel times within the territories needed to attend to customers or service incidents (Kalcsics et al. 2005).

Together with the addressed planning criterion specific to the territory design problem, models also incorporate conditions such as disjointness, contiguity, and compactness of the final territories to be honored. For example, compactness condition assures that the shapes of the final territories are not too long and thin. Thus, rectangular and circular districts are to be preferred. Disjointness assures that the territories do not overlap but it is also required by the contiguity feature that a territory cannot be disconnected, in other words, any two points within the territory can be connected through a path remaining in the same territory. For example, in electrical power districting problem, the aim is to partition the physical power grid into territories such that each maintain approximately equal earning potential. Besides, compactness is required so that managing will be easier and more economical.

Spatial considerations such as compactness are taken into account by minimizing a weighted distance between the areas and the territorial centers in order to design compact territories (Fleischrnann and Paraschis 1998). Depending on the type of problem and objectives, there are different approaches to represent the distances in the literature such as the use of Euclidean distances, straight line distances, and real network distances or travel time spent in each area (Hess and Samuels 1971; Marlin 1981; Zoltners and Sinha 1983; Lodish 1976).

In general, the methods for solving districting problems employ a sequence of exact optimization routines and/or heuristics and exhibit the following pattern (Fleischrnann and Paraschis 1998):

(a) Definition of one or several planning activity measures a_j;
(b) Definition of j basic areas and calculation of the activity demand of each area;
(c) Selection of i points as territory centers and the specification of their activity supply;
(d) Assignment of areas to territories in order to minimize (or maximize) some objective function.

The approaches for solving the districting problem can be divided into those that depend entirely upon heuristics and those that utilize more formalized mathematical programming techniques. Heuristics solution techniques proposed for territory design problem in the literature include greedy heuristics where the boundaries are adjusted successively to achieve uniform workload in each territory (Easingwood 1973; Lodish 1975), local search where a given territorial structure is improved stepwise by switching single areas between the territories (Bourjolly et al. 1981), geometry-based heuristics where the complete problem is recursively partitioned geometrically using lines into smaller subproblems until an elemental level is reached so that the territory design problem for each of the elemental subproblem can be solved efficiently (Forrest 1964; Kalcsics 2005) and meta-heuristics which presents more advanced heuristic routines such as tabu search

(Bozkaya et al. 2003), simulated annealing (Ricca 1996), and genetic algorithms (Forman and Yue 2003; Bergey et al. 2003). The interested reader may refer to the studies of Howick and Pidd (1990) and Ricca and Simeone (1997).

Among these approaches, modeling the territory design problem as a location–allocation problem has been studied in the literature extensively. The initial effort for developing this mathematical programming approach was presented as a political districting problem (Hess et al. 1965). In the location part of the problem, the new facility to be located is the territory center. The allocation part of the problem is the assignment of basic areas to the territories which are constructed by the basic areas assigned to each territory. The two parts, location and allocation are solved simultaneously. However, as the problem scale gets large, computational complexity of the problem gets quite large for an exact solution due to combinatorial nature. Hence, location and allocation stages may be decomposed into two independent problems and the two independent problems are solved by an iterative two-stage approach where steps (c) and (d) are repeatedly solved until a satisfactory result is achieved. In this two-stage approach, the location problem seeks to find the center of each territory obtained in the last allocation phase. The most commonly used procedure is to find the center of each territory by solving a 1-median problem in which the basic area to be the center in the next iteration is found to be the area which give the minimum sum of the distances with all other basic areas of that territory. (Fleischrnann and Paraschis 1998; George et al. 1997). Kalcsics et al. (2001) also presented a local search technique to refine the centers for the next iteration. The selection of centers has a significant impact on the final design of the territories.

In the second stage of this approach, the allocation problem has been commonly solved using transportation algorithms in the literature (Marlin 1981; George et al. 1997). These algorithms enable to deal with large-scale problems and yield optimal solutions satisfying the activity constraints. The allocation model is given in Eqs. (6.3–6.6).

$$\min \sum_{j \in J} \sum_{i \in I} a_j d_{ij} x_{ij} \tag{6.3}$$

$$\text{s.t.} \sum_{i \in I} x_{ij} = 1 \quad \forall j \in J \tag{6.4}$$

$$(1 - t)\mu \leq \sum_{j \in J} a_j x_{ij} \leq (1 + t)\mu \quad \forall i \in I \tag{6.5}$$

$$x_{ij} \in \{0, 1\} \quad \forall j \in J,\ i \in I \tag{6.6}$$

where x_{ij} is the decision variable representing the assignment of basic area j to the territory center i, a_j is the activity measure of basic area j, d_{ij} is the distance between the territory center i to basic area j, μ is the average activity measure of territories which may be calculated using Eq. (6.7), where $a(J)$ is the total activity measure of all basic areas and t is the tolerance value for the deviation of the actual total activity measure of the territories from μ and p is the number of territories.

$$\mu = a(J)/p \tag{6.7}$$

The integrality constraint for the binary decision variable in the model is relaxed to obtain a linear transportation model as given in Eqs. (6.8–6.11).

$$\min \sum_{j \in J} \sum_{i \in I} a_j d_{ij} x_{ij} \tag{6.8}$$

$$\text{s.t.} \sum_{i \in I} x_{ij} = 1 \quad \forall j \in J \tag{6.9}$$

$$\sum_{j \in J} a_j x_{ij} = \mu \quad \forall i \in I \tag{6.10}$$

$$x_{ij} \geq 0 \quad \forall j \in J,\, i \in I \tag{6.11}$$

Whereas the issue arising in the linear transportation algorithms is that one basic area may be assigned to more than one territory (Fleischrnann and Paraschis 1998). The assignment of one basic area to multi territories is then resolved using additional split resolution techniques in the literature. A simple technique named AssignMAX, which exclusively assigns the split areas to the territory which owns the largest share of the split area was proposed by Hess and Samuels (1971).

6.4 Modeling for Independent Regions Using Distributed Green Energy Resources

Recent advances in energy technologies have enabled to solve the challenges in energy planning and the environmental issues by a new approach: decentralized energy systems. The wind and Solar energy are seen as promising distributed GE resources which may be produced and used locally for decentralized energy systems. There are several benefits in coordinating energy use locally within clusters of resources in place of centrally coordinating all resources. The transmission and distributions costs will be reduced compared to the centralized energy systems. System robustness is improved since a point of failure will not affect the whole system as it is in central energy systems. Decentralized energy models will shorten the planning time required and reduce its cost due to easier communication within the local region between different parties involved in the planning process. As well, the scalability of the system will be easier as adaptation to the changes in the system will require less time compared to the central energy systems (Ogston 2007).

In this study, we investigate the use of linear transportation model for a large-scale energy territory planning problem in Turkey. The aim of the proposed model is to determine green energy planning territories in Turkey, so that the energy need in the territories may be satisfied using GE potential in each territory. We find the optimum solution for the LP model and then apply AssignMAX (Hess and Samuels 1971), which exclusively assigns the split areas to the territory.

The activity measure in the defined problem is the balance of energy consumption and GE potential in each territory. We simply aim to construct territories whose GE potential is equal to energy demand (consumption). For this sake, we first identify the demand and GE potential which constitutes the activity measure in the problem. We then present the collected data and explain the technique used for finding the spatial distribution of energy demand and GE (i.e. wind and solar energy) potentials in the application region. Finally, we present the model and the results obtained in the following subsections.

6.4.1 Data for the Case of Turkey

In this chapter, we seek for independent regions with respect to energy balance of demand and supply using a territory design model. The territory design model aims to group small geographical areas into larger area clusters with respect to a planning criterion. We first need to identify the level of geographical areas which will be used as basic areas to be grouped into larger regions. We have selected these basic areas to be the administrative districts in Turkey because energy related data for administrative districts which is collected and updated by the Turkish Statistics Institution (TUIK) can be easily accessible. There are in total 933 administrative districts in Turkey which is an appropriate number for handling the problem in a proper level of detail. Other options for the basic areas could have been the cities whose number in total is 81 in Turkey. This option would have yielded a rough solution due to low number of basic areas. On the other side, the basic areas could have been chosen further smaller than districts such as subdistricts. In this case, data related to each subdistrict may not be available and the problem could have been too complex to be dealt using the linear transportation model. As a result, the 933 districts in Turkey have been chosen to be the basic areas in the distributed GE Territory design problem.

Data used for modeling independent regions in which the energy need in the regions may be satisfied using GE potential in each region is basically the energy consumption levels and the GE potential in the basic areas. In this study, we assumed to balance the electricity consumption using solar and wind energy. Solar and wind energy are seen as promising GE technologies as well characterized as being spatially distributed resources (Angelis-Dimakis et al. 2011). Thus, solar and wind energy may be illustrated as the two major GE sources for decentralized energy systems.

We have used the data of annual electricity consumption of each city presented by TUIK as the energy demand. The available latest data set of electricity consumption of the cities is from year 2010, yielding a total of 172 million MWh in

Turkey. Since the basic areas used in the study are the districts, we need to identify the electricity consumption of each district using the electricity consumption data of the cities. Using the population of each district, we have distributed the electricity consumption of each city to the districts of the cities since population has been found to be a major factor influencing the energy consumption in many studies (Mazur 1994; Parikh and Painuly 1994). Another important factor for electricity consumption is the development level of the region. In this application, we distribute the total energy consumption of a city to its districts. Thus, we may neglect the differences of the development levels of districts which will not differentiate particularly within a city. As a result, the electricity consumption of a district is formulated as Eq. (6.12), where c_j and c_k is the electricity consumption of districts and the cities respectively and n_j and n_k are the populations of the districts and the cities respectively.

$$c_j = \frac{n_j}{n_k} c_k, \text{ where } n_k = \sum_{j=1}^{j \in J_k} n_j \tag{6.12}$$

The electricity consumption of the cities and the districts is illustrated in a grayscale figure in Figs. 6.1 and 6.2 respectively.

Next, we need to identify the solar and wind energy potential of each district. Parallel to the practices in the literature, we have used the data collected by the meteorological measurement stations. Data of year 2011 was accessible from 59 solar measurement stations and 346 wind measurement stations along the land of Turkey. Various measurements related to solar and wind energy may be used in order to predict the potential of solar and wind energy using different prediction models or simulations. Since, the aim of this study is only to generate independent regions with respect to energy, we have not developed a model to predict the

Fig. 6.1 Consumption of the cities

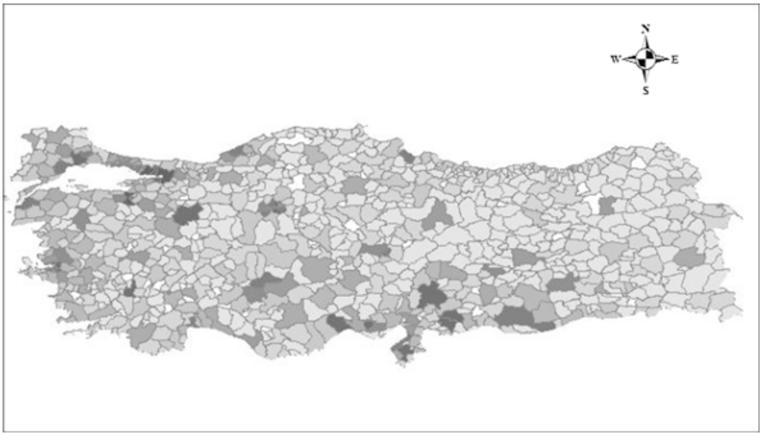

Fig. 6.2 Electricity consumption of districts

potential of solar and wind energy but we have used the available predictions given in Table 6.1 for the total solar and wind energy potential of Turkey.

We, then, used an interpolation method, named as ordinary kriging which is based on least-square linear regression algorithms to obtain the spatial distribution of the energy potentials. The details of the method is presented in Sect. 6.2.2. In this way, we acquire the interpolated estimations of solar and wind energy potential for anywhere in the territory in question.

For solar energy, we have used the annual solar radiation measurements available at the solar energy measurement stations. Based on the spatial pattern of the available data, we predicted the solar radiation values at any location in Turkey. For identifying wind energy, we used average annual wind speed measurements at the meteorological measurement stations. Using available data, estimation of wind speed values of any location in Turkey are obtained using ordinary kriging as a built-in procedure in Esri ArcGIS v.10. The meteorological measurement stations and the obtained prediction surfaces for solar radiation and wind speed are given separately at Figs. 6.3 and 6.4.

We, then, obtain the radiation and wind speed values at the centroid of each district using the predicted surface. Finally, we have distributed the total solar (p_k^s) and wind energy potential (p_k^{ws}) of Turkey given in Table 6.1 to the centroids of the districts based on the predicted radiation ($\hat{r}_j$) and wind speed values ($\hat{ws}_j$),

Table 6.1 Potential of wind and Solar energy sources

Type of energy	Technical potential (MW)	Economic potential (MW)	Potential (MWh)
Wind	80,000	20,000	45,000,000
Solar	56,000	<56,000	136,752,000
Total	136,000	<76,000	181,752,000

Data source Ministry of Energy and Natural Resources (2010)

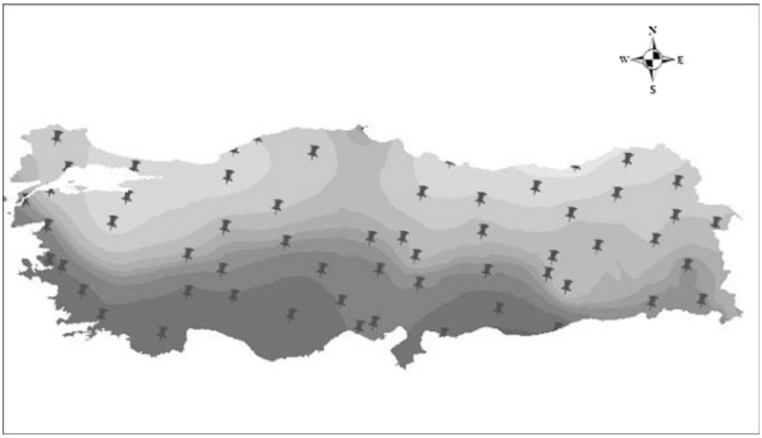

Fig. 6.3 Meteorological measurement stations and kriging prediction surface for solar radiation: the case of Turkey

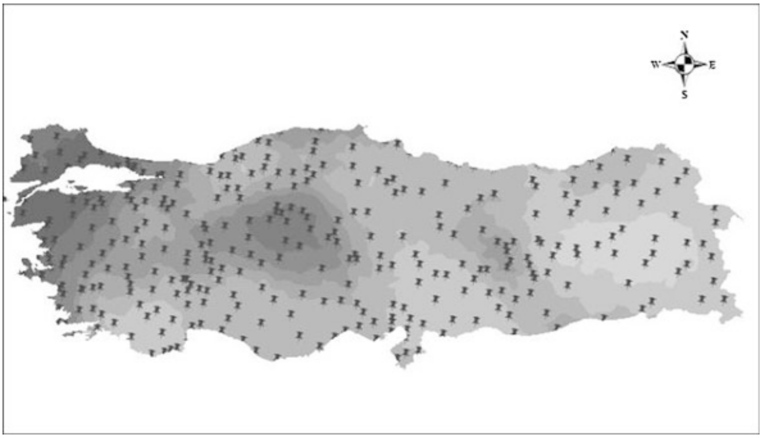

Fig. 6.4 Meteorological measurement stations and kriging prediction surface for wind speed: the case of Turkey

respectively, at the centroids of the districts using Eqs. (6.13) and (6.14). The total potential of distributed GE potential of each basic area (p_j) had been calculated as summing up the calculated solar energy potential and wind energy potential as in Eq. (6.15).

$$p_j^s = \frac{\hat{r}_j}{\hat{r}_k} p_k^s, \text{ where } \hat{r}_k = \sum_{j=1}^{j \in J} \hat{r}_j \tag{6.13}$$

$$p_j^{ws} = \frac{\hat{ws}_j}{\hat{ws}_k} p_k^{ws}, \text{ where } \hat{ws}_k = \sum_{j=1}^{j\in J} \hat{ws}_j \tag{6.14}$$

$$p_j = p_j^s + p_j^{ws} \tag{6.15}$$

6.4.2 Territory Design Model and Solution

The aim of the territory design problem formulated in this study is to generate independent regions which will satisfy the electricity demand of the region locally, using distributed GE resources, specifically solar and wind energy resources. Hence, the total of the solar and wind energy potential of each region should be equal or greater than the total electricity consumption of the region. The problem is formulated as a linear transportation model for the case of Turkey. The model is presented in Eqs. (6.16–6.19).

$$\min \sum_{j\in J} \sum_{i\in I} |a_j| d_{ij} x_{ij} \tag{6.16}$$

$$\text{s.t.} \sum_{i\in I} x_{ij} = 1 \quad \forall j \in J \tag{6.17}$$

$$\sum_{j\in J} a_j x_{ij} \geq 0 \quad \forall i \in I \tag{6.18}$$

$$0 \leq x_{ij} \leq 1 \quad \forall j \in J,\ i \in I \tag{6.19}$$

where x_{ij} is the decision variable representing the assignment of basic area j to the region center i, a_j is the activity measure of the basic area j, d_{ij} is the distance between the region center i to the basic area j. The distances have been calculated as Euclidean distances between the coordinates of the basic areas and centers.

The basic areas for the case of Turkey are defined as the 933 districts of Turkey. We have selected to generate a fix number of regions as seven, because the country has been divided into seven administrative regions. However, the number of regions (clusters) is a parameter which could be modified according to the purposes of energy planning. A center has been associated with each territory and has been chosen arbitrarily among the set of basic areas. In order to select these initial centers, similar to a geometry-based partitioning, the area in consideration has been partitioned into seven areas by rule of thumb and the center for each territory has been chosen randomly among the basic areas in these seven areas.

The objective function is given in Eq. (6.12) ensuring the compactness of the regions by minimizing the total weighted distance. Activity measure, a_j, is formulated as $a_j = p_j - c_j$, where p_j is the total of solar and wind energy potential of basic area j and c_j is the total electricity consumption of basic area j. Since, the

Table 6.2 The assignment values of split areas to region centers

Basic area ID	Region center ID							
	1	2	3	4	5	6	7	Total
A22747328				0.22	0.78			1
A22748031						0.24	0.76	1
A22748371			0.04				0.96	1
A22748882			0.30	0.70				1
A22749786	0.22	0.78						1
A23434067	0.69				0.31			1

difference may be a negative value, absolute value of a_j has been defined in the objective function. Equation (6.13) ensures that each basic area is allocated to exactly one region center which guarantees the disjointness of the regions. Equation (6.14) makes certain that the total energy potential and consumption difference is greater than zero, meaning that the total of the solar and wind energy potential of each region should be equal or greater than the total electricity consumption of the region. Equation (6.15) assures that the decision variable, the assignment of basic area j to region center i, may take the values between 0 and 1 which is obtained after the relaxation of the integer programming model. Since we deal with a LP model after the relaxation, we have used an LP solver. In this study, we employed GAMS v.21.6 using the Cplex solver in order to find the optimum solution of the model. Then, we apply AssignMAX (Hess and Samuels 1971), which exclusively assigns the split areas to the region owning the largest share of the split area. Before applying AssignMAX, split areas have found to be distributed among two regions for each split case and the number of splitted basic areas has been six as listed in Table 6.2. As the assignment values of each basic area to two different region centers differ significantly from each other, we have applied

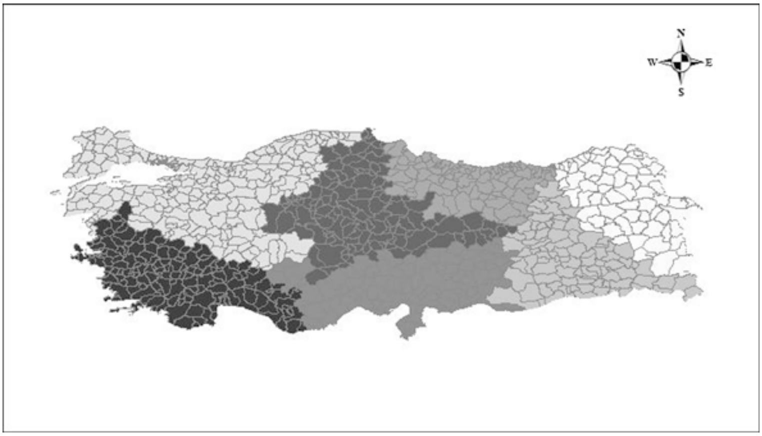

Fig. 6.5 Independent regions using distributed green energy resources in Turkey

the simple tie breaking rule, AssignMAX. Since the areas obtained after the first iteration yield compact clusters, the iterative location–allocation heuristics has been terminated.

Finally, we obtain the clusters of basic areas as independent regions which satisfy the electricity demand of the region locally, using distributed GE resources, namely solar and wind energy resources. In Fig. 6.5, the generated seven independent regions are depicted on the map of Turkey.

6.5 Conclusion

In this chapter, we investigate the use of territory design modeling for the purposes of energy planning. The aim of the formulated territory design model is to find independent regions in which distributed GE resources will be produced and used locally for decentralized energy systems. Decentralized energy model is seen as a promising approach offering several benefits such as improvement of system robustness and scalability, shortening of planning time and reduction in transmission and distribution costs. The presented study may be useful for energy planning and energy investments in Turkey in this framework.

The solution of the presented territory design model clusters the basic areas into independent regions which may be treated as a balanced unit with respect to the electricity consumption and wind and solar energy potential for energy planning. Hence, there are more questions involved with the territory design problem for decentralized energy systems. One of the major questions is the assessment of the relative costs and benefits of clustering the regions. In addition, different approaches to create clusters may be investigated. For example, number of clusters or the size of the clusters may be studied as important decisions which may have significant impacts on the outputs of the resulting energy systems. On the other side, various other clustering criteria may be considered in the territory design model. The model may be extended to consider the daily differences in energy consumption and supply, by defining and balancing more than one attribute per district. Our approach in this study assumed that all conventional energy sources have already been replaced completely by GE sources. As another approach, it would be interesting to extend the model in order to include the current energy sources and to model on how to replace them, step by step, by GE sources over the next years or decades. The solution methods may be also investigated which will allow large-size complex problems to be solved by complex solution algorithms such as hybrid methods or metaheuristics. Thus, further studies would be useful to extend the research in this area.

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Chapter 7
A Cumulative Belief Degree Approach for Prioritization of Energy Sources: Case of Turkey

Özgür Kabak, Didem Cinar and Gulcin Yucel Hoge

Abstract Energy planning is difficult to model owing to its complex structure, with numerous decision makers, criteria, and scenarios. Fortunately, decision-making methods can be helpful for the sustainable development of energy, by the evaluation of different energy sources with regard to multiple aspects, for example, economic, environmental, political etc. In this study, a methodology based on a cumulative belief degree approach is proposed for the prioritization of energy sources. The approach enables the use of all types of evaluations, without the loss of any information. It also allows for incomplete expert evaluations which may occur in the energy sources prioritization problem. Turkey, like many countries, generates most of energy from fossil fuels, which are imported mostly from other countries. However, the enormous increase in oil prices, and an emerging energy demand, owing to economic growth and environmental issues, is forcing Turkey to improve its sustainable energy planning. Therefore, the proposed methodology is applied to the energy sources prioritization of Turkey. Results show that solar power and wind should be considered as the priori sources of energy in Turkey.

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7.1 Introduction

The rapid increase in population and industrialization in the twentieth century resulted in a huge energy demand across the world. According to the International Energy Association (IEA), world energy demand will expand by 45 % in 2030 (Url-1, 2009). However, the major energy demand has some unintended consequences around the world, such as the increase in greenhouse gas emissions, and the risk of extinction of fossil fuels. Energy has a vital role in economic sustainability but it is not possible to provide sustainable development without protecting the environment, and taking economic conditions into account (Baris and Kucukali 2012). Sustainable development means the satisfaction of present needs while guaranteeing the ability of future generations to meet their own needs. Sustainability can also be defined as a balance of social and economic activities and the environment. Fortunately, decision-making methods for energy supply system options, planning, management, and the economy can be helpful for sustainable development (Wang et al. 2009).

However, decision making for sustainable energy planning requires methods that allow for the complexities of socioeconomic and biophysical systems, which address uncertainties of long-term consequences (Kowalski et al. 2009). According to the literature survey, multi-criteria decision-making (MCDM) methods have been applied to deal with the complexity of energy sources selection. In particular, fuzzy MCDM methods have been proposed and applied to the energy source selection problem, to deal with uncertainness caused by the different perspectives of several Stakeholders in the problem. Energy source selection problems are usually analyzed depending on the experts' knowledge. In most practices, the experts from different perspectives usually have different means of making evaluations. For instance, they prefer to use different scales to evaluate the same set of criteria. Moreover, their expertise may be inadequate for a particular part of the problem. Therefore, in this study, a cumulative belief degree (CBD) approach (Kabak and Ruan 2011a) is proposed for the energy sources prioritization problem. The CBD approach allows the aggregate of expert opinions, which can be expressed in different scales. It can also deal with the missing values owing to the lack of expertise, or scarce information.

Turkey generates 71 % of its energy demand from fossil fuels, which are imported from other countries. On the other hand, energy demand is expected to increase by 50 % until 2023. However, in the last 15 years, oil and natural gas prices have increased by 500 %, and fossil fuels energies have had irreparable harm on the environment. Furthermore, plans to build two nuclear power plants in Turkey keep the nuclear debate alive. These situations force Turkey to improve its sustainable energy planning. Therefore, this study aims to find out which energy sources can contribute to the transition toward a sustainable energy future for Turkey, from technological, economic, environmental, social, and political aspects. With this aim, a methodology based on a CBD approach is proposed, to prioritize energy sources for Turkey. In the first step of the methodology, factors for each perspective were defined based on a literature review. Then, these factors were refined and weighted by local experts by considering economic, environmental, and sociopolitical circumstances of Turkey. Wind, solar, geothermal, biomass, biofuel, hydroelectric, coal, petrol, natural gas, and nuclear energy options are evaluated in the decision model.

The rest of the chapter is organized as follows: the literature survey, including the evaluation criteria of alternative energy sources, is given in Sect. 7.2. The proposed methodology is presented in Sect. 7.3. The application of the methodology for energy policy evaluation in Turkey is given in Sect. 7.4. Finally, concluding remarks and suggestions for further studies are given in Sect. 7.5.

7.2 Literature Survey

Energy planning is difficult to model owing to its complex structure with numerous decision makers, criteria, and scenarios. As a result of the multi-dimensionality and complexity of energy planning, MCDM methods have become increasingly popular for sustainable energy policies. MCDM methods, which can help the policymakers to develop sustainable energy plans and policies, are reviewed in detail by Pohekar and Ramachandran (2004) and Wang et al. (2009). In this study, the studies published since 2009 are investigated, alongside the detailed review in Wang et al. (2009).

Wang et al. (2009) evaluated energy resources for China using a hierarchical decision model to determine which energy resource was important. Coal, petroleum, natural gas, nuclear energy, and renewable resources were taken as energy alternatives. According to the results, coal was the most preferred energy alternative for China, followed closely by renewable energy. Among availability, current energy infrastructure, price, safety, environmental impacts and social impacts, current energy infrastructure was found to be the most critical criterion for energy resource selection. Ren et al. (2009) applied the analytic hierarchy process (AHP) and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) method to select a residential energy supply system for a typical residential building in Kitakyushu, Japan. They indicated that although different results may be found by different MCDM methods, the general trend is always similar. Jovanovic et al. (2009) evaluated five future sustainability scenarios for Belgrade, using a multi-criteria method based on fuzzy sets considering economic, social, and environmental aspects. Tsoutsos et al. (2009) evaluated four energy policy scenarios for sustainable development on the Island of Crete, in Greece. The best scenario found by applying PROMETHEE was renewable energy investments, which included the installation of wind farms. Phdungsilp (2010) analyzed the sustainability of 16 scenarios constructed for Bangkok. All these scenarios were based on transport sectors, and evaluated by Web-HIPRE, which is an interactive Java-applet that supports multi-attribute value theory-based methods and AHP. Amer and Daim (2011) evaluated the energy alternatives with AHP for the case of Pakistan. The computation results indicated that biomass energy and wind energy emerged as the preferred alternatives. Economical and technological criteria are the most important factors for the selection and ranking of wind, solar photovoltaic, solar thermal, and biomass energy investment. Experts emphasized especially the investment cost, operation and maintenance cost, and power generation cost, because of the economic recession, as well as the weaker economy of Pakistan as a developing country. Ruan et al. (2013) developed an ordered weighted averaging operator-based CBD approach, to evaluate eight scenarios for a long-term energy policy in Belgium. Cristóbal (2011) used a Compromise Ranking Method which is known as the VIKOR method, to select a renewable energy project for Spain. VIKOR was combined with AHP, in order to weight the importance of the various criteria. According to the experimental results, a biomass plant alternative was the best option.

Atmaca and Basar (2012) applied Analytic Network Process (ANP) to determine the most appropriate energy resource for Turkey. They found that nuclear power was the best alternative. Baris and Kucukali (2012) commented on the current and future situations of renewable energy sources in Turkey, from the European Union (EU) perspective. The performance of various renewable energy technologies were evaluated with a multi-criteria analysis tool. The results showed that biomass is the most appropriate alternative because of its high social benefit.

Both qualitative and quantitative attributes form the complex structure of energy planning. Fuzzy sets have been used to express the judgments of experts under vague and hard environment. In recent years, fuzzy sets have been applied to many energy decision-making problems. Kahraman and Kaya (2010) compared the energy alternatives for Turkey with respect to technological, environmental, sociopolitical, and economic criteria, through the use of fuzzy AHP. Wind energy came out as the most attractive energy resource for Turkey. Talinli et al. (2010) compared three scenarios by fuzzy AHP, to determine the most appropriate energy production process for Turkey. Nuclear power plant projects, wind power plant projects, and already existing fossil fuel-based thermal power plants were compared, with respect to technical, economic, social, and environmental factors. They emphasized that Turkish authorities must have public acceptance when constructing new nuclear plants, because social acceptability was found to be the main agent in decision making. Wind power was found to have a greater priority than both nuclear and thermal power, so thermal power plants should be replaced by renewable energy sources. Doukas et al. (2010) proposed linguistic TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to evaluate renewable energy sources options. Ten renewable energy sources interventions in tertiary, household, industrial, transport, and electricity generation sectors of Greece were considered as alternative options. Solar collectors in the household sector and wind park installation were determined as the most competitive options, regarding their maturity rate, penetration ratio in the international market, and adaptability to the Greek energy market. Kaya and Kahraman (2011) developed a modified fuzzy TOPSIS methodology, to utilize linguistic variables in the evaluation of energy sources alternatives, and applied an energy planning decision-making problem. Jing et al. (2012) assessed various energy sources, used for a combined cooling, heating, and power (CCHP) system, which has been widely used in buildings to solve building-related energy problems and environmental issues. A fuzzy MCDM method was used for the evaluation of five alternatives. The results indicated that the best alternative was the CCHP system, based on a gas-steam combined cycle. Kahraman et al. (2009) compared fuzzy axiomatic energy approach with fuzzy AHP, to find the best renewable energy alternative for Turkey. Although a fuzzy axiomatic design approach determines the best alternative that most satisfies the functional requirements, while fuzzy AHP selects the best alternative according to the pairwise comparisons, they found the same results. Both methodologies found wind energy to be the best energy alternative. Kaya and Kahraman (2010) developed an integrated VIKOR-AHP approach, to evaluate alternative renewable energy options and production sites for Istanbul which is the biggest city in Turkey. They found that wind energy was the best renewable energy alternative for Istanbul.

In this study, a three-stage methodology, based on a CBD approach, is proposed to evaluate different energy sources. In the first stage, the criteria used for energy sources evaluation are listed and evaluated by experts. Based on the results of the first stage, the most important criteria for energy sources selection are obtained, and then the experts evaluate the different energy sources with respect to these criteria. In the final stage, energy alternatives are prioritized, using a CBD approach. One of the main reasons for using a CBD approach is that all types of expert evaluations, in different scales or with different linguistic terms, can be utilized without the loss of any information. The approach can also deal with incomplete expert evaluations.

The criteria used to evaluate energy alternatives depend on the specific conditions, characteristics, and development needs of each country (Doukas et al. 2010). The main and subcriteria used to evaluate different energy sources have been selected from a set of sustainability indicators from the literature, and are shown in Table 7.1. The criteria for the energy resource assessment reflect five main aspects: technological, economic, environmental, social, and political criteria. Technical properties of energy resources, which are considered during the decision-making process, are involved with the technological aspect. The economic aspect contains the subcriteria considered to obtain profitability of energy investment. The effects of waste and resource utilization on the environment and humanity are handled as environmental criteria. Social criteria encapsulate progress, prosperity, and acceptability aspects from the social perspective. Finally, the national economic benefits of energy resource investment are included in the political criterion. To our best knowledge, there is no study that uses all of these aspects together.

Some subcriteria taken from the literature are eliminated to avoid redundant elaborations such as exergy efficiency, fuel cost etc. The brief explanations of each criterion, and the reasons for using them for the evaluation process of alternative energy policies, are given in the following subsections.

Table 7.1 Evaluation criteria of alternative energy sources

ID	Criteria	Studies
Technological criteria		
1	Efficiency	Wang et al. 2009; Baris and Kucukali 2012; Talinli et al. 2010; Kaya and Kahraman 2011, 2010; Atmaca and Basar 2012; Jovanovic et al. 2009
2	Safety	Wang et al. 2009, 2010; Jing et al. 2012
3	Reliability	Wang et al. 2009; Kahraman and Kaya 2010; Baris and Kucukali 2012; Kahraman et al. 2009; Tsoutsos 2009
4	Maturity	Wang et al. 2009, 2010; Jing et al. 2012; Tsoutsos 2009
5	Continuity and predictability of performance	Kahraman and Kaya 2010; Kahraman et al. 2009
6	Deployment time/duration	Amer and Daim 2011; Baris and Kucukali 2012; Cristóbal 2011; Kahraman et al. 2009
7	Distribution grid availability	Amer and Daim 2011
8	Resource availability to generate energy	Amer and Daim 2011; Wang et al. 2010; Atmaca and Basar 2012
9	Resource depletion	Phdungsilp 2010; Atmaca and Basar 2012
10	Local technical know-how	Kahraman and Kaya 2010; Jing et al. 2012; Kahraman et al. 2009
Economical criteria		
11	Investment cost	Wang et al. 2009; Baris and Kucukali 2012; Jing et al. 2012; Doukas et al. 2010; Kaya and Kahraman 2011, 2010; Ren et al. 2009; Jovanovic et al. 2009; Tsoutsos 2009
12	Operation and maintenance cost	Wang et al. 2009; Phdungsilp 2010; Amer and Daim 2011; Talinli et al. 2010; Cristóbal 2011; Kaya and Kahraman 2011, 2009, 2010; Atmaca and Basar 2012; Ren et al. 2009; Tsoutsos 2009
13	Payback period	Wang et al. 2009; Jing et al. 2012; Kahraman et al. 2009
14	Service life	Wang et al. 2009; Cristóbal 2011
15	Equivalent annual cost	Wang et al. 2009; Jing et al. 2012
16	Availability of funds	Kahraman and Kaya 2010, 2009
Environmental criteria		
17	Impacts of air pollution on human health: mid–term	Laes 2006; Ruan et al. 2010
18	Impacts of air pollution on human health: long-term	Phdungsilp 2010; Laes 2006; Ruan et al. 2010; Talinli et al. 2010
19	Impacts on occupational health	Laes 2006; Ruan et al. 2010; Talinli et al. 2010; Atmaca and Basar 2012; Jovanovic et al. 2009
20	Radiological health impacts	Laes 2006; Ruan et al. 2010; Talinli et al. 2010; Atmaca and Basar 2012
21	Visual impact on landscape	Laes 2006; Ruan et al. 2010
22	Noise amenity	Laes 2006; Ruan et al. 2010; Talinli et al. 2010; Jing et al. 2012
23	Impact on natural ecosystems–air pollution: mid-term	Laes 2006; Ruan et al. 2010

(continued)

Table 7.1 (continued)

ID	Criteria	Studies
24	Impact on natural ecosystems—air pollution: long-term	Baris and Kucukali 2012; Laes 2006; Ruan et al. 2010; Wang et al. 2010; Talinli et al. 2010; Jing et al. 2012; Cristóbal 2011; Doukas et al. 2010; Kaya and Kahraman 2011, 2010; Kahraman et al. 2009; Ren et al. 2009; Jovanovic et al. 2009; Tsoutsos 2009
25	Environmental impact from solid waste—coal	Laes 2006; Ruan et al. 2010; Talinli et al. 2010
26	Land use	Laes 2006; Ruan et al. 2010; Wang et al. 2010; Jing et al. 2012; Kaya and Kahraman 2011, 2010; Kahraman et al. 2009; Atmaca and Basar 2012
27	Water use	Laes 2006; Ruan et al. 2010
28	Need for long-term management of HLW (high-level waste)	Laes 2006; Ruan et al. 2010; Talinli et al. 2010; Kahraman et al. 2009
Social criteria		
29	Social acceptability	Wang et al. 2009; Phdungsilp 2010; Kahraman and Kaya 2010; Amer and Daim 2011; Baris and Kucukali 2012; Laes 2006; Ruan et al. 2010; Talinli et al. 2010; Kaya and Kahraman 2011, 2010; Kahraman et al. 2009; Atmaca and Basar 2012; Tsoutsos 2009
30	Job opportunities	Wang et al. 2009; Phdungsilp 2010; Kahraman and Kaya 2010; Amer and Daim 2011; Baris and Kucukali 2012; Laes 2006; Ruan et al. 2010; Wang et al. 2010; Doukas et al. 2010; Kaya and Kahraman 2011, 2010; Kahraman et al. 2009; Atmaca and Basar 2012
31	Social benefits	Wang et al. 2009; Amer and Daim 2011
Political		
32	National energy security	Amer and Daim 2011; Laes 2006; Ruan et al. 2010; Doukas et al. 2010; Tsoutsos 2009
33	National economic benefits	Amer and Daim 2011; Laes 2006; Ruan et al. 2010; Doukas et al. 2010; Tsoutsos 2009
34	Compatibility with the national energy policy objectives	Phdungsilp 2010; Kahraman and Kaya 2010; Kahraman et al. 2009

7.2.1 Technological Criteria

Efficiency: Efficiency is the indicator of how much useful energy can be obtained from an energy source. The efficiency of a power plant refers to the ratio of the output energy to the input energy. Efficient energy usage is essential to reduce energy consumption and dependence on imported energy resources. This is the most used technological criteria in studies evaluating energy systems (Wang et al. 2009). The capacity factor has also been considered as a sub criterion of the technological aspect (Baris and Kucukali 2012; Talinli et al. 2010). The capacity factor is the ratio of the actual production of a power plant during a time period to its production at continuous full power operation, during the same period. Since both efficiency and capacity factors are related to the amount of useful energy obtained from a source, efficiency is taken into account as an evaluation criterion in this study. Exergy efficiency is also one of the technological criteria used in some of the studies (Wang et al. 2009; Jing et al. 2012; Kaya and Kahraman 2011). Exergy efficiency is a technicality, which refers to the efficiency of a process, taking the second law of thermodynamics into account. Since the aim of this study is to generate a framework to evaluate an effective country-wide energy policy, this criterion is not considered in the scope of this study.

Safety: Safety is used for the technological concerns that represent the avoidance of injury risks, as well as danger or loss caused by power plants. Changes in technology, environmental regulations, and public safety concerns make the safety of energy systems extremely vital for society and national development (Wang et al. 2009). All energy resources have an impact on the safety of society and the environment. Some energy resources have the possibility to cause irreversible and irreparable harm on society and the environment, such as nuclear leaks (Wang et al. 2010).

Reliability: Reliability, which evaluates the technology of energy resource, can be stated as the capacity and ability of a technology or system to perform as intended under specific conditions, for a stated period of time (Wang et al. 2009; Amer and Daim 2011). The quality and maintenance of equipment, the design of the system, and the type of fuel are all determinants of reliability (Wang et al. 2009). Interruptions in the energy supply can cause instability in the electricity network (Tsoutsos et al. 2009).

Maturity: Maturity is used to state the prevalence of the technology at both national and international level (Amer and Daim 2011; Tsoutsos et al. 2009). It also cares about the improvement phase of the technology; i.e., whether the technology has the potential to improve, or if it has reached its theoretical limit (Amer and Daim 2011). It deals with whether the technology is new, still improving, or consolidated (Wang et al. 2009).

Continuity and predictability of performance: Continuously and confidently operated technology is important for determination of an appropriate energy policy. This criterion evaluates the operation and performance of the technology (Kahraman and Kaya 2010).

Deployment time/duration: The preparation time needed to be ready for the production of a power plant is referred as deployment time. It includes installation, testing, and commissioning time (Amer and Daim 2011). Simplicity is also used by Baris and Kucukali (2012) to specify the construction and implementation period of the power plant.

Distribution grid availability: Power transmission should be considered during the construction of power plant. Whether the distribution grid is available and close to end users is an important criterion for energy policy (Amer and Daim 2011).

Resource availability to generate energy: Availability refers to the fact that the resource is suitable and ready for energy production. According to this criterion, an energy type with a more available resource is preferable. Accessible and proven reserves of the energy resource, as well as ready technologies for accessing the energy sources, are the indicators of availability (Wang et al. 2010).

Resource depletion: Interruption of the energy resource decreases economic prosperity and living standard intensely. Besides greenhouse gas emissions, the depletion of fossil fuel sources forced the authorities to find sustainable and continuous energy sources. Renewable energy resources are seen as the biggest alternative to fossil fuels because they are considered to be unlimited (Wang et al. 2010).

Local technical know-how: This criterion regards the local capacity for operation and maintenance support for the related technology (Kahraman and Kaya 2010; Kahraman et al. 2009). When the structure of energy sources change, the facilities and the technology of energy production will change, with a huge cost for the national economy (Wang et al. 2010).

7.2.2 Economic Criteria

Investment cost: Investment cost is one of the most considered economic criterion to evaluate energy alternatives or scenarios. It includes the procurement and installation of technical equipment, the construction of connections to the national grid, engineering services, drilling, and other construction work. Labor costs and maintenance costs are out of content (Wang et al. 2009).

Operation and maintenance cost: Operation and maintenance cost is the other most used criterion during decision making on energy policy. Operation cost consists of employees' wages, production costs, and service costs. The expenditure to avoid failures, which is smaller than the repair cost of system failure, constitutes the maintenance cost (Wang et al. 2009). It can also be handled as two subcategories: fixed and variable costs. Maintenance costs and wages of full-time employees form fixed costs, while breakdown costs and wages of part-time employees constitute variable cost (Atmaca and Basar 2012).

Payback period: This criterion evaluates the period of time to repay the sum of the original investment (Jing et al. 2012; Wang et al. 2009). Entrepreneurs prefer shorter payback periods rather than longer ones (Wang et al. 2009).

Service life: Service life or useful life (Cristóbal 2011) refers to the expected lifetime of a system used in service. Entrepreneurs prefer a longer service time during the selection of investment alternatives (Wang et al. 2009).

Equivalent annual cost: The annual operating and owning costs of an asset over its entire lifespan gives the equivalent annual cost. Equivalent annual cost (EAC) is the ratio of the net present value of a project to the present value of an annuity factor, and is used as a decision-making tool if the alternative projects have a different lifespan (Wang et al. 2009).

Availability of funds: According to Kahraman et al. (2009) and Kahraman and Kaya (2010), this criterion represents the national and international sources of funds and government support. In the scope of this study, the availability of funds refers only to the national and international support for funds.

7.2.3 Environmental Criteria

Impacts of air pollution on human health (*mid-term*): The impacts of emissions released by power plant operations—such as NO_x, CO_2, CO, SO_2, small particles etc.—on public health is evaluated by this criterion (Laes 2006). Emissions of gases and small particles are handled separately in various studies. To provide comprehensiveness and avoid elaboration, these emissions are considered as a single criterion. On the other hand, since the effects of air pollution changes over time, both mid-term and long-term impacts are taken into account.

Impacts of air pollution on human health (*long-term*): This criterion evaluates the long-term impacts of emissions released by power plant operations—such as NO_x, CO_2, CO, SO_2, small particles etc.—on public health. Carcinogenic and epidemiologic problems are some long-term impacts of air pollution (Talinli et al. 2010).

Impacts on occupational health: Explosions, accidents, and fires cause minor injuries, major injuries, or death of employees (Atmaca and Basar 2012). Accidents during coal mining and transport of coal or waste materials, radon exposure which causes lung cancer, coal dust which induces chronic bronchitis and chronic cough, are some of factors that should be considered, to evaluate the impact on occupational health for each energy source.

Radiological health impacts: Radioactive fallout to the atmosphere is one of the drawbacks of both coal-fired and nuclear power plants. Nuclear power plants have catastrophic nuclear risks, and medium- and high-level radioactive waste, which is stored in geological depots. If the atmosphere is exposed to a significant radioactive inventory in the core of a nuclear reactor, an irreversible health hazard will occur (Adamantiades and Kessides 2009).

Visual impact on landscape: Power plants can have functional and esthetic impacts on the landscape and sea views. Roads, high-voltage transmission lines, energy production facilities, pipelines, etc. are some of the reasons that ruin the environment visually (Laes 2006).

Noise amenity: Noise is not a direct factor that destroys the environment, but machine-created noise impairs the quality and balance of natural life for both people and animals (Wang et al. 2009; Jing et al. 2012). It has negative effects on both the physiological and psychological health of people. Noise-induced hearing loss can arise in energy plants (Wang et al. 2009).

Impact on natural ecosystems—air pollution (*mid-term*): Fuel cycles cause damage to ecosystems. In particular, acidic and nitrogenous depositions, and photo-oxidants have the most serious and widespread impacts (Laes 2006).

Impact on natural ecosystems—air pollution (*long-term*): This criterion evaluates the long-term effect of power plants on natural ecosystems (Laes 2006).

Environmental impact from solid waste: Solid waste can be a byproduct during some type of energy production. The waste materials, gases, and substitutes from the mining, burning, and transport of coal seriously damage the environment (Laes 2006).

Land use: Every power plant has land requirement, which may affect the landscape and increase the project cost. As the land required for an energy project increases, this criterion becomes a great concern for its evaluation (Kaya and Kahraman 2011).

Water use: This criterion evaluates the amount of water used to facilitate the power plant (Laes 2006). Since water is vital for the balance of ecological life, less water consumption is preferred when selecting the type of energy plant.

Need for long-term management of high level waste (*HLW*): This criterion concerns whether an alternative policy is needed to reduce damage to the quality of life. Nuclear waste disposal is an important consideration in decisions to expand nuclear plants (Adamantiades and Kessides 2009).

7.2.4 Social Criteria

Social acceptability: Energy investments have critical importance for sustainable development. The benefit of an energy system cannot be evaluated without considering social acceptance. Economic and environmental effects influence people's opinions. Potential danger to local ecosystems that have unfavorable effects on agriculture can be one of the economic reasons. Potential damage to the landscape, as well as noise and air pollution, are some of the environmental and health concerns that cause misery to and opposition from the public (Tsoutsos et al. 2009). The pressure of the people also causes not to be completed the construction of facility in desired time period (Wang et al. 2009).

Job opportunities: New energy investments create employment opportunities and new professional figures, especially for local communities (Amer and Daim 2011; Kahraman and Kaya 2010). This criterion is as important as social acceptability on the decision-making process for energy systems.

Social benefits: This criterion refers to social progress in the local society and region, by initiating an energy project (Amer and Daim 2011). Social life and income generation are placed within the scope of this criterion (Wang et al. 2009).

7.2.5 Political Criteria

National energy security: National energy security can be augmented by utilizing domestic and renewable energy sources, and reducing the import resources. The alternative contributing to the energy independence of country is more preferable (Amer and Daim 2011; Doukas et al. 2010).

National economic benefits: Both local and regional development is involved in this criterion. Whether the energy investments create new workplaces, develop new chains of enterprise, or expand the local enterprises in the region is considered (Doukas et al. 2010; Tsoutsos et al. 2009).

Compatibility with the national energy policy objectives: This criterion evaluates the concordance between the national energy policy and the suggested energy alternative (Kahraman and Kaya 2010).

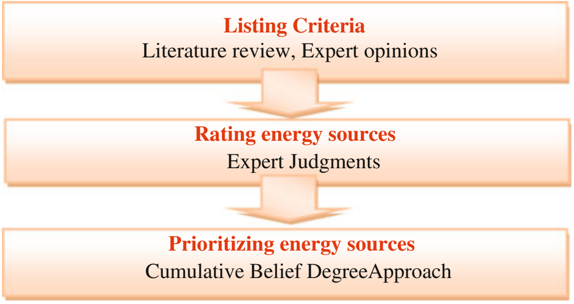
7.3 Methodology

The objective of the methodology is to analyze different sources of energy with respect to the relevant criteria in a country. A three-stage methodology is developed for this purpose. First, the relevant criteria are listed through a literature review and expert opinions. Second, energy sources are rated according to the criteria, based on expert judgments. Finally, the energy sources are prioritized using a CBD approach. Framework of the methodology is presented in Fig. 7.1.

7.3.1 Listing the Criteria

In the first stage of the methodology, a list of criteria is suggested to evaluate the energy sources. The generic list of criteria introduced in the second section is used as a reference to start with. The methodology is proposed to investigate the situation in a specific country. Therefore, the relevancy of these indicators for the country is determined through a Web-based survey. Experts are asked to grade the relevancy of the criteria to the country's energy policy evaluation. Experts make the grading on a scale of 1–10 (1: the criteria is not related to the country's energy policy evaluation; 10: the concept is closely related to country's energy policy evaluation). Experts are also asked to indicate new criteria that are specifically important for the country. Afterward, the average of the grades that these criteria received from all the experts is taken, and a threshold is determined. Criteria that scored above the threshold form the final list of criteria.

Fig. 7.1 Framework of the proposed methodology



7.3.2 Rating Energy Sources

The purpose of the second stage is to rate the different energy sources with respect to the criteria listed in the previous stage. According to the literature, the possible energy sources are various and potential sources are to be specified for the specific country. Some possible sources of energy can be listed as follows: oil, coal and lignite, natural gas, biomass, geothermal, hydroelectric, solar, wind, nuclear etc.

Experts are asked to evaluate the energy sources with respect to each criterion on a personal scale; that is, a [1-n] scale, where n is a parameter determined by the expert. The idea of using a personal scale is to make the expert use the scale that is appropriate to them. 1 means that the energy source is very weak according to the criteria; n means that energy source is very strong according to the criteria.

7.3.3 Prioritizing Energy Sources

The second stage of the methodology results in ratings of the energy sources according to the relevant criteria. The aim of the third stage is to aggregate these ratings and prioritize the energy sources. This problem is a MCDM problem. However, as it contains subjective judgments of the experts and aggregation of multiple evaluations, it is complicated owing to various uncertainties. Moreover, some evaluations of the experts may be missing because of a lack of knowledge, or the irrelevancy of some indicators for some energy sources. Therefore, a CBD approach is used (Kabak and Ruan 2011a) to aggregate ratings.

The CBD approach was developed originally for the evaluation of nuclear safeguards evaluation, based on fuzzy linguistic terms and belief structure (Kabak and Ruan 2011a). It is also applied to energy evaluation problem (Ruan et al. 2013). One of the important features of the approach is that it can be applied to incomplete expert evaluations, which may be the situation in the energy sources prioritization problem. Another important strength of the approach is that it can be used to aggregate different scales of expert evaluations without losing information. Finally, it can provide linguistic results that are more understandable for the policymakers.

7.3.3.1 The Cumulative Belief Structure

The cumulative belief structure depends on fuzzy linguistic terms (Zadeh 1975) and belief structure (Yang 2001). Fuzzy linguistic terms are used to represent the information by the belief structure. Let $S = \{s_i\}$, $i \in \{0,\ldots,m\}$ be a finite and totally ordered term set. Any label, s_i, represents a possible value for a linguistic variable. The semantics of the finite term set S is given by fuzzy numbers, which are defined in the [0, 1] interval, and by their membership functions. Linguistic term sets can be defined according to the nature of the problem. For the current study, for instance, the energy sources can be evaluated with a five-term set, $S = \{s_i\}$, $i \in \{0,\ldots,4\}$, in which the following meanings to the terms are assigned as follows: s_0: very low, s_1: low, s_2: medium, s_3: high, and s_4: very high.

The belief structure is designed to model an expectation in multiple attribute decision analysis problems (Yang 2001). The evidential reasoning approach uses an expectation to model qualitative assessments with uncertainty, on the basis of decision theory and the Dempster-Shafer theory of evidence (Yang and Sen 1994; Yang and Singh 1994). In Kabak and Ruan (2011a, b) neither the evidential reasoning approach nor the Dempster-Shafer theory of evidence is used. The belief structure is used to represent the belief of experts on their evaluation of the criteria.

The belief structure can be defined as follows:

$$\beta^e(I_j) = \left\{\left(\beta_{ij}^e, s_i\right), i = 0,\ldots,m\right\}, \forall j, \forall e, \sum_{i=0}^{m} \beta_{ij}^e \leq 1, \forall j, \forall e, \tag{7.1}$$

where j and e are indices for criteria and experts, respectively, and β_{ij}^e is the belief degree of expert e for criteria j at s_i level.

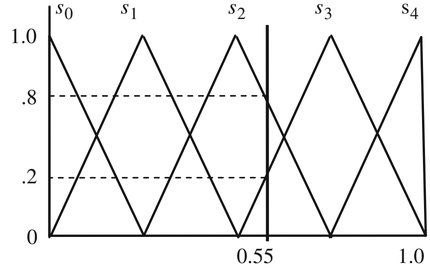
One important feature of belief structures is that all other types of evaluations, including numerical value assignments, interval value assignments, linguistic terms, and 2-tuples, can be all transformed to belief structures without any loss of information (see Kabak and Ruan 2011a for details). For the case of an energy source prioritization problem, the expert evaluations are [1-n] scale. An evaluation of an expert is first normalized to 0–1 scale (the best score is 1 and the worst score is 0) as follows:

$$N = \frac{x-1}{n-1} \tag{7.2}$$

where N is the normalized score, x is the evaluation of the expert, and n is the expert-specific parameter. Furthermore, the membership degrees of the normalized score to the fuzzy sets, defined in Fig. 7.2, are determined as the belief degrees. For instance, if the normalized score is 0.55, then the related belief structure is $B(I) = \{(s_2, 0.8), (s_3, 0.2)\}$ (see Fig. 7.2).

After expert evaluations are obtained and transformed to belief structures, they are aggregated to the belief structures of the criteria. Suppose that every expert is

Fig. 7.2 Fuzzy sets for transforming the expert evaluations to belief structure



assigned an importance value for expertise and experience, w_e, for any e. Then the total belief of the performance of the energy source, for the criteria at s_i level, can be found by the weighed sum of belief degrees of the experts for s_i. The belief structure related to criteria k can be formed as follows:

$$B(I_j) = \{(\beta_{ij}, s_i), i = 0, \ldots, m\}, \forall j \tag{7.3}$$

where β_{ij} stands for the belief degree of the performance of the energy source for criterion j at s_i level, and is calculated according to the belief degrees of the experts as follows:

$$\beta_{ij} = \frac{\sum_e w_e \beta_{ij}^e}{\left(\sum w_e | e, \sum_i \beta_{ij}^e > 0\right)} \tag{7.4}$$

The numerator of this equation is the weighted sum of experts' belief degrees, and the denominator is the summation of the weights of all the experts who make assignments. Notice that if incompleteness occurs in the belief structure of an expert, the aggregated belief structure will also be incomplete. However, if an expert evaluation is missing completely (i.e., *no information* case), then it is not considered in the denominator. Therefore, it will not cause incompleteness in the aggregated belief structure.

The CBD is proposed to make operations on belief structures (Kabak and Ruan 2011a). CBD at certain linguistic term levels can be defined as the aggregated belief degrees of greater or equal terms of the related linguistic term. For the case of energy source prioritization problem, suppose that the minimum performance of an energy source w.r.t. a criterion is determined according to a threshold value, which is determined as one of the linguistic terms. Then the belief degrees of the terms that are greater than, or equal to the threshold would give the total belief on the minimum performance of the energy source. For instance, when s_3 is determined as the threshold, s_3, s_4,…,s_m indicate the minimum performance of the indicator. Therefore, the belief degrees of these terms can be summed up to find the CBD at this threshold level.

Considering γ_{ij} is CBD related to minimum performance of the energy source for criteria j at a threshold level s_i, the cumulative belief structure is defined as follows:

$$C(I_j) = \{(\gamma_{ij}, s_i), i = 0, \ldots, m\}, \forall j, \gamma_{ij} = \sum_{k=i}^{m} \beta_{kj} \tag{7.5}$$

7.3.3.2 Aggregations

After the experts' evaluations are combined as CBDs, they are aggregated to find the total performance of the energy sources. Suppose w_j is the weight of criterion j, reflecting the importance of the criterion for energy policy evaluation, T_i, total performance of an energy source at s_i linguistic term set level is found as follows:

$$T_i = \sum_j w_j \gamma_{ij}, \forall i \tag{7.6}$$

where T_i is represented as a CBD. After being calculated for each energy source T_i is used to prioritize the energy sources for the country in the consideration.

7.4 A Case of Energy Policy Evaluation in Turkey

The proposed methodology is applied to prioritizing energy sources for Turkey. Turkey has the second highest rate of growth in the world. Parallel to its economic growth, the energy demand of Turkey has increased greatly. For instance, Turkish electricity demand increased from 129 billion kilowatt in 2002 to 211 billion kilowatt by 2010, and it is expected to double by 2023, with 450 billion kilowatt. Despite this increasing energy demand, approximately 71 % of the demand in Turkey has been provided by imported fossil fuels. However, the fossil fuel resources are limited, and their prices are increasing. In the last 15 years, oil and natural gas prices have increased by 500 %. To reduce import dependency in the energy sector, Turkey announced long-term targets for electricity energy to produce more electricity from national sources. The two main targets are defined as increasing the use of renewable energy resources as an alternative to the fossil fuels, and the integration of nuclear energy into the composition of electricity energy production (Url-2 2012). Also, the EU has adopted an energy policy for non-member countries such as Turkey, aiming to maximize the use of renewable energy sources to reduce the dependence on fossils fuels, to minimize emissions from carbon sources, and to decouple energy costs from oil prices (Baris and Kucukali 2012). In brief, the current trend of rising fossil fuel prices and environmental issues are forcing Turkey to improve sustainable energy planning. Therefore, this study aims to find out which energy sources can contribute to the transition toward a sustainable energy future for Turkey.

7.4.1 Listing the Criteria

The criteria listed in Sect. 7.2 are used to evaluate energy sources for Turkey. Since the criteria are determined according to the economic and sociopolitic circumstances of Turkey, some criteria, which have not been placed in the investigated studies, are taken into consideration, such as opportunity cost, subventions, and EU environmental policies. These criteria are designated by the experts. The definitions of these criteria are as follows:

Table 7.2 List of criteria

ID	Type	Indicator	Average score
1	Technical	Efficiency	8
2	Technical	Production safety	8.5
3	Technical	Technology reliability	8
4	Technical	Continuity and predictability of technologic performance	7
5	Technical	Distribution grid availability	7.5
6	Technical	Resource availability to generate energy	9
7	Economical	Investment cost (Macro)	7.75
8	Economical	Equivalent annual cost (EAC)	7.75
9	Economical	Availability of funds	7.5
10	Economical	Payback period	8.5
11	Environmental	Impacts of air pollution on human health: mid-term	7.75
12	Environmental	Impacts of air pollution on human health: long-term	9
13	Environmental	Impacts on occupational health—coal and gas fuel cycle	7.25
14	Environmental	Radiological health impacts-nuclear	7.5
15	Environmental	Impact on natural ecosystems-air pollution: mid-term	7
16	Environmental	Impact on natural ecosystems-air pollution: long-term	8.5
17	Environmental	Environmental impact from solid waste-coal	8
18	Environmental	Need for long-term management of HLW (high-level waste)	7.75
19	Social	Job opportunities	7.25
20	Social	Social benefits	8
21	Political	National energy security	8.25
22	Political	National economic benefits	8

Subventions: This criterion evaluates whether the government supports the investment with subventions. For developing countries, such as Turkey, direct or indirect government economic support to the producers affects the decision of energy investors.

Opportunity Cost: Opportunity cost is also an economic sub-criterion, which is recommended by energy experts consulted in the scope of this study. It refers to the cost of the original investments after making a choice.

Compatibility with EU environmental policy: Maximizing the use of renewable energy sources to reduce dependence on fuel from non-member countries, minimizing greenhouse gas emissions, and reducing the coupling of energy costs from oil prices are the aims of EU energy policy (Baris and Kucukali 2012). Turkish government and energy authorities scrutinized and determined national policy by taking the EU policy into account. Therefore, the experts in this study approved the compatibility with the EU environmental policy.

As a result, experts were asked to grade the relevancy of the 39 criteria for Turkey's energy policy evaluation. Four experts made the grading on a scale of 1–10 (1: the criteria are not related, 10: the concept is very closely related). Then, all the criteria were listed according to their average grades, and the criteria graded 7 and above were chosen as the appropriate ones to be used in the model. The final list of criteria and their average scores are listed in Table 7.2.

7.4.2 Rating Energy Sources

The study aims to prioritize Turkey's energy sources. Therefore, experts were asked to evaluate the alternatives for the benefit of the country, instead of focusing only on limited views such as investors' views or customers' views. The idea was to provide recommendations to the government for energy policy selection, based on a systematic energy prioritization methodology.

Experts rated the energy sources with respect to the criteria listed in the previous stage. Current energy sources for Turkey are thermal, hydroelectric, geothermal, solar, and wind. In thermal stations, natural gas (47.2 %), lignite (23.7 %), coal (12.7 %), fuel–oil (3.5 %), and mixed oil (12.3 %) are used. It also plans to build two nuclear reactors by 2023 (Url-3, 2012). Therefore experts evaluated these energy sources—namely, oil, coal and lignite, natural gas, biomass, geothermal, hydroelectric, solar, wind, and nuclear—according to the criteria.

Three academics from different fields contributed the study. One of the experts is a nuclear scientist working in an energy institute. Another is an industrial engineer, who has conducted extended studies on energy evaluation projects. Finally, the last academic works on energy policymaking.

The questionnaire was prepared on an Excel spreadsheet in a table format, where the criteria and their explanations are the rows, and types of energy sources are the columns. Experts were first asked to determine the scale to make the evaluation, and to fill the table according to the scale they determined. The first expert preferred a 1–5 scale, while the other two experts chose to use a 1–10 scale. The evaluations of the 2nd expert are given in Table 7.3 as an example.

In order to aggregate the evaluations using a CBD approach, they were transformed to belief structure for each energy source. For instance, for "oil" and criterion 1, expert evaluations were 4 in the 1–5 scale, 9 in the 1–10 scale, and 6 in the 1–10 scale. Corresponding normalized scores were calculated using Eq. 7.2 as 0.75, 0.889, and 0.667, respectively. Their belief degrees are specified as follows, using the fuzzy sets given in Fig. 7.2:

$$\beta^1(I_1) = \{(1, s_3)\} \tag{7.7}$$

$$\beta^2(I_1) = \{(0.444, s_3), (0.556, s_4)\} \tag{7.8}$$

$$\beta^3(I_1) = \{(0.778, s_2), (0.222, s_3)\} \tag{7.9}$$

If the experts expressed that they had no knowledge related to an energy source with respect to an indicator, it is considered that the evaluation can be at any level. Therefore, a related belief structure is specified as distributed equally to all linguistic term levels; i.e., $\beta^e(I_j) = \{(0.2, s_0), (0.2, s_1), (0.2, s_2), (0.2, s_3), (0.2, s_4)\}$

Furthermore, belief degrees for each criterion are calculated using Eq. 7.4. The importance of the experts is considered as equal. For instance, for "oil" and criterion 1, the belief degree at s_3 level is calculated as (1 + 0.444 + 0.222)/3 = 0.556. The complete belief degrees for "oil" are given in Table 7.4.

Table 7.3 Evaluations of Expert 2 in 1–10 scale

ID	Oil	Coal and lignite	Natural gas	Biomass	Geothermal	Hydroelectric	Solar	Wind	Nuclear
1	9	9	9	3	5	6	1	2	7
2	7	7	7	8	7	7	8	8	7
3	8	8	8	7	5	6	2	2	9
4	8	8	8	6	6	4	2	2	9
5	10	8	9	5	5	3	4	2	9
6	7	7	7	7	5	5	6	4	7
7	8	7	9	8	8	7	9	9	6
8	6	6	6	8	8	10	10	10	10
9	9	7	8	9	9	7	9	9	7
10	8	8	9	9	9	7	9	9	7
11	4	2	4	6	7	8	9	9	9
12	4	2	4	6	7	8	9	9	9
13	4	2	4	6	7	8	9	9	9
14	NK	NK	NK	NK	NK	NK	NK	NK	6
15	5	4	6	7	8	7	7	6	9
16	NK	NK	NK	NK	NK	NK	NK	NK	
17	NK	NK	NK	NK	NK	NK	NK	NK	
18	NK	NK	NK	NK	NK	NK	NK	NK	6
19	7	7	7	5	5	7	6	6	7
20	7	7	7	7	7	7	7	7	7
21	3	7	3	8	8	8	8	8	6
22	3	7	3	8	8	8	8	8	6

Finally, CBDs are calculated using Eq. 7.5. For instance, for "oil" and criterion1, CBD at s_3 level is calculated as follows:

$$\gamma_{31} = \sum\nolimits_{k=3}^{4} \beta_{k1} = \beta_{31} + \beta_{41} = 0.556 + 0.185 = 0.741 \tag{7.10}$$

To compare the energy sources, the CBD for each criterion is combined to a cumulative belief structure. For this purpose, the average scores of the criteria given in Table 7.2 are normalized, to be used as the importance weights of the criteria. CBDs for the energy sources in consideration are calculated using Eq. 7.6, as given in Table 7.5 and Fig. 7.3.

Results indicate that wind and solar power are the best choices at very high level (i.e., s_4). This result means that the benefits of wind and solar power are at a very high level, with approximately 40 % belief of the experts. The superiority of wind and solar energy is also validated by the CBDs at a high level (s_3), which refers to the belief at high and very high levels.

While interpreting CBDs, a 50 % threshold level can be used for the final level of the alternatives. The highest linguistic level that has a CBD greater than 50 % is determined as the performance of the alternative. For the current results, the performance of hydroelectric, solar, wind, and nuclear power are at a high level,

Table 7.4 Belief degrees and CBDs for the energy source "oil"

ID	Belief degrees					Cumulative belief degrees				
	s_0	s_1	s_2	s_3	s_4	s_0	s_1	s_2	s_3	s_4
1	0	0	0.259	0.556	0.185	1	1	1	0.741	0.185
2	0	0.074	0.370	0.556	0	1	1	0.926	0.556	0
3	0	0	0	0.444	0.556	1	1	1	1	0.556
4	0	0.333	0	0.593	0.074	1	1	0.667	0.667	0.074
5	0	0	0.333	0.296	0.370	1	1	1	0.667	0.370
6	0	0.074	0.704	0.222	0	1	1	0.926	0.222	0
7	0.037	0.296	0	0.296	0.370	1	0.963	0.667	0.667	0.370
8	0	0.222	0.370	0.074	0.333	1	1	0.778	0.407	0.333
9	0.333	0	0	0.481	0.185	1	0.667	0.667	0.667	0.185
10	0.333	0	0	0.296	0.370	1	0.667	0.667	0.667	0.370
11	0.667	0.222	0.111	0	0	1	0.333	0.111	0	0
12	0.667	0.222	0.111	0	0	1	0.333	0.111	0	0
13	0.370	0.519	0.111	0	0	1	0.630	0.111	0	0
14	0.133	0.133	0.133	0.133	0.467	1	0.867	0.733	0.600	0.467
15	0.400	0.141	0.326	0.067	0.067	1	0.600	0.459	0.133	0.067
16	0.467	0.133	0.133	0.133	0.133	1	0.533	0.400	0.267	0.133
17	0.400	0.400	0.067	0.067	0.067	1	0.600	0.200	0.133	0.067
18	0.400	0.400	0.067	0.067	0.067	1	0.600	0.200	0.133	0.067
19	0	0	0.111	0.370	0.519	1	1	1	0.889	0.519
20	0.667	0	0.111	0.222	0	1	0.333	0.333	0.222	0
21	0.037	0.296	0.333	0.296	0.037	1	0.963	0.667	0.333	0.037
22	0.222	0.444	0.333	0	0	1	0.778	0.333	0	0

Table 7.5 Comparison of the energy sources with CBDs

	s_0 Very low	s_1 Low	s_2 Medium	s_3 High	s_4 Very high
Oil	1.000	0.764	0.588	0.403	0.169
Coal and lignite	1.000	0.738	0.661	0.445	0.136
Natural gas	1.000	0.837	0.597	0.409	0.157
Biomass	1.000	0.913	0.701	0.471	0.142
Geothermal	1.000	0.942	0.738	0.466	0.194
Hydroelectric	1.000	0.972	0.808	0.590	0.217
Solar	1.000	0.921	0.784	0.657	0.387
Wind	1.000	0.936	0.791	0.661	0.396
Nuclear	1.000	0.766	0.670	0.523	0.236

while the performance of oil, coal and lignite, natural gas, biomass, and geothermal are at a medium level.

Consequently, the study finds wind and solar energy to be the main choices for Turkey. The Turkish Ministry of Energy and Natural Sources announced that the two main targets for energy production are distributing the use of renewable energy resources and producing nuclear energy (Url-2 2012). Based on the results,

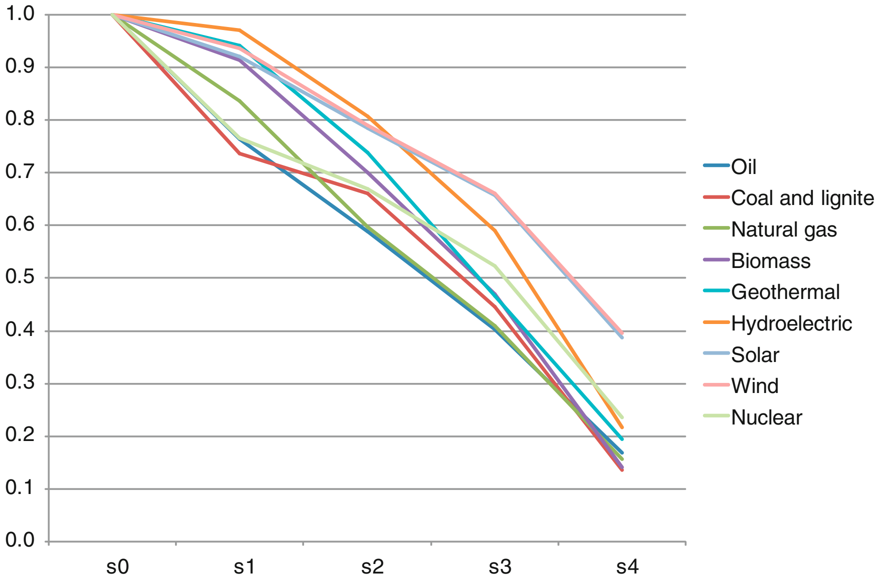


Fig. 7.3 Comparison of the energy sources

the study recommends that the government invests in wind and solar energy as a first choice. If the whole energy demand cannot be supplied from these energy sources, other choices, such as hydroelectric and nuclear power, can be considered. Although this study uses a broader criteria set and a novel approach, the results are similar to studies in the literature, which inferred that wind is the most exciting alternative for Turkey (Topcu and Ulengin 2004; Kahraman and Kaya 2010; Talinli et al. 2010). These results show that the energy investment need of Turkey has not been changed for a decade.

7.5 Conclusions

Energy source prioritization is very difficult to plan because of its complicated nature with multiple decision makers and criteria. Therefore, in this study, a methodology based on a CBD approach is proposed for the prioritization of energy sources for developing sustainable energy. The approach enables the aggregate of the experts' evaluations of different energy sources, with respect to multiple criteria.

One of the important contributions of the study is the list of criteria for evaluating energy sources. As a result of an extended literature survey, 34 generic criteria classified into five classes were determined. Such a list of criteria, derived from the literature and experts' opinion, provides a comprehensive resource for further similar studies.

Since the energy source planning has several aspects, evaluations of different experts from different areas of speciality are combined to find appropriate energy sources. Experts can prefer different types of judgment formats, such as linguistic terms, direct value assignment, and interval value assignment. The proposed model enables the combination of different types of judgment formats, by transforming them to belief degrees without loss of information. The proposed approach can also be applied when some expert evaluations are missing owing to not having adequate information, or a lack of expertise for some part of the evaluations. For instance, in the case study, two of the experts indicated that they had no complete knowledge of some particular criteria. The proposed method could effectively deal with this missing information by considering the evaluations to be at any level with the same belief degree.

Turkey, like in many countries, generates most of its energy from fossil fuels, which are imported mostly from other countries. However, the volatility of oil prices, emerging energy demand owing to economic growth, and environmental issues are forcing Turkey to improve its sustainable energy planning. Therefore, the application of the proposed methodology to Turkish energy source prioritization is valuable. Results show that solar and wind power should be considered as the priori sources of energy in Turkey.

Further research can be conducted by applying the proposed methodology to energy source prioritization in other countries. To improve the proposed methodology, an order weighted averaging (OWA) operator can be used to aggregate the CBDs of the criteria at the last step. This will enable to control for the compensation of criteria.

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Chapter 8
MCDA: Measuring Robustness as a Tool to Address Strategic Wind Farms Issues

Maria de L. Vazquez, Jean-Philippe Waaub and Adrian Ilinca

Abstract Sustainable wind energy development takes into account sociocultural variables that can be identified from citizens' concerns about the use of this renewable energy. These concerns are included in a multicriteria decision aid process, and, expressed as postulates in this study; they are subject to a robustness analysis. The approach is described and applied to the Baie-des-Sables (Canada) Wind farm case study. While this academic post-installation assessment does not affect the current operation of the farm which started back in November 2006, we conclude that if these concerns were considered, another wind farm scenario would have got a higher rating. Robustness analysis with respect to communication tools or type of ownership of the wind farm made it possible to identify objective rules based on changes in the ranking of scenarios. This change was verified using evaluation matrices containing different, maximum and proportional values with respect to the values of the original matrix. The robustness analysis results made it possible to identify, in a conflict situation, opportunities to remove obstacles to wind farm implementation.

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8.1 Introduction

Implementing a wind farm in Quebec Province (Canada), as in many other locations, might be rather controversial. It raises complex issues and involves stakeholders having potential conflicting positions. Vazquez et al. (2013) have proposed an approach called Territorial Intelligence Modeling Energy Development (TIMED) (see Sect. 8.1.4 for more details). This approach was developed to provide a transparent and participatory decision-making process for the implementation of a wind farm. It was successfully tested as a pilot project at Baie-des-Sables (Quebec, Canada) in a post-installation context, mostly to benefit from existing data and stakeholder experience. The TIMED approach involves two multicriteria methods: Multi-Criteria Decision Aid (MCDA) and participatory and collaborative Geographic Information Systems (GIS). It provides "decision makers" with a set of conditions for a transparent and participatory process during the implementation of wind farms" (Vazquez et al. 2013). The ranking of different scenarios of wind farm configurations (location, number, height, power of turbines) has been computed and discussed. They are important inputs for further recommendations to decision makers. However, robust conclusions taking into account strategic concerns are needed for strong legitimacy of decision to be taken. This contribution aims to focus on this issue of producing such robust analysis. Conceptual clarifications are first provided about sensitivity, robustness, and robustness concerns analysis. The TIMED approach and the methodological framework for robustness analysis are described. Additional results for the case of Baie-des-Sables wind farm are computed and discussed to illustrate actual situation.

8.1.1 Four TIMED Approach Modules: Literature Review

8.1.1.1 Multi-Criteria Decision Analysis

MCDA is a procedure that helps solve a complex decision problem. The main stages of this procedure are: recognition of the stakeholders, definition and development of scenarios, definition of criteria and their relative importance, preparation of evaluation matrices, application of a comparison procedure, establishment of the final ranking, robustness and sensitivity analysis (André et al. 2003; Roy and Bouyssou 1993). The MCDA improves decision making and eases negotiations by incorporating non-economic objectives and focusing on well-defined and well-targeted objectives (Corsair et al. 2009). When used in a participatory manner that involves all of the stakeholders in the decision-making process, it fosters a learning process based on local know-how and systematic knowledge as a means to reach sustainable solutions to the analyzed problem (Van Buuren and Hendriksen 2010). This is therefore an MCDA process in a multi-stakeholder and multi-decision maker context. It is applied to territorial management and in any situation involving resource-use conflicts, and this, in a participatory and collaborative perspective. In other words, whereas the single decision-maker approach tends to be hierarchically vertical and techno-scientific, the multiple decision-maker approach integrates different knowledge systems (scientific knowledge and knowledge of local stakeholders).

8.1.1.2 Geographic Information Systems

The analysis relies on spatially referenced numerical databases with storage, recording, updating, querying, and presentation features (Malczewski 1999; Nobre et al. 2009; Chakhar and Martel 2003; Longley et al. 2011). These databases make the exchange and analysis of information easier (Joliveau 2006). GIS improves the selection of solutions to territorial management problems (Malczewski 1999). Territory's biophysical characteristics must be factored with the socioeconomic and cultural traits of the communities living in this territory (Lovett and Appleton, 2008). This is why territorial management decisions are very complex (Laaribi et al. 1996). However, current GISs do not provide an efficient data analysis when there are multiple and contradictory criteria. To promote analysis, the GIS therefore needs to rely on a mechanism that integrates stakeholders' preferences and proposes choices in the context of an evaluation of conflicting criteria (Chakar and Martel 2004).

8.1.1.3 Contributory Stakeholder Involvement

The stakeholder is a concept linked to an action and more specifically to a collective action. The stakeholder's aim is to act during the decision-making process. An individual or a group of individuals can represent a stakeholder. The stakeholders create the exchange of legal, human, infrastructural, cognitive, monetary, interactive, political, and temporal exchanges between the systems they represent (political-administrative, sociocultural, and socioeconomic), even though these resources are unevenly distributed between the stakeholders. During this exchange of resources, the stakeholders get involved, are integrated, or fragmented (Larrue 2000). It is recommended that all of the stakeholders who are affected by the situation (Baburoglu and Garr 1993) be included. There are four categories to represent the type of active involvement of all of the possible stakeholders in a territory management project (Prades et al. 1998). These categories are divided into: civil society, private sector, public sector, and experts. This division is important due to the fact that each category has its own preference system.

8.1.1.4 Scientific Knowledge: Local Knowledge

In a multi-stakeholder decision-making process, the integration of several levels of knowledge becomes a necessity (Failing et al. 2007; Kain and Söderberg 2008). In Europe as well as in North America, the integration of science and local know-how during decision making becomes an unavoidable task (Failing et al. 2007). This local know-how includes all knowledge that does not come from conventional scientific expertise and could provide particular nuances in a decision-making process, for example specific expertise that is related to the local conditions and context. This local knowledge could identify indirect impacts that the proposed actions might have on biological resources (Failing et al. 2007). Moreover, new knowledge could emerge: one, which is an outcome of the coupling of empirical, expert, and theoretical knowledge in order to respond to a particular need (Kain and Söderberg 2008).

8.1.2 An Extended Concept of Robustness

Different decision-making methods exist to respond to increasingly complex financial or environmental management problems that society must deal with. Among these methods, we find Herbert Simon’s IDC (Intelligence, Design, Choice) model, others works based on Economics (i.e., Utility theory) and others that integrate decision-maker preferences based on a set of criteria (Figueira et al. 2005), such as MCDA.

Robustness analysis, which is carried out before the final decision is made, is one of the main steps of MCDA, and aims at establishing the right basis for a recommendation. Its main objective is to verify whether the recommendation resulting from the multicriteria procedure is robust, and if not, to identify what changes produce this result (Roy and Bouyssou 1993). This analysis seeks to “determine the range of parameter variations within which a recommendation is stable.”and it is used to “develop recommendations that are as synthetic as possible, and acceptable to a wide range of parameter values.”(Maystre et al. 1994), thus separating the strong conclusions from the weak ones. The parameters to be tested can be the weighting of the criteria or others.

Robustness analysis can be performed either by applying different sets of parameters reflecting contrasted views, or by designing multiple sensitivity analysis. Sensitivity analysis consists in “repeating the original multicriteria analysis by varying the values originally assigned to the method’s different parameters.”(Maystre et al. 1994). Thanks to this repetition, we can observe how “a variation around a central position affects the results obtained” (Roy and Bouyssou 1993).

However, the robustness analysis should not be restricted solely to confirming solutions; it can also be used to “answer questions about the stakeholders concerns and needs” (Roy 2002).

Indeed, it is recognized that the concept of robustness is vast and that there are different approaches, including requiring that the solution satisfy the robustness conditions for it to be considered robust (Aloulou et al. 2005). In addition, it is also recognized that robustness depends on the problem's context (Vincke 1999).

One must also consider that the term "robustness concern" is broader than "robustness analysis" because this concern is already present "in the problem formulation phase" and it aims at identifying weaknesses in the formal problem representation (Roy 2007), to determine whether the recommendation is or not solid.

Finally, returning specifically to robustness analysis, it is accepted that the weighting of criteria is a parameter whose variation may be subjected to this analysis, but that it is also possible to apply it to "the values of one or several evaluations" (Brans and Mareschal 2002).

8.1.3 Broadened Robustness as an Answer to the Modeling of Strategic Concerns

The authors have established (Vazquez et al. 2013; see also Sect. 8.1.3) that the stakeholders expressed two kinds of concerns: those that can be translated into evaluation criteria of the selected turbine sites and those related to the strategic development of the wind power sector. The latter can become socially controversial issues at a specific wind farm negotiation table, and end up being part of its specific analysis (Côté 2011) during the discussions on the turbines' site selection.

The above-mentioned paper (Vazquez et al. 2013) includes the results produced by the application of the MCDA to the first kind of concerns that are also included in the current framework used for the implementation of wind farm in Quebec.

The purpose of this contribution is to answer the following questions: what happens with the strategic concerns? How strong is the result of the existing framework regarding these strategic concerns? Thus, we consider that these questions basically have as much to do with the formulation of the real problem expressed by the involved stakeholders as with the above-mentioned robustness "concern."

It is important to answer these questions as TIMED approach tries to model accurately the concerns and needs expressed by citizens in 2005 about the implementation of Baie-des-Sables (Quebec) wind farm. Since a sensitivity analysis can address robustness concern (Roy 2007), we will apply conventional robustness analyses to the evaluation matrices. In short, to address the robustness concern issue, it is necessary to do a robustness analysis. For this purpose, the robustness analysis carried out for the first concern type will be expanded to the strategic concerns. To do this, scenarios' performance using pre-established criteria will vary according to the new evaluation matrices.

8.1.4 Understanding the TIMED Approach to Understand the Construction of Matrices Subject to the Robustness Analysis

Matrices subject to robustness analysis were built in 2011 during the test of the TIMED approach.

8.1.4.1 The TIMED Approach

The TIMED approach (see Fig. 8.1) is made up of four modules: MCDA, participatory and collaborative GIS, contributory stakeholder involvement (CSI), and scientific knowledge/local knowledge (SK-LK). The goal of these modules is to guarantee transparency and participation to promote a sustainable energy development of wind energy. Since TIMED approach is an instrument to find consensus between different interests, it also describes the negotiation procedure to be

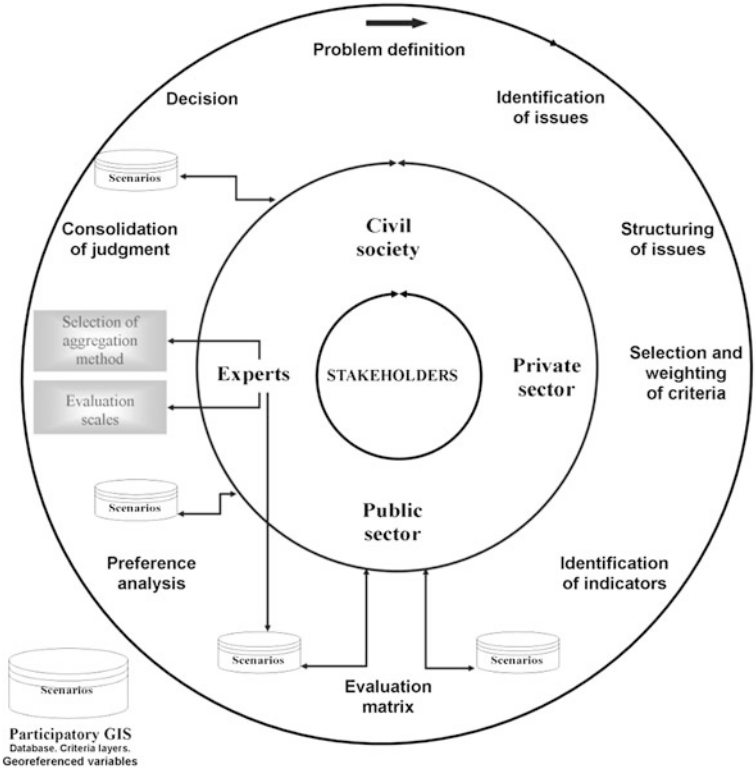

Fig. 8.1 TIMED approach coupling MCDA and GIS (taken from Vazquez et al. 2013)

followed, while ensuring that the different stakeholders' knowledge is integrated in the process and that the periods of participation and involvement are included.

The four modules are contained in three circles (see Fig. 8.1). The outer circle illustrates the MCDA and GIS procedures. The inner and middle circles show the stakeholders' involvement. Taken together, the three circles present the knowledge of all of the stakeholders. We have chosen to use a circle to illustrate the MCDA-GIS process as a negotiation facilitator, and to show the continuous and unrestrained feedback during the stakeholders' participation and involvement.

These stakeholders are placed at the heart of the process to emphasize their dominant role. The functions carried out exclusively by experts, such as the choice of the evaluation method and the choice of the evaluation scale, are represented in a rectangle. Moreover, other functions can be carried out exclusively by experts, such as criteria selection and identification of indicators, as long as all the stakeholders consent to this. The arrows tied to a circle indicate the participation of all of the stakeholders in a given activity such as the construction of a participatory database in the GIS. Arrows crossing circles indicate an activity to be carried out by a specific stakeholder such as an expert.

All of the stages in the MCDA process are indicated in the approach's outer circle: problem definition, identification of issues, selection and weighting of criteria, identification of indicators, evaluation matrices, preference analysis, decision consolidation, and decision. This module creates opportunities for the sustainable management of energy resources since it helps to co-build the preferences system of the stakeholders actively involved with the decision maker when the consequences of the proposed actions are examined. This module enables stakeholders to identify their own preferences and concerns in a collaborative manner and to structure them in a coherent family of criteria. The criteria serve to structure and model the problem. Once the criteria are established, they are evaluated according to their qualitative and quantitative nature with the help of indicators. The process of defining these indicators and criteria can help resolve conflicts. Moreover, decision-making support tools imply "the integration of values and preferences of one or several stakeholders in the decision-making process" (Roy and Bouyssou 1993); the preference system of the stakeholders much be clearly expressed and the weighting of the criteria must accurately reflect these values. Furthermore, the results of the preference analysis show the arguments for and against the different wind farm scenarios and these will be ranked by preference. Logically, this multi-stakeholder approach entails a multi-criteria context in order to assess the environmental, economic, and social issues.

The GIS module is participative due to the fact that the geospatial indicators (thematic layers) were presented to the negotiation table, in order to allow a group discussion on the elements of the territory that are to be analyzed. The scenarios to be analyzed in this module are taking into account the proximity to the residences, sugar bushes, and roads together with new electrical lines to be constructed in agricultural zones, the speed of the wind, and the type of land that is affected. Exclusion zones (buffers) can be created to ascertain the potential wind turbine installation sites. The distances can be determined by taking into account a documentation review (i.e., regulations of the municipalities of the Gaspésie, Quebec, Canada). Scenario design requires: data loading and integration, preprocessing (i.e., buffer creation or weighting), processing (operations on the tables and layers), and production of output (maps). The maps helped make the stakeholders aware of any relevant information and to work directly on layers to visualize and highlight elements that were originally not included in the maps. This helped improve communications as well as the analysis of ideas expressed verbally. For example, to help design the scenarios, different hypotheses regarding the separation distances of the wind turbines can be tested. This information can be used to design different scenarios with other separation distances and different numbers of wind turbines.

The CSI module includes four categories of stakeholders: civil society, public sector, private sector, and experts. These categories represent the type of active involvement of all of the possible stakeholders in a territory management project (Prades et al. 1998). This division is important due to the fact that each category has its own preference system. However, a simple classification of the stakeholders remains insufficient when analyzing the decision-making process and the relative weight of the decisional power of each category needs to be determined. This weight could be the same for each category or unequal, in which case the most favored sector would have more influence on the decision. In this way, clear rules will be followed from the beginning of the negotiations and during the search for a consensus, and will ensure a better integration of the wind farm project in the host community.

In SK-LK module, the sharing of scientific knowledge as well of local knowledge allows for the building of a framework with a cognitive basis that takes into account all Stakeholders and their values (Vazquez et al. 2013). Scientific knowledge and local knowledge interact at each stage of the process, support the multicriteria analysis, generate new knowledge, and sustain the software technical framework.

Moreover, the four modules are associated with scenario modeling postulates as well as decisional weighting for every stakeholder involved in the decision-making process. In (Vazquez et al. 2013), we had explored the possibilities of a first postulate (the *Current Situation* postulate) and an evaluation matrix for the existing framework of wind farm was constructed. An example of the original evaluation matrix will be introduced later (see Table 8.3) and it is directly in this matrix that modifications for robustness analysis are done.

8.2 Robustness Analysis of the Strategic Concerns: A Simulation to Address the Robustness Concerns

First, the strategic concerns will be formulated using postulates. Second, the methodology for analyzing each strategic-level postulate will be established while also identifying the elements to be considered, the evaluation matrices related to the number of necessary models, the criteria which may be modified and that are to be included in the analysis, the representativeness of the postulates to be analyzed as well as the design of matrices with three different types of grades.

8.2.1 Strategic-Level Postulates

The strategic concerns were extracted from the official and public documents submitted to the Quebec Government's Office of Public Hearings on the Environment (BAPE), in 2005, for a specific wind farm. These concerns were then structured into four strategic-level postulates, which are located upstream of the multicriteria decision aid process:

1. *Current situation*: describes the current conditions. It is the set of all the conditions in which wind farms are currently being developed (i.e. call for tender conditions, annual voluntary contributions, municipal visibility funds, and regulatory framework of separation distances included in the PCRs—Provisional control regulations).
2. *Ownership*: refers to concerns related to the *Type of ownership of the Wind farm.*
3. *Communication tools*: refers to concerns related to the type of approach used to communicate with the host community.
4. *Taxation and royalties*: refers to elements related to income sharing, for example, the creation of wind farm revenue redistribution and sharing formulas.

Thus, the concerns that are not part of the existing conditions lead to three others postulates (*Type of ownership of the wind farm, Communication Tools and Taxation)*. Two postulates are subdivided. *Type of Ownership of the Wind farm* is subdivided into three sub-postulates: *Public*, *Large Private Company,* and *Public–Private Partnership* (this includes community wind farm as well as joint wind farms involving municipalities and private companies). *Communication Tools* is subdivided into three sub-postulates: *Information Meeting*, *Consultation,* and *Negotiation Table.* The postulates *Current Situation* and *Taxation and Royalties* do not have sub-postulates (see Table 8.1). Therefore, there are a total of four postulates and eight sub-postulates.

8.2.2 Methodology of the Robustness Analysis of Strategic-Level Postulates

8.2.2.1 Factors Considered

Each strategic-level postulate defined earlier needs to be analyzed. The *Current situation* postulate has already been analyzed (see Vazquez et al. 2013, Sect. III Results). It was analyzed for each one of the four designed scenarios, using one of the three different decision-making power weightings and one evaluation matrix (*Original evaluation matrix*). It should be noted that we could have tested all four designed scenarios for each of the three decision-making power weightings (see

Vazquez et al. 2013, Sect. 1.2 The TIMED approach-fourth paragraph); however, in this chapter we will only illustrate one example with one of the three weightings.

The remaining three assumptions (*Type of ownership of the wind farm, Communication tools,* and *Taxation and royalties*) shall be analyzed with these three elements: the designed scenarios, one of the three weighting options and the evaluation matrix (see Vazquez et al. 2013, Sect. 1.2 The TIMED approach—fourth paragraph—and Sect. 2.1.9 Evaluation matrix). Again, the only decision-making power weighting that will be used is each stakeholder with the same decision power percentage (all equal).

8.2.2.2 The Models Required and Their Evaluation Matrices

Among other things, we must consider that each sub-postulate (or postulate, as is the case) has its own evaluation matrix. The *Current situation* postulate is named NOri (N, grade; Ori, original) and was designed by the multicriteria decision aid team and validated by all the stakeholders involved in the case study of the TIMED approach (see Vazquez et al. 2013, Sect. 2.1.9). The analysis of the other three strategic-level postulates shall be done by making grade changes in this NOri matrix. Overall (see Table 8.1), to carry out this analysis, 24 models were configured using the D-Sight Software and taking into account: four scenarios, three decision-making power weighting options, eight sub-postulates, and eight evaluation matrices (see Table 8.1).

8.2.2.3 Identification of Criteria to be Included in the Robustness Analysis

In addition to the number of models that are to be developed, we must identify criteria that has already been defined (see Vazquez et al. 2013, Sect. 2.1.5 Selection of the criteria) whose evaluation is subject to change (likeliness criteria see Table 8.2). It should be noted that in the present work, we have excluded the possibility of designing new criteria.

8.2.2.4 Representativeness of Postulates Subjected to the Robustness Analysis

Once the criteria whose evaluation can be modified are identified, it is necessary to conduct the robustness analyses. To avoid making the 24 models listed in Table 8.1, and in order to draw conclusions from them, the most representative postulates were selected. This representativeness of all the models were determined based on the variations in the number of criteria which can be modified: three for *Communication tools*, nine for *Type of ownership of Wind farm* and two for *Taxation and royalties*. Thus, the robustness analysis will be done on the

Table 8.1 Models and matrices required according to the different scenarios, postulates, and power weighting options considered in the robustness analysis

Modeling	Scenarios	Postulate	Sub-postulate	Decisional power weight option	Number of Matrices
1	1, 2, 3, 4	Current situation	Current situation	1	1
2				2	
3				3	
4	1, 2, 3, 4	Communication tools	Information meeting	1	2
5				2	
6				3	
7			Consultation	1	3
8				2	
9				3	
10			Negotiation table	1	4
11				2	
12				3	
13	1, 2, 3, 4	Type of property of Wind farm	Large private company	1	5
14				2	
15				3	
16			Public–private partnership	1	6
17				2	
18				3	
19			Public	1	7
20				2	
21				3	
22	1, 2, 3, 4	Taxation and royalties	Taxation	1	8
23				2	
24				3	

Decisional power weighting option
1. Equal power weighting for each stakeholder (regardless of the category)
2. 25 % for each category
3. 50 % private sector; 25 % public sector; 12.5 % experts; 12.5 % civil society

Scenarios
1. 73 turbines each one of 1.5 MW
2. 38 turbines each one of 1.5 MW
3. 38 turbines each one of 3 MW
4. 0 turbines, 0 MW

Communication tools and *Type of property of Wind farm* postulates. As for *Taxation and royalties*, whose variability is lower, it will be the subject of a special comment at the end of discussion results section.

Therefore, the sub-postulates *Negotiation table* and *Public–private partnership* (which belong to the first two postulates) were chosen and their criteria which are likely to be re-evaluated will receive a new grade in their corresponding matrices, in order to show how different values affect the results of these postulates in connection with robustness concerns.

8.2.2.5 Designing Matrices Responding to the Robustness Concerns

Matrix notation procedure used in the evaluation of strategic postulates

The grading of the evaluation matrices has undergone one of the two procedures:

1 Grading proposed by the decision-aid team and validated by the negotiation table.
2 Grading proposed by the decision-aid team and not validated by the negotiation table.

The first case corresponds to the matrix of the *Current situation* postulate, validated by the stakeholders participating in the negotiation table, because this table was established in 2010–2011 only to evaluate this postulate.

The second case corresponds to the three others postulates (see Table 8.2), which require the formulation of new matrices. These will be created through the reformulation of the NOri matrix while at the same time considering the existing issues related to the use of communication tools, the type of wind farm property and the criteria whose evaluation is likely to be modified. To make this reformulation, the decision-aid team changed the grades of these likely criteria. All the other criteria kept their original values validated by the negotiation table (Table 8.3).

Matrices with maximum, proportional, and different grades

To start the analysis that will answer whether the results of the *Current situation* postulate are robust compared with the other three strategic postulates, it is necessary to consider three new criteria performance grades:

1 A first one that includes different values (Dif).
2 A second one with maximum values (Max).
3 A third one whose value is the result of a proportional improvement (Pro).

This produces three new evaluations matrices, which increases further the number of models to create. Thus, the NDif matrix (see Table 8.4) refers to different grades, the NMax matrix (see Table 8.5) refers to maximum grades and the NPro matrix refers to proportional grades. This last one is combined with the NMax matrix to create the NMax–NPro matrix (see Table 8.6). Each of the three postulates (or sub-postulates) to be analyzed uses the NDif, NMax, and NMax–NPro matrices, respectively.

The utility of having different value performance grades is discussed with the stakeholders and with the expert MCDA team, as well as values that are reasonable to be analyzed based on available resources (i.e., funding, time, etc.). The objective is to analyze different performance scenarios for each postulate and to compare them in order to test the robustness of a decision. In our test, these value performances were related to a specific context and should assist stakeholders to understand what happens if we change the evaluation matrices value by grading the scenario performances in a specific manner. Basic mathematical concepts

Table 8.2 Identification of criteria that are likely to be evaluated

Postulate	Sub-Postulate	Code of criteria* and type	Criterion whose evaluation is likely to be changed (likeliness criteria)
Communication tools	Information meeting	None	None
	Consultation (does not cause any major changes in the wind farm)	ScVa06 Qualitative	Taking into account population's values and needs (Maximize) (allow communication)
	Negotiation table (does not cause any major changes in the wind farm)	ScPa03 Qualitative	Significant places (physical aspect) (Maximize) (negotiate access to places)
		ScVa06 Qualitative	Taking into account the population's values and needs (Maximize) (allow communication)
Type of ownership of Wind farm	Large private company	None	None
	Public–private partnership (community wind farm designed by municipalities and private companies) (does not cause any major changes in the wind farm)	ScPa05 Qualitative	Becoming of a landscape (sociopolitical aspect) (Maximize) (i.e., framed through municipal regulations)
		ScVa06 Qualitative	Taking into account the population's values and needs (Maximize) (allow communication)
		ScPa03	Significant places (physical aspect) (Maximize) (negotiate access to places)
		EcCo08 Quantitative	Local financial benefits (Maximize) (i.e., framed through municipal regulations)
		EcCo10 Quantitative	Employment (Maximize) (i.e., framed through municipal regulations)
		EcRe11 Quantitative	Regional socioeconomic benefits (Maximize) (i.e., framed through municipal regulations)
	Public	EcCo08 Quantitative	Local financial benefits (Maximize) (i.e., framed through municipal regulations)
		EcCo10 Quantitative	Employment (Maximize) (i.e., framed through municipal regulations)
		EcRe11 Quantitative	Regional socioeconomic benefits (Maximize) (i.e., framed through municipal regulations)

(continued)

Table 8.2 (continued)

Postulate	Sub-Postulate	Code of criteria* and type	Criterion whose evaluation is likely to be changed (likeliness criteria)
Taxation and royalties	Fixed taxation, legal obligation Fee per kWh	EcCo08 Quantitative	Local financial benefits (Maximize) (i.e., payment of taxes to the municipality)
		EcRe11 Quantitative	Regional socioeconomic benefits (Maximize) (i.e., redistribution of municipal taxes and fees at the regional level)

Code of criteria* ScVa06 (Taking code of criteria* ScVa06 (Taking into account the values and needs of people), ScPa03 (Significant places), ScPa05 (Becoming a landscape), EcCo08 (Local financial benefits), EcCo10 (Employment), EcRe11 (Regional socio-economic benefits)

(different, maximum, and proportional) were then chosen to easily illustrate these questions, using whole numbers and percentages. Nevertheless, depending on the context, another value performance grades could be used if the stakeholders and the MCDA team agree (i.e., concepts as the average or median) but it is important to have every time the control over the number of new evaluation matrix to be designed because their number must be in accordance with the available resources.

In this way, different, maximum, and proportional improvement were chosen to represent the difference or maximal performance obtained if we use communications tools or not and to determine if a better scenario could be obtained depending of the type of ownership of wind farm.

8.3 Results

8.3.1 Postulate: Current Situation

8.3.1.1 Original Evaluation Matrix (NOri)

In this matrix, all criteria and their grades were validated by the negotiation table, in different bases. For example, the criterion ScPa03 (significant places) is rated 4 in scenario 4 because the non-construction of the Wind farm allows all of the activities that took place before the advent of the Wind farm to be carried out without restrictions (Fig. 8.2, Table 8.3).

Table 8.3 Original evaluation matrix

	Criteria												
	ScSS01	ScSS02	ScPa03	ScPa04	ScPa05	ScVa06	ScNA07	EcCo08	EcCo09	EcCo10	EcRe11	EnPh12	EnBi13
Scenario 1	158	150	2	2	2	1	159	139.5	329	160	98.4	80	460
Scenario 2	0	78	3	3	3	2	84	87	175	78	51.2	0	220
Scenario 3	0	78	3	3	3	3	108	144	175	106	102.4	0	220
Scenario 4	0	0	4	4	4	4	0	0	0	0	0	0	0

Table 8.4 Evaluation matrix with different grades for the *Communication tools—Negotiation table* postulates

	Criteria												
	ScSS01	ScSS02	ScPa03	ScPa04	ScPa05	ScVa06	ScNA07	EcCo08	EcCo09	EcCo10	EcRe11	EnPh12	EnBi13
Scenario 1	158	150	1	2	2	1	159	139.5	329	160	98.4	80	460
Scenario 2	0	78	4	3	3	4	84	87	175	78	51.2	0	220
Scenario 3	0	78	4	3	3	4	108	144	175	106	102.4	0	220
Scenario 4	0	0	0	4	4	0	0	0	0	0	0	0	0

Table 8.5 Evaluation matrix Maximum grade of the *Communication tools—Negotiation table* postulate

	Criteria												
	ScSS01	ScSS02	ScPa03	ScPa04	ScPa05	ScVa06	ScNA07	EcCo08	EcCo09	EcCo10	EcRe11	EnPh12	EnBi13
Scenario 1	158	150	4	2	2	4	159	139.5	329	160	98.4	80	460
Scenario 2	0	78	4	3	3	4	84	87	175	78	51.2	0	220
Scenario 3	0	78	4	3	3	4	108	144	175	106	102.4	0	220
Scenario 4	0	0	4	4	4	4	0	0	0	0	0	0	0

Table 8.6 Combined evaluation matrix for the grading of the postulate *Type of ownership of Wind farm—Public–private partnership*

	Criteria												
	ScSS01	ScSS02	ScPa03	ScPa04	ScPa05	ScVa06	ScNA07	EcCo08	EcCo09	EcCo10	EcRe11	EnPh12	EnBi13
Scenario 1	158	150	4	2	4	4	159	153.45	329	176.0	108.24	80	460
Scenario 2	0	78	4	3	4	4	84	95.70	175	85.8	56.32	0	220
Scenario 3	0	78	4	3	4	4	108	158.40	175	116.6	112.64	0	220
Scenario 4	0	0	4	4	4	4	0	0	0	0	0	0	0

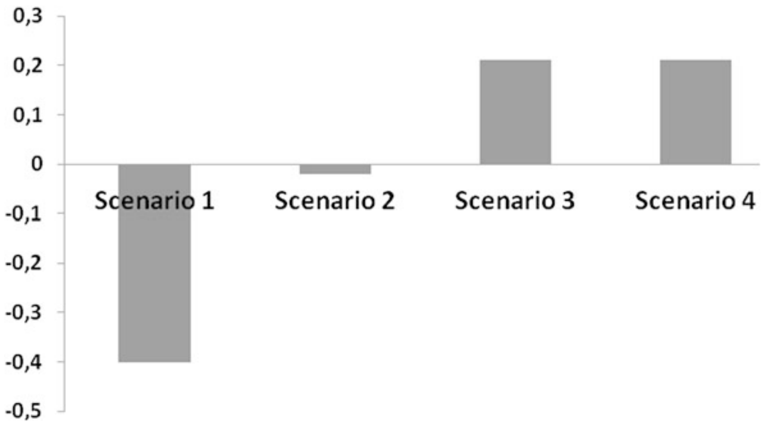

Fig. 8.2 Ranking according to the original evaluation matrix of the *Current situation* postulate

8.3.2 Postulate: Communication Tools

8.3.2.1 Sub-Postulate: Negotiation Table

NDif Evaluation Matrix

In this matrix, the criteria that are likely to be changed (ScPa03 and ScVa06) received a new grade. For example, the ScPa03 criterion (significant places) is graded 0 in scenario 4 because no communication tool would be used to discuss about the issues of this criterion.

Similarly, the same criterion is rated 4 in scenarios 2 and 3 since those scenarios are designed in a participatory manner and using communication tools (Fig. 8.3, Table 8.4).

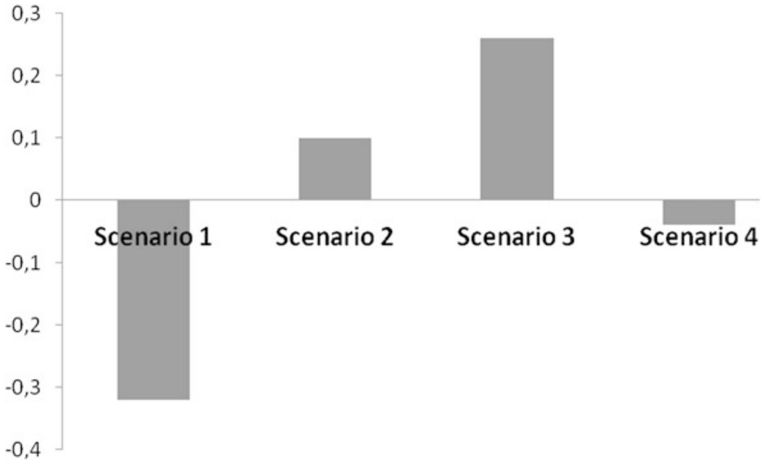

Fig. 8.3 Ranking of scenarios using the NDif evaluation

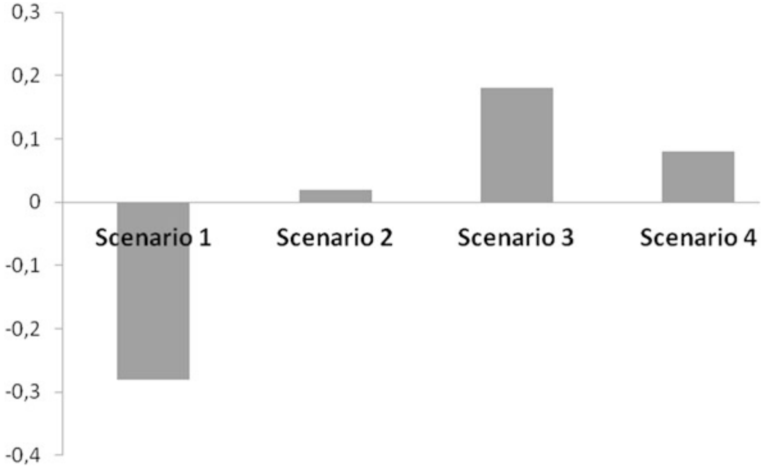

Fig. 8.4 Ranking of scenarios from maximum grade evaluation matrix of the *Communication tools—Negotiation* postulate

Evaluation matrix NMax

In this matrix, the criteria that are likely to change (ScPa03 et ScVa06) received the highest possible rating, 4, indicating that in all cases, we maximized the use of communication tools to discuss issues about values, needs, and significant places for people (Fig. 8.4, Table 8.5).

NPro evaluation matrix

The criteria that are likely to change are ScPa03 and ScVa06. In this case, proportional values are added to each of the chosen criteria in the NOri evaluation matrix. For this proportional grade, change is also proportional and the ranking obtained is equal to that of the NOri matrix (therefore there is no need to illustrate the results for this evaluation matrix). In this case, the PROMETHEE method already gives the answer and there is no longer a need to make systematic evaluations. This is because, in this case of the ordinary function used for these criteria, the performance differences between the scenarios remain the same.

8.3.3 Postulate: Type of Ownership of Wind Farm

8.3.3.1 Sub-Postulate: Public–Private Partnership

NMax–NPro (combined) evaluation matrix

To analyze the *Type of ownership of wind farm* postulate, in addition to the ScPa03 and ScVa06 criteria, it is also necessary to consider the ScPa05, EcCo08, EcCo10, and EcRe11 criteria. The latter three are, respectively, related to benefits

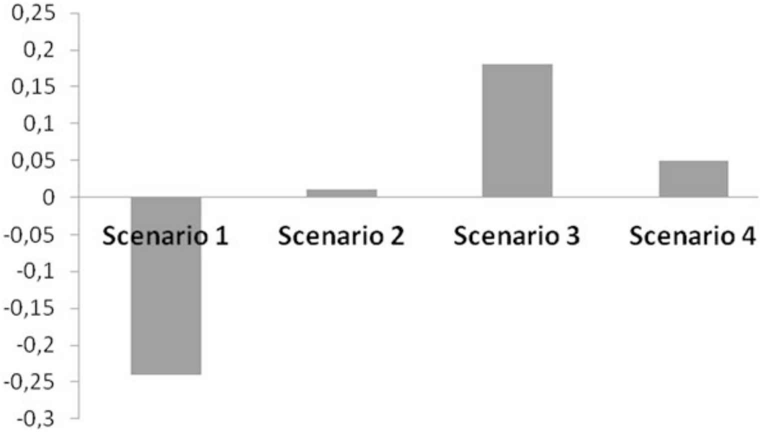

Fig. 8.5 Ranking of Scenarios using the combined NMax–NPro evaluation matrix of the *Type of ownership of Wind farm—Public–private partnership* postulate

and local and regional employment. In the postulate matrix, the ScPa03 and ScVa06 criteria receive a score of 4 to indicate a maximum benefit, as in the previous postulate. The ScPa05 criterion also receives the maximum grade since the future of the landscape is taken into account in the best possible way in every scenario. Compared with the NOri matrix, in the NMax–NPro matrix, the grades of the benefits and employment criteria are given a proportional increase to take into account the results of potential negotiations between the municipality and its private partner. Although other percentage increases could have been considered, we arbitrarily chose 10 % to illustrate the case (Fig. 8.5, Table 8.6).

8.4 Discussion

8.4.1 *Criteria*

8.4.1.1 Communication Tools *Postulate*

Situation in Which Criteria Receive Different Grades, NDif Matrix

Several assessments of this matrix were made by changing the grades of criteria ScPa03 and ScVa06, by assuming that the grades of scenarios 2 and 3 (participatory wind farm) were always more advantageous (grade equal to 4) than that of scenario 1 (promoter wind farm, grade equal to 1), by assigning to scenario 4 (no wind farm construction, grade equal to 0) the worst grade, that of not using any communication. During these evaluations, in all cases, although the net flux values varied, the ranking results were the same: scenario 3 (build the wind farm, participatory wind farm) represented the best option. It can be noted that the use of communication tools contributes to the implementation of wind farm.

Situation in Which the Criteria Receive the Same Grade, NMax Matrix

All the criteria that are likely to be changed (ScPa03 and ScVa06) receive the same maximum grade, which is defined in a previously constructed scale (see Vazquez et al. 2013, Sect. 2.1.8, Selection of the Preference scale). Here, this grade shows that significant community spaces, as well as the need to communicate and be heard, are taken into consideration, without differences in each of the four scenarios. We can see that the ranking of the scenarios shows that the improved grades of the social criteria favor the implementation of a wind farm, i.e., the construction of a participatory wind farm rather than no construction.

Moreover, if we modify this matrix by excluding the criteria that are likely to change, the new ranking obtained will be the same as the one obtained when these criteria are included: therefore, these criteria do not change the result, because they are all equally effective. This result is due to the fact that the concerns expressed by the stakeholders are taken into account. These criteria that do not have an impact on the scenario rankings obtained with the PROMETHEE methodology are therefore considered to be non-discriminating. Thus, in our example, we note that the maximum grade makes it possible to evaluate what happens if the constraints related to the *Significant places* and *Taking into account the population's needs and values* criteria are removed:

- When selecting the site where the wind turbines are to be installed, it is no longer necessary to consider this postulate because this issue has already been resolved. As a result, the original definition problem has changed and it is no longer necessary to answer the question of the use of communication tools to analyze the criteria that are likely to be changed.
- The highest ranked scenario is the participatory construction of a wind farm.

Situation in Which the Criteria Receive a Grade that Implies a Proportional Improvement, NPro Matrix

The Ranking of the Scenarios remains the same: the new matrix does not provide any new information.

8.4.1.2 Postulate Type of Ownership of the Wind Farm

Situation in Which the Criteria Receive a Combined Grade, NMax–NPro Matrix

Here again, the ranking obtained shows that the improved grades of the social criteria support the implementation of the wind farm: scenario 3 (participatory construction wind farm) represents the best option, while in the original matrix, the construction and the non-construction of the wind farm received the same grade. The final grade obtained (net flow) is a combination of maximum grades (value equal to 4) for the Usual function and of proportional grades, through an increase of 10 % for the V-Shape functions.

8.4.2 Flow Results

8.4.2.1 Net Flow Between the Rankings of the NOri and NMax Matrices

If we eliminate from the evaluation matrices the criteria that have received the maximum grade, the ranking of two matrices will be equal (flow: −0.28, 0.02, 0.18, and 0.08), and this is the case for the *Communication tools* postulate and its *Negotiation table* sub-postulate as well as for the *Current situation* postulate, since both matrices will be the same.

In addition, in the evaluation of the NOri matrix of the *Current situation* postulate, if we remove the non significant criteria identified in NMax matrix, the original ranking (flow: −0.40, −0.02, 0.21, and 0.21) changes and the grades of one of the wind farm construction options (scenario 3, participatory wind farm, flow = 0.18) and of the no construction option (scenario 4, flow = 0.08) are no longer equal. Indeed, a construction option, the one of the participatory scenario, is clearly preferred and becomes, according to the calculations, the best option. We note that:

- Based on the flow results, to address strategic issues upstream of the decision-making process in a wind farm promotes its execution: flow equal to 0.18 for the construction (scenario 3) compared with a flow of 0.08 with no construction (scenario 4). The *Significant places* and *Population's needs and values* criteria analyzed here are related to access to land rights that people had before the existence of the wind farm. For example, interim control regulations could have resolved these problems. If these issues are not addressed early on the decision process, they reappear in the construction stage of a given project (Côté 2011).
- So, no answer is given to these questions, we are faced with a negotiation: in the NOri evaluation matrix the resulting flows are equal to 0.21 for both the construction (scenario 3) and the no construction (scenario 4) options. This will require the identification of criteria to be negotiated and, in our case, these would be non discriminatory criteria identified for the *Communication tools* postulate.
- If there is no answer to the strategic questions upstream of the decision-making process and if we remove from the NOri matrix (*Current situation* postulate), the criteria ScPa03 (Significant places) and ScVa06 (taking into account the population's values and needs) the ranking changes and the construction of the

wind farm is inaccurately identified as the best option (flow = 0.18). However, this will not identify the improvements that address the concerns of the population, due to the loss of one of the advantages of the MCDA, that of the negotiation process.

This shows that if the strategic question of the communications tools comes back to the negotiation table, the use of such tools would further encourage the implementation of the wind farm.

8.4.2.2 Net Flow Between the NOri and NMax–NPro Matrix Rankings

As noted earlier, the proportional changes made to the criteria belonging to *Usual* function do not change the result, unlike those made on the V-Shape functions in which a 10 % increase changes the proportion of the performance difference between the scenarios (actions). This change in the differences affects the linear *V-Shape* function, and produces different net flows in the NOri (−0.40, −0.02, 0.21 and 0.21) and NMax–NPro (−0.24, 0.01, 0.18 and 0.05) matrices.

8.4.2.3 Net Flow Between the NDif and NMax Matrix Rankings (Communication Tools Postulate)

First, it is necessary to consider that scenarios 2 and 3 already had the best grade (4) in both matrices: since the beginning, these scenarios involved a communication process. As for scenarios 1 and 4 of the NDif matrix, we consider that this communication process did not exist or was incomplete. This is why we need to understand the new grade (4) of scenario 1 of the NMax matrix as the result of a promotion of discussions on the proposed initial wind farm proposal, while the new grade (4) of scenario 4 of the same matrix represents the increased discussion on the issues related to the non-construction of the wind farm.

We then target the discussions on the conflicting elements, i.e., the best and worst options and on whether or not the construction wind farm is carried out. In both these matrices, scenario 3 is the best option while scenario 1 is the worst.

Scenario 3 represents the possibility of going forward with the construction of the wind farm (participatory wind farm) and scenario 4, no construction wind farm. The NDif matrix rankings (see Table 8.4) indicate a greater difference between the best and the worst options (interval difference between −0.32 and 0.26 = |58|), compared with that of the NMax matrix (see Table 8.5) (interval difference between −0.28 and 0.18 = |46|). In addition, there is a greater difference between the construction (scenario 3) and the non-construction of the wind farm (scenario 4) of the NDif matrix (interval difference between 0.26 and −0.04 = |30|) compared to the NMax matrix (interval difference between 0.18 and 0.08 = |10|). These two differences are therefore greatest in the “unimproved” NDif matrix.

On the one hand, the reduction in the difference between the best and the worst options of the NMax matrix (|46|) is explained by the fact that the grades of the two likely criteria (ScPa03 and ScVa06) of scenario 1 (worst option) were improved, although in scenario 3 (best option) the grades of these same criteria did not change. On the other hand, the reduction of the difference (|10| for NMax) between the construction (scenario 3) and the no construction (scenario 4) options of the wind farm can be explained by fact that the grades of those likely criteria improved for scenario 4 in the NMax matrix, while the grade for scenario 3 remained the same. These grade changes for some of the criteria of some scenarios cause a net flow redistribution: the scenarios that improved their grades earn points (+0.04 and +0.12 for scenarios 1 and 4, respectively) while those who do not undergo any change lose points (−0.08 and −0.08 for scenarios 2 and 3, respectively). These «won» or «lost» points (i.e., +0.16 [+0.04 and +0.12] and −0.16 [−0.08 and −0.08]) have no effect on the net flow of NMax matrix.

Despite losing points in the NMax matrix, scenario 3 continues to be ranked as the best option in both matrices. Therefore, in the NMax matrix, the worst option (scenario 1) and the no construction option (scenario 4) improved their net flows, causing a decrease in their differences between the best and the worst option and between the construction or no construction scenarios (|58| vs. |46| and |30| vs. |10|). In this way, communication, which is at the base of the postulate analyzed above, was used to improve the wind farm (scenarios), while maintaining scenario 3 as the best option.

8.4.2.4 Net Flow Between the NMax and NMax–NPro Matrix Rankings

Once again, we focus the discussion on the conflicting elements (best and worst option/construction of the wind farm or no construction), this time by modifying social and economic criteria since this is a requirement of the *Type of ownership of Wind farm* postulate. In this case, the interval difference between the best and worst options (interval difference −0.28 and 0.18 = |46|) of the NMax matrix (see Table 8.5) is equal to that of the NMax–NPro matrix (see Table 8.6) (interval difference −0.24 and 0.18 = |42|). The best option continues to be scenario 3 and the worst, scenario 1. The difference between building the wind farm (scenario 3, participatory wind farm) and not building it (scenario 4) in NMax matrix (interval difference 0.18 and 0.08 = |10|) is lower than that of the NMax–NPro matrix (interval difference 0.18 and 0.05 = |13|). We note here, for the NMax–NPro matrix, that there is a decrease in the difference of deviation between the best and the worst option (|46| and |42|), and at the same time there is an increase in the difference of deviation between building and not building the wind farm (|10| and |13|).

In the redistribution of the total flows of this example, scenario 3 is unchanged and retains a flow equal to 0.18. The three remaining scenarios undergo changes with either an increased or decreased flow. This explains the increase or the reduction of the difference shown above. In the NMax–NPro matrix, the scenarios

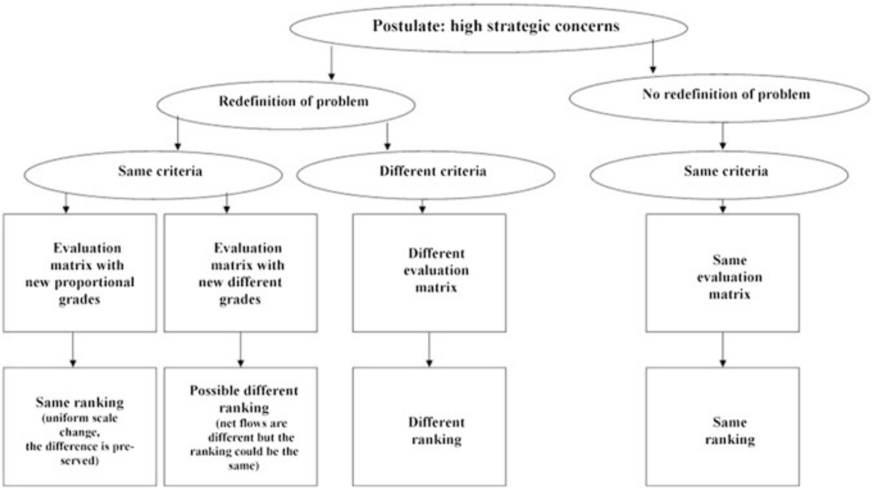

Fig. 8.6 Rules followed for the changes in the scenario rankings

whose grades for the likely criteria have improved the most get points (+0.04 for scenario 1), while the scenarios that keep the same grades as those of the NMax matrix loses points (−0.01 for scenario 2 and −0.03 for scenario 4).

Just like in the previous case, the points that are "won" or "lost" (i.e. +0.04, −0.01 and −0.03) have no effect on the net flow of the NMax–NPro matrix. Scenario 3 continues to be ranked as the best option. Especially in the NMax–NPro matrix, the improvement of the net flow of the worst option (scenario 1) (+0.04) is greater than that of the best option (0). This explains the decrease in the difference between these two options (|46| and |42|) of the two matrices analyzed here. The no construction scenario has a reduced net flow because it does not contribute anything to the job creation and local financial benefits criteria, while the construction of the wind farm does improve the results of these criteria. The grades of the other three scenarios are increased by 10 %. This is why the difference between the scenarios "construction and no construction of the wind farm is greater in the NMax–Npro matrix (|13|) than in the NMax matrix (|10|), a result that supports even more the possibility of building the park."

8.5 The Redefinition of the Problem: *Taxation and Royalties* Postulate

No robustness analysis of the taxation and royalties postulate was done because it has a reduced number of likely criteria. This is why this postulate was chosen as an example for discussion on the redefinition of the problem. This postulate has been exclusively designed to highlight the current benefit distribution landscape of wind farms. It is not an analysis of the effects of increased taxation or royalties of wind farms here in Quebec or elsewhere (i.e., en France). Neither is it intended as a proposal. It is simply designed to structure logically concerns expressed by stakeholders in order to respond to the strategic question regarding the redistribution and sharing formulas of revenues generated by wind farms.

If we consider that these formulas are based on a regulatory framework, setting a tax could be considered as an option. If such a tax existed in Quebec, and depending on the concerns expressed by the stakeholders, the sharing of benefits could be done according to one of the following five formulas:

- Municipal property tax;
- Municipal property tax and municipal royalties;
- Municipal property tax and direct royalties for the land owners;
- Municipal property tax, municipal royalties and direct royalties to the land owners;
- Municipal property tax, municipal royalties, direct royalties for the land owners and royalties for citizens living within a given distance of turbines.

Although these sharing formulas structure and represent the stakeholders' concerns, they are not the only possible formulas. To identify them, new analyses would be required in which other factors such as the maximum amount of community benefits would be defined by the wind farm promoter. Such an amount could be based on a cost-benefit study. Other considerations could include a special tax regime for wind farm developers. Such a tax regime would need to take into account its impacts on the local benefits and the actual conditions required for it to really produce benefits for the community.

8.6 Conclusion

First, the robustness of the *Current situation* postulate results with respect to communication tools or type of ownership of the wind farm, made it possible to identify objective rules based on changes in the ranking of scenarios. This change was verified through a robustness analysis using evaluation matrices containing different, maximum, and proportional values with respect to the values of the original matrix. Nevertheless, this analysis always involves a subjective aspect. This subjectivity comes from the values of the qualitative scale of some of the criteria indicators that were used to build the new evaluation matrices.

The observed relationships between the results of the different postulate matrices lead to the following rules (also represented in the diagram below, see Fig. 8.6):

1 Same criteria and same evaluation matrix: nothing changes (it is not necessary to redefine the problem) (NOri Matrix).

2 Same criteria and a matrix with proportional improvements (constant change): the ranking will be the same (a proportional improvement of the criteria grades does not affect the ranking) (NPro matrix).
3 Same criteria and a matrix with maximum improvements: the ranking changes: All criteria receive a maximum improvement that becomes non discriminatory. These criteria can then be removed from the evaluation matrix because their improvement eliminates a constraint (strategic concern). By removing the constraint, the problem definition changes: this postulate and negotiations on these concerns are no longer needed because the problem has changed (NMax matrix).
4 Same criteria and a matrix with different grades (a different grade and a combined grade): this implies a possible ranking change and a negotiation to improve disadvantaged criteria (NDif and NMax–NPro matrices).
5 Different criteria. In this case, there is another problem, another evaluation matrix and the whole MCDA process has to be started over again.

Second, to achieve this robustness analysis, three evaluation matrices were built. However, several others could have been designed as, for example, the 24 listed in Table 8.1. The number of matrices could have increased because it would have been necessary to add matrices with different, maximum, and proportional grades, which would have multiplied the total number of matrices. This is why, to quickly carry out a robustness analysis on a large number of matrices reflecting several strategic postulates, it is necessary to use automation in the corresponding module of the software.

Third, the robustness analysis results made it possible to identify, in a conflict situation, opportunities to remove obstacles to wind farm because:

- Communication is a tool that can be used to improve wind farm.
- Taking into account both social and economic criteria, in conjunction with the use of communication tools and the type of ownership of the wind farm, favors the construction of a wind farm.

Finally, as noted earlier, the strategic postulates were developed in 2011, by structuring the concerns expressed in public documents submitted to the BAPE in 2005. This was done on the basis that there are concerns not only about where the turbines will be located but also about the strategic planning of wind farm. The design of such postulates must adequately reflect the issue because it can bring to light several possibilities that could warrant an analysis. The design of such postulates is still relevant today because, for some stakeholders, strategic concerns continue to be at the center of public debate, as shown in the last public report of the BAPE[1] related to a wind farm.

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[1] Public Hearing Report 288, July 2012 [online] Available at http://www.bape.gouv.qc.ca/sections/rapports/publications/bape288.pdf (Accessed October 2nd, 2012).

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Chapter 9
Assessment of Energy Efficiency Technologies: Case of Heat Pump Water Heaters

Tugrul U. Daim, Craig Kensel and Kenny Phan

Abstract Technology Assessment (TA) is an approach used to evaluate and characterize technologies for multiple perspectives. Prior research used TA to model the future state of technologies (technological forecasting) or the future diffusion of technologies (technology adoption). This abstract will assess an emerging energy efficiency technology in the United States (US). A hierarchical decision model is used for the assessment. The technology of interest in this case is the heat pump water heater (HPWH). By providing much improved efficiency when compared to regular water heaters, HPWHs contribute to sustainability of the future energy supply. This approach can easily be duplicated for any other region or technology. Technology assessment results provide an insight into manufacturers as well as policy makers on what attributes to focus for faster adoption of this technology toward a sustainable future.

9.1 Introduction

Heat Pump Water Heaters

As time goes by, the idea of having unlimited energy resources becomes less and less feasible. The population of our world and the rate of consumption of resources increase each year. The future has us looking at alternative energy

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sources that will drive the need for better methods of extraction of natural energy's like wind, water, solar, geothermal heat, and other various types of natural resources.

There is a need to focus on developing more energy efficiency of current products to lessen the demand on current energy sources. Primarily powered by electricity, one of the areas to focus on energy efficiency is the heat pump water heater (HPWH). In the Northwest states (Washington, Montana, Oregon, Idaho) about 60–65 % of households use electricity as the primary source of power (Verinnovation 2012). Heating water can consume anywhere from 15 to 25 % of the home total energy consumption (BPA 2012). The engineering behind the HPWH does not generate its own heat while running. Rather the HPWH uses the ambient air surrounding the water heater and functions in revers of a refrigeration or air conditioning system (Dubay et al. 2009; Hepbasli and Kalinci 2009).

According to Energy star:

> HPWH takes the heat from surrounding air and transfers it to water in an enclosed tank. A low-pressure liquid refrigerant is vaporized in the heat pump's evaporator and passed into the compressor. As the pressure of the refrigerant increases, so does its temperature. The heated refrigerant runs through a condenser coil within the storage tank, transferring heat to the water stored there. As the refrigerant delivers its heat to the water, it cools and condenses, and then passes through an expansion valve where the pressure is reduced and the cycle starts over. (Energy Star a).

Studies have shown that a large majority of households have a very inefficient water heater in place (Verinnovation 2012). The HPWH is a very energy efficient appliance and can provide significant cost-effective reduction in energy use to provide hot water to a residence. The HPWH can also provide other climate benefits by acting as a dehumidifier once installed.

There is a push to have energy efficient appliances in every home and there is a need to increase awareness of improved distribution system and hot water load/use reduction technologies (Navigant Consulting 2011).

Energy Trust of Oregon is a nonprofit organization that was created to help Oregonians invest in energy efficiency and renewable resources. The goal they have is that one day all Oregon homes and businesses will be powered by cleaned, affordable energy (Energy Trust).

ENERGY STAR is a joint program of the U.S. Environmental Protection Agency and the U.S. Department of Energy helping us all save money and protecting the environment through energy efficient products and practices (Energy Star b).

The ENERGY STAR labeling will help increase consumers' awareness of the potential energy use and savings of advanced equipment. There are many benefits to many organizations if every home had an Energy Star rating, but that is not the case currently. Energy Trust is trying to understand and figure out ways to increase the adoption of more environmentally and energy saving appliances. There are consumers that are unaware of the ratings for energy efficient appliances and what they entail.

Assessment of Energy Technologies

As outlined by Tran and Daim (2008), technology assessment methods varied significantly between private and public sectors. Daim and Kocoaglu (2009) found that the goals of a company determine the technology assessment strategies. As demonstrated by Chatzimouratidis and Pilavachi (2007, 2008a); Daim et al. (2012), many perspectives including technical and non-technical need to be assessed for a comprehensive technology assessment. These approaches underline the requirement for sustainability which needs to be analyzed through multiple perspectives.

Methodologies used to assess technologies for sustainability purposes include hierarchical models (Iskin et al. 2012; Amer and Daim 2011; Daim and Cowan 2010; Daim and Intarode 2009; Wang et al. 2010; Daim et al. 2009) which are used to characterize technologies across multiple criteria.

Assessments have also been done for forecasting purposes (Daim et al. 2011; Harrel and Daim 2009), planning purposes (Lamb et al. 2012; Amer and Daim 2010) for portfolio building purposes (Daim et al. 2010).

This chapter will build a Technology Assessment tool based on a hierarchical decision model. The model will have multiple criteria to address multiple aspects of sustainability. Heat pump water heaters will be the application in this chapter. We will assess this technology with the goal of understanding what impacts the adoption of this technology. Faster and wider adoption of this technology would improve the sustainable energy supply in this case.

9.2 Research Model

There are factors and subfactors that are affecting the adoption of the Heat Pump Water Heater. The factors we have identified are economic, politic, social, technical, and environmental. The subfactors (elements) will be constructed at a later time and into the HDM model to find the causes that affect the adoption of heat pump water heater.

9.2.1 Technical Factors

When looking into the technical factors of the HPWH we find there are many different types of HPWH, as well as preferred environments and locations to install them for maximum performance (Hudon et al. 2012).

Compression heat pumps are always powered by electrical means while absorption heat pumps are powered by electrical and or heat. Many HPWH use coolant just like an air conditioner, only the heat is transferred to the water and the cold is transferred to the outside air (Heat Pump Water Heaters n.d.; Hudon et al. 2012).

The Mitsubishi ESA20 is a prime example, as it uses CO_2 refrigerant to exchange heat in the systems (MHI n.d.). The absorption HPWH uses heat from other sources and in turn heats the water (Heat Pump Water Heaters: Design Details n.d.; Wikipedia Heat Pump n.d.). An example of this is a HPWH that had a ducting kit added to it so that it draws warm air from another source (Ducted Heat Pumps 2012; Heat Pump Water Heaters 2012). Ducting does cost more, but can be using wasted heat from other appliances or sources. Most HPWH are hybrids and use several technologies' together to get the most hot water out of the energy put into them (GeoSpring n.d.).

The two different stage types of HPWH's in the market are a single stage and a two-stage system. The single stage systems use an air-to-water heat pump and are effective down to 40 °F. The higher the ambient temperature is the more efficient the HPWH (Shapiro et al. 2012). These single systems range in size and typically come as a complete packaged system (Heat Pump Water Heaters n.d.). The other type of system is a two-stage HPWH sized form. This system uses an air-to-water heat pump, called the first stage, which feeds a water-to-water heat pump, called the second stage. The first stage operates alone until the air drop to around 40 °F. A two-stage HPWH can operate efficiently down to 15 °F (Heat Pump Water Heaters n.d.; Liu et al. 2010).

There are several size issues to consider when purchasing a HPWH.

The physical size of the water heater must be determined. Will the HPWH fit in the location designated for it and is there enough air flow or capacity for a heat pump to work correctly with access to the unit for maintenance (Water heater, heat pump: Energy Star, n.d.; Review-GE-heat-pump-water-heater n.d.).

The water storage size of the HPWH is also a very important factor when deciding to purchase one. Most storage water heaters start at 20 gallons and go up to 120 gallons for normal house hold use. The average size is 40–80 gallons in most homes (Vandervort 2012; Water Heater Guide n.d.).

There are many installation locations that can be utilized when installing a HPWH. Some of the more common locations are basements, attics, garage, and closets. Attics are not recommended due to weight, ambient temperature flux and weight of the unit (Shapiro et al. 2012). The locations are limited due to the need for a heat source or sources and structure support for the HPWH as it is normal twice the weight of a standard electric (Shapiro et al. 2012). It is recommended not to install the HPWH near kitchens due to grease clogging the air filter (Shapiro et al. 2012). Ideally, when installing a HPWH the best locations are the ones that can maintain a temperature between 65 and 70° or more (Holladay 2012; Heat Pump Water Heaters 2012). When the ideal location is not available other means of providing heat is needed. With these kinds of locations you can encounter problems with the HPWH. There can be issues with cooling the air in the location and maintaining an ample amount of heat for the system to work. Condensation build-up and poor performance of the equipment due to the environment or location can lead to more maintenance than is standard over the life of the product (Heat Pump Water Heaters 2012; Heat Pump Water Heaters DOE n.d.; Holladay 2012). System efficiency is less due to less water usage and lower water temperature and more due to use of the heating elements (Shapiro et al. 2012). Noise and exhaust should be taken into consideration when placing the HPWH in and or around the home (Heat Pump Water Heaters 2012; Holladay 2012).

Bonneville Power Administration (BPA) has conducted field experiments on a selection of Energy Star rated HPWH in the Northwest. According to its BPA lab report, the areas that they will be focusing within the Northwest are in the Seattle and Portland areas. The areas that BPA have the most intense interest of conducting its experiment within the residential home are at the garage and unheated basements. These locations are being studied due to the area being influenced by the ambient area conditions. The data is being influenced by the Typical Meteorological Year 3 (TMY3) weather data. And will be formed into three typical Northwest heating zones, using the same weighting scale as in the Sixth Northwest Conservation and Electric Power Plan (6th Power Plan of the Northwest Power and Conservation Council. The direction that BPA was going with the weighting scale is to create a climate that is suitable for the region as a whole (Larson et al. 2011). The BPA conducted two scenarios of insulation between the garage and the house (Larson et al. 2011). One scenario, having high levels of insulation between the house and garage, produce a garage with lower temperatures (Larson et al. 2011). The second scenario, having minimal insulation between the house and garage would have much warmer temperatures (Larson et al. 2011).

The results indicated that having low insulation gives the opportunity for the house and the garage to be much closer together. This would benefit in allowing the house to supply more heat to the garage, impacting more of the space heating system.

Many of the HPWH’s are Energy Star compliant and in essence can save home owners hundreds of dollars a year (Energy Star Qualified Heat Pump Water Heaters 2012). The GE Geo Spring Hybrid Water Heater is an example of multiple technologies put together to bring forth a high efficient unit that can save the home owner money over time. For every watt of energy applied to the unit, 2.85 watts of heating energy is recovered (GeoSpring n.d.; Water Heater Guide n.d.; Save Money n.d.). As manufactures develop better and better designs and functional HPWH’s, more digital technology is being integrated including the design such as digital displays and controls for optimal usage and operation (GeoSpring n.d.; Water Heater Guide n.d.; Rheem Hybrid Electric Water Heater Features n.d.). Newer models of the HPWH are more reliable and last just as long as standard electric water heaters (Shapiro et al. 2012; Hudon et al. 2012).

9.2.2 Environmental Factors

When looking at the environmental factors that affect the adoption of the HPWH in the market place. In the design of the HPWHs some environmental factors should be considered such as energy source (temperature of heat source, temperature of air source), air flow, and buffer storage.

However, Portland is not as warm as San Francisco even if they are in the same zone (Homeowner information n.d.; Rheem Hybrid Electric Water Heater: Efficience Zones n.d.). Most of the Pacific Northwest is in zone 2 were only an estimated 60 % energy efficiency is estimated. The HPWH is more efficient if the ambient temperature is higher like in San Francisco.

Noise and exhaust should be taken into consideration when placing the HPWH (Heat Pump Water Heaters 2012; Holladay 2012). If the exhaust is ducted out of the location to the outside, then warm air is being sent out of the location and into the environment. This is ok for summer, but not for winter as your heating bill will go up and it could add wear and tear to the HPWH fan as it is forced to push air through duct works (Holladay 2012). Depending on the location the fan noise may or may not be an issue. It all depends on the location and environment the unit is placed in.

If considerations are not made with researching and buying a HPWH then major issues can cause damage to property or even affect serious health issues. A HPWH must have at least 500 feet of air flow, but 1,000 or more feet is better.

Location, building code requirements, and safety issues must be addressed when installing a HPWH (Heat Pump Water Heaters: DOE n.d.). Avoid environments with high levels of dust and dirt, as it may clog the air filter. Keep flammable vapors away from the HPWH, as it could ignite them. The home owner needs to have the HPWH surge protected and high enough off the floor to avoid flooding (Review n.d.).

Customers should be aware of the environmental impact of heat pump water heaters. Qualified and efficient heat pump water heaters are labeled by the U.S. Department of Energy and the Environmental Protection Agency (EPA) to show that they are energy efficient (Snyder 2012). An energy start rating is a good indication of a qualified energy efficient water heater (Energy Star n.d.). Another important factor in reducing environmental impacts is the type of the fuel used to power the heat pump water heater (EECA Energywise n.d.).

9.2.3 Social Factors

In researching the social factors of the adoption of the HPW, NEEA was found as a good source. The Northwest Energy Efficiency Alliance (NEEA), a non-profit organization that works with over 100 Northwest utilities, conducted a 2011 market survey on residential water heaters (Verinnovation 2012). NEEA has partnered with Verinnovation to update its 2006 report on the residential water heater market. The water heater survey was conducted from June 2011 to October 2011(Verinnovation 2012). The main focus of this survey was to allow NEEA to get a better understanding of the consumers in the Northwest behavior and attitudes toward water heaters. As well as being able to continue learning about other high efficiency water heaters. To have a better understanding of the current market it will give more opportunities to get more high efficiency water heater into consumer homes.

With internet sites like Moving to Portland and Regreen ASID & USGB partnering to set up a residential remodeling program to help consumers who are buying a home or remodeling get direction in order to find the resources needed to make the right purchases (Regreen n.d.).

The media has stories of awards given or some group or company giving a city or a state an award for being so green or ecofriendly. The Pacific Northwest has had its share of awards and recognition due to so many people being environmentally conscious and persuading their friends to do the same (Law 2011).

There is an ever increasing movement for building green communities such as the Mosier Creek Green Community. By utilizing high efficient appliances and producing some of its own electricity, Mosier Creek was able to use 69 % less energy than the national standard (Mosier Creek n.d.)

The data that NEEA and Verinnovation have gathered showed signs that consumers are aware of the heat pump water heater technology, but are more aware and interested in tank less models (Verinnovation 2012). At the same time, installers are skeptical that heat pump water heaters will be able to work as efficient in the Northwest climate (Verinnovation 2012). The problem maybe on arise is that lack of understanding how the device actually works. To overcome this challenge its important is to give consumers and installers accurate and up-to-date information on heat pump water heaters technology and proof that it actually works.

The Consortium for Energy Efficiency (CEE) is trying to do just that and is devoted to advancing efficiency for the public good (Home Depot n.d.; CEE n.d.).

This may be the key thing that the market needs to get consumers to embrace this technology.

Due to poor information being provided to the consumer and a low/lack of training to the sales force, customer reviews have been mixed and many people do not realize when buying a HPWH what they are getting into. Some companies have training videos on line for their particular brand and model of HPWH. Others simply have the instruction book and their staff is not up- to-date on the training that is needed to pass on the information to the customer for proper maintenance (Rheem EcoSense n.d.; GE 50 n.d.).

The research that NEEA and Verinnovation has gathered from the internet search metrics indicates when consumers search for heat pump water heater they will seek out product reviews and information on financial incentives. The correlation behind this is that consumers will plan out their water heater purchases in order for buyers to be motivated. Through countless interviews with sales representatives and installers has confirmed this trend and it is believed that when tax credit ends it will expect the high energy water heater sales to decline (Verinnovation 2012).

In our research we contacted some local suppliers of the HPWH. We talked to Lowe's and Home Depot in the local area. Both sites had reps that new the HPWH and new it well. It was just the opposite of what we thought we would find. The two biggest things came from talking to them was that most people look at the

HPWH and compare the price with the tank less water heater. They have in most cases gone with the tank less even though it has a 3-year warranty. The other down side to tank less water heaters is that they have what they call a load rating compare to a gallon rating. We found that the prices were comparable between the stores. At the time of the research the Lowe's price was lower due to a sale. The prices were as follows: Home Depot $1,200.00 and Lowe's $999.99.

9.2.4 Economical Factors

Economical factors of the HPWH that need to be looked at are the initial cost and the operating (annual) cost should be taken into account to see how cost-effective HPWH is when comparing it to the conventional water heating systems. In fact, although initial cost for heat pump water heaters is higher than conventional water heaters, operating costs are lower (Heat Pump Water Heaters: DOE n.d.).

The average life of a high efficiency tank storage water heater that is powered by electric, gas, or oil is 8–13 years + , with an average energy savings of 10–20 %. The average life of a tank less gas or electric water heater is 20 years, with an average energy savings of 45–60 %. The heat pump water heater has an average life expectancy of 10 years with an efficiency of 65 % (Heat Pump Water Heaters: DOE n.d.; High Efficiency n.d.; InterNACHI n.d.). Due to the varying designs and technologies built into the many different models it is hard to find a set life expectancy standard. As technology improves and becomes cheaper to build, it is expected that many of the devices will last longer and use less energy.

Once the water heater has reached the end of its use full life, in many parts of the country there are companies and programs that will pick up your old water heater for a few dollars or charge you a fee to remove it (Water Heater | appliance recycling. n.d.). The starting purchase price of an all-inclusive HPWH starts at around a thousand dollars. The more efficient the HPWH is, the higher the price. Add on units start around $700(Heat Pump Water Heater Prices n.d.; Heat Pump Water Heater: Compare Prices n.d.).

The operating cost is hard to calculate due to the fluctuation in outside temperatures and other factors including models, locations placement, and steward ship of the equipment (Review n.d.; Residential EnergySmart Library n.d.). However, the operating cost of the GE HPWH without the annual maintenance shown is $195.00 compared to $520.00 for a standard electric water heater (Efficient Water Heater: GE n.d.). Inspectors are recommended for periodical maintenance and the cost varies from company to company (Shapiro et al. 2012).

The current economic outlook for both local and the United States is showing a slow and steady growth and is expected to continue for the next 2 years and job creation will be slow as well. Oregon is still below the start of the recession levels and is only making meager gains and is not expected to fully recover to pre-recession highs until 2014 (Oregon economic and revenue forecast summary Leading Economic Indicators 2011). The US as a whole is even in a worse condition than Oregon with many workers with college degrees under paid or unemployed (UNRATE-FRED n.d.; Horrible Statistics 2012).

It seems that cost can be one of the important adoption factors for buyers. Records show that in spite of the cost-effectiveness and higher efficiency that HPWH has comparing to the standard Water heating technologies, its market adoption rate is still much lower (Dubay et al. 2009). On the other hand, electric heat pump water heater not only can cut yearly energy cost, but also has a good payback potential over the years which make them promising for residential energy uses (Dubay et al. 2009).

There are many incentives to attract potential customers to buy HPWH to help reduce the initial investment costs and in order to boost the deployment of renewable energy technology. There are federal and state tax credits that are available (Amer and Daim 2010). Current Oregon Tax Credit for Heat Pump systems includes a Tax Credit in the amount of $300.00–$430.00 and requires a heating Season Performance Factor (HSPF) of 9.0 or higher and Energy Efficiency Ratio (EER) of 12 or higher (ODOE n.d.; Federal Tax: EnergyStar n.d.).

Many brand have rebates like GeoSpring, Rheem, GE, Whirlpool, Bosch, Voltex, Stiebel, and American Water heater companies to name a few, offer rebates from time to time along with stores that give discount prices. Many local and federal government tax credits have run out at the end of 2011 and it is hard to find information right now.

9.2.5 Political Factors

Some of the political factors found when looking at the adoption of the HPWH statistics are ties to the economy, supply, and demand. The Energy Policy Act of 2005 was an attempt to take on the growing energy problem by providing tax incentives and loans for energy production and conservation of various types (2012; Iskin et al. 2012). As of 2008, there were a small number of US manufacturers of the HPWH's. Due to the small number of manufactures, it limits the number of jobs that are generated from this market. If the popularity of the HPWH would increase, it could have a direct impact on the number of jobs in the US. It will depend on what type of HPWH generates the most demand. If the demand for the unit increases, the US manufacturers could see an increase in demand, thus creating more jobs. In general, if the demand for the HPWH goes up there will be demand for more to be made in the US. If the US manufactures would create their own products, then again the job demand would go up. If this scenario does exist there will be many jobs that manufactures can create. As has been identified in the literature review there are many specific jobs in the energy sector. The journal article has broken it down into three main categories which are direct, indirect, and induced jobs (Iskin et al. 2012). Direct jobs refer to job opportunities which involve construction, manufacturing, and operations. Indirect jobs refer to job opportunities which involve providing indirect goods and services for plant construction. Examples can be suppliers, maintenance, engineering, and repair services. Induced jobs refer to job opportunities which evolve because of industrial expansion. Examples can be shopping, housing, and education related jobs (Iskin et al. 2012).

With the ending of the residential energy tax credit as of January 1, 2012 there is no new incentive to purchase HPWH from the Oregon state legislature. However, the Energy Trust of Oregon still offers incentives and solutions to customers of PGE, Pacific Power, NW Natural, and Cascade Natural Gas (SEDCOR.COM n.d.). Other utilities around Oregon and Washington do offer incentive as well, such as Eugene Water and Electric board and Seattle city Light (Seattle City Light Conservation n.d.; EWEB n.d.). However, the political movement that needs to be there to support those who want to buy better and more efficient home utility's is not available since the January 1, 2012.

9.3 Research Methodology

Based on literature search, experts' opinions, and technical evaluation of the Heat Pump Water Heater, an HDM model has been developed. The major factors of this model are based on the evaluation approach developed earlier at Portland State University (RISE).

9.3.1 Hierarchical Decision Model

Hierarchical decision models were introduced by Saaty (1980); Kocaoglu (1983). Further information on the methodology details can be found in these references.

AHP/HDM-based models have been used in the energy sector as well–specifically when evaluating power plant alternatives (Akash et al. 1999; Chatzimouratidis and Pilavachi 2007, 2008a, b, 2009a, b). Lee et al. (2008) used a similar model for the hydrogen technology, whereas Lee et al. (2007) used it for energy efficiency.

In the HDM, the whole structure of the system is broken down into a tree diagram by showing various elements and their subgroups which may include mission, goals, strategy, objectives, or alternatives. Depending on the type of the problem, some of these levels may not exist in the HDM. Figure below (9.1) can be shown as an example for Hierarchical Decision Model.

After choosing the appropriate criteria, pairwise comparisons are done by panel of the experts to measure the preferences; a total of 100 points should be allocated for each pair that is being analyzed (Kocaoglu 1983).

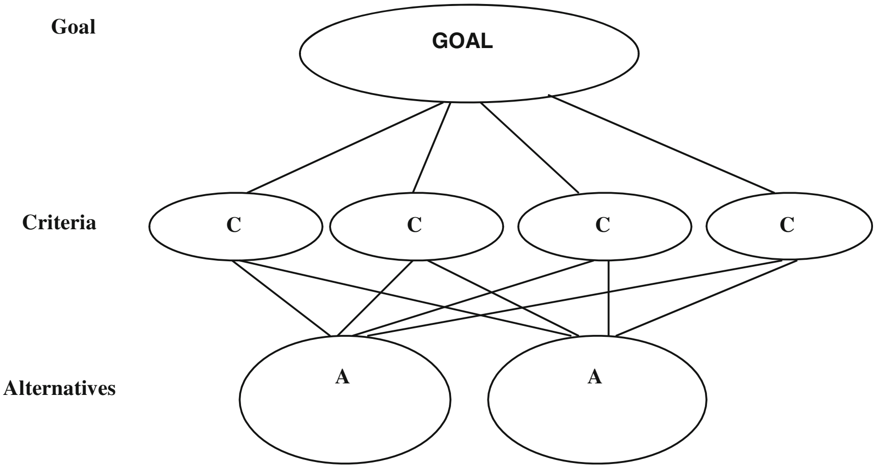

Fig. 9.1 A typical hierarchy model

9.3.2 Model Design

Based on the literature review, we gathered influential factors on adoption of heat pump water heaters and tried to categorize similar criteria; we ended up having 5 main categories for our criteria level: Economical, Social, Environmental, Political, and Technical. The figure below (9.2) shows the framework of our HPWH adoption model. The lowest level includes the subcategories for each main criterion.

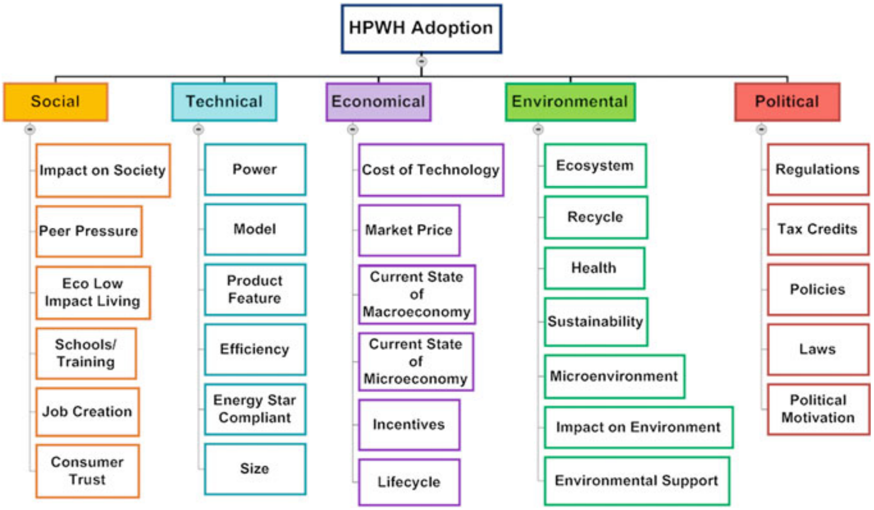

Fig. 9.2 HPWH adoption decision model

All the criteria and their subcategories are explained below:

1. ***Social***: It explains how consumers' behaviors and attitude can influence the adoption trend.
   - *Impact on Society*: The degree to which the use of the device might impact the living style of families.
   - *Peer Pressure*: The degree to which different users of the device can influence on each other to adopt the technology.
   - *Eco Low Impact Living*: Also known as environmentally friendly low impact living—is your overall environmental footprint.
   - *Training*: The degree to which increasing information and level of awareness about the technology can encourage more people to use it.
   - *Consumer Trust*: The impact of knowledge and trust about accurate functionality and use of the device.
   - *Job Creation*: *Buying products made in the USA promote job creation.*
2. ***Technical***: The degree to which a technology is evaluated in detail; it explains the technology and the device in terms of its size, performance, and features.
   - *Size*: The degree of effectiveness of dimensions on adoption.
   - *Power*: *How much energy the unit consumes to produce gallons of hot Water per hour.*
   - *Models*: Having different representatives from the same family product which vary in some features.
   - *Product Feature*: Explains the capabilities of the product comparing to the similar devices in the field.
   - *Efficiency Feature*: Quality degree of the device in terms of saving energy.
   - *Energy Star Compliant*: Energy Star is a government-backed labeling program for products that have superior energy efficiency.
3. ***Economical***: It shows the role of cost and market in adoption process.
   - *Cost of Technology*: Expenditure associated with acquisition, development, implementation, or maintenance of technology assets.
   - *Market Price*: Economic price for which the product is being offered in the marketplace. It can also be the degree to which the product is being valued in the market.
   - *Life Cycle*: Refers to the different phases that the product until it does not perform as it was designed and expected to be.
   - *Incentives*: Financial contribution that an agent or person can expect from an organization in exchange for acting in a particular way.
   - *Current state of micro economy*: The degree to which behavior of individuals, companies, and industries can affect the adoption rate.
   - *Current state of macro economy*: The degree to which economy in larger scale such as unemployment, inflation, domestic production can be effective.

4. ***Environmental***

   - *Ecosystem*: The degree to which ecosystem can be changed.
   - *Impact on Environment*: The degree to which the device or technology can have both positive and negative influences on the environment.
   - *Health*: The degree to which overall health of people and environment will be affected.
   - *Recycle*: The degree to which useful material can be extracted from disposed device in order to be reused.
   - *Sustainability*: The degree to which the product can provide environmental benefits while protecting the environment over its life cycle.
   - *Environmental Support*: The degree to which a device is clean and environmental friendly based on its technology.

5. ***Political***

   - *Regulations*: The degree to which administrative legislation that constitutes or constrains rights and allocates responsibilities can be influential.
   - *Tax Credits*: Degree to which a person's or agent's tax will be reduced by adopting the new technology or device.
   - *Policies*: A degree to which rules and principles will affect buying decisions.
   - *Laws*: The degree to which enforced guidelines by some institutions will affect the adoption decisions.
   - *Political Motivation*: *Politics are involved that affect the buying decision.*

Our panel of experts consisted of 2 people in the field of heat pump water heating systems. While this is a limitation, it provides a good demonstration of the methodology. One energy expert and one utility expert were chosen to provide us with the pairwise comparison and appropriate weighting for each criterion. Our energy expert is more specialized in consumption side and has better reach to customers while the utility expert thinks more in terms of the benefits for the customers. All experts are completely familiar with the technology and the regulations; however, along with the list of the criteria, explanations were provided. We also contacted 2 local consumers who provided pairwise comparison and weighting for each criterion as well.

9.4 Results

After receiving pairwise comparisons from experts and consumers, weights have been calculated (Kocaoglu 1983). Since experts and consumers have different points of view about use of heat pump water heating systems, separate models have been developed for experts and consumers. The results from expert analysis are shown in Tables 9.1, 9.2, 9.3, 9.4, 9.5, 9.6, 9.7, and 9.8:

Table 9.1 Overall comparisons of criteria

	Social	Technical	Economic	Environmental	Political
Energy expert	0.05	0.09	0.16	0.05	0.66
Utility expert	0.20	0.28	0.34	0.09	0.08
User 1	0.09	0.29	0.36	0.17	0.09
User 2	0.08	0.29	0.29	0.29	0.04

Table 9.2 Comparison of social criterion

	Impact on society	Peer pressure	Eco low impact living	Schools/ training	Job creation	Consumer trust
Energy expert	0.06	0.06	0.08	0.09	0.07	0.64
Utility expert	0.15	0.10	0.12	0.09	0.15	0.31
User 1	0.13	0.07	0.09	0.23	0.18	0.29
User 2	0.11	0.1	0.15	0.18	0.18	0.28

Table 9.3 Comparison of technical criterion

	Power	Models	Product features	Efficiency	Energy star compliant	Size
Energy expert	0.19	0.06	0.10	0.40	0.19	0.06
Utility expert	0.17	0.09	0.13	0.24	0.24	0.15
User 1	0.1	0.1	0.05	0.12	0.36	0.27
User 2	0.08	0.01	0.11	0.3	0.45	0.05

Table 9.4 Comparison of economic criterion

	Cost of technology	Market place	Current state of macro economy	Current state of micro economy	Incentive	Lifecycle
Energy expert	0.24	0.14	0.15	0.17	0.25	0.05
Utility expert	0.11	0.23	0.29	0.08	0.12	0.16
User 1	0.09	0.02	0.07	0.07	0.07	0.49
User 2	0.03	0.03	0.04	0.11	0.53	0.26

Our comparison of experts and users among top 5 criteria clearly indicates political factor is most important factor impacting the lesser adoption of HPWH while economic front is most impacting for home users and interestingly, political factor hold least importance for them. Another highlight of the results was the environmental impact which was least important for experts but home users considered it as an important factor while purchasing HPWHs.

Table 9.5 Comparison of environmental criterion

	Eco system	Recycle	Health	Sustainability	Micro environment	Impact on environment	Environmental support
Energy				expert	0.12	0.13	0.21
0.15	0.13	0.13	0.13				
Utility				expert	0.16	0.12	0.08
0.18	0.17	0.16	0.16				
User 1	0.02	0.01	0.23	0.27	0.14	0.1	0.13
User 2	0.11	0.14	0.19	0.17	0.12	0.16	0.12

Table 9.6 Comparison of political criterion

	Regulations	Tax credits	Policies	Laws	Political motivation
Energy expert	0.22	0.04	0.1	0.33	0.3
Utility expert	0.44	0.25	0.11	0.12	0.07
User 1	0.18	0.25	0.18	0.23	0.15
User 2	0.16	0.29	0.24	0.19	0.12

Table 9.7 Order of importance of factors on top level

Experts	Users
Political	Economic
Economic	Technical
Technical	Environmental
Social	Social
Environmental	Political

Table 9.8 Top 10 highest impacting subcriteria

Experts	Users
Regulations	Life cycle
Laws	Energy star compliant
Political motivation	Incentives
Consumer trust/efficiency	Efficiency
Tax credit	Sustainability
Market price	Health
Cost of technology	Size
Current state of macro economy/life cycle	Market price
Policies	Microenvironnement/impact on environment/ environmental support
Energy star compliant	Current state of macro economy

9.5 Conclusions

Interpretations of the results of our analysis are mentioned below:

- Experts consider regulations as the most important factor affecting the adoption rate of the HPWH. Therefore, current low adoption rate of HPWH indicates that regulations are not promoting the use of heat pump water heaters. Having established laws and regulations for HPWH requires federal and state political support.
- Laws have the second rank among experts and current situation of HPWH shows that there are not effective laws on the use of HPWH. Including HPWH in the building codes can make manufacturers to meet some minimums on efficiency of HPWH.

In order to increase adoption of HPWHs, one should focus upon these recommendations:

Regulations:

Have better regulations and laws to encourage better functioning and high energy efficiency of the water heater units. More corporate tax incentives should be there for producing better HPWH.

Manufacturers:

- Develop cheap and efficient heat pump water heaters that follow federal and state laws and regulations. [Energy Star Compliant].
- Develop HPWH with equivalent maintenance and physical requirements as current electrical and gas water heaters. [Efficiency].
- Better warranties on equipment [Customer Trust], offer incentives to retailers to sell HPWH. [Life cycle].
- Not to incorporate other features that raise costs without any energy benefit.
- Feature relatively easy installation and low maintenance—are generally taller and require more space for proper performance—both these impose some installation constraints (at least match that of current of HW systems).
- Develop some sort of Fault Detection and Diagnostic (FDD) systems—that notifies the user when performance deteriorates so corrective action may be taken.

Utilities:

- Offer more rebates and incentives [micro economy].
- Offer an insurance/maintenance program through local utilities company. [Customer Trust].
- Work with contractor in choosing what water heaters should go into newly built homes.
- Education/Awareness.

Government:

- Set new regulations for building code. If the water heater are going to be bigger than normal water heaters. (So they will not have any difficultly in installing the HPWH).
- Have longer incentives—at least maybe cover the installation cost.
- Education/Awareness/Training.
- Work closely with venders to push out the most efficient heat pump water heaters.
- Do some sort of test pilot in cities.

Retailers:

- Keep price of the HPWH lower than $500.00 [Market place].
- Advertise the benefits of the HPWH and requirements [Health]. Demonstrate its reliability compared to current electric and gas water heaters. [Customer Trust].

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Part II
Fuzzy Inference, Artificial Neural Net, Algorithm Genetics

Chapter 10
A Fuzzy Paradigm for the Sustainability Evaluation of Energy Systems

Evangelos Grigoroudis, Vassilis S. Kouikoglou and Yannis A. Phillis

Abstract A vital part of sustainable development is the provision of adequate, reliable, and affordable energy, in conformity with social and environmental requirements. Energy is one of the most crucial factors that power modern economies subject to a volatility in price and supply, while at the same time it is responsible for major environmental consequences with global warming topping the list. In this chapter we develop a model that provides a general mechanism to measure the sustainability of energy sectors. Sustainability is an inherently vague concept, and for this reason the model uses fuzzy logic, which has the ability to deal with such an ambiguous, complex, and polymorphous concept. The proposed model follows the principles of SAFE (Sustainability Assessment by Fuzzy Evaluation), a model for the numerical assessment of sustainability. To consider the cumulative effects of past policies, we use exponential smoothing on sustainability data, while an imputation procedure is applied in order to overcome the problem of missing values. The model is applied to a large set of countries, which are ranked according to their sustainable energy development.

10.1 Introduction

Sustainable development is defined as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (UNEP 1987). A vital part of sustainable development is the provision of

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adequate, reliable, and affordable energy, in conformity with social and environmental requirements.

Energy is one of the most crucial factors, if not the single most important one, that power modern economies and guarantee economic growth. However, much of the current energy supply and use is deemed environmentally unsustainable, since it is mostly based on limited resources (IAEA 2005). In addition, energy production or conversion generates pollution that often has severe health and environmental consequences. Even if a technology does not generate significant amounts of harmful substances at the point of use, emissions and wastes may be associated with manufacture or other parts of the energy life cycle (IAEA 2005).

The International Atomic Energy Agency (IAEA), in cooperation with various other international organizations, including the International Energy Agency (IEA), the United Nations Department of Economic and Social Affairs (UNDESA), and some Member States of the IAEA started a long-term program addressing indicators for sustainable energy development. As in several other sustainability studies, they suggest that the set of indicators should consider the economic, social, environmental, and institutional dimensions of sustainable development (UNDESA 2007):

- *Economic dimension*: These indicators measure how the use and production patterns of energy, as well as the quality of energy services, affect progress in economic development, and how the status of the energy sector and its trends in a country may improve the chances for sustainable economic development. The available energy services can foster economic and social development by raising productivity and facilitating income generation. Indicators in the economic dimension include energy use, production and supply; energy supply efficiency and end-use energy intensity; energy pricing, taxation and subsidies; energy security; and energy diversity.
- *Social dimension*: Indicators in the social dimension measure the impact that available energy services may have on social well-being. Availability of energy services has implications on poverty, employment opportunities, education, community development and culture, demographic transition, indoor pollution and health, as well as gender and age-related issues. This dimension deals primarily with accessibility, affordability, and disparity in energy supply and demand.
- *Environmental dimension*: The production, distribution, and use of energy create pressures on the environment at a national, regional, and global level. Environmental indicators measure the impact of energy systems on land, water, and air quality. The main issues related to the environmental dimension include global climate change, air pollution, water pollution, wastes, land degradation, and deforestation.
- *Institutional dimension*: These indicators assess the availability and adequacy of the institutional framework necessary to support an effective and efficient energy system. The institutional dimension links and addresses the response actions and policy measures designed to influence trends in all the previous dimensions, i.e.,

> social, economic, and environmental. For example, institutional indicators may assess the effectiveness of a national sustainable energy development strategy and the adequacy and effectiveness of investments in capacity building, education, or research and development. They could also contribute in monitoring progress toward appropriate and effective legislative, regulatory and enforcement measures to foster efficient energy systems.

It should be emphasized that, although a large number of sustainability indicators for energy development has been proposed, there is no widely accepted aggregation approach (IAEA 2005; UNDESA 2007). The majority of previous studies focuses on the sustainability evaluation of national/regional energy systems rather than on ranking of countries according to their sustainable energy development. The aim of this chapter is to develop a model that provides a general mechanism to measure the sustainability of energy sectors. Sustainability is an inherently vague concept, and for this reason the model uses fuzzy logic, which has the ability to deal with ambiguous, complex, and polymorphous concepts. The proposed model follows the principles of SAFE (Sustainability Assessment by Fuzzy Evaluation), a model for the numerical assessment of sustainability introduced in Phillis and Andriantiatsaholiniaina (2001) and developed further in Phillis et al. (2003, 2011), Andriantiatsaholiniaina et al. (2004), Kouloumpis et al. (2008).

The main advantage of the model is that it can provide an explicit and comprehensive description of the concept of sustainability. Using linguistic variables and rules, the model gives quantitative measures of sustainability from the ecological and societal points of view. SAFE considers also the cumulative effects of past policies, using exponential smoothing on sustainability data, while an imputation procedure is incorporated in order to overcome the problem of missing values. Finally, a sensitivity analysis of the model permits to determine the most important aspects of sustainable development for a given country.

10.2 Sustainability Assessment of Energy Systems

10.2.1 A SAFE Model of Energy Development

The structure of the SAFE model is shown in Fig. 10.1. It is assumed that the overall energy sustainability (OSUS) of a country is a combination of two primary components: ecological sustainability (ECOS) and human sustainability (HUMS). The ecological input comprises two secondary components: air quality (AIR) and soil quality (LAND). The human components of energy sustainability are social (ACCESSIBILITY) and economic (PRODUCTION, CONSUMPTION, SECURITY). Each secondary component is assessed using certain basic indicators which are the inputs of the system.

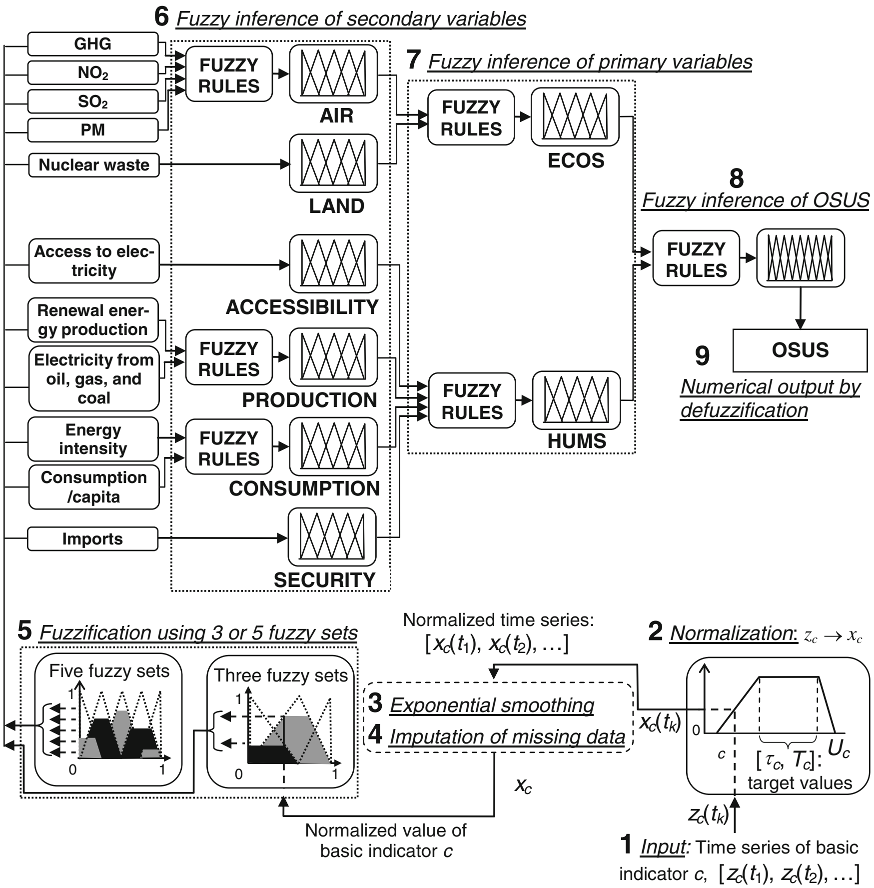

Fig. 10.1 Hierarchical structure of the SAFE model of energy systems: (1–5) input, normalization, exponential smoothing, imputation, and fuzzification of basic indicators; (6–8) fuzzy inference of composite indicators and overall sustainability of energy development; (9) defuzzification

SAFE uses fuzzy sets to represent the basic indicators of energy development and fuzzy logic to combine them according to expert knowledge and finally give a value of the overall sustainability. Fuzzy sets are an effective means of extracting information from precise or imprecise data expressed in numerical or qualitative form. Fuzzy logic has the ability to process information about vague and complex concepts and make concrete assessments without a detailed mathematical description.

The sequence of data processing of SAFE is the following:

- Collection of available data;
- Normalization in [0, 1];
- Exponential smoothing;

- Data imputation;
- Fuzzification;
- Fuzzy assessment of sustainability;
- Sensitivity analysis and decision making.

A total of 11 basic indicators are used for 128 countries. The basic indicators are normalized in [0, 1] by linear interpolation between sustainable and unsustainable indicator values, which are specified by international agreements and norms, laws and regulations, and expert opinion. The set of basic indicators is presented in Table 10.1 (see Appendix for a detailed description). Table 10.2 gives the upper and lower thresholds of unsustainable values, U_c and υ_c respectively, and a range $[\tau_c, T_c]$ of sustainable or target values for each basic indicator c. For a given country, let $z_c(t)$ be the value of indicator c in year t. The corresponding normalized value is calculated from:

$$x_c(t) = \begin{cases} 0, & z_c(t) \le \upsilon_c \\ \frac{z_c(t)-\upsilon_c}{\tau_c-\upsilon_c}, & \upsilon_c < z_c(t) < \tau_c \\ 1, & \tau_c \le z_c(t) \le T_c \\ \frac{U_c-z_c(t)}{U_c-T_c}, & T_c < z_c(t) < U_c \\ 0, & U_c \le z_c(t) \end{cases} \tag{10.1}$$

Normalization facilitates the comparison and combination of different indicators by assigning the value 1 to best performance and 0 to the worst.

SAFE uses the most recent indicator data to estimate the human components of energy development for each country. Time series data are used for the environmental components so as to take into account cumulative effects of past environmental pressures. A smoothing filter outlined below is applied to these time series. Suppose that K measurements of indicator c are available for some country. Let $x_c(t_1)$, $x_c(t_2)$, …, $x_c(t_K)$ be the normalized values in years t_1, t_2, …, t_K. These years need not be consecutive due to missing data. We define the weighted average of indicator data *prior to* year t_k by:

$$\hat{x}_c(t_1) = 0 \text{ and } \hat{x}_c(t_{k+1}) = \frac{x_c(t_k) + x_c(t_{k-1})\beta^{t_k-t_{k-1}} + \cdots + x_c(t_1)\beta^{t_k-t_1}}{1 + \beta^{t_k-t_{k-1}} + \cdots + \beta^{t_k-t_1}} \; k = 1, \ldots, K \tag{10.2}$$

in which older observations are assigned geometrically decreasing weights with parameter $\beta \in [0, 1]$. The smoothing parameter β is chosen so as to minimize the mean squared error:

$$[x_c(t_1) - \hat{x}_c(t_1)]^2 + \cdots + [x_c(t_K) - \hat{x}_c(t_K)]^2 \tag{10.3}$$

An aggregate value x_c for indicator c is given by:

$$x_c = \hat{x}_c(t_{K+1}) \tag{10.4}$$

Table 10.1 Basic indicators used in the SAFE model of energy systems

Component	Basic Indicator[a]	Main sources of data
AIR	GHG (tons of CO_2 equivalent per capita)	United Nations Environment Program (http://geodata.grid.unep.ch/options.php?selectedID=1930&selectedDatasettype=National)
AIR	NO_2 (μg/m^3 of air)	Esty et al. (2005), Environmental Sustainability Index 2001, 2002 (www.yale.edu/esi)
AIR	SO_2 (μg/m^3 of air)	Esty et al. (2005), Environmental Sustainability Index 2001, 2002 (www.yale.edu/esi)
AIR	PM10 (μg/m^3)	United Nations Environment Program (http://geodata.grid.unep.ch/options.php?selectedID=1930&selectedDatasettype=National)
LAND	Nuclear waste (tons of heavy metals per capita)	OECD (2005), United Nations Environment Program (http://geodata.grid.unep.ch/mod_download/download_xls.php?selectedID=1543)
ACCESSIBILITY	Access to electricity (percent of population)	IEA (2002; 2010), World Resources Institute (2006)
PRODUCTION	Renewable energy production (percent of total primary energy supply)	IEA (http://www.iea.org); Human Development Report (http://hdr.undp.org)
PRODUCTION	Electricity from oil, gas, and coal sources (percent of total electricity production)	IEA (2011a, b, c, d), World Bank (http://data.worldbank.org/indicator/EG.ELC.FOSL.ZS?page = 4)
CONSUMPTION	Energy intensity (kg of oil equivalent per $1,000 GDP, constant 2005 PPP)	World Bank (http://data.worldbank.org/indicator/ EG.USE.COMM.GD.PP.KD)
CONSUMPTION	Energy use (kg of oil equivalent per capita)	IEA (http://www.iea.org/stats/index.asp)
SECURITY	Imports (percent of energy use)	IEA (http://www.iea.org/stats/index.asp)

[a] Measurement unit in an annual basis

Table 10.2 Least and most desirable values for the basic indicators

Basic Indicator	Type[a]	Thresholds[b]	Comments[c,d]
GHG (tons of CO_2 equivalent per capita)	SB	$T = 0.0075$, $U = 0.0368$	T is set at the average of EU-14 reduced by 30 % in accordance with the EU target of 2020, $U = \text{MAX}$
NO_2 (μg/m^3 of air)	SB	$T = 18.2$, $U = 109.16$	T = minimum of EU-14, $U = \text{MAX}$
SO_2 (μg/m^3 of air)	SB	$T = 1.33$, $U = 97.07$	T = minimum of EU-14, U = MAX (excluding 1 % outliers)
PM10 (μg/m^3)	SB	$T = 6.4769$, $U = 174.6720$	$T = \text{MIN}$, $U = \text{MAX}$
Nuclear waste (tons of heavy metals per capita)	SB	$T = 0$, $U = 0.0593$	$T = \text{MIN}$, $U = \text{MAX}$
Access to electricity (percent of population)	LB	$\upsilon = 9.0$, $\tau = 100.0$	$\upsilon = \text{MIN}$, $\tau = \text{MAX}$
Renewable energy production (percent of total primary energy supply)	LB	$\upsilon = 0$, $\tau = 20$	$\upsilon = \text{MIN}$, τ = EU target
Electricity from oil, gas, and coal sources (percent of total electricity production)	SB	$T = 0$, $U = 100$	$T = \text{MIN}$, $U = \text{MAX}$
Energy intensity (kg of oil equivalent per $1,000 GDP, constant 2005 PPP)	SB	$T = 50.4970$, $U = 1176.7054$	$T = \text{MIN}$, $U = \text{MAX}$
Energy use (kg of oil equivalent per capita)	SB	$T = 66.7045$, $U = 11{,}402.0571$	$T = \text{MIN}$, $U = \text{MAX}$
Imports (percent of energy use)	SB	$T = 0$, $U = 97.3847$	$T = \text{MIN}$, $U = \text{MAX}$

[a] SB = smaller is better; LB = larger is better; NB = nominal is best

[b] υ, τ, T, and U are thresholds of target (sustainable) and unsustainable values. Values in the interval $[\tau, T]$ are assigned the sustainability index 1. Values $\leq \upsilon$ or $\geq U$ indicate poor performance and are assigned the sustainability index 0. Values in (υ, τ) or (T, U) are scaled in (0, 1) by linear interpolation

[c] MAX (MIN) = maximum (minimum) value over all countries (based on most recent values)

[d] EU-14: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, United Kingdom. These countries and Luxemburg are the countries in the European Union before the expansion of May 1, 2004. Luxemburg has not been taken into account due to its very small population

In the formulas given above, the weights β differ among countries as well as among indicators. If no indicator data are available for some country, a value x_c is imputed using an approach to be described in a separate section.

Normalized basic indicators are fuzzified and combined into composite ones using a hierarchical fuzzy inference process. Each inference stage uses various indicators as inputs and computes a composite indicator, which is then passed to another inference stage, and so forth until OSUS is assessed.

To fuzzify normalized basic indicators we use three fuzzy sets with linguistic values *Weak* (W), *Medium* (M), and *Strong* (S). Sustainable indicator values belong to S whereas unsustainable ones belong to W. Thus, for example, if the time series for indicator 'GHG' (greenhouse gas emissions) comprises very low values, then the corresponding normalized value x_{GHG} is close to 1 which in turn has a high grade of membership to S. For composite indicators (primary and secondary components) five linguistic values are used: *Very Bad* (VB), *Bad* (B), *Average* (A), *Good* (G), and *Very Good* (VG). Certain components depend only on a single basic indicator. For example LAND depends only on 'Nuclear waste.' In such cases, the basic indicators are represented using five fuzzy sets. Finally, the overall sustainability is measured using nine fuzzy sets: *Extremely Low* (EL), *Very Low* (VL), *Low* (L), *Fairly Low* (FL), *Intermediate* (I), *Fairly High* (FH), *High* (H), *Very High* (VH), and *Extremely High* (EH).

Each indicator value x belongs to one or more fuzzy sets with certain membership grades. For simplicity, triangular membership functions $\mu(x)$ are used, as shown in Fig. 10.2. Consider, for example, a basic indicator whose normalized value is 0.4. As shown in Fig. 10.2a, this value belongs to the fuzzy sets Weak with membership grade $\mu_{\mathrm{W}}(0.4) = 0.333$, Medium with membership grade $\mu_{\mathrm{M}}(0.4) = 0.667$, and Strong with grade $\mu_{\mathrm{S}}(0.4) = 0$.

Each inference engine is equipped with "if–then" linguistic rules which relate input indicators to a composite indicator. A rule has the form "if *premise* (inputs) then *consequence* (output)." Examples of "if–then" rules used in the model are:

if 'GHG' is Medium *and* 'NO_2' is Strong *and* 'SO_2' is Medium *and* 'PM' is Strong, *then* AIR is Good;
if AIR is Good *and* LAND is Very Bad, *then* ECOS is Bad;
if ECOS is Bad *and* HUMS is Good, *then* OSUS is Intermediate.

The inference engine combines rules from its rule base and membership grades of its input variables using product–sum algebra. Products represent conjunctions ("and") and sums aggregate the rule outputs whenever a single combination of inputs invokes several rules of the rule base. The inference process is described below by means of an example.

The *firing strength* of a rule measures the degree to which the rule matches the inputs. As an example, suppose that ECOS is A (Average) with membership grade

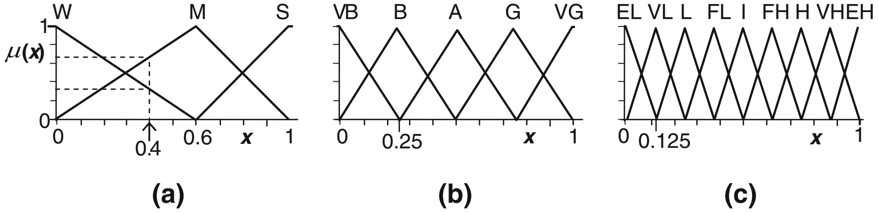

Fig. 10.2 Fuzzy sets and corresponding membership functions $\mu(x)$. **a** Basic indicator, **b** composite indicator, **c** overall sustainability

0.4 and G (Good) with grade 0.6, and HUMS is A with membership grade 0.8 and G with grade 0.2. Consider four rules of the rule base for OSUS:

R_1: *if* ECOS is A *and* HUMS is A, *then* OSUS is I (Intermediate)
R_2: *if* ECOS is A *and* HUMS is G, *then* OSUS is FH (Fairly High)
R_3: *if* ECOS is G *and* HUMS is A, *then* OSUS is FH (Fairly High)
R_4: *if* ECOS is G *and* HUMS is G, *then* OSUS is H (High).

The firing strengths of these rules are given by the products of the corresponding input membership grades. These values are passed to the membership grade of the output to the corresponding fuzzy sets. Thus,

firing strength of $R_1 = 0.4 \times 0.8 = 0.32 =$ membership grade of OSUS to I
firing strength of $R_2 = 0.4 \times 0.2 = 0.08 =$ membership grade of OSUS to FH
firing strength of $R_3 = 0.6 \times 0.8 = 0.48 =$ membership grade of OSUS to FH
firing strength of $R_4 = 0.6 \times 0.2 = 0.12 =$ membership grade of OSUS to H.

If several rules assign the same fuzzy set to the output variable (here we have a disjunction or union of rules), then the overall membership grade of the output is the sum of the individual firing strengths. In the above example, both rules R_2 and R_3 assign the fuzzy set FH to OSUS. Thus, the output of the inference engine is:

$$\mu_{\mathrm{I}}(\mathrm{OSUS}) = 0.32,\ \mu_{\mathrm{FH}}(\mathrm{OSUS}) = 0.08 + 0.48 = 0.56,\ \mu_{\mathrm{H}}(\mathrm{OSUS}) = 0.12.$$

Finally, a crisp value for OSUS (step 9 in Fig. 10.1), is computed via the height method of defuzzification,

$$\mathrm{OSUS} = \frac{\sum\limits_{\substack{\text{all fuzzy sets} L \\ \text{of OSUS}}} y_L \mu_L(\mathrm{OSUS})}{\sum\limits_{\substack{\text{all fuzzy sets} L \\ \text{of OSUS}}} \mu_L(\mathrm{OSUS})} \tag{10.5}$$

where y_L is the peak value of the fuzzy set L, i.e., the value of OSUS for which the membership function of L is maximized. For the example given above, only I, FH, and H are involved in the defuzzification. It is seen in Fig. 10.2c that $y_{\mathrm{I}} = 0.5$, $y_{\mathrm{FH}} = 0.625$, and $y_{\mathrm{H}} = 0.75$. Therefore, the overall sustainability is given by

$$\mathrm{OSUS} = \frac{0.5 \times 0.32 + 0.625 \times 0.56 + 0.75 \times 0.12}{0.32 + 0.56 + 0.12} = 0.6 \tag{10.6}$$

The overall sustainability must be a monotonic function of the normalized inputs. That is, whenever a basic indicator of energy sustainability is improved OSUS must also increase or at least not decrease. The use of product-sum algebra in inference engines ensures that the hierarchical fuzzy system is monotonic (Kouikoglou and Phillis 2009).

10.2.2 Rule Bases

Each rule base expresses linguistically the dependence of a composite indicator (output) on other, more elementary indicators (inputs). The number of rules of a rule base grows geometrically with the number of inputs. For example, AIR depends on four inputs (‘GHG,’ ‘NO_2,’‘SO_2,’ ‘PM10’) and each input is represented by three fuzzy sets (W, M, S). The rule base for AIR contains $3^4 = 81$ rules. A compact representation of the rule bases is done according to an approach proposed by Kouloumpis et al. (2008), which is outlined below:

- The fuzzy sets of Fig. 10.2 are assigned integer values 0, 1, 2, …, where 0 corresponds to the fuzzy sets with the lowest sustainability. For example the fuzzy set W in Fig. 10.2a is assigned the value 0, M is assigned the value 1, and S is assigned the value 2. Similarly, for the fuzzy sets of Fig. 10.2b we have VB → 0, B → 1,…, VG → 4, and for those of Fig. 10.2c we set EL → 0, L → 1,…, EH → 8.
- Each input indicator is also assigned a positive weight according to its relative importance against the other inputs. Currently, all inputs of the SAFE inference engines are assigned the weight 1.
- For each rule, the weighted sum of inputs is computed. For example, consider the rule:
  if ‘GHG’ is *M and* ‘NO_2’ is *S and* ‘SO_2’ is *M and* ‘PM’ is *S*, *then* AIR is *G*
  The weighted sum of its inputs is:

$$\begin{aligned} \text{sum} &= \sum_{\text{allinputs}} [\text{weight of each input}] \times [\text{integer value of fuzzy set}] \\ &= 1 \times 1 + 1 \times 2 + 1 \times 1 + 1 \times 2 \\ &= 6 \end{aligned} \tag{10.7}$$

- The resulting sum is assigned an output fuzzy set. The larger the sum the larger or better the fuzzy set of the output. For example, the 81 rules of AIR are compactly stored as follows:

$$\text{AIR} = \begin{cases} \text{VB, if sum} = 0, 1 \\ B, \text{ sum} = 2, 3 \\ A, \text{ sum} = 4, 5 \\ G, \text{ sum} = 6, 7 \\ \text{VG, sum} = 8 \end{cases} \tag{10.8}$$

The rule bases used to assess the other composite indicators are given below. Secondary components with two inputs:

$$\left\{\begin{array}{c}\text{PRODUCTION}\\ \text{CONSUMPTION}\end{array}\right\} = \begin{cases} \text{VB}, & \text{if } \text{sum} = 0 \\ \text{B}, & \text{sum} = 1 \\ \text{A}, & \text{sum} = 2 \\ \text{G}, & \text{sum} = 3 \\ \text{VG}, & \text{sum} = 4 \end{cases} \tag{10.9}$$

Primary component with two inputs:

$$\text{ECOS} = \begin{cases} 0 = \text{VB}, & \text{if sum} = 0, 1 \\ 1 = \text{B}, & \text{sum} = 2, 3 \\ 2 = \text{A}, & \text{sum} = 4, 5 \\ 3 = \text{G}, & \text{sum} = 6, 7 \\ 4 = \text{VG}, & \text{sum} = 8 \end{cases} \tag{10.10}$$

Primary component with four inputs:

$$\text{HUMS} = \begin{cases} \text{VB}, & \text{if sum} = 0, 1, 2, 3 \\ \text{B}, & \text{sum} = 4, 5, 6, 7 \\ \text{A}, & \text{sum} = 8, 9, 10, 11 \\ \text{G}, & \text{sum} = 12, 13, 14 \\ \text{VG}, & \text{sum} = 15, 16 \end{cases} \tag{10.11}$$

Finally, the rule base of the overall sustainability index is:

$$\text{OSUS} = \begin{cases} \text{EL}, & \text{if sum} = 0 \\ \text{VL}, & \text{sum} = 1 \\ \text{L}, & \text{sum} = 2 \\ \text{FL}, & \text{sum} = 3 \\ \text{I}, & \text{sum} = 4 \\ \text{FH}, & \text{sum} = 5 \\ \text{H}, & \text{sum} = 6 \\ \text{VH}, & \text{sum} = 7 \\ \text{EH}, & \text{sum} = 8 \end{cases} \tag{10.12}$$

As mentioned previously, equal weights are assigned to the input indicators of each rule base. This choice is made in most aggregation methods used in the assessment of sustainability.

10.2.3 Data Imputation

The SAFE model for energy development uses 11 basic indicators per country as inputs to assess all aspects of sustainability. A total of $128 \times 11 = 1{,}408$ normalized inputs are required for the 128 countries considered herein. However, 94 values (approximately 6.7 % of the data) are missing.

The problem of data unavailability is common in many sustainability studies (see, for example, Esty et al. 2005). Although there are several data imputation methods that can overcome this problem (Little and Rubin 1987), most of them are model-based and do not fit the proposed fuzzy reasoning model, while simple approaches such as listwise deletion or mean substitution are less efficient.

In this study the data imputation approach proposed by Phillis et al. (2011) is applied. It is similar to a hot deck imputation procedure, which is an intuitively simple and popular method for handling missing data. According to this approach, unknown values are imputed from other similar countries for which data are available. These similarities are shown schematically in Fig. 10.3 and are assessed according to geographic and economic criteria. Mathematically, they are modeled by a square matrix S with elements s_{ij} that quantify the degree of similarity between country i and country j,

$$s_{ij} = \begin{cases} 0 \text{ for no similarity} \\ 1 \text{ for moderate similarity for } i,j = 1,2,\ldots,128 \\ 2 \text{ for highsimilarity} \end{cases} \tag{10.13}$$

Data imputation is applied separately for each sustainability component (group of basic indicators). Suppose that some basic input from indicator group g is not available for country i. Let j be an index of countries similar to i, i.e., $s_{ij} = 1$ or 2. For each pair (i, j), the Euclidean distance d_{ijg} is computed using those normalized indicators of group g for which data are available for both i and j. The Euclidean distance is given by the square root of the average of squared indicator differences:

$$d_{ijg} = \sqrt{\frac{\sum_{c \in A_{ij}^{g}} \left(x_{ic} - x_{jc}\right)^2}{\operatorname{card}\left(A_{ij}^{g}\right)}} \tag{10.14}$$

where x_{ic} is the normalized value of indicator c for country i, which is obtained by exponential smoothing (step 3 of Fig. 10.1), A_g^{ij} is the set of group g indicators available for both i and j, and card(·) is the cardinality function. If $A_g^{ij} = \emptyset$ the corresponding Euclidean distance is assumed to be infinite, i.e., $d_{ijg} = \infty$.

Missing values are imputed by taking averages on a set of countries with maximum similarity and minimum Euclidean distance. More specifically, suppose that an indicator of group g is not available for country i. The following algorithm is used to find countries that meet the similarity and distance criteria (j refers to those countries for which the indicator to be imputed is available):

1. Compute d_{ijg} for each country j in the same group as i ($s_{ij} = 2$). Find those countries for which $d_{ijg} \leq 0.1$ (10 % of the maximum value of a normalized indicator). If no countries are found, then go to step 2.
2. Compute d_{ijg} for all moderately similar countries ($s_{ij} = 1$). Choose those countries for which $d_{ijg} \leq 0.1$. If no country satisfies this, then go to step 3.

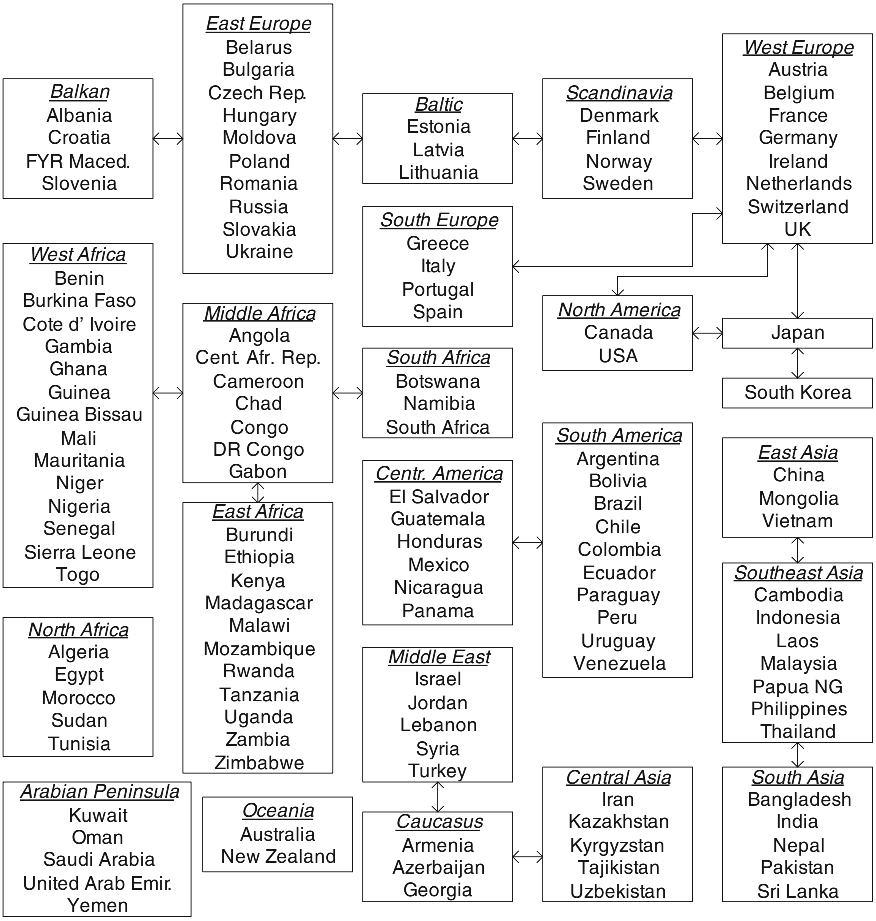

Fig. 10.3 Countries with high similarity (*boxes*) and moderate similarity (*arrows*)

3. Find countries in the same group as i ($s_{ij} = 2$) for which $d_{ijg} \leq 0.2$ (20 % of the maximum value of a normalized indicator). If no countries are found, then go to step 4.
4. Find moderately similar countries ($s_{ij} = 1$) for which $d_{ijg} \leq 0.2$. If no countries are found, then go to step 5.
5. Compute d_{ijg} for each unrelated country j ($s_{ij} = 0$) and select those with the minimum distance.

In this study all missing inputs were imputed using only steps 1–4 of the above algorithm. Step 5 is introduced to ensure that the data imputation method will give a result even in the extreme case where only one group g indicator is available.

This data imputation approach has been validated by an experimental procedure, as presented by Phillis et al. (2011).

10.3 Results

10.3.1 Energy Sustainability of Countries

Table 10.3 gives the overall, ecological, and human sustainability assessments for 128 countries. The basic indicators cover a period of 22 years (1990–2011). The six highest-ranking countries are: Albania, Paraguay, Norway, Brazil, Colombia, and Latvia.

The results of Table 10.3 reveal the following:

1. European and South American countries occupy the top places of the ranking whereas the bottom places are occupied by East European countries and South Korea.
2. The five top scorers have also the highest human component of energy sustainability, whereas Lebanon, South Korea, Belarus, Moldova, and Jordan have the lowest values of HUMS.
3. Latvia, Lithuania, and Kyrgyzstan have the highest scores in the ecological component; East European countries (Moldova, Belarus, Bulgaria, and Russia) have the lowest scores in ECOS.
4. Economic development does not seem to play an important role in the overall sustainability ranking of countries (the squared correlation coefficient R^2 between GNI per capita and OSUS is less than 0.026). Moreover, ecological and human sustainability of energy development are not correlated ($R^2 = 0.014$).

10.3.2 Use of SAFE for Sustainability Improvement

A sensitivity analysis of OSUS with respect to each basic input can be used by policy makers to find those indicators that affect sustainability critically, and then focus on their improvement so as to improve overall sustainability.

Let OSUS(x_1, …, x_c, …) be the overall sustainability of energy development for some country for which the normalized values of basic indicators are x_c, $c = 1,\ldots, 11$. If indicator c were to be improved to the value $x_c + \delta$, $\delta > 0$, and all the other indicators remained unaltered, then the new sustainability score would be OSUS(x_1, …, $x_c + \delta$, …). The divided difference

$$\Delta_c = \frac{\mathrm{OSUS}(x_1, \ldots, x_c + \delta, \ldots) - \mathrm{OSUS}(x_1, \ldots, x_c, \ldots)}{\delta} \tag{10.15}$$

gives the rate of improvement of OSUS with respect to each indicator c. Ranking the indicators by the magnitude of $\varDelta_c$ reveals the most efficient practices towards a sustainable energy development. However, it is usually less costly to improve an indicator with low sustainability than one with high sustainability by the same magnitude. From this observation, Phillis et al. (2011) provide an economic justification for using the products

Table 10.3 Ranking of 128 countries by energy sustainability

	Country	OSUS	ECOS	HUMS
1	Albania	0.8870	0.8582	0.9158
2	Paraguay	0.8631	0.7500	0.9761
3	Norway	0.8504	0.8090	0.8918
4	Brazil	0.8465	0.7500	0.9429
5	Colombia	0.8426	0.7500	0.9352
6	Latvia	0.8123	0.9133	0.7114
7	Vietnam	0.7986	0.7903	0.8069
8	Tajikistan	0.7892	0.8182	0.7601
9	Kyrgyzstan	0.7804	0.9072	0.6536
10	New Zealand	0.7798	0.7673	0.7924
11	Peru	0.7795	0.7464	0.8126
12	Nepal	0.7785	0.8477	0.7094
13	Papua NG	0.7670	0.8500	0.6840
14	Denmark	0.7664	0.7735	0.7594
15	Tunisia	0.7616	0.8186	0.7046
16	Venezuela	0.7609	0.7499	0.7720
17	Ecuador	0.7576	0.7662	0.7490
18	Lithuania	0.7564	0.9100	0.6028
19	Switzerland	0.7541	0.7737	0.7345
20	Chad	0.7501	0.7500	0.7502
21	Ghana	0.7496	0.8186	0.6806
22	Georgia	0.7476	0.8238	0.6714
23	Bolivia	0.7463	0.7500	0.7425
24	Sierra Leone	0.7456	0.8019	0.6892
25	Cameroon	0.7452	0.7587	0.7316
26	Gabon	0.7427	0.8226	0.6629
27	Congo	0.7401	0.7550	0.7251
28	El Salvador	0.7324	0.7500	0.7148
29	Argentina	0.7309	0.7500	0.7118
30	Philippines	0.7304	0.7667	0.6942
31	Mexico	0.7296	0.7479	0.7113
32	Zimbabwe	0.7288	0.8188	0.6389
33	Guatemala	0.7253	0.7500	0.7005
34	Sweden	0.7242	0.7048	0.7436
35	Uruguay	0.7240	0.7499	0.6980
36	Guinea	0.7225	0.7558	0.6892
37	Cote d'Ivoire	0.7201	0.7976	0.6426
38	Mali	0.7196	0.7500	0.6892
39	Mauritania	0.7196	0.7500	0.6892
40	Niger	0.7196	0.7500	0.6892
41	Malaysia	0.7186	0.7890	0.6483
42	Indonesia	0.7185	0.7500	0.6871
43	Angola	0.7151	0.7552	0.6750
44	Nigeria	0.7136	0.8131	0.6141
45	Nicaragua	0.7132	0.8526	0.5738
46	Austria	0.7096	0.8047	0.6145
47	Mozambique	0.7073	0.8889	0.5256
48	Rwanda	0.7005	0.8903	0.5107
49	Algeria	0.6994	0.7522	0.6465
50	Sudan	0.6987	0.7500	0.6474
51	Sri Lanka	0.6975	0.7500	0.6450
52	Estonia	0.6949	0.8183	0.5715
53	China	0.6923	0.6724	0.7123
54	Zambia	0.6874	0.8013	0.5734
55	Panama	0.6854	0.7957	0.5751
56	Pakistan	0.6851	0.7500	0.6202
57	Thailand	0.6841	0.7509	0.6172
58	Honduras	0.6840	0.7905	0.5775
59	FYR Maced.	0.6837	0.8123	0.5552
60	Azerbaijan	0.6831	0.7986	0.5676
61	Malawi	0.6828	0.8559	0.5097
62	Laos	0.6823	0.7829	0.5817
63	Egypt	0.6810	0.6711	0.6908
64	India	0.6810	0.7571	0.6050
65	Kazakhstan	0.6795	0.8524	0.5067
66	Chile	0.6754	0.7500	0.6008
67	Madagascar	0.6747	0.8006	0.5487
68	Syria	0.6731	0.7500	0.5961
69	Croatia	0.6712	0.7783	0.5642
70	Australia	0.6700	0.7500	0.5901
71	Burundi	0.6692	0.8278	0.5107
72	Togo	0.6665	0.8210	0.5121
73	Uganda	0.6665	0.8233	0.5097
74	Tanzania	0.6600	0.8104	0.5096
75	Armenia	0.6584	0.8031	0.5136
76	Centr Afr R	0.6584	0.8167	0.5000
77	Czech Rep	0.6570	0.7587	0.5553
78	South Africa	0.6570	0.7711	0.5429
79	Iran	0.6550	0.7500	0.5600
80	Cambodia	0.6546	0.8171	0.4920
81	Ethiopia	0.6529	0.7592	0.5466
82	Uzbekistan	0.6481	0.7865	0.5097
83	Poland	0.6462	0.7598	0.5326
84	Portugal	0.6444	0.7715	0.5174
85	Slovakia	0.6426	0.7586	0.5267
86	Netherlands	0.6425	0.7471	0.5380

(continued)

Table 10.3 (continued)

	Country	OSUS	ECOS	HUMS		Country	OSUS	ECOS	HUMS
87	Kenya	0.6424	0.7774	0.5074	108	Senegal	0.6200	0.7500	0.4901
88	DR Congo	0.6421	0.7843	0.5000	109	Benin	0.6198	0.7770	0.4626
89	Bangladesh	0.6417	0.7500	0.5335	110	Morocco	0.6194	0.7784	0.4605
90	Germany	0.6415	0.7825	0.5004	111	Spain	0.6169	0.7357	0.4981
91	Lebanon	0.6404	0.8544	0.4265	112	Italy	0.6133	0.7500	0.4765
92	Hungary	0.6398	0.7624	0.5172	113	Belgium	0.6116	0.7275	0.4958
93	France	0.6377	0.6858	0.5896	114	Israel	0.6103	0.7810	0.4395
94	UK	0.6335	0.7275	0.5394	115	USA	0.5973	0.6658	0.5289
95	Namibia	0.6334	0.7817	0.4851	116	Ireland	0.5932	0.7483	0.4380
96	Guinea-Bissau	0.6286	0.7547	0.5025	117	Japan	0.5912	0.7127	0.4698
97	Burkina Faso	0.6281	0.7500	0.5061	118	Canada	0.5849	0.4123	0.7576
98	Botswana	0.6280	0.7644	0.4917	119	Romania	0.5748	0.4401	0.7096
99	Mongolia	0.6275	0.7500	0.5051	120	Jordan	0.5724	0.7705	0.3744
100	Gambia	0.6263	0.7500	0.5025	121	Finland	0.5716	0.5231	0.6201
101	Turkey	0.6263	0.7500	0.5026	122	Slovenia	0.5421	0.5370	0.5471
102	United Arab E	0.6250	0.7500	0.5000	123	South Korea	0.5394	0.6571	0.4218
103	Oman	0.6247	0.7495	0.5000	124	Ukraine	0.4655	0.4184	0.5126
104	Saudi Arabia	0.6244	0.7487	0.5000	125	Bulgaria	0.3927	0.2465	0.5389
105	Greece	0.6241	0.7491	0.4991	126	Moldova	0.3863	0.3899	0.3827
106	Kuwait	0.6241	0.7482	0.5000	127	Russia	0.3603	0.1932	0.5273
107	Yemen	0.6241	0.7500	0.4983	128	Belarus	0.3554	0.3185	0.3923

$$(1 - x_c)\Delta_c \tag{10.16}$$

rather than Δ_c as a criterion for policymaking with limited budgets.

The quantities $\Delta_c(1 - x_c)$ for all basic indicators are calculated and ranked by magnitude. To compute Δ_c, each indicator is increased by 1 % or $\delta = 0.01$. Table 10.4 shows the most important indicators for selected countries.

Table 10.4 Most important indicators to improve energy sustainability for selected countries

COUNTRY: Indicators	COUNTRY: Indicators	COUNTRY: Indicators
USA: Renewable energy production, nuclear waste, imports, GHG emissions	CHINA: NO_2 emissions, SO_2 emissions, electricity production from oil, gas, and coal, PM10 emissions	SOUTH KOREA: Imports, electricity production from oil, gas, and coal, renewable energy production, nuclear waste
GERMANY: NO_2 emissions, imports, consumption/cap, GHG emissions	RUSSIA: Nuclear waste, SO_2 emissions, renewable energy production, NO_2 emissions	ITALY: Imports, renewable energy production, electricity production from coal etc., consumption/cap
SPAIN: Imports, NO_2 emissions, nuclear waste, PM10 emissions	BELGIUM: Nuclear waste, NO_2 emissions, consumption/cap, GHG emissions	GREECE: Imports, electricity production from oil, gas, and coal, renewable energy production, NO_2 emissions

We see that the critical factors for USA, Germany, and Spain are ecological as well as human. The most important problems of energy systems in China, Russia, and Belgium are mainly ecological. The problems of South Korea, Italy, and Greece are mainly human.

10.4 Conclusions

A sustainability measurement model called SAFE has been applied to assess the sustainability of energy development of countries. SAFE uses basic indicators of sustainability, rule bases, and hierarchical fuzzy reasoning to compute an overall measure of sustainability. Sustainability is defined globally by considering ecological as well as societal points of view. More specifically, energy sustainability is defined as an aggregate index of two and then six inputs. The model can handle exact or imprecise data and knowledge about factors that affect the energy sustainability of a country, and can easily be modified to take into account new knowledge about the environment and the society.

SAFE is consistent with the methodological frameworks discussed in the introduction for measuring the sustainability of energy development. It computes a sustainability index but also, going backwards, performs a sensitivity analysis to aid policy makers. Also, SAFE uses fuzzy logic which does not require an explicit mathematical model of its indicators and it can process quantitative as well as qualitative information. Fuzzy logic avoids the use of weights which are often arbitrary or cannot be easily extracted from a decision maker. Moreover, SAFE is a rather simple model that respects the non-compensability property, while it is the only approach that evaluates sustainability taking into account the time dimension using exponential smoothing of data.

On the other hand SAFE has certain shortcomings that are found in other models as well (Phillis et al. 2011). It is subjective to some extent and it does not possess a mechanism whereby the number of inputs is limited to the absolutely necessary ones. Also, because of limited data availability, a number of relevant indicators, such as energy prices, disparities and security, are currently not included; however, the software implementation of the model is flexible enough so that it can accept new inputs with little user intervention. The rule bases of SAFE put equal weights of importance to the input variables, as is done in other aggregation methods. More work remains to be done to refine these weights and the membership functions of certain indicators such as GHG emissions and nuclear waste in order to capture emerging sustainability issues as reality changes.

A.1 10.5 Appendix: Basic Indicators

Definitions of indicators are taken from Esty et al. (2005), OECD (2005), IEA (2002, 2010, 2011a, b, c, d), World Resources Institute (2006), as well as from the websites of the World Bank (http://data.worldbank.org), the Environmental Sustainability Index (www.yale.edu/esi), the Human Development Report (http://hdr.undp.org), and the United Nations Environment Program (http://geodata.grid.unep.ch).

- *Greenhouse gas (GHG) emissions per capita* (tons of CO_2 equivalent): Emissions of total GHG (CO_2, CH_4, N_2O, hydrofluorocarbons (HFC's), perfluorocarbons (PFC's), and SF_6), excluding land-use change and forestry. To convert all emissions to CO_2 equivalent, the global warming potential (GWP) is used. GWP is an index used to translate the level of emissions of various gases into a common measure in order to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWP is the ratio of the warming caused by a substance to the warming caused by the same mass of CO_2.
- *Atmospheric concentrations of* NO_2 *and* SO_2 ($\mu g/m^3$ of air): The values were originally collected at the city level. The number of cities with data provided by each country varies. Within each country, the values have been normalized by city population for the year 1995, and then summed to give the total concentration for the given country. High concentrations decrease air sustainability.
- *PM10* ($\mu g/m^3$ of air): Particulate matter concentrations refer to fine suspended particulates less than 10 microns in diameter that are capable of penetrating deep into the respiratory tract and causing significant health damage.
- *Nuclear waste* (tons of heavy metals per capita per year): Nuclear waste is primarily due to spent fuel from nuclear power plants. It is assumed that nuclear waste influences land sustainability negatively due mainly to generation of heavy radioactive metals.
- *Access to electricity* (percent of population): Access to electricity is the percentage of population with access to electricity. Electrification data are collected from industry, national surveys and international sources.
- *Renewable resources production* (percent of total primary energy supply): The higher the proportion of renewable energy sources is, the less a country relies on environmentally damaging sources such as fossil fuel and nuclear energy.
- *Electricity production from oil, gas, and coal sources* (percent of total electricity production): Sources of electricity refer to the inputs used to generate electricity. Oil refers to crude oil and petroleum products. Gas refers to natural gas but excludes natural gas liquids. Coal refers to all coal and brown coal, both primary (including hard coal and lignite-brown coal) and derived fuels (including patent fuel, coke, oven coke, gas coke, coke oven gas, and blast furnace gas). Peat is also included in this category.
- *Energy intensity* (kg of oil equivalent per $1,000 GDP - constant 2005 PPP): Energy intensity is a measure of the energy efficiency of a nation's economy. It

is calculated as units of energy per unit of GDP. High energy intensities indicate a high price or cost of converting energy into GDP. Low energy intensity indicates a lower price or cost of converting energy into GDP. Energy intensity, as defined here, should not be confused with Energy Use Intensity (EUI), a measure of building energy use per unit area.

- *Energy use* (kg of oil equivalent per capita): It refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.
- *Energy imports* (percent of energy use): Net energy imports are estimated as energy use less production, both measured in oil equivalents. A negative value indicates that the country is a net exporter. Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.

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Chapter 11
Artificial Neural Networks and Genetic Algorithms for the Modeling, Simulation, and Performance Prediction of Solar Energy Systems

Soteris A. Kalogirou

Abstract In this chapter, two of the most important artificial intelligence techniques are presented together with a variety of applications in solar energy systems. Artificial neural network (ANN) models represent a new method in system modeling and prediction. An ANN mimics mathematically the function of a human brain. They learn the relationship between the input parameters, usually collected from experiments, and the controlled and uncontrolled variables by studying previously recorded data. A genetic algorithm (GA) is a model of machine learning, which derives its behavior from a representation of the processes of evolution in nature. GAs can be used for multidimensional optimization problems in which the character string of the chromosome can be used to encode the values for the different parameters being optimized. The chapter outlines an understanding of how ANN and GA operate by way of presenting a number of problems in different solar energy systems applications, which include modeling and simulation of solar systems, prediction of the performance, and optimization of the design or operation of the systems. The systems presented include solar thermal and photovoltaic systems.

11.1 Introduction

Human beings visualized the possibility of developing a machine that would "think" from many decades. In the Medieval times (1637), the French philosopher and mathematician Rene Descartes declared that it would never be possible to make a machine that thinks as humans do, whereas 300 years after this declaration

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(1950), the British mathematician and computer pioneer Alan Turing predicted that one day there would be a machine that could duplicate human intelligence in every way.

In its broadest sense, Artificial Intelligence (AI) indicates the ability of a machine or artifact that performs the same kinds of functions that characterize human thought. Therefore, the term AI has been applied to computer systems and programs capable of performing tasks more complex than straightforward programming. These, however, are still far from the realm of actual thought. Artificial intelligence is the division of computer science dealing with the design of intelligent computer systems, i.e., computer systems that exhibit the characteristics we associate with intelligence in human behavior-understanding, language, learning, reasoning, and problems solving. It should be appreciated, however, that solving a computation does not necessarily indicate understanding, something a human being solving a problem would have, as human reasoning is not based solely on the rules of logic but involves perception, emotional preferences, awareness, values, experience, generalization abilities, and many more.

It is also well-known that machinery can outperform humans in the physical effort required to do a job. In a similar way, computers can outperform mental functions in limited areas such as in the speed of mathematical calculations, as the fastest computers developed are able to perform more than 10 billion calculations per second. It should be noted, however, that making computers that are more powerful will not mean that the machine/computer is capable to think. Additionally, computer programs operate according to set procedures or logic steps, forming an algorithm, and most computers perform serial processing, i.e., one computation at a time, whereas the human brain works in parallel processing, performing a number of operations simultaneously. In an attempt to achieve simulated parallel processing, some supercomputers have been constructed lately with multiple processors which allow several algorithms to run at the same time.

Artificial neural networks and genetic algorithms are two of the main branches of artificial intelligence. For the modeling, prediction of performance, and control of solar energy systems, analytic computer codes are often used. The algorithms employed are usually complicated involving the solution of complex differential equations, which require large computer power and need a considerable amount of time to give accurate predictions. Instead of complex rules and mathematical routines, artificial neural networks are able to learn the key information patterns within a multidimensional information domain. In addition, they are fault tolerant, robust, and noise immune (Rumelhart et al. 1986). Data from solar energy systems, being inherently noisy are good candidate problems to be handled with ANNs.

Genetic algorithms are inspired by the way living organisms adapt to the harsh realities of life in a hostile world by evolution and inheritance. The algorithm imitates in the process the evolution of population by selecting only fit individuals for reproduction. Therefore, a GA is an optimum search technique based on the concepts of natural selection and survival of the fittest. It works with a fixed-size population of possible solutions of a problem, called individuals, which are evolving in time. A GA utilizes three principal genetic operators: selection, crossover, and mutation.

When dealing with research and design associated with solar energy systems, difficulties encountered often in handling situations where there are many variables involved. To adequately model and predict the behavior of solar energy systems requires consideration of nonlinear multivariate inter-relationships, often in a ‘noisy’ environment. Usually, in a physical system the precise interactions of these variables are not fully understood or cannot easily be modeled.

The objective of this chapter is to introduce neural networks and genetic algorithms and present various applications in solar energy systems. The objective is to demonstrate the possibilities of applying these techniques to solar energy systems modeling, optimization, and performance prediction. The applications are presented in a thematic rather than a chronological or any other order. The applications reviewed include modeling and simulation of solar systems, prediction of the performance, and optimization of the design or operation of the systems. The systems presented include solar thermal systems, solar thermal collector design, development of a fault diagnostic system, sizing of photovoltaic systems and modeling, simulation, and control of stand-alone photovoltaic (SAPV) systems. This will show the capability of artificial neural networks and genetic algorithms to be used as tools in solar energy processes prediction, modeling, optimization, and control.

11.2 Artificial Neural Networks

The concept of ANN analysis has been discovered nearly 50 years ago, but it is only in the last 25 years that application software has been developed to handle practical problems. The history and theory of neural networks have been described in a large number of publications and will not be repeated in this chapter except for a very brief overview of how neural networks operate.

ANNs are good for some tasks while lacking in some others. Specifically, they are good for tasks involving incomplete data sets, fuzzy, or incomplete information, and for highly complex and ill-defined problems, where humans usually decide on an intuitional basis. They can learn from examples, and are able to deal with nonlinear problems. Furthermore, they exhibit robustness and fault tolerance. The tasks that ANNs cannot handle effectively are those requiring high accuracy and precision as in logic and arithmetic. ANNs have been applied successfully in a number of application areas (Kalogirou 2000a).

ANNs have been applied successfully in a various fields of mathematics, engineering, medicine, economics, meteorology, psychology, neurology, and many others. Some of the most important ones are: in pattern, sound, and speech recognition, in the analysis of electromyographs and other medical signatures, in the identification of military targets, and in the identification of explosives in passenger suitcases. They have also being used in weather and market trends forecasting, in the prediction of mineral exploration sites, in electrical and thermal load prediction, in adaptive and robotic control, and many others. Neural networks have also been used for process control, because they can build predictive models of the process from multidimensional data customarily collected from sensors.

Neural networks obviate the need to use complex mathematically explicit formulas, computer models, and impractical and costly physical models. Some of the characteristics that support the success of ANNs and distinguish them from the conventional computational techniques are (Nannariello and Frike 2001):

- The direct manner in which ANNs acquire information and knowledge about a given problem domain (learning interesting and possibly nonlinear relationships) through the 'training' phase.
- The ability to work with numerical or analog data that would be difficult to deal with by other means because of the form of the data or because there are so many variables.
- The fact that the analysis can be conceived of as a 'black box' approach so the user does not require to have sophisticated mathematical knowledge.
- The compact form in which the acquired information and knowledge is stored within the trained network and the ease with which it can be accessed and used.
- The fact that the solutions obtained can be robust even in the presence of 'noise' in the input data.
- The high degree of accuracy reported when artificial neural networks are used to generalize over a set of previously unseen data (not used in the 'training' process) from the problem domain.

While neural networks can be used to solve complex problems, they do suffer from a number of shortcomings. The most important of them are:

- The data used to train neural nets should contain information, which ideally, is spread evenly throughout the entire range of the system operation.
- There is limited theory to assist in the design of neural networks, usually carried out with trial and error.
- There is no guarantee of finding an acceptable solution to a problem.
- There are limited opportunities to rationalize the solutions provided.

In the following sections, it is briefly explained how from a biological neuron the artificial one is visualized and the steps required to set-up a neural network.

11.2.1 Biological and Artificial Neurons

A highly simplified model of an artificial neuron, which may be used to stimulate some important aspects of the real biological neuron, is shown in Fig. 11.1. In brain, there is a flow of coded information (using electrochemical media, the so-called neurotransmitters) from the synapses toward the axon. The axon of each neuron transmits information to a number of other neurons. The neuron receives

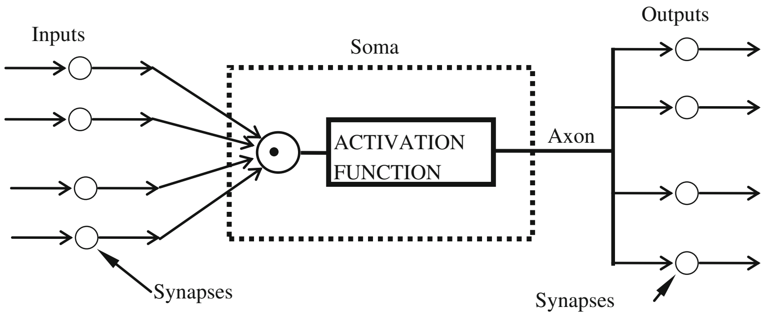


Fig. 11.1 A simplified model of an artificial neuron

information at the synapses from a large number of other neurons. It is estimated that each neuron may receive signals from as many as 10,000 other neurons. In a living system groups of neurons are organized into subsystems and the integration of these subsystems forms the brain. An ANN is a group of interconnected artificial neurons, interacting with one another in a concerted manner. This by no means can reach the human brain which is estimated that has got around 100 billion interconnected neurons. In such a system, excitation is applied to the input of the network. Following some suitable operation, it results in a desired output. At the synapses, there is an accumulation of some potential, which in the case of the artificial neurons is modeled as a connection weight. These weights are continuously modified, based on suitable learning rules (Kalogirou 2000a).

11.2.2 Artificial Neural Networks Principles

ANN resembles the human brain because the knowledge is acquired by the network through a learning process, and inter-neuron connection strengths known as synaptic weights are used to store the knowledge.

ANN models may be used as an alternative method in engineering analysis and prediction. They operate like a “black box” model, requiring no detailed information about the system and its characteristics. Instead, they learn the relationship between the input parameters and the controlled and uncontrolled variables by studying previously recorded data, similar to the way a nonlinear regression performs in a simplified way. Another advantage of using ANNs is their ability to handle complex systems with a large number and interrelated parameters. They seem to simply ignore the not so important or insignificant input parameters and concentrate on the more important inputs.

A schematic of a typical multilayer feedforward neural network architecture is shown in Fig. 11.2. An ANN usually consists of an input layer, one or more hidden layers, and an output layer. In its simple form, each single neuron is connected to other neurons of a previous layer through adaptable synaptic weights. Knowledge

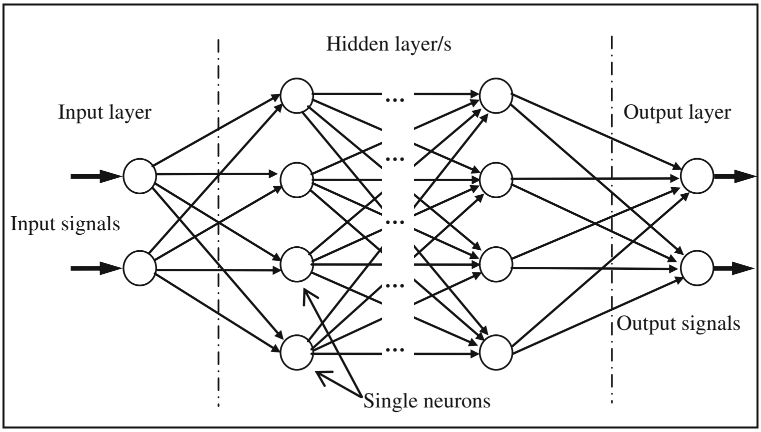


Fig. 11.2 Schematic of a multilayer feed forward neural network

is usually stored as a set of connection weights. Training is the process of modifying the connection weights in some orderly fashion using a suitable learning method. The network uses a learning mode, in which an input is presented to the network together with the desired output and in the process the weights are adjusted, so that the network attempts to predict the desired output. The weights before training are random and have no meaning, whereas after training contain meaningful information (Kalogirou 2000a).

Figure 11.3 illustrates how information is processed through a single node. The node receives weighted activation of other nodes through its incoming connections. First, these are added up (summation). The result is then passed through an activation function; the outcome is the activation of the node. For each of the outgoing connections, this activation value is multiplied with the specific weight and transferred to the next node (Kalogirou 2000a).

A training set is a group of combined input and output patterns. These are used for training the network, by suitable adaptation of the synaptic weights. The outputs are the dependent variables that the network produces for the

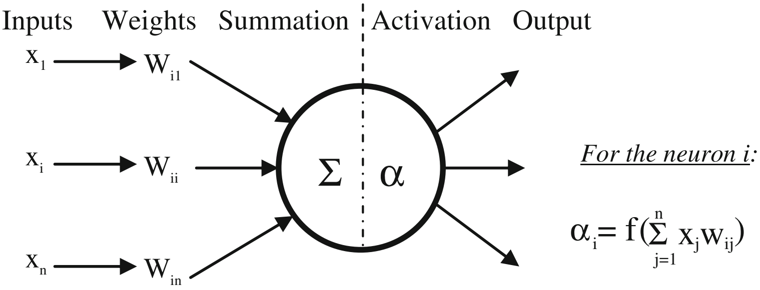


Fig. 11.3 Information processing in a neural network unit

corresponding inputs. When each pattern is read, the network uses the input data to produce an output, which is then compared to the training pattern, i.e., the correct or desired value. If there is a difference, the connection weights are modified in such a way that the error is decreased. The network runs through all the input patterns repeatedly until the error is smaller than the maximum desired tolerance. When the training reaches a satisfactory level, the network training stops, the weights are kept constant and the trained network can be used to identify patterns, make decisions, or define associations in new input data sets not used to train it.

Learning in a neural network (Haykin 1994) is a process by which the free parameters are adapted through a continuing process of simulation by the environment in which the network is embedded. Thus, learning is usually achieved through any change, in any characteristic of a network, so that meaningful results are achieved. Thus, learning could be achieved, among others, through network structure modifications, synaptic weight modification, through appropriate choice of activation functions, and others. By meaningful results, it is meant that the desired objective is met with a satisfactory degree of success, usually quantified by a suitable criterion or cost function. Therefore, learning is usually the process of minimizing an error function or maximizing a benefit function, which is like an optimization process and a GA, which is an optimum search technique (see Sect. 11.3) can also be employed to train artificial neural networks.

Several algorithms can be used to achieve the minimum error quickly and the suitability of an appropriate paradigm and strategy for application is very much dependent on the type of problem to be solved.

The most popular learning algorithms are the back-propagation (BP) and its many variants (Werbos 1974). The BP algorithm is one of the most powerful learning algorithms in neural networks. The training set has to be a representative collection of input–output examples. Back-propagation training is a gradient descent algorithm. It tries to improve the performance of the neural network by reducing the total error by changing the weights along its gradient. The error is expressed by the root-mean-square value (RMS), which can be calculated by:

$$E = \frac{1}{2}\sqrt{\sum_{p}\sum_{i}\left|t_{ip} - o_{ip}\right|^{2}} \tag{11.1}$$

Where (E) is the RMS error, (t) the network target (output), and (o) the desired output vectors over all patterns (p). An error of zero would indicate that all the output patterns computed by the ANN perfectly match the expected values and the network is well trained. Details of back-propagation are given in (Kalogirou et al. 1999b; Kalogirou and Bojic 2000).

11.3 Genetic Algorithms

The GA is a model of machine learning, which derives its behavior from a representation of the processes of evolution in nature. This is done by the creation within a computer of a population of individuals represented by chromosomes, i.e., a set of character strings that are analogous to the chromosomes found in the DNA of human beings. The individuals in the population then go through a process of evolution.

The processes of evolution in nature are usually evidenced by different individuals competing for resources in the environment. Some are better than others are, and those that are better are more likely to survive and propagate their genetic material.

In nature, the encoding for the genetic information typically results in offspring that are genetically identical to the parent. Sexual reproduction allows the creation of genetically radically different offspring that are still of the same general species. Simplistically, at the molecular level a pair of chromosomes bump into one another, exchange chunks of genetic information and drift apart. This is called the recombination operation, which in GAs is termed as crossover because of the way genetic material crosses over from one chromosome to another.

In GAs, the crossover operation happens in an environment where the selection of who gets to mate is a function of the fitness of the individual, i.e., how good the individual is at competing in its environment. Some GAs use a simple function of the fitness measure to select probabilistically individuals to undergo the genetic operations which is a fitness-proportionate selection. Other implementations use a model in which certain randomly selected individuals in a subgroup compete and the fittest is selected, which is called tournament selection. The two processes that most contribute to evolution are crossover and fitness-based selection/reproduction. Mutation also plays a role in this process.

GAs are used for a number of different application areas such as in multidimensional optimization problems in which the character string of the chromosome can be used to encode the values for the different parameters being optimized.

This genetic model of computation can be implemented in practice by having arrays of bits or characters to represent the chromosomes. Simple bit manipulation operations allow the implementation of crossover, mutation, and other operations.

When the GA is executed, it is usually done in a manner that involves a cycle which starts with the evaluation of the fitness of all of the individuals in the population, creation of a new population by performing operations such as crossover, fitness-proportionate reproduction, and mutation on the individuals whose fitness has just been measured, discarding the old population and iterate using the new population. One iteration of this loop is referred to as a generation.

In each generation, individuals are selected for reproduction according to their performance with respect to the fitness function. This selection gives a higher chance of survival to better individuals. Subsequently, genetic operations are applied in order to form new and possibly better offspring. The algorithm is terminated either after a certain number of generations or when the optimal solution has been found.

The initial generation of this process operates on a population of randomly generated individuals. From there on, the genetic operations, in concert with the fitness measure, operate to improve the population. More details on GA can be found in Goldberg (1989), Davis (1991), and Michalewicz (1996).

During each step in the reproduction process, the individuals in the current generation are evaluated using a fitness function, which is a measure of how good the individual solves the problem. Subsequently, each individual is reproduced in proportion to its fitness, i.e., the higher the fitness, the higher is its chance to participate in mating (crossover) and to produce an offspring. A small number of newborn offspring undergo the action of the mutation operator. After many generations, only those individuals who have the best genetics, with respect to the fitness function, survive, and the individuals that emerge from this ‘survival of the fittest’ process are the ones that represent the optimal solution. Therefore, GAs are suitable for finding the optimum solution in problems were a fitness function is present by seeking to breed an individual, which either maximizes, minimizes, or it is focused on a particular solution of a problem.

It should be pointed out that the larger the breeding pool size, the greater is its potential to produce a better individual. However, as the fitness value produced by every individual must be compared with all other fitness values of all other individuals on every reproductive cycle, larger breeding pools take longer time to reach the optimum solution. After testing all of the individuals in the pool, a new “generation” of individuals is produced for testing.

During the setting up of the GA, the user has to specify the adjustable chromosomes, i.e., the parameters that would be modified during evolution to obtain the required value of the fitness function as well as the ranges of these values called constraints. The GA is usually stopped after best fitness remained unchanged for a number of generations or when the optimum solution is reached.

A genetic algorithm is not gradient based, and uses an implicitly parallel sampling of the solutions space. The population approach and multiple sampling indicated that the possibility to be trapped to local minima is much lower than traditional direct approaches. They can also navigate a large solution space with a highly efficient number of samples. Although not guaranteed to provide the globally optimum solution, GAs have been proven to be highly efficient at reaching a very near optimum solution in a computationally efficient manner.

The GA parameters to be specified by the user usually are:

Population size

Population size is the size of the genetic breeding pool. If this parameter is set to a low value, there may be not enough different kinds of individuals to solve the problem satisfactorily. On the contrary, if there are too many individuals in the population, a good solution will take longer time to be found, because the fitness function must be calculated for every individual in every generation.

Crossover rate
Crossover rate determines the probability that the crossover operator is applied to a particular chromosome during a generation. This parameter is usually near 90 %.
Mutation rate
Mutation rate determines the probability that the mutation operator is applied to a particular chromosome during a generation. This parameter is usually very small, near 1 %.

Generation gap
Generation gap determines the fraction of those individuals that do not go into the next generation. It is sometimes desirable that individuals in the population are allowed to go into next generation. This is especially important if individuals selected are the fittest ones in the population. This parameter is usually near 95 %.

Chromosome type
Populations are composed of individuals, and individuals are composed of chromosomes, which are equivalent to variables. Chromosomes are composed of smaller units called genes. There are two types of chromosomes, continuous and enumerated. Continuous chromosomes are implemented in the computer as binary bits. The two distinct values of a gene, 0 and 1, are called alleles. Multiple chromosomes make up the individual. Each partition is one chromosome, each binary bit is a gene, and the value of each bit (1, 0, 1, 0, 1, 0) is an allele. The genes in a chromosome can take a wide range of values between the minimum and maximum values of the associated variables. One variation of continuous chromosomes is the 'integer chromosomes' which are used in problems that they require to take only integer values of chromosomes and genes.

Enumerated chromosomes consist of genes, which can have more allele values than just 0 and 1, and these values are usually visible to the user. These are suitable for a category of problems, usually called combinatorial problems. Usually, two different types of enumerated chromosomes are provided: 'repeating genes' and 'unique genes'.

11.4 Applications

ANNs and GAs have been used by various researchers and by the author for modeling and predictions in the field of solar energy systems. This section presents various such applications in a thematic rather than a chronological or any other order and includes mainly details on the most recent work of the author in the area.

11.4.1 Solar Steam Generator

ANNs have been applied to model various aspects of a solar steam generator. The system employs a parabolic trough collector, a flash vessel, a high pressure circulating pump, and the associated pipe work. Some of the work done on this system is described here below.

(a) *Intercept factor*

A comparative study of various methods employed in order to estimate the collector intercept factor is detailed by Kalogirou et al. (1996a). The intercept factor is defined as the ratio of the energy absorbed by the receiver to the energy incident on the concentrator aperture. From the value of the intercept factor the collector optical efficiency can be determined, which is a very important parameter in the determination of the overall effectiveness of solar concentrating collectors. ANNs have been able to calculate the intercept factor with a difference confined to a less than 0.4 % as compared to the much more complex estimation of the Energy DEPosition (EDEP) computer code.

(b) *Local concentration ratios*

The radiation profile on the receiver of the collector is not uniform and is represented in terms of the local concentration ratios at various points on the periphery of the receiver. It is very important to measure this profile because in this way the collector optical efficiency can be determined. This measurement must be carried out at various incidence angles and also at normal incidence angle ($\theta = 0°$). This is usually difficult to perform due to the size of the collector. ANNs have been used to learn the radiation profile from readings at angles that experiments could be performed and make prediction for the other angles including the normal incidence angle (Kalogirou 1996). The predictions of ANN as compared to the experimental values have a maximum difference of 3.2 %, which is satisfactory.

(c) *Starting-up of the solar steam generating plant*

ANNs have been used also to model the starting-up of the system stated above (Kalogirou et al. 1996b). It is very important for the designer of such systems to be able to make such predictions, because the energy spent during starting-up in the morning has a significant effect on the system performance. It should be noted that this energy is lost due to the diurnal cycle of the sun and the resulting cooling down of the system during the night. This problem is very difficult to handle with analytic methods as the system operates under transient conditions. ANNs could predict the profile of the temperatures at various points of the system, as shown in Table 11.1, to within 3.9 %, which is considered adequate for design purposes. From the profiles of two sets of flash vessel top and bottom temperatures versus time, the energy invested during the heat-up period can be easily estimated.

Table 11.1 Statistical analysis of program predictions and resulting maximum percentage error

Temperature	Correlation coefficient	R^2-value	Maximum % error
Collector outlet	0.999	0.9987	3.9
Collector inlet	1.000	0.9996	1.3
Flash vessel bottom	1.000	0.9992	2.3
Flash vessel top	1.000	0.9992	3.3

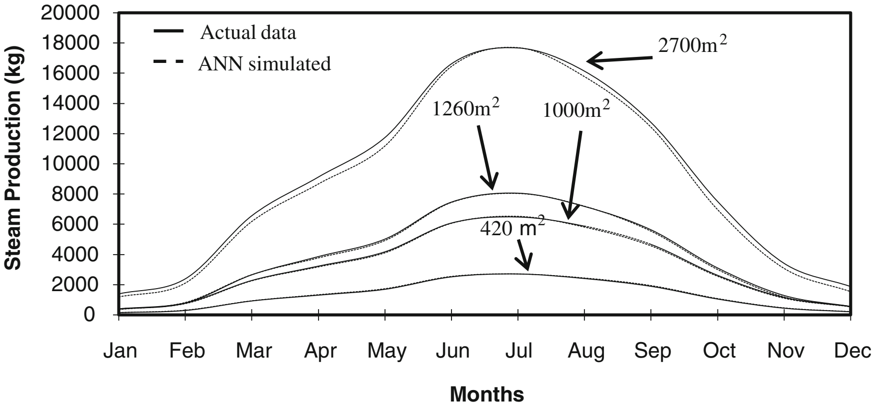


Fig. 11.4 Comparison of predicted and actual (simulated) results for different collector areas

(d) *Mean monthly average steam production*

An important parameter required for the design of such systems is the mean monthly average steam production of the system. A network was trained with performance values for a number of collector sizes ranging from 3.5 to 2160 m^2 and was able to make predictions both within and outside the training range (Kalogirou et al. 1997). A neural network was able to predict the mean monthly average steam production of the system as shown in Fig. 11.4.

The maximum difference confined to less than 5.1 % as compared to simulated values which is considered acceptable. The matching of the predicted and actual values in each case is excellent. In fact the pairs of two lines, shown in Fig. 11.4, are almost indistinguishable.

11.4.2 Solar Water Heating Systems

Various Solar Water Heating Systems were modeled and simulated, including both forced circulation and natural circulation (thermosiphon) units.

(a) *Modeling of solar domestic water heating (SDHW) systems*

An ANN has been trained based on 30 known cases of SDHW systems, varying from collector areas between 1.81 and 4.38 m^2 (Kalogirou et al. 1999b). Open and closed SDHW systems have been considered both with horizontal and vertical storage tanks. In addition to the above, an attempt was made to consider a large variety of weather conditions. In this way, the network was trained to accept and handle a number of unusual cases. The data presented as input were the collector area, storage tank heat loss coefficient (U-value), tank type, storage volume, type of system, and then readings from real experiments of total daily solar radiation, mean ambient air temperature, and the water temperature in the storage tank at the beginning of a day. The network output is the useful energy extracted from the system and the stored water temperature rise. Unknown data were used to investigate the accuracy of prediction. Typical results are shown in Tables 11.2 and 11.3 for the useful energy extracted from the system and the stored water temperature rise respectively. These include systems considered for the training of the network at different weather conditions (systems 11 and 12) and completely unknown systems (systems 15, 32, and 43). Predictions within 7.1 and 9.7 % were obtained respectively (Kalogirou et al. 1999b). It should be noted that the cases shown in Tables 11.2 and 11.3 are specifically selected to show the range of accuracy obtained and in particular the minimum and maximum deviations. These results indicate that the proposed method can successfully be used for the estimation of the useful energy extracted from the system and the stored water temperature rise. The advantages of this approach compared to the conventional algorithmic methods are the speed, the simplicity, and the capacity of the network to learn from examples. This is done by embedding experiential knowledge in the network. Additionally, actual weather data have been used for the training of the network, which leads to more realistic results as compared to other modeling programs, which rely on typical meteorological year (TMY) data that are not necessarily similar to the actual environment in which a system operates.

Table 11.2 Comparison between actual and predicted results for the useful energy extracted

System #	Actual Q_{out} (MJ)	ANN predicted Q_{out} (MJ)	% difference
11	20.6	20.6	0.0
	19.0	19.3	1.5
12	22.3	22.4	0.4
	17.1	18.4	7.1
15	20.5	22.4	8.5
	12.2	12.7	3.9
32	16.2	16.6	2.4
	15.6	15.4	−1.3
43	23.1	22.6	−2.2
	32.7	35.9	8.9

Table 11.3 Comparison between actual and predicted results for the temperature rise of the water in the storage tank

System #	Actual temperature (°C)	ANN predicted temperature (°C)	% difference
11	64.1	62.6	−2.3
	61.0	60.8	−0.3
12	53.0	52.2	−1.5
	45.1	45.6	1.1
15	60.9	62.4	2.4
	47.9	44.8	−6.9
32	45.7	42.8	−6.8
	44.1	41.5	−6.3
43	45.1	41.1	−9.7
	56.5	57.0	0.9

(b) *Performance prediction of a thermosiphon solar domestic water heating system*

An ANN has been trained using performance data for four types of systems, all employing the same collector panel under varying weather conditions (Kalogirou et al. 1999a). The output of the network is the useful energy extracted from the system and the stored water temperature rise. Predictions with maximum deviations of 1 MJ and 2.2 °C were obtained for the two parameters respectively. Random data were also used both with the performance equations obtained from the experiments and with the ANN to predict the above two parameters. The predicted values obtained were very comparable. These results indicate that the ANN can successfully be used for the estimation of the performance of the particular thermosiphon system at any of the different types of configurations used here. Comparative results which show the order of the obtained accuracy are shown in Tables 11.4 and 11.5. One case which is of particular interest is the one shown in Tables 11.4 and 11.5 at the fourth row for system number 1. The data refer to a completely overcast day and a very low ambient temperature (5.8 °C). As can be seen the neural network was able to give good predictions even for this unusual case.

(c) *Solar domestic water heating systems long-term performance prediction*

Thirty thermosiphon solar domestic water heating (SDWH) systems have been tested and modeled according to the procedures outlined in the standard ISO 9459-2 at three locations in Greece (Kalogirou and Panteliou 2000). From these, data for 27 systems were used for training and testing the network while data for the remaining three for validation. Two ANNs have been trained using the monthly data produced by the modeling program supplied with the standard. The first network was trained to estimate the solar energy output of the system (Q) for a draw-off quantity equal to the storage tank capacity and the second one to estimate the solar energy output of the system (Q) and the average quantity of hot water per month (V_d) at demand temperatures of 35 and 40 °C. The input data in both

Table 11.4 Comparison between actual and predicted values for the useful energy extracted

System #	Actual Q_{out} values (MJ)	ANN predicted Q_{out} values (MJ)	Difference between actual and predicted values (MJ)
1	12.67	12.1	−0.57
	24.6	25.07	+0.47
	25.84	26.1	+0.26
	3.28	3.6	+0.32
	25.34	25.89	+0.55
2	8.88	8.57	−0.31
	20.93	21.72	+0.79
3	28.4	28.97	+0.57
	20.91	20.19	−0.72
	22.38	23.41	+1.03
	18.79	18.53	−0.26
4	20.7	21.03	+0.33
	10.13	10.51	+0.38
	26.04	26.47	+0.43
	6.23	6.77	+0.54
	28.76	28.95	+0.19

Table 11.5 Comparison between actual and predicted values for the stored water temperature rise

System #	Actual temperature values (°C)	ANN predicted temperature values (°C)	Difference between actual and predicted values (°C)
1	40.2	40.8	+0.6
	56.7	55.1	−1.6
	59.3	57.1	−2.2
	17.6	19.8	+2.2
	57.7	56.6	−1.1
2	34.4	32.2	−2.2
	52.7	53.4	+0.7
3	56.6	55.7	−0.9
	49	46.8	−2.2
	51	50.8	−0.2
	41.1	40.4	−0.7
4	39	38.3	−0.7
	27.5	25.7	−1.8
	48.3	48.6	+0.3
	21.3	20	−1.3
	52.3	52.6	+0.3

networks are similar to the ones used in the program supplied with the standard. These were the size and performance characteristics of each system and various climatic data. In the second network, the demand temperature was also used as input. The statistical coefficient of multiple determination (R^2-value) obtained for the training data set was equal to 0.9993 for the first network and 0.9848 and

0.9926 for the second for the two output parameters respectively. Unknown data were subsequently used to investigate the accuracy of prediction. Predictions with R^2-values equal to 0.9913 for the first network and 0.9733 and 0.9940 for the second were obtained (Kalogirou and Panteliou 2000). Comparative graphs are shown in Figs. 11.5, 11.6, and 11.7.

A similar approach was followed for the long-term performance prediction of three forced circulation type SDWH systems (Kalogirou 2000b). The maximum percentage differences obtained when unknown data were used, were 1.9 and 5.5 % for the two networks respectively which is again very satisfactory.

(d) *Thermosiphon system long-term performance prediction using the dynamic system testing method and artificial neural networks*

The performance of a solar hot water thermosiphon system was tested with the dynamic system method according to Standard ISO/CD/9459.5. The system is of

Fig. 11.5 Actual against ANN predicted values for the validation data set for the solar energy output (*Q*) (network #1)

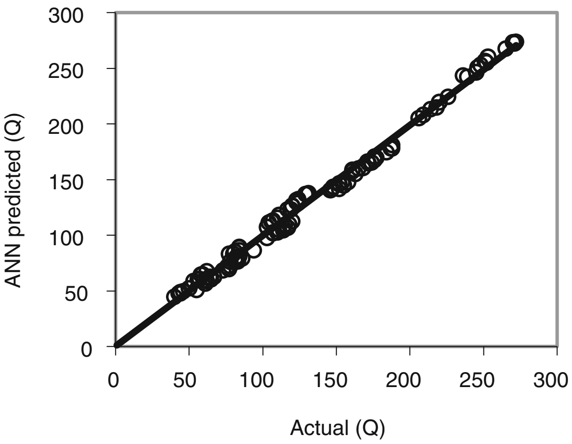


Fig. 11.6 Actual against ANN predicted values for the validation data set (network #2). Solar energy output (*Q*)

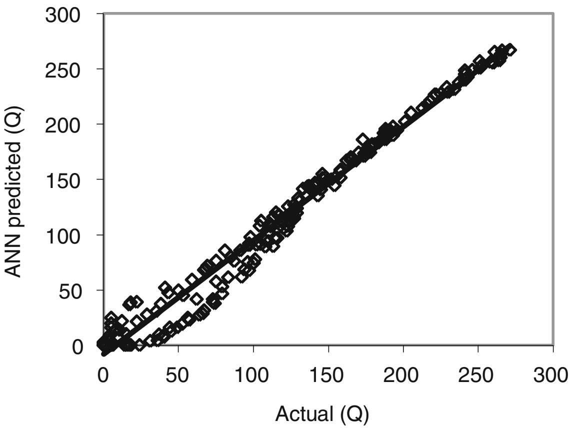
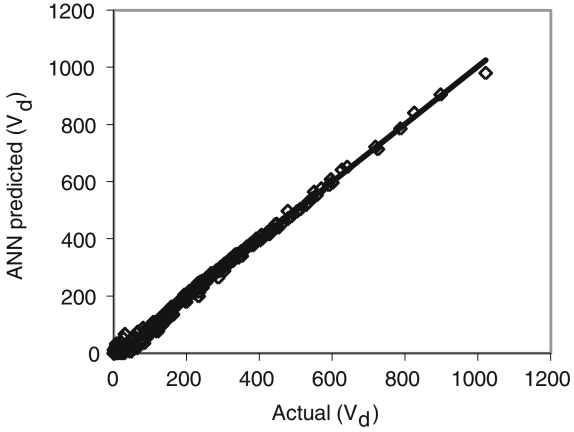


Fig. 11.7 Actual against ANN predicted values for the validation data set (network #2). Monthly hot water quantity (V_d)



closed circuit type and consists of two flat-plate collectors with total aperture area of 2.74 m^2 and of a 170 L hot water storage tank. The system was modeled according to the procedures outlined in the standard with the weather conditions encountered in Rome. The simulations were performed for hot water demand temperatures of 45 and 90 °C and volume of daily hot water consumption varying from 127 to 200 L. These results have been used to train a suitable neural network to perform long-term system performance prediction (Kalogirou and Panteliou 1999). The input data were learned with adequate accuracy with correlation coefficients varying from 0.993 to 0.998, for the four output parameters. When unknown data were used to the network, satisfactory results were obtained. The maximum percentage difference between the actual (simulated) and predicted results is 6.3 %. These results prove that artificial neural networks can be used successfully for this type of predictions. A comparison of the actual and ANN predicted results for the delivered power are shown in Fig. 11.8.

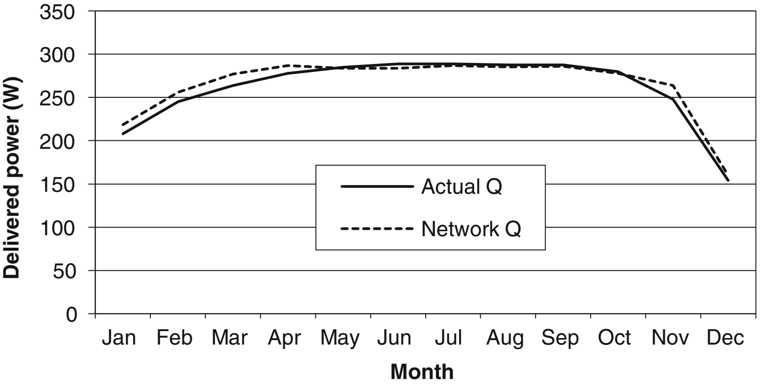


Fig. 11.8 Comparison of actual (simulated) data with ANN predicted data for delivered power

11.4.3 Photovoltaic Systems

(a) *Modeling and Simulation of stand-alone PV (SAPV) systems*

In this work, an adaptive ANN is used for modeling and simulation of a SAPV system operating under variable climatic conditions (Mellit et al. 2007). The ANN combines the Levenberg–Marquardt algorithm (LM) with an infinite impulse response (IIR) filter in order to accelerate the convergence of the network. SAPV systems are widely used in renewable energy system (RES) applications and it is important to be able to evaluate the performance of installed systems. The modeling of the complete SAPV system is achieved by combining the models of the different components of the system (PV-generator, battery, and regulator). A global model can identify the SAPV characteristics by knowing only the climatological conditions. In addition, a new procedure proposed for SAPV system sizing is presented in this work. Different measured signals of solar radiation sequences and electrical parameters (photovoltaic voltage and current) from a SAPV system installed at the south of Algeria have been recorded during a period of 5 years. These signals have been used for the training and testing the developed models, one for each component of the system and a global model of the complete system. The ANN model predictions allow the users of SAPV systems to predict the different signals for each model and identify the output current of the system for different climatological conditions. The comparison between simulated and experimental signals of the SAPV gave good results. The correlation coefficient obtained varies from 90 to 96 % for each estimated signals, which is considered satisfactory. A comparison between multilayer perceptron (MLP), radial basis function (RBF) network and the proposed LM–IIR model is presented in order to confirm the advantage of this model.

11.4.4 Applications of ANN and GA Combined

(a) *Optimization of solar systems*

In this work two artificial intelligence methods, artificial neural-networks and genetic algorithms, were used to optimize a solar energy system in order to maximize its economic benefits (Kalogirou 2004). The system is modeled using a TRNSYS computer program and the climatic conditions of Cyprus, included in a TMY file. An ANN is trained using the results of a small number of TRNSYS simulations, to learn the correlation of collector area and storage-tank size on the auxiliary energy required by the system from which the life-cycle savings can be estimated. Subsequently, a GA is employed to estimate the optimum size of these two parameters, for maximizing life-cycle savings; thus the design time is reduced substantially. As an example, the optimization of an industrial process heat system employing flat-plate collectors is presented. The optimum solutions obtained from the present methodology give increased life-cycle savings of 4.9 and 3.1 % when subsidized and nonsubsidized fuel prices are used respectively, as compared to solutions obtained by the traditional trial-and-error method. The present method greatly reduces the time required by design engineers to find the optimum solution and in many cases reaches a solution that could not be easily obtained from simple modeling programs or by trial and error, which in most cases depend on the intuition of the engineer.

(b) *Sizing of PV systems*

In this work, an artificial neural network-based genetic algorithm (ANN-GA) model was developed for generating the sizing curve of stand-alone photovoltaic (SAPV) systems (Mellit et al. 2010). First, a numerical method is used for generating the sizing curves for different loss of load probability (LLP) corresponding to 40 sites located in Algeria. The inputs of ANN-GA are the geographical coordinates (Latitude, Longitude, and Altitude) and the LLP while the output is the sizing curve represented by $C_A = f(C_S)$. Subsequently, the proposed ANN-GA model has been trained by using a set of 36 sites, whereas data for four sites which are not included in the training data set have been used for testing the ANN-GA model. The results obtained are compared and tested with those of the numerical method. In addition, two new regression models have been developed and compared with the conventional regression models. The results show that, the proposed exponential regression model with three coefficients presents more accurate results than the conventional regression models. A new ANN has then been used for predicting the sizing coefficients for the best regression model. These coefficients can be used for developing the sizing curve in different locations in Algeria. The results obtained showed that the coefficient of multiple determination (R^2) is 0.9998, which can be considered as very promising.

11.4.5 Other Applications

(a) *Prediction of flat-plate collector performance parameters*

In this work, ANNs were used for the prediction of the performance parameters of flat-plate solar collectors (Kalogirou 2006). Six ANN models have been developed for the prediction of the standard performance collector equation coefficients, both at wind and no-wind conditions, the incidence angle modifier coefficients at longitudinal and transverse directions, the collector time constant, the collector stagnation temperature, and the collector heat capacity. Different networks were used due to the different nature of the input and output required in each case. The data used for the training, testing, and validation of the networks were obtained from a commercial database. The results obtained when unknown data were presented to the networks are very satisfactory and indicate that the proposed method can successfully be used for the prediction of the performance parameters of flat-plate solar collectors. The advantages of this approach compared to the conventional testing methods are speed, simplicity, and the capacity of the network to learn from examples. This is done by embedding experiential knowledge in the network.

(b) *Fault diagnostic system for solar thermal applications*

In this work, the development of an automatic solar water heater (SWH) fault diagnosis system (FDS) is presented. The FDS system consists of a prediction module, a residual calculator, and the diagnosis module (Kalogirou et al. 2008). A data acquisition system measures the temperatures at four locations of the SWH system and the mean storage tank temperature. In the prediction module a number of ANNs are used, trained with values obtained from a TRNSYS model of a fault-free system operated with the TMY for Nicosia, Cyprus and Paris, France. Thus, the neural networks are able to predict the fault-free temperatures under different environmental conditions. The input data to the ANNs are various weather parameters, the incidence angle, flow condition, and one input temperature. The residual calculator receives both the current measurement data from the data acquisition system and the fault-free predictions from the prediction module. The system can predict three types of faults; collector faults and faults in insulation of the pipes connecting the collector with the storage tank and these are indicated with suitable labels. The system was validated by using input values representing various faults of the system.

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Chapter 12
Artificial Neural Network Based Methodologies for the Estimation of Wind Speed

Despina Deligiorgi, Kostas Philippopoulos and Georgios Kouroupetroglou

Abstract Recent advances in artificial neural networks (ANN) propose an alternative promising methodological approach to the problem of time series assessment as well as point spatial interpolation of irregularly and gridded data. In the field of wind power sustainable energy systems ANNs can be used as function approximators to estimate both the time and spatial wind speed distributions based on observational data. The first part of this work reviews the theoretical background, the mathematical formulation, the relative advantages, and limitations of ANN methodologies applicable to the field of wind speed time series and spatial modeling. The second part focuses on implementation issues and on evaluating the accuracy of the aforementioned methodologies using a set of metrics in the case of a specific region with complex terrain. A number of alternative feedforward ANN topologies have been applied in order to assess the spatial and time series wind speed prediction capabilities in different time scales. For the temporal forecasting of wind speed ANNs were trained using the Levenberg–Marquardt backpropagation algorithm with the optimum architecture being the one that minimizes the Mean Absolute Error on the validation set. For the spatial estimation of wind speed the nonlinear Radial basis function Artificial Neural Networks are compared versus the linear Multiple Linear Regression scheme.

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12.1 Introduction

During the past few decades, there has been a substantial increase in the interest on artificial neural networks (ANN). ANNs have been successfully adopted in solving complex problems in many fields. Essentially, ANNs provide a methodological approach in solving various types of nonlinear problems that are difficult to deal with using traditional techniques. Often, a geophysical phenomenon exhibits temporal and spatial variability, and is suffering by issues of nonlinearity, conflicting spatial and temporal scale, and uncertainty in parameter estimation (Deligiorgi and Philippopoulos 2011). ANNs have been proved to be flexible models that have the capability to learn the underlying relationships between the inputs and outputs of a process, without needing the explicit knowledge of how these variables are related. Kalogirou presented a detailed review of the application of ANN in a variety of renewable energy systems (Kalogirou 2001).

Wind power renewable energy generation is growing rapidly in the past two decades. The accurate forecasting of wind speed is critical for wind power generation in order to reduce the reserve capacity and to increase the wind power penetration (Lei et al. 2009). One can find a review on the history of wind speed short-term prediction for wind power generation (Costa et al. 2008). Traditional spatial interpolation methods have been used to estimate wind speed at unsampled locations, using point observations within the same region under study. Cellura et al. have employed the Inverse distance weighted method and the Kriging geostatistical approach to produce wind speed maps for the island of Sicily (Cellura et al. 2008). Furthermore, Luo et al. compared seven spatial interpolation methodologies in order to determine their suitability for estimating daily mean wind speed surfaces in England and Wales and found that the cokriging scheme was most likely to produce the best estimation of a continuous wind speed surface (Luo et al. 2008). In the field of wind speed prediction, conventional time series models have been widely employed to generate short-term wind speed predictions (Cadenas and Rivera 2007; Kamal and Jafri 1997; Poggi et al. 2003). Torres et al. (2005) utilized ARMA models for forecasting wind speed up to 10 h in advance in Navarre, Spain and found that they outperform the persistence model especially in the longer term forecasts.

A classification of the various methods with different time scales for the estimation of wind speed has been presented recently (Soman et al. 2010). Among them, ANNs are characterized as an accurate approach for the short-term (i.e., 30 min–6 h ahead) prediction and their hybrid structures useful for the medium to long-term forecasts. Beyer et al. (1994) used an ANN with a rather simple topology for wind speed prediction, while more complex ANN structures did not improve the results further. Kariniotakis et al. developed a recurrent high order ANN for the prediction of the power output profile of a wind park (Kariniotakis 1996). Mohandes et al. (1998) applied an ANN for wind speed prediction and compared its performance with an autoregressive model for the area of Jeddah, Saudi Arabia. More and Deo (2003) used both Feed Forward as well as recurrent

ANNs to forecast daily, weekly as well as monthly wind speeds at two coastal locations in India. Barbounis and Theocharis used local recurrent ANNs with online learning algorithms, based on the recursive prediction error, for the wind speed prediction in wind farms (Barbounis and Theocharis 2007). Li and Shi presented a comparative study on the application of three typical ANN in one-hour-ahead wind speed forecasting for two sites in North Dakota (Li and Shi 2010). Fadare used ANNs to produce monthly maps for the assessment of wind energy potential for different locations within Nigeria (Fadare 2010). In order to improve the performance of the wind speed prediction process, Bouzgou, and Benoudjit proposed a multiple architecture system that combines ANNs, Multiple Linear Regression (MLR), and Support Vector Machines (Bouzgou and Benoudjit 2011). Finally, Philippopoulos and Deligiorgi assess the spatial predictive ability of ANNs to estimate mean hourly wind speed values in a region with complex topography and compare the results with five traditional spatial interpolation schemes (Philippopoulos and Deligiorgi 2012). Moreover, in their work the effect of the inclusion of wind direction is assessed and the ANNs are examined for their capacity to incorporate the mean wind characteristics in the study area.

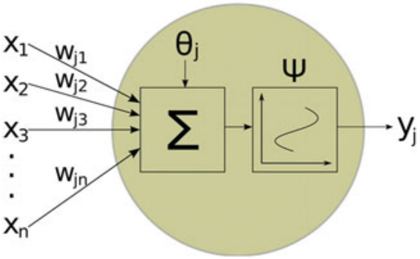
An important aspect of a wind resource assessment program is the wind resource evaluation, which relies heavily on the quality and the availability of wind speed data. A common approach to overcome the problem of limited on-site data availability is the measure–correlate–predict (MCP) method, which makes use of the long-term wind data from nearby climatological stations and a short-term wind speed record from the site under study. The method, based on various correlation techniques, employs the statistical relationship between the two wind speed time series. Under this framework, ANNs have been used as a nonlinear MCP model (Oztopal 2006; Bilgili et al. 2007) and are found, compared to linear MCP algorithms, to decrease significantly the associated wind speed estimation error (Velázquez et al. 2011).

In this work first we review the theoretical background, the mathematical formulation, the relative advantages, and limitations of ANN methodologies applicable to the field of wind speed time series and spatial modeling. In the second part we focus on implementation issues and on evaluating the accuracy of the aforementioned methodologies using a set of metrics in the case of a specific region with complex terrain at Chania, Crete Island, Greece. A number of alternative feedforward ANN topologies are applied in order to assess the spatial and time series wind speed prediction capabilities in different time scales.

12.2 Artificial Neural Networks

Artificial neurons are process element (PE) that attempt to simulate in a simplistic way the structure and function of the real physical biological neurons. A PE in its basic form can be modeled as nonliner element (see Fig. 12.1) that first sums its weighted inputs x_1, x_2, x_3,…x_n (coming either from original data, or from the

Fig. 12.1 Functional model of an artificial neuron or process element (*PE*)



output of other neurons in a neural network) and then passes the result through an activation function Ψ (or transfer function) according to the formula:

$$y_i = \Psi\left(\sum_{i=1}^{n} x_i w_{ji} + \theta_j\right) \tag{12.1}$$

where y_j is the output of the artificial neuron, θ_j is an external threshold (or bias value) and w_{ji} are the weight of the respective input x_i which determines the strength of the connection from the previous PE's to the corresponding input of the current PE. Depending on the application, various nonlinear or linear activation functions Ψ have been introduced (Fausett 1994; Bishop 1995) like the: signum function (or hard limiter), sigmoid limiter, quadratic function, saturation limiter, absolute value function, Gaussian and hyperbolic tangent functions (Fig. 12.2). ANN are signal or information processing systems constituted by an assembly of a large number of simple Processing Elements, as they have been described above. The PE of a ANN are interconnected by direct links called connections and cooperate to perform a Parallel Distributed Processing in order to solve a specific computational task, such as pattern classification, function approximation, clustering (or categorization), prediction (or forecasting or estimation), optimization, and control. One of the main strength of ANNs is their capability to adapt themselves by modifying the interaction between their PE. Another important feature of ANNs is their ability to automatically learn from a given set of representative examples.

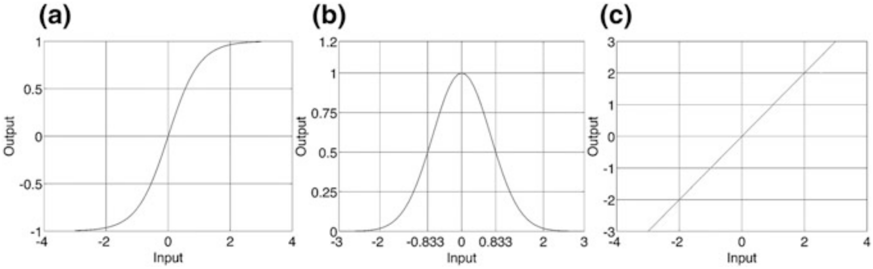


Fig. 12.2 Examples of activation functions Ψ: **a** hyperbolic tangent sigmoid transfer function, **b** Gaussian: radbas(n) = exp(−n2) and **c** linear

The architectures of ANNs can be classified into two main topologies: (a) Feedforward multilayer networks (FF-ANN) in which feedback connections are not allowed and (b) Feedback recurrent networks (FB-ANN) in which loops exist. FF-ANNs are characterized mainly as static and memory-less systems that usually produce a response to an input quickly (Jain et al. 1996). Most FF-ANNs can be trained using a wide variety of efficient conventional numerical methods. FB-ANNs are dynamic systems. In some of them, each time an input is presented, the ANN must iterate for a potentially long time before it produces a response. Usually, they are more difficult to train FB-ANNs compared to FF-ANNs.

FF-ANNs have been found to be very effective and powerful in prediction, forecasting or estimation problems (Zhang et al. 1998). Multilayer perceptrons (MLPs) (Fig. 12.3) and Radial basis function (RBF) topologies (Fig. 12.4) are the two most commonly used types of FF-ANNs. Essentially, their main difference is the way in which the hidden PEs combine values coming from preceding layers: MLPs use inner products, while RBF constitutes a multidimensional function which depends on the distance $r = \|x - c\|$ between the input vector x and the center c (where $\|\cdot\|$ denotes a vector norm) (Powell 1987). As a consequence, the training approaches between MLPs and RBF-based FF-ANN is not the same, although most training methods for MLPs can also be applied to RBF ANNs. In RBF FF-ANNs the connections of the hidden layer are not weighted and the hidden nodes are PEs with a RBF, however, the output layer performs simple weighted summation of its inputs, like in the case of MLPs. One simple approach to approximate a nonlinear function is to represent it as a linear combination of a number of fixed nonlinear RBFs $\{z_i(x)\}$, according to:

$$\Phi(x) = \sum_{i=1}^{l} z_i(x) w_i \tag{12.2}$$

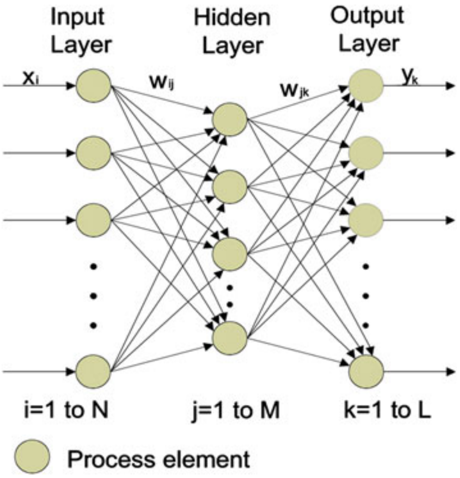
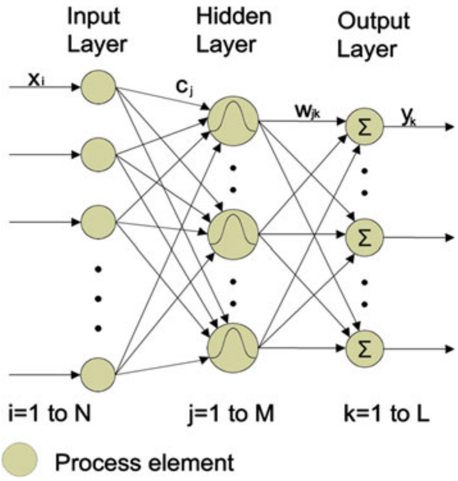


Fig. 12.3 Multilayer perceptron Feedforward ANN network architecture

Fig. 12.4 Radial basis function FF-ANN architecture



Typical choices for RBFs $z_i = F(\|x - c\|)$ are: piecewise linear approximations, Gaussian function, cubic approximation, multiquadratic function, and thin plate splines.

A MLP FF-ANN can have more than one hidden layer. But theoretical research has shown that a single hidden layer is sufficient in that kind of topologies to approximate any complex nonlinear function (Cybenco 1989; Hornik et al. 1989).

There are two main learning approaches in ANNs: (1) supervised, in which the correct results are known and they are provided to the network during the training process, so that the weights of the PEs are adjusted in order its output match the target values and (2) unsupervised, in which the ANN performs a kind of data compression, looking for correlation patterns between them and by applying clustering approaches. Moreover, hybrid learning (i.e., a combination of the supervised and unsupervised methodologies) has been applied in ANNs. Numerous learning algorithms have been introduced for the above learning approaches (Jain et al. 1996).

The introduction of the back propagation learning algorithm (Rumelhart et al. 1986) to obtain the weight of a multilayer MLP could be regarded as one of the most significant breakthroughs for training ANNs. The objective of the training is to minimize the training mean square error E_{mse} of the ANN output compared to the required output for all the training patterns:

$$E_{mse} = \sum_{k=1}^{p} E_k = \frac{1}{2N} \sum_{j=Y} \sum_{k=1}^{p} \left(y_i - d_{kj}\right)^2 \qquad (12.3)$$

where: E_k is the partial network error, p is the number of the available patterns and Y the set of the output PEs. The new configuration in time $t > 0$ is calculated as follows:

$$w_{ji}(k) = w_{ji}(k-1) - \alpha \frac{\partial E}{\partial w_{ji}} + \beta\left[w_{ji}(k-1) - w_{ji}(k-2)\right] \tag{12.4}$$

where $0 < \alpha < 1$ is the speed of learning, β is the momentum and the constant α determines the speed of the training. If a low α value is set, the network weights react very slowly. On the contrary, high α values cause divergence, i.e., the algorithm fails. Therefore, the parameter α is set experimentally.

To speed up the training process, the faster Levenberg–Marquardt Back propagation Algorithm has been introduced (Yu and Wilamowski 2011). It is fast and has stable convergence and it is suitable for training ANN in small-and medium-sized problems. The new configuration of the weights in the $k + 1$ step is calculated as follows:

$$w(k+1) = w(k) - \left(J^T J + \lambda I\right)^{-1} J^T \varepsilon(k) \tag{12.5}$$

The Jacobian matrix for a single PS can be written as follows:

$$J = \begin{bmatrix} \frac{\partial \varepsilon_1}{\partial w_1} & \cdots & \frac{\partial \varepsilon_1}{\partial w_n} & \frac{\partial \varepsilon_1}{\partial w_0} \\ \vdots & & \vdots & \vdots \\ \frac{\partial \varepsilon_p}{\partial w_1} & \cdots & \frac{\partial \varepsilon_p}{\partial w_n} & \frac{\partial \varepsilon_p}{\partial w_0} \end{bmatrix} = \begin{bmatrix} x_{1_1} & \cdots & x_{n_1} & 1 \\ \vdots & & \vdots & \vdots \\ x_{1_p} & \cdots & x_{n_p} & 1 \end{bmatrix} \tag{12.6}$$

where: w is the vector of the weights, w_0 is the bias of the PE and ε is the error vector, i.e., the difference between the actual and the required value of the ANN output for the individual pattern. The parameter λ is modified based on the development of the error function E.

12.3 Application of ANN in Wind Speed Estimation

The present work aims to quantify the ability of ANNs to estimate and model the temporal and spatial wind speed variability at a coastal environment. We focus on implementation issues and on evaluating the accuracy of the aforementioned methodologies in the case of a specific region with complex terrain. A number of alternative ANN topologies are applied in order to assess the spatial and time series wind speed prediction capabilities in different time scales.

Moreover, this work presents an attempt to develop an extensive model performance evaluation procedure for the estimation of the wind speed using ANNs. This procedure incorporates a variety of correlation and difference statistical measures. In detail, the correlation coefficient (R), the coefficient of determination (R^2), the mean bias error (MBE), the mean absolute error (MAE), the root mean square error (RMSE), and the index of agreement (d) are calculated for the examined predictive schemes. The formulation and the applicability of such measures are extensively reported in (Fox 1981; Willmott 1982; Willmott et al. 1985).

12.3.1 Area of Study and Experimental Data

The study area is the Chania plain, located on the northwestern part of the island of Crete in Greece. The greater area is constricted by physical boundaries, which are the White Mountains on the south, the Aegean coastline on the northern and eastern part, and the Akrotiri peninsula at the northeast of Chania city (Fig. 12.5). The topography of the region is complex due to the geophysical features of the region. The influence of the island of Crete on the wind field, especially during summer months and days where northerly etesian winds prevail, is proven to cause a leftward deflection and an upstream deceleration of the wind vector (Koletsis et al. 2009, 2010; Kotroni et al. 2001). Moreover, the wind direction of the local field at the broader area of Chania city varies significantly due to the different topographical features (Deligiorgi et al. 2007).

In this study, mean hourly wind speed and direction data are obtained from a network of six meteorological stations, namely TEI, Souda, Platanias, Malaxa, Pedio Volis, and Airport (Fig. 12.5). The measurement sites cover the topographical and land-use variability of the region (Table 12.1). TEI, Souda, and Malaxa stations are situated along the north–south axis, perpendicular to the Aegean coastline. Moreover, TEI and Platanias stations are representative of the coastal character of the region and the climatological station at the Airport of the meteorological conditions that prevail at the Akrotiri peninsula. TEI station is located at the east and in close proximity to the densely populated urban district of Chania city and in this application it will be used as the reference station for examining the performance of the temporal and spatial ANN models. Its wind speed characteristics are presented in Fig. 12.6 in terms of the resulting wind rose

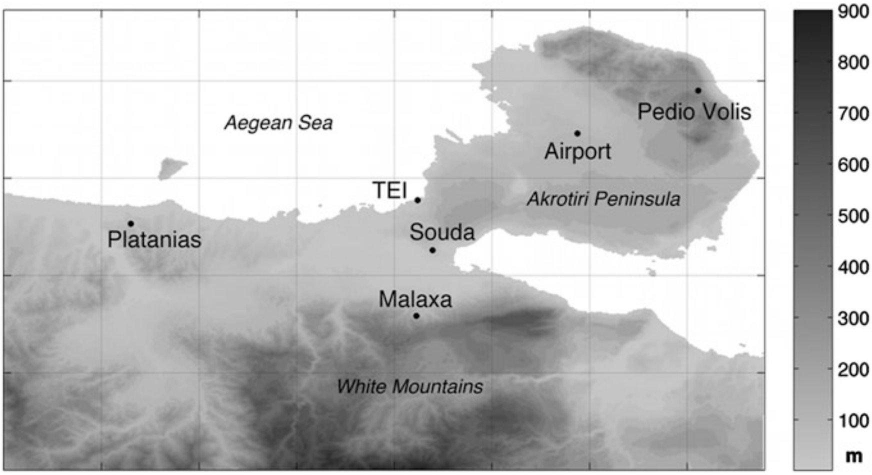


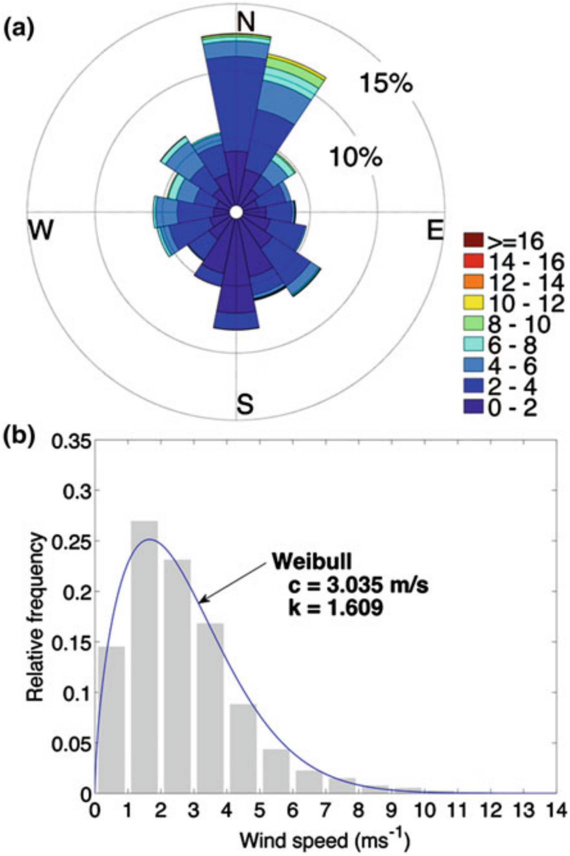
Fig. 12.5 Area of study and location of meteorological stations

Table 12.1 Geographical characteristics of the meteorological stations

	Latitude (°N)	Longitude (°W)	Elevation (m)	Characterization
TEI	35°31′09″	24°02′33″	38	Suburban–Coastal
Souda	35°30′30″	23°54′40″	118	Suburban
Platanias	35°29′46″	24°03′00″	23	Rural–Coastal
Malaxa	35°27′57″	24°02′33″	556	Rural
Pedio Volis	35°34′11″	24°10′20″	422	Rural

diagram (Fig. 12.6a), the wind speed distribution for the overall experimental period along with the corresponding Weibull distribution fit (Fig. 12.6b). The mean wind speed is 2.706 ms^{-1} and the higher wind speed values are associated with northern to northeastern flows during the cold and the transitional (spring and autumn) periods of the year, as a consequence of the combined effect of the synoptic, regional, and small-scale systems.

Fig. 12.6 Wind speed characteristics for the meteorological station TEI



12.3.2 Temporal Forecasting of Wind Speed

12.3.2.1 ANN Implementation Methodology

For the temporal forecasting of wind speed, ANNs are used as function approximators aiming to estimate the wind speed in a location using the current and previous wind speed observations from the same site.

In this application the FeedForward Neural Network architecture with one hidden layer is selected for predicting the wind speed time series. The wind speed characteristics (rose diagrams and wind speed frequency distributions) for the meteorological station of TEI are presented in Fig. 12.6.

Separate ANNs are trained and tested for predicting the 1 h (ANN_T1), 2 h (ANN_T2), and 3 h (ANN_T3) ahead wind speed at TEI, based on the current and the five previous wind speed observations from the same site. Therefore, the input in each ANN is the wind speed at t, $t-1$, $t-2$, $t-3$, $t-4$, and $t-5$ and the output is the wind speed at: $t+1$ for the ANN_T1, $t+2$ for the ANN_T2, and $t+3$ for the ANN_T3.

The study period is from August 2004 to September 2006 and due to missing observations the input datasets consist of 11,607 samples of six consecutive hourly observations for the ANN_T1 model, 11,537 and 11,540 six-element vectors for the ANN_T2, and ANN_T3 models, respectively. In all cases, the first 60 % of the dataset is used for training the ANNs, the subsequent 20 % for validation and the remaining 20 % for testing.

The optimum architecture (number of PEs in the hidden layer) is related to the complexity of the input and output mapping, along with the amount of noise and the size of the training data. A small number of PEs result to a non-optimum estimation of the input–output relationship, while too many PEs result to overfitting and failure to generalize (Gardner and Dorling 1998). In this study the selection of the number of PEs in the hidden layer is based on a trial and error procedure and the performance is measured using the validation set. In each case, ANNs with a varying number from 5 to 25 PEs in the hidden layer were trained using the Levenberg–Marquardt backpropagation algorithm with the optimum architecture being the one that minimizes the MAE on the validation set.

The dimensioned evaluations of model-performance error should be based on MAE (Willmott and Matsuura 2005), although the RMSE or the Mean Square Error (MSE) are widely used in the literature. A drawback of the backpropagation algorithm is its sensitivity to initial weights.

During training, the algorithm can become trapped in local minima of the error function, preventing it from finding the optimum solution (Heaton 2005). In this study and for eliminating this weakness, each network is trained multiple times (50 repetitions) with different initial weights. A hyperbolic tangent sigmoid transfer function $\text{tansig}(n) = 2/(1 + \exp(-2n)) - 1$ (Fig. 12.2a) was used as the activation function Ψ for the PEs of the hidden layer. In the output layers, PEs with a linear transfer function were used (Fig. 12.2c).

Table 12.2 Optimum ANN architecture—number of PEs at the input, hidden, and output layer

ANN_T1	ANN_T3	ANN_T2
6-7-1	6-20-1	6-15-1

12.3.2.2 Results

The optimum topologies of the selected ANNs that minimized the MAE on the validation set are presented in Table 12.2. In all cases, the architecture includes six PEs in the input layer and one PE in the output layer. The results indicate that the number of the neurons in the hidden layer is increased as the lag for forecasting the wind speed is increased.

The model evaluation statistics for the TEI station are presented in Table 12.3 and the observed and predicted time series are compared in the scatter plots of Fig. 12.7 and in Fig. 12.8, where a fraction of both time series is illustrated. A general remark is that the ANNs performance is decreased with increasing the forecasting lag. In all cases the MAE is less than 1 ms^{-1} and the explained variance decreases from 79.74 % for the ANN_T1 to 55.98 % for the ANN_T3 model.

The ANN_T1 model exhibits very good performance, as it is observed from the limited dispersion along the optimum agreement line of the 1 h wind speed prediction (Fig. 12.7a). The data dispersion for the ANN_T2 (Fig. 12.7b) and for the ANN_T3 (Fig. 12.7c) scatter plots is increased and a small tendency of overestimation of the low wind speed values along with an under estimation of the high wind speed values is observed. The effect of this finding in the overall model performance is minimal for the ANN_T2 model (Fig. 12.8b) and becomes relatively important for the 3 h ahead prediction (Fig. 12.8c). Regarding the residuals distributions (Fig. 12.9), the errors for the ANN_T1 and for the ANN_T2 are approximately centered at 0 ms^{-1}, while for the ANN_T3 model the maxima of the distribution is shifted to the left (negative residual values).

12.3.3 *Spatial Estimation of Wind Speed*

12.3.3.1 ANN Implementation Methodology

For the spatial estimation of wind speed the nonlinear RBF-ANN are compared versus the linear MLR scheme.

Table 12.3 ANN-based model performance

	R	R^2	MBE (ms^{-1})	MAE (ms^{-1})	RMSE (ms^{-1})	d
ANN_T1	0.8930	0.7974	0.0150	0.5942	0.8969	0.9377
ANN_T2	0.8056	0.6490	0.0070	0.8156	1.1801	0.8855
ANN_T3	0.7482	0.5598	−0.0258	0.9494	1.3149	0.8321

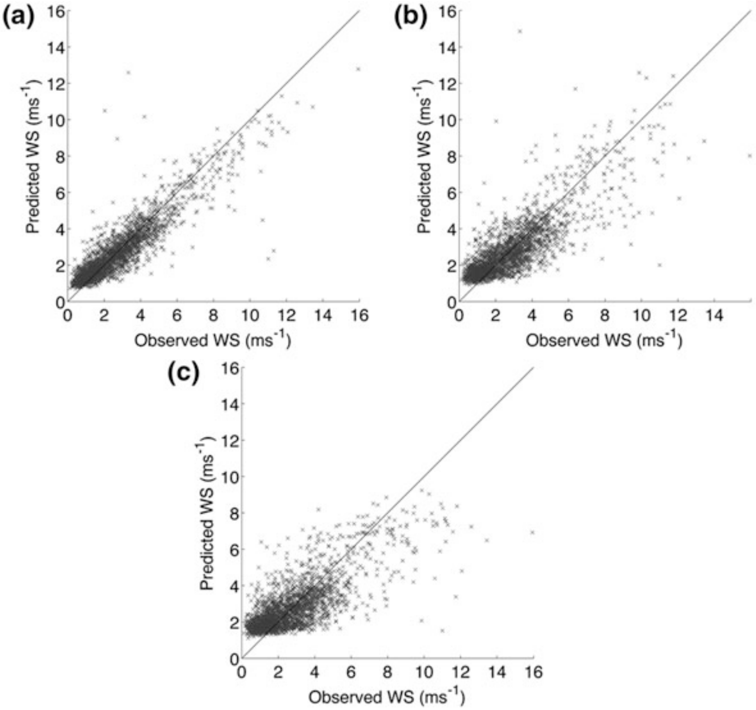


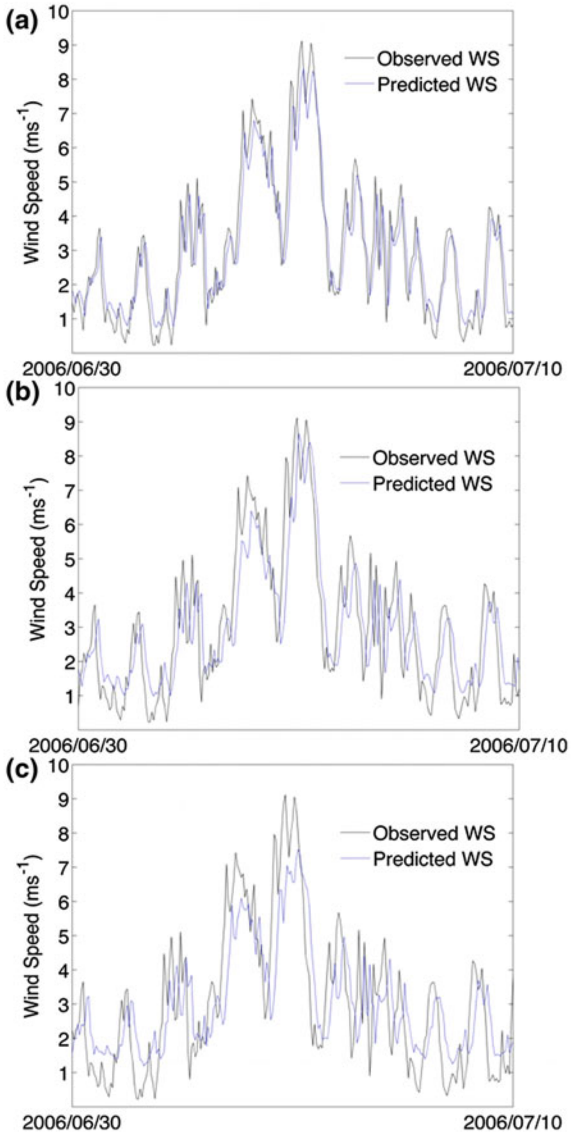
Fig. 12.7 Comparison of the observed and ANN-based predicted wind speed values for $t + 1$ (**a**), $t + 2$ (**b**) and $t + 3$ (**c**)

The target station is located at TEI, while the concurrent wind speed observations from the remaining sites—control stations (Souda, Malaxa, Platanias, PedioVolis, and Airport) are used as inputs in the RBF-ANN model. In an analogous procedure for the MLR scheme, the wind speed at TEI is regarded as the response variable and the wind speed observations at the control stations as the explanatory variables.

The 60 % of the available data (7,300 cases) was used for building and training the models (training set), the subsequent 20 % as the validation set and the remaining 20 % (2433 cases from 2006/01/24 to 2006/08/31) as the test set which is used to examine the performance of both the RBF-ANN and the MLR models. In the case of the RBF-ANN, the validation set is used for selecting the optimum value of the spread parameter, using the trial and calculating the error procedure by minimizing the MAE.

The ANN used had five inputs, a hidden layer with radial basis with 7,300 artificial neurons with Gaussian activation functions $\text{radbas}(n) = \exp(-n^2)$ (Fig. 12.2b) and the output layer has one PE with linear activation function (Fig. 12.2c).

Fig. 12.8 Time series comparison from 2006/06/30 to 2006/07/10 for $t + 1$ (**a**), $t + 2$ (**b**) and $t + 3$ (**c**)



12.3.3.2 Results

The parameters of the MLR equation calculated from the experimental data were:

$$\begin{aligned} \mathrm{WS}_{\mathrm{TEI}} = & -0.2031 + 0.3762\mathrm{WS}_{\mathrm{SOU}} + 0.4064\mathrm{WS}_{\mathrm{PLA}} \\ & + 0.0318\mathrm{WS}_{\mathrm{MAL}} + 0.0577\mathrm{WS}_{\mathrm{PBK}} + 0.0370\mathrm{WS}_{\mathrm{AIR}} \end{aligned} \tag{12.7}$$

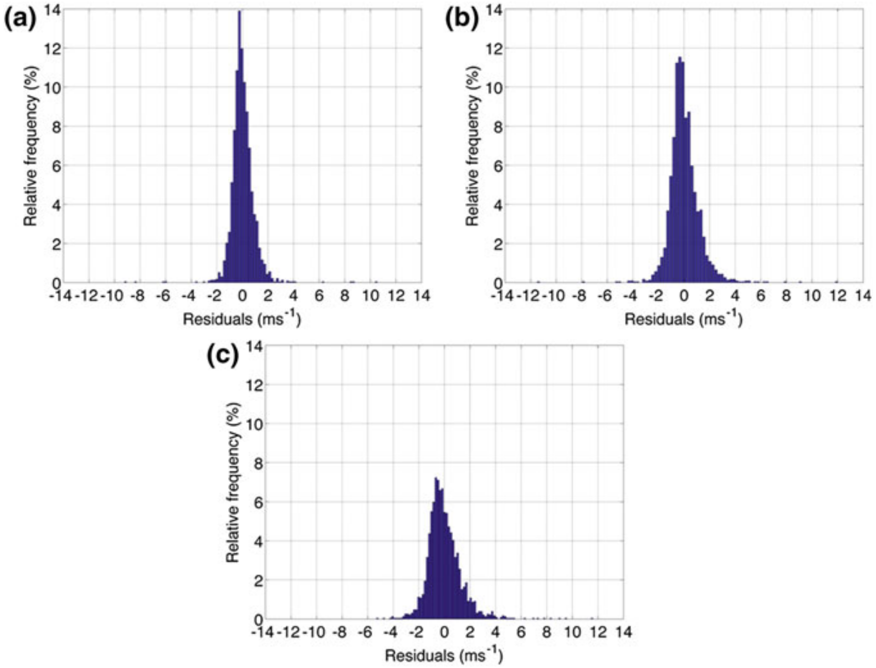


Fig. 12.9 Residuals' distributions for $t + 1$ (**a**), $t + 2$ (**b**) and $t + 3$ (**c**) ANN-based predictions

The higher partial regression coefficients are associated with the wind speed at Platanias (0.4064) and at Souda station (0.3782), attributed to the coastal characteristics of the TEI and Platanias stations and to the proximity of the TEI and Souda measurement sites.

Regarding the RBF-ANN model and the selection of the optimum spread parameter value, the minima of the MAE error on the validation set is observed after a sharp MAE decrease. In this spread parameter region the neurons do not respond to overlapping regions of the input space. For larger values, the MAE error increases gradually, reaching a secondary maximum and remains constant thereafter as all the neurons respond with the same manner.

The model evaluation statics for the TEI station for both RBF-ANN and MLR approaches are presented in Table 12.4. A general remark is that the nonlinear RBF-ANN model outperforms the linear MLR scheme and that both models perform reasonably well. The explained variance is 73.77 % for the RBF-ANN model and close to 70 % (69.1 %) for the MLR scheme and both scheme exhibit high index of agreement values (0.9213 and 0.8925 respectively) and minimal bias errors.

The comparison of the observed and the predicted wind speed values for both models are presented in Fig. 12.10 scatter plots and the respective residuals'

Table 12.4 Model performance metrics for the TEI station

	R	R^2	MBE (ms^{-1})	MAE (ms^{-1})	RMSE (ms^{-1})	*d*
MLR	0.8313	0.6910	0.0089	0.7487	1.0760	0.8925
RBF-ANN	0.8589	0.7377	0.0092	0.6944	0.9853	0.9213

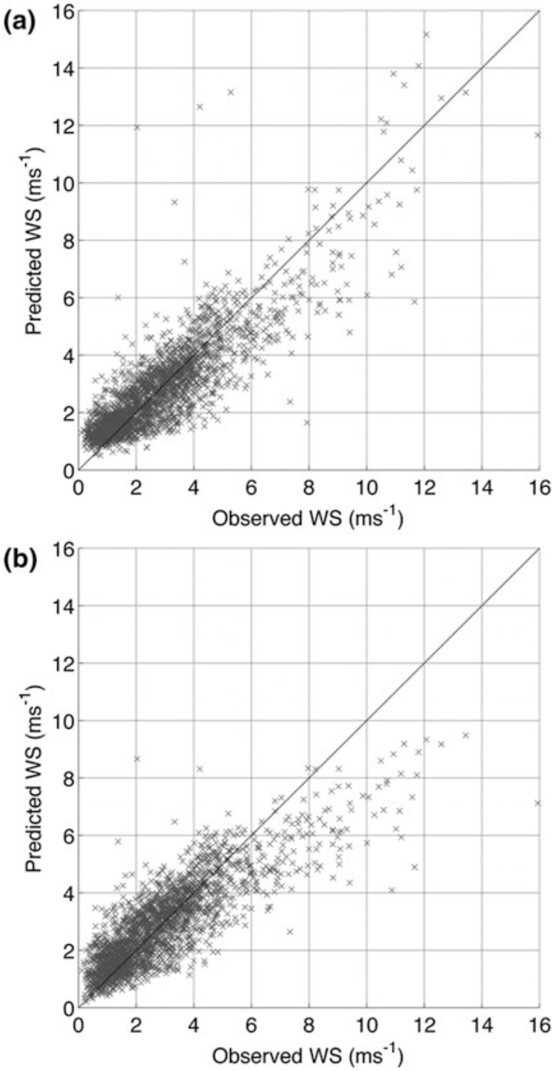


Fig. 12.10 Comparison of the predicted and observed wind speed at the TEI station for the RBF-ANN (**a**) and for the MLR scheme (**b**)

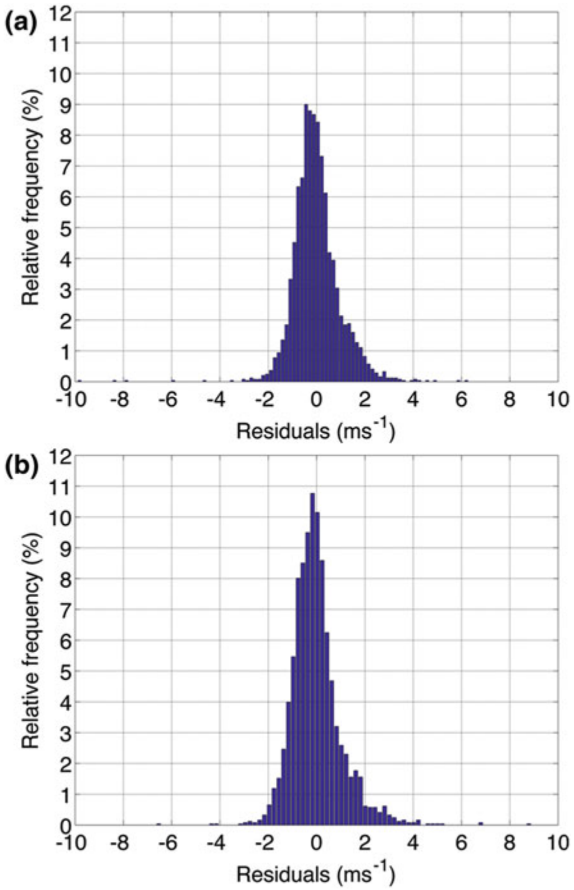


Fig. 12.11 Residuals distribution for the RBF-ANN (**a**) and the MLR (**b**) model

distributions are given in Fig. 12.11. Limited data dispersion is observed for both models, while the linear model exhibits signs of under-prediction for the higher wind speed values. In both cases the residuals are symmetrically distributed around 0 ms^{-1}.

Moreover, a time series comparison between the observed and the predicted wind speed from the RBF-ANN model are presented in Fig. 12.12 for the period 21/6/2006–19/7/2006. The predicted wind speed time series follows closely the observed values with no signs of systematic errors. An additional statistical comparison of the observed and the RBF-ANN predicted time series is performed based on their resulting wind speed frequency distributions and the corresponding two-parameter Weibull distribution fits (Fig. 12.13). The two Weibull probability density functions are assessed for statistically significant differences, using the paired *t* test. The null hypothesis that the frequency differences have zero mean is accepted the 0.05 significance level (p value = 0.6439).

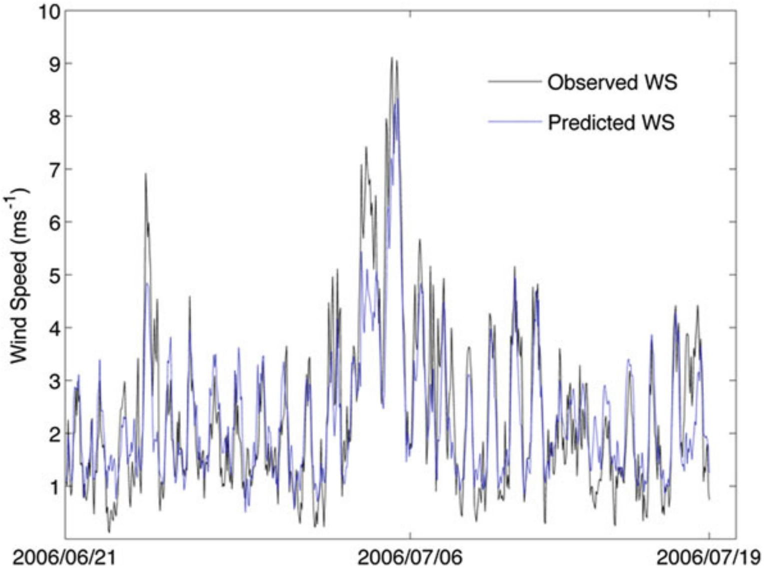
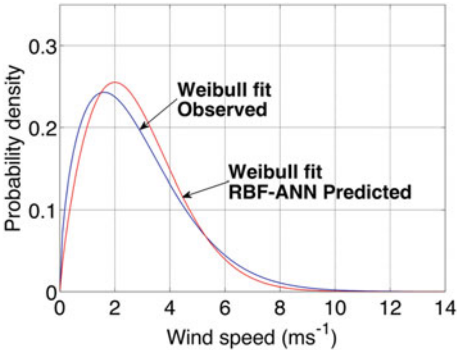


Fig. 12.12 Time series comparison of wind speed between observed and RBF-ANN-based estimation

Fig. 12.13 Weibull probability distributions fits to the observed time series ($k = 1.558$ and $c = 3.102$ ms^{-1}) (**a**) and to the RBF-ANN predicted time series ($k = 1.794$ and $c = 3.148$ ms^{-1})



12.4 Conclusions

The ability of neural networks to spatial estimate and predict short-term wind speed values is studied extensively and is well established. We reviewed the theoretical background, the mathematical formulation, the relative advantages, and limitations of ANN methodologies applicable to the field of wind speed time series and spatial modeling. Then, we have applied ANNs methodologies in the case of a specific region with complex terrain at Chania coastal region, Crete island, Greece. Details of the implementation issues are given along with the set of metrics for evaluating the accuracy of the methodology. A number of alternative feedforward

ANN topologies have been applied in order to assess the spatial and time series wind speed prediction capabilities. For the 1, 2, and 3 h ahead wind speed temporal forecasting at a specific site ANNs were trained based on the current and the five previous wind speed observations from the same site using the Levenberg–Marquardt backpropagation algorithm with the optimum architecture being the one that minimizes the MAE on the validation set. For the spatial estimation of wind speed at a target site the nonlinear RBF-ANN were compared versus the linear MLR scheme, using the concurrent wind speed observations from five sites at the same region. The underlying wind speed temporal and spatial variability is found to be modeled efficiently by the ANNs.

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Chapter 13
The Use of Genetic Algorithms to Solve the Allocation Problems in the Life Cycle Inventory

Maurizio Cellura, Sonia Longo, Giuseppe Marsala, Marina Mistretta and Marcello Pucci

Abstract One of the most controversial issues in the development of Life Cycle Inventory (LCI) is the allocation procedure, which consists in the partition and distribution of economic flows and environmental burdens among to each of the products of a multi-output system. Because of the use of the allocation represents a source of uncertainty in the LCI results, the authors present a new approach based on genetic algorithms (GAs) to solve the multi-output systems characterized by a rectangular matrix of technological coefficients, without using computational methods such as the allocation procedure. In this Chapter, the GAs' approach is applied to an ancillary case study related to a cogeneration process. In detail, the authors hypothesized that there are the following multi-output processes in the case study: (1) cogeneration of electricity and heat; (2) co-production of diesel and light fuel oil; (3) co-production of copper and recycled copper. The energy and mass balances are respected by means of specific bonds that limit the space in which the GA searches the solution. The results show low differences between the inventory vector derived from the GA application and that one obtained applying

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the substitution method and the allocation procedure based on the energy content of the outputs. To avoid the allocation, the application of GA to calculate the LCI seems to be a promising method.

13.1 Introduction

The life cycle inventory analysis (LCI), involving the compilation and quantification of inputs and outputs for a product throughout its life cycle, can be carried out applying the matrix method. It allows to calculate the inventory vector g of a specific process, also called eco-profile, by solving the following linear equation system (Heijungs and Suh 2002; Ardente et al. 2004; Cellura et al. 2009):

$$A\,s = f \tag{13.1}$$

where A is the matrix of technological coefficients that represents the flows within the examined process, s is the solution vector or scaling vector, and f is the functional unit vector and represents the economic outputs of the investigated process, whose amount is fixed by the analysts.

If the A matrix is square, and thus it is invertible, and if $Det(A) \neq 0$, it is possible to calculate a unique value of the scaling vector s:

$$s = A^{-1} f \tag{13.2}$$

Known the vector s, it can be used to estimate the inventory vector g, which shows the environmental flows associated with the selected functional unit, by means of the following equation:

$$g = B\,s \tag{13.3}$$

where B is called the environmental matrix and it includes the environmental flows of each unit process that constitutes the examined system.

However, there are various cases in which the A matrix is rectangular and thus not invertible:

- Case 1: in the examined system there are specific economic flows for which no data on the productive process are available;
- Case 2: a specified process produces more than one economic flow (multifunctionality);
- Case 3: in a specified process, in addition to the main output, there is a closed-loop recycle of wastes that are used as secondary raw materials in the same system.

In these cases, the matrix method cannot be used to calculate the g vector, because of the system is over-determined.

Various solutions have been identified to transform the rectangular A matrix in a square matrix (Marvuglia et al. 2010; Heijungs and Suh 2002).

For the Case 1 is commonly applied the cut-off of the economic flow for which no data are available; for the Case 2 is used the allocation procedure, which allows to allocate the environmental input and output flows of the process to each economic output; the Case 3 can be solved using the substitution method: the recycled flow is eliminated from the matrix and, using a corrective factor, is included in the primary flow.

However, the above solutions can introduce uncertainty in the LCI results (Cellura et al. 2011).

In the scientific literature, the multi-functionality problem often is solved in the Consequential Life Cycle Assessment (CLCA)[1] by the system expansion: the boundaries of the system are expanded so as to include those processes which are affected by the consequences of a decision at hand (Zamagni et al. 2012). Considering that the CLCA studies the environmental consequences of future changes between alternative product systems and allows to inform policy makers on the broader impacts of policies (Brander et al. 2009), the system expansion appears to be a valid approach to avoid allocation, even if the application of CLCA is generally hard (Brander et al. 2009) and affected by several limitations concerning the completeness, the accuracy, and the relevance of the study (Ekwall 2002).

However, most of the LCA studies are referred to the microlevel (attributional LCA—ALCA[2]) and for these the system expansion to handle co-products is optional, while co-product allocation is most frequently used (Thomassen et al. 2008), included the economic allocation that is one of the most common procedures for allocation in LCA and is used in several different production sectors (Ardente and Cellura 2012).

To solve the multi-functionality problem in the ALCA, Marvuglia et al. (2010) proposed an approach based on the regression techniques of least squares (LS) method, solved using an iterative algorithm, and applied it to a productive process of bricks. The results showed that the scaling vector s and inventory vector g obtained applying the regression techniques are very different from those obtained with the physical and economic allocation. In addition, analyzing the method it can be observed that any bond is imposed for the respect of the energy and mass balances. This represents a limit of the proposed method.

In this chapter, the authors propose an original method for ALCA to calculate the g vector starting from a rectangular A matrix, based on the use of Genetics Algorithms (GAs). The application of GAs allows to minimize the error function related to the regression techniques of LS using a bounded algorithm. In addition, the GAs allow the analysts to avoid the use of computational procedures as cut-off,

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[1] CLCA identifies and models all processes in the background system of a system in consequence of decisions made in the foreground system (European Union 2010).

[2] ALCA inventories the inputs and output flows for all processes of a system as they occur (European Union 2010).

allocation, and substitution methods reducing the uncertainty of LCI results, respecting the energy and mass balances.

13.2 Least Square Methods

The LS method is a standard approach to the approximate solution of overdetermined systems (more equations than unknowns), reflected by a matrix with more rows than columns (Marvuglia et al. 2010), that is the case when the *A* matrix is rectangular.

Let to consider a process that is constituted by the economic flow vector ($a_1, a_2, \ldots, a_n$) and the functional unit vector ($f_1, f_2, \ldots, f_n$). The unknown of the system is the scaling vector *s*. The LS method allows to calculate the value of the scaling vector *s* that fits the empirical data, minimizing the sum of the squares of the errors made in the results of every single equation.

Different kinds of error functions can be chosen to be minimized, the choice of which is made on the basis of which part of the matrix equation contains uncertainties. Three LS techniques exist: the ordinary least squares (OLS), the total least squares (TLS), and the data least squares (DLS) which arise when errors are, respectively, present only in *f* or both in *A* and in f or only in *A*.

In the mono-dimensional case (n = 1), the resolution of the LS problem consists in determining the angular coefficient *s* of the straight line of equation $A \cdot s = f$.

The LS technique solves for this problem by calculating the value of *s* which minimizes the sum of squares of the distances among the elements (A_i, f_i), with $i = 1, \ldots, m$, and the line itself. The differences among the various LS techniques are summarized in Table 13.1.

The three above LS methods can be combined in the generalized TLS approach, where the error function is:

Table 13.1 LS methods

Method	Objective function (error function) to be minimized	Main hypothesis
Ordinary least squares (OLS)	$E_{\mathrm{OLS}} = \frac{1}{2}\,(A \cdot s - f)^{\mathrm{T}} \cdot (A \cdot s - f)$	The error is localized only in the vector f; the A matrix is known: $A \cdot s_{\mathrm{OLS}} = f + \Delta f$
Data least squares (DLS)	$E_{\mathrm{DLS}} = \frac{1}{2}\,(A \cdot s - f)^{\mathrm{T}} \cdot (A \cdot s - f) / (s^{\mathrm{T}} \cdot s)$	The error is localized only in the A matrix; the vector f is known: $(A + \Delta A) \cdot s_{\mathrm{DLS}} = f$
Total least squares (TLS)	$E_{\mathrm{TLS}} = (A \cdot s - f)^{\mathrm{T}} \cdot (A \cdot s - f) / (1 + s^{T} \cdot s)$	The error is localized both in the A matrix and in the f vector: $(A + \Delta A) \cdot s_{\mathrm{TLS}} \cdot = f + \Delta f$

$$E_{\mathrm{OLS}}, \mathrm{TLS}, \mathrm{DLS} = \frac{1}{2} \cdot \frac{(A \cdot s - f)^T \cdot (A \cdot s - f)}{1 - \zeta + \zeta \cdot s^T \cdot s} \tag{13.4}$$

When $\zeta = 0$, $\zeta = 0.5$ and $\zeta = 1$, the Eq. (13.4) represents the OLS, TLS, and DLS approach, respectively (Marvuglia et al. 2010; SungEun and Sang 2004; Cirrincione et al. 2000).

13.3 The Genetic Algorithms

The GAs were developed by Holland et al. (1975) and belong to the group of evolutionary algorithms, that are heuristic strategies to solve problems of global research, based on the natural evolution theorized by Darwin.

This theory deals with the survival, the development, and the adaptation to the environment of individuals that constitute a population. Darwin highlighted that only the individuals able to adapt to the environment have high possibility to reproduce theirself, handing down their gene pool to the sons.

The starting point of the GA (Haupt RL and Haupt SE 2004; Reeves and Rowe 2003; Sivanandam and Deepa 2008) is a population of individuals that, using mechanism similar to the sexual reproduction and to the genetic mutation, creates new generations more and more adapted to the environment. In the particular case of the inventory problem, the population is constituted by different scaling vectors s, that allow to obtain different eco-profiles g.

The single component of a population, that is a single solution of the scaling vector s, is called chromosome; it represents the genetic information (or genotype) of one possible solution of the problem and is constituted by strings (usually binary strings). Each string, called gene, is generally constituted by values of the binary alphabet (0, 1) and represents a specific character of the chromosome (Chipperfiel et al. 1994).

The steps made by a GA to find an optimal solution of the problem are described in the following (Sivanandam and Deepa 2008; Mitchell 1998):

1. Coding of the problem, that is the transformation of all the possible solutions in strings of constant length. As example, in Fig. 13.1 a binary coding of a chromosome is shown.
2. Creation of a random population in a space of research that is defined by the imposition of specific bonds. The creation function of the algorithm is called "feasible population." The dimension N of the population, that is constant during the genetic evolution, depends on the complexity of the problem.[3] Usually, N is variable from 30 to 100 individuals and, given m the length of the chromosome, it is $N \geq 2\ m$ (Haupt RL and Haupt SE 2004).

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[3] In this case, the complexity of the problem is linked to the dimension of the A matrix.

Fig. 13.1 Coding of a solution of the problem

$$cromosome = \left[\underbrace{1111001001}_{gene_1}\,\underbrace{0011011111}_{gene_2}\ldots\underbrace{0000101001}_{gene_{Nvar}}\right]$$

3. Assessment of the fitness of each chromosome, by means of the fitness function, that gives a score for each individual, which is a measure of the goodness of the solution and an indication on the individuals that are more adapt to the reproduction.
4. Fitness scaling, that converts the raw fitness scores that are returned by the fitness function to values in a specific range, that is suitable for the selection function. The individuals with higher scaled values have a higher probability to be selected as parents for the next generation. Usually the chosen scaling operator is the “rank scaling,” which scales the scores of each individual on the basis of its rank.[4]
5. Creation of a new population:
   - Selection of a couple of chromosomes that represent the parents that will procreate the next generation. This selection is made on the base of the fitness of each chromosome. There are different selection methods. Usually the roulette wheel selection can be used (Chipperfield et al. 1994). It is based on the sum T of the expected values[5] of the N individuals that constitute the population. To apply the method, the following process have to be repeated N times: (1) to choose a casual value r included between 0 and T; (2) to analyze the list of individuals and sum their expected values; and (3) to stop the procedure when, summing the expected value of an individual i, the obtained result is higher than r. The individual i will be chosen as parent.
   - Crossover: the gene pool of the two parents is mixed to generate sons. The percentage of population that is created with the crossover is defined by the “crossover fraction” (variable from 0 to 1). Usually the operator of crossover “arithmetic” was selected; it generates sons starting from an arithmetic mean of the parents:

$$\text{son} = \alpha \text{ parent}_1 + (1 - \alpha) \text{ parent}_2 \tag{13.5}$$

where α is a random number.

- Mutation of the sons’ genes, which generates a random inversion of one or more genes of an individual to create a new son that respects the imposed bonds; it allows to introduce a “noise” in the genetic information and to avoid that the algorithm can be trapped in a local minimum. The mutation function of the algorithm is called “adaptive feasible.”

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[4] Individuals are classified according to their fitness score. The position of an individual in the classification represents its rank.

[5] The expected value of an individual (number of times that is expected that the individual is chosen for the reproduction) is its fitness divided by the medium fitness of the population.

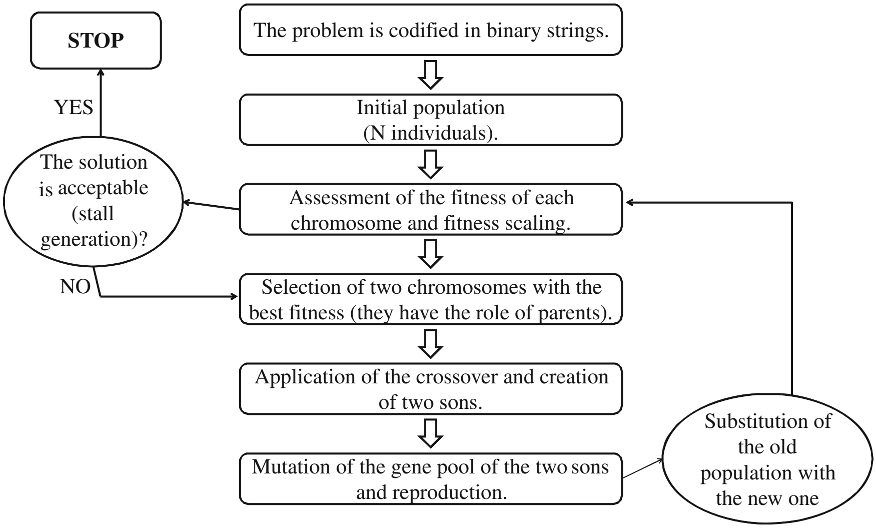

Fig. 13.2 Application of the GA

- Reproduction: the generation of new components of the population can be made, besides with the crossover and the mutation, with an elitist principle: the better individuals that are characterized by the best fitness assessed in the step 3, usually two, of the old generation are copied in the new one.

6. Substitution of the old population with the new one.
7. Repetition of step 3 until the stop of the GA, which occurs when, after a number of generations called *stall generations* and fixed by the analyst, the weighted average change in the fitness function value is less than a fixed tolerance, that usually is 10^{-4}.

The application of the GA is summarized in Fig. 13.2.

13.4 The GA Applied to the Inventory Problem

The application of GA to the inventory problem in the case of multi-output processes allows to find a unique solution of the Eq. (13.1) by the minimization of the objective function (13.4), without using computational procedures such as the allocation.

In detail, the GA can be used in two different cases:

- Case A: the multi-functionality is due to secondary processes. In this case, known the scaling vector s, the GA allows to assess the eco-profile g of one single functional unit. For example, examining the productive process of tiles that uses electricity and heat obtained by cogeneration, the multi-functionality is secondary and the functional unit can be 1 ton of tiles.

- Case B: the multi-functionality characterizes the main process. In this case, the examined functional unit is constituted by all the outputs of the system. For example, if the examined process is the cogeneration of heat and electricity, the GA allows to calculate the eco-profile of a double functional unit constituted by a specific amount of heat and a specific amount electricity.

In both cases, the GA allows to solve the problem starting from a rectangular matrix and avoiding the use of the allocation or other procedures.

The use of GA to solve the inventory problem has been computerized through the construction of a codified procedure in the MatLab software. In this way, it is possible to apply an objective and repeatable computational procedure.

To start the procedure, the analyst has to introduce in the software the A matrix, the B matrix, and the functional unit f. The following parameters have to be introduced:

- ζ: $\zeta = 0$ for the OLS method, $\zeta = 0.5$ for the TLS method, $\zeta = 1$ for the DLS method;
- dimension N of the population, usually from 30 to 100;
- stall generation (from 1 to 600);
- number of multi-functionalities λ.

In this application, the GA is used to minimize the TLS and DLS objective functions, described in the Sect. 13.2. The OLS function is ruled-out being not realistic the hypothesis to distribute the error only in the f vector.

The use of GA allows to calculate the following items:

- the solution vector s_{AG};
- the functional unit vector $\tilde{f}$, corresponding to s_{AG}, that is different from the functional unit vector f because of the LS method provides an approximate fit of the real solution of the problem and not the exact solution;
- the discrepancy vector $d = f—\tilde{f}$;
- the residual, that is the Euclidean norm $\|d\|_2$ of the discrepancy:

$$||d||2 = \left[\sum\nolimits_{i=1}^{p} (d_i)^2\right]^{1/2} \tag{13.6}$$

where p is the number of components of the discrepancy vector d.

To help the GA in the research of the best solution, avoiding the stall in local minima, a specific bond is imposed on the inventory vector g_{GA}:

$$g_{\mathrm{DOWN}} \leq g_{\mathrm{GA}} \leq g_{\mathrm{UP}} \tag{13.7}$$

The GA searches the best solution, respecting the bond described in 13.7.

The two vectors g_{DOWN} and g_{UP} are calculated automatically by the software simulating an allocation procedure of the A matrix and varying, for each multi-functionality, all the allocation and/or the corrective factors from 0 to 1, so that their sum is 1. From all the possible g vectors obtained, the algorithm selects the two that have the minima and maxima values.

The definition of the bond allows to reduce the space of research and the calculation time. In addition, it allows to calculate a unique solution physically acceptable, which respects the energy and mass balances, and mathematically acceptable, that minimizes the residual.

In order to assess the validity of the GA approach, in this first experimentation on the use of GA, the solution obtained with its application is compared with those obtained using computational procedures as the allocation and the substitution method.

13.4.1 The Case Study

The GA approach is applied to solve the inventory problem for a multi-functional problem in an ancillary case study related to a cogeneration process (De Gaetano 2012), where electricity and heat are produced using 8000 kWh of natural gas. The process allows to transform the 37 % of natural gas in electricity (2,960 kWh) and the 53 % in heat (4,240 kWh). The 10 % of energy is losses during the process.

The two energy outputs of the process are characterized by a different quality. In this case study, the functional unit is constituted by two outputs (electricity and heat). The two outputs have to be characterized by the same unit of measure and by the same quality. Then, to make comparable electricity and heat, they are transformed in primary energy E_p, using a conversion factor of 1.16 for heat and of 2.17 for electricity (Italian Authority for electricity and natural gas 2008): $E_{p,\text{heat}} = 4.92$ MWh; $E_{p,\text{electricity}} = 6.42$ MWh.

The examined cogeneration processes is constituted by 18 processes, 22 economic flows, and 17 environmental flows and it is partially derived from (Prè 2010) and partially elaborated by authors. In Appendix, the A matrix (Table 13-A.1) for the cogeneration process is shown. The B matrix and further details on the case study can be found in (De Gaetano 2012).

The f vector is:

$$f_i = \left\{ \begin{array}{r} 0\text{–with\_i} = 1, \ldots, 20 \\ 6.42\text{–with\_i} = 21 \\ 4.92\text{–with\_i} = 22 \end{array} \right\} \tag{13.8}$$

The authors hypothesized that the examined system is characterized by the following multi-functionalities:

- Co-production of electricity and heat;
- Co-production of diesel and light fuel oil;
- Co-production of copper and recycled copper.

In order to assess the reliability of the results obtained applying the GA, they are compared with those obtained applying the allocation and the substitution methods described in the Sect. 13.1.

The allocation and the substitution methods are applied as described in the following:

- The co-production of electricity and heat is removed with the allocation considering that the electricity and the heat represent, respectively, the 57 % and the 43 % of the total primary energy in output (that is 11.34 MWh). Then, the used allocation factors are 0.57 for electricity, 0.43 for heat. Because of the cogeneration process has a third output, that is the recycled lubricant oil, it is removed with the substitution method using a corrective factor of 0.6.
- The co-production of diesel and light fuel oil is removed with the allocation based on the energy content of the two outputs. In detail, considering a calorific value of 45.66 MJ/kg for diesel and of 44.4 MJ/kg for light fuel oil (IEC 2008), the used allocation factors are 0.58 for diesel and 0.42 for light fuel oil.
- The co-production of copper and recycled copper are removed with the substitution method, considering a corrective factor of 0.7. The square *A* matrix obtained using the allocation and the substitution methods is shown in Appendix (Table 13-A.2).

The application of GA starts with the construction of the bonds, which have to be imposed to orient the GA in the research of the best solution.

The imposed bonds g_{DOWN} and g_{UP} are shown in Table 13.2, while Table 13.3 reports the genetic parameters chosen for the application of the GA. The operators of Table 13.3 are selected according to the description made in the Sect. 13.3. The other genetic parameters are chosen by the authors, following the indications given in the Sect. 13.3.

Figures 13.3 and 13.4 show the trend of the medium value and the best fitness for each generation of solutions in the TLS and DLS approach, respectively. It can be noted that the algorithm converges immediately, thanks to the limited space of research imposed by the bonds. Since the first iterations, the medium fitness of each population is near the fitness of the best individual. This indicates a fast convergence of the GA and a fast reduction of the diversity of the individuals.

The comparison between the *s* vector obtained with allocation and substitution methods and those obtained with the GA for the TLS and the DLS functions is shown in Table 13.4, while the obtained *g* vectors are shown in Table 13.5.

The *g* vectors obtained with the three methods are very similar, due to the imposed bonds that reduce the space in which the GA searches the solution and they are included in the range given by the bonds g_{up} and g_{down}.

The rightmost columns of Table 13.5 show the percentage difference between the inventory vector obtained with the GA and those obtained with the allocation. This percentage is very low (<0.5 %) for both AG_{TLS} and AG_{DLS}, with some exceptions, where it varies from about 1.5 % to about 3 %.

Table 13.2 The imposed bonds on the eco-profile vector

		g_{DOWN}	g_{UP}
Air emissions (kg)	CO_2, fossil	1958.224	1959.320
	CO, fossil	5.4052	5.4070
	NO	0.1565	0.1565
	CH_4, fossil	11.550	11.554
	NO_x	2.9216	2.9255
	NMVOC	0.937	0.944
	Particulates	0.0312	0.0316
Water emissions (kg)	SO_2	0.914	0.923
	BOD_5	0.200	0.231
	Chloride	5.4212	5.5064
	Nitrates	8.09E − 04	8.29E − 04
	Oils	0.0532	0.0629
Soil emissions (kg)	Ca	0.0168	0.0171
	F	2.17E − 04	2.2E − 04
	Fe	9.29E − 03	9.43E − 03
	Mg	3.35E − 03	3.41E − 03

Table 13.3 Genetic parameters of the GA in the TLS and DLS methods

Genetic parameter	Value: TLS method	Value: DLS method
Dimension of population	50	50
Operator "creation"	Feasible population	Feasible population
Operator "fitness scaling"	Rank scaling	Rank scaling
Operator "selection"	Roulette wheel selection	Roulette wheel selection
Operator "crossover"	Arithmetic crossover	Arithmetic crossover
Operator "mutation"	Adaptive feasible	Adaptive feasible
Crossover fraction	0.4	0.65
Elitism	2	2
Termination	Stall generation = 250	Stall generation = 250

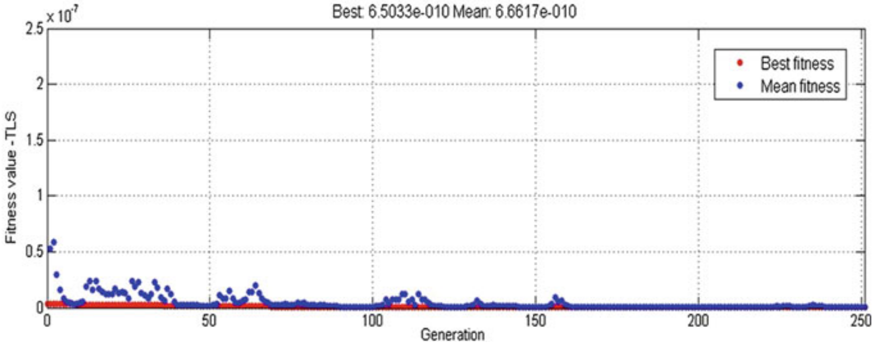

Fig. 13.3 Medium value and best fitness for each generation of solutions in the TLS approach

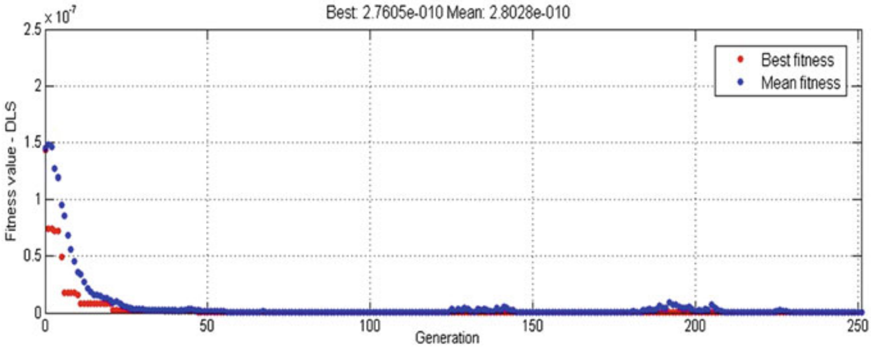

Fig. 13.4 Medium value and best fitness for each generation of solutions in the DLS approach

Table 13.4 Scaling vectors *s*

Process	*s* vector: allocation	*s* vector:AG_{TLS}	*s* vector: AG_{DLS}
Cogen. unit, components for electricity	1.48E − 04	5.48E − 04	3.57E − 04
Generator	1.85E − 04	1.16E − 05	6.96E − 05
Cast iron	0.285	9.31E − 03	0.088
Copper	0.035	0.002	0.034
Natural gas, burned in industrial furnace	3.054	0.12	1.099
Electricity, medium voltage	0.412	0.117	0.296
Iron scrap	0.118	0.034	0.081
Natural gas, low pressure	30495.08	30490.37	30490.78
Cogen. unit, components for heat	1.34E − 04	1.66E − 04	1.67E − 04
Cogen. unit, components for electricity and heat	1.40E − 04	1.21E − 04	1.29E − 04
Lubricating oil	0.649	0.394	0.536
Electricity, low voltage	0.01	0.03	0.047
Electricity, high voltage	0.416	0.059	0.302
Gas motor	1.75E − 04	1.91E − 06	5.93E − 05
Diesel	0.863	0.193	0.451
Light fuel oil	0.053		
Steel	0.035	0.011	0.046
Water	7.09E − 04	0.016	0.025
Electricity	1	0.9998	0.9999
Heat	1		

This implies that the GA gives a good solution of the inventory problem, working with a rectangular matrix and avoiding the use of the allocation procedure.

Each of the three methods (allocation, AG_{TLS} and AG_{DLS}) produces a functional unit $\tilde{f}$ that not fully agrees with the functional unit *f*. The obtained functional units $\tilde{f}$ are shown in Table 13.6. The discrepancy vector *d* obtained for each

Table 13.5 Eco-profile vectors g for the functional unit constituted by 6.42 MWh of electricity and 4.92 MWh of heat

Environmental flows	$g_{\text{allocation}}$ (kg)	g_{AGTLS} (kg)	g_{AGDLS} (kg)	g_{AGTLS}-$g_{\text{allocation}}$ (%)	g_{AGDLS}-$g_{\text{allocation}}$ (%)
CO_2, fossil	1958.658	1959.32	1959.106	0.034	0.023
CO, fossil	5.406	5.406	5.407	−0.001	0.022
NO	0.156	0.156	0.156	−0.003	0.002
CH_4, fossil	11.552	11.55	11.551	−0.013	−0.007
NO_x	2.923	2.922	2.924	−0.027	0.034
NMVOC	0.94	0.937	0.939	−0.303	−0.095
Particulates	0.031	0.031	0.031	−0.178	0.401
SO_2	0.917	0.92	0.92	0.282	0.284
BOD_5	0.213	0.207	0.213	−2.681	−0.057
Chloride	5.457	5.443	5.4574	−0.256	0.017
Nitrates	0.0008	0.0008	0.0008	1.447	1.964
Oils	0.0571	0.0553	0.0057	−3.17	−0.124
Ca	0.0169	0.0168	0.0169	−0.32	0.001
F	0.0002	0.0002	0.0002	−0.354	0
Fe	0.0093	0.0093	0.0094	−0.2	−0.122
Mg	0.0034	0.0034	0.0034	−0.315	−0.01

Table 13.6 Functional units $\tilde{f}$

Process	$\tilde{f}$allocation	$\tilde{f}AG_{TLS}$	$\tilde{f}AG_{DLS}$
Cogen. unit, components for electricity	1.36E − 20	4.0E − 04	2.1E − 04
Generator	−8.13E − 20	−6.7E − 04	−3.7E − 04
Cast iron	−1.11E − 16	5.0E − 04	−1.2E − 02
Copper	−6.94E − 18	7.0E − 04	2.0E − 04
Natural gas, burned in industrial furnace	−2.22E − 16	−1.0E − 04	5.0E − 04
Electricity, medium voltage	5.12E − 17	−5.3E − 02	4.4E − 03
Iron scrap	5.55E − 17	2.9E − 02	3.9E − 02
Natural gas, low pressure	−1.82E − 12	−7.0E − 04	−3.6E − 03
Cogen. unit, components for heat	6.78E − 21	3.2E − 05	3.2E − 05
Cogen. unit, components for electricity and heat	0	−1.9E − 05	−1.1E − 05
Lubricating oil	5.55E − 17	−0.5	−0.4
Electricity, low voltage	3.04E − 18	−2.7E − 02	4.0E − 02
Electricity, high voltage	0	−5.9E − 02	2.1E − 03
Gas motor	2.71E − 20	−1.0E − 04	−1.0E − 04
Diesel	−2.22E − 16	−0.3	−0.2
Light fuel oil	0	0.1	0.3
Steel	−6.94E − 18	1.0E − 02	3.4E − 02
Water	1.08E − 19	1.6E − 02	2.4E − 02
Electricity	6.437	6.436	6.436
Heat	4.91	4.916	4.916

Table 13.7 Discrepancy vector d and Euclidean norm $||d||_2$

Economic flow	$d_{allocation}$	d_{AGTLS}	d_{AGDLS}
Cogen. unit, components for electricity (unit)	−1.36E − 20	−4.00E − 04	−2.09E − 04
Generator (unit)	8.13E − 20	6.73E − 04	3.76E − 04
Cast iron (kg)	1.11E − 16	−5.18E − 04	1.25E − 02
Copper (kg)	6.94E − 18	7.44E − 04	−2.04E − 02
Recycled copper (kg)	–	8.69E − 05	−8.19E − 03
Natural gas, burned in industrial furnace (MJ)	2.22E − 16	7.73E − 05	−5.03E − 04
Electricity, medium voltage (kWh)	−5.12E − 17	5.36E − 02	−4.40E − 03
Iron scrap (kg)	−5.55E − 17	−2.97E − 02	−3.89E − 02
Natural gas, low pressure (MJ)	1.82E − 12	6.93E − 04	3.57E − 03
Cogen. unit, components for heat (unit)	−6.78E − 21	−3.16E − 05	−3.22E − 05
Cogen. unit, components for electricity and heat (unit)	0	1.85E − 05	1.07E − 05
Lubricating oil (kg)	−5.55E − 17	5.20E − 01	3.78E − 01
Recycled lubricant oil (kg)		−4.43E − 01	−4.43E − 01
Electricity, low voltage (kWh)	−3.04E − 18	−2.69E − 02	−4.00E − 02
Electricity, high voltage (kWh)	0	5.99E − 02	−2.11E − 03
Gas motor (unit)	−2.71E − 20	1.49E − 04	1.02E − 04
Diesel (kg)	2.22E − 16	3.31E − 01	2.62E − 01
Light fuel oil (kg)	0	−1.39E − 01	−3.16E − 01
Steel (kg)	6.94E − 18	−1.09E − 02	−3.45E − 02
Water (kg)	−1.08E − 19	−1.62E − 02	−2.47E − 02
Electricity (MWh of primary energy)	0	9.94E − 04	9.06E − 06
Heat (MWh of primary energy)	0	7.59E − 04	6.92E − 04
	$\|\|d\|\|_{2\mathrm{allocation}}$	$\|\|d\|\|_{2AGDLS}$	$\|\|d\|\|_{2AGDLS}$
Euclidean norm $\|\|d\|\|_2$	**1.82E − 12**	**0.78**	**0.72**

method is shown in Table 13.7. It is calculated using data shown in (13.8) and in Table 13.6.

It can be observed that the lower d vector is related to the allocation method, with values lower than 1*E^{-12}, and this can explained as artifacts due to round-off (Heijungs and Suh 2002). Discrepancy vectors lower than 1*E^{-01} are obtained with the TLS and DLS methods. This result indicates that the functional unit $\tilde{f}$ obtained with the GA is very similar to the real functional unit f.

The Euclidean norm for the TLS and the DLS methods is 0.78 and 0.72, respectively.

The Euclidean norm obtained with the traditional methods (allocation and substitution) and that obtained with the GA approach are lower than 1. In addition, the low value of the d vector indicates that the GA approach is reliable.

Furthermore, it is important to outline that while the traditional solution can vary significantly with the choice of allocation or corrective factors, the solution based on the GA is unique and it shows the eco-profile of a double functional unit, constituted by electricity and heat.

13.5 Conclusions

The application of the GA represents an innovative approach to obtain a reliable solution of the inventory problem in the case of multi-functional processes.

The advantage to use the GA approach consists in the possibility to avoid the application of allocation procedure, substitution method, and/or system expansion to transform the rectangular *A* matrix in a square, and thus invertible, matrix.

The case study examined in this chapter compares the solution obtained with the traditional methods (allocation and substitution methods) and that obtained with the GA approach for a cogeneration system, characterized by three multi-functional processes, with a 22 × 18 rectangular *A* matrix.

The obtained results highlighted that the eco-profiles calculated with the GA approach are not affected by subjective choices made by the analyst, with the only exception of some genetic parameters (e.g., the dimension of population). Instead, the eco-profiles obtained with traditional methods are significantly affected by the choices of the analyst, as the allocation factors.

In conclusion, the GA approach shows interesting features for solving the inventory problems characterized by a rectangular matrix by the application of a codified procedure which limits the introduction of subjective assumptions that can affect the final results of the analysis.

Appendix

Tables (13-A.1, 13-A.2)

Table 13-A1 Rectangular *A* matrix of the cogeneration process

Processes Economic flows	A	B	C	D-E	F	G	H	I	J	K	L-M	N	O	P	Q-R	S	T	U-V
A	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−1.5E − 04
B	−1.25	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	−595	1	0	0	0	0	0	0	0	0	0	0	−1000	0	0	0	0
D	0	−200	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	−55	0	0.35	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	−9080	0	0	1	0	0	0	0	0	0	0	0	−7880	0	0	0	0
G	0	−185	−0.42	0	0	1	−0.01	0	0	0	−0.3	−1.1	0	−161	0	0	−3.9E − 04	0
H	0	0	−0.39	−0.22	0	0	1	0	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	−3.0E + 04
J	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	−1.3E − 04
K	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−1.4E − 04
L	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	−0,91
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,44
N	0	0	0	0	−0.001	0	0	0	0	0	0	1	0	0	−0.013	0	0	0
O	0	0	0	0	0	−1.01	0	0	0	0	0	0	1	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	−1.25	0	0	0	1	0	0	0	0
Q	0	0	0	0	0	0	0	0	0	0	−1.3	0	0	0	1	0	0	0
R	0	−210	0	0	0	0	0	0	0	0	0	0	0	0	0.732	0	0	0
S	0	0	0	0	0	0	0	0	0	0	0	0	0	−200	0	1	0	0
T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−0.001	0	1	0
U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.42
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.92

A Cogen. unit, components for electricity (unit); *B* Generator (unit); *C* Cast iron (kg); *D* Copper (kg); *E* Recycled copper (kg); *F* Natural gas, burned in industrial furnace (MJ); *G* Electricity, medium voltage (kWh); *H* Iron scrap (kg); *I* Natural gas, low pressure (MJ); *J* Cogen. unit, components for heat (unit); *K* Cogen. unit, components for electricity and heat (unit); *L* Lubricating oil (kg); *M* Recycled lubricating oil (kg); *N* Electricity, low voltage (kWh); *O* Electricity, high voltage (kWh); *P* Gas motor (unit); *Q* Diesel (kg); *R* Light fuel oil (kg); *S* Steel (kg); *T* Water (kg); *U* Electricity (MWh of primary energy); and *V* Heat (MWh of primary energy)

Table 13-A.2 Square *A* matrix of the cogeneration process

Processes Economic flows	A	B	C	D	F	G	H	I	J	K	L	N	O	P	Q	R	S	T	U	V
A	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−8.5E − 05	−6.4E − 05
B	−1.25	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	−595	1	0	0	0	0	0	0	0	0	0	0	−1000	0	0	0	0	0	0
D	0	−238.5	0	1.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	−9080	0	0	1	0	0	0	0	0	0	0	0	−7880	0	0	0	0	0	0
G	0	−185	−0.42	0	0	1	0.01	0	0	0	−0.3	−1.1	0	−161	0	0	0	−3.9E − 04	0	0
H	0	0	−0.39	−0.22	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	−17E + 03	−13E + 03
J	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	−7.4E − 05	−5.6E − 05
K	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	−8.0E − 05	−6.0E − 05
L	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−0.7	−0.5
N	0	0	0	0	−0.001	0	0	0	0	0	0	1	0	0	−7.5E − 03	-5.4E − 03	0	0	0	0
O	0	0	0	0	0	−1.01	0	0	0	0	0	0	1	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	−1.25	0	0	0	1	0	0	0	0	0	0
Q	0	0	0	0	0	0	0	0	0	0	−1.3	0	0	0	1	0	0	0	0	0
R	0	−210	0	0	0	0	0	0	0	0	0	0	0	0	0	0.732	0	0	0	0
S	0	0	0	0	0	0	0	0	0	0	0	0	0	−200	0	0	1	0	0	0
T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−5.8E − 04	−4.2E − 04	0	1	0	0
U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.42	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.92

A Cogen. unit, components for electricity (unit); *B* Generator (unit); *C* Cast iron (kg); *D* Copper (kg); *F* Natural gas, burned in industrial furnace (MJ); *G* Electricity, medium voltage (kWh); *H* Iron scrap (kg); *I* Natural gas, low pressure (MJ); *J* Cogen. unit, components for heat (unit); *K* Cogen. unit, components for electricity and heat (unit); *L* Lubricating oil (kg); *N* Electricity, low voltage (kWh); *O* Electricity, high voltage (kWh); *P* Gas motor (unit); *Q* Diesel (kg); *R* Light fuel oil (kg); *S* Steel (kg); *T* Water (kg); *U* Electricity (MWh of primary energy); and *V* Heat (MWh of primary energy)

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Chapter 14
Design and Implementation of Maximum Power Point Tracking Algorithm Using Fuzzy Logic and Genetic Algorithm

Adnane Messai and Adel Mellit

Abstract Recent advances in artificial intelligent techniques embedded into a field programmable gate array (FPGA) allowed the application of such technologies in real engineering problems (robotic, image and signal processing, control, etc.). However, the application of such technologies in the solar energy field is relatively limited. The embedded intelligent algorithm into FPGA can play a very important role in the control of solar energy systems. In this chapter, an intelligent approach based fuzzy logic and genetic algorithm (GA) is developed using a description language (VHDL standing for VHSIC Hardware Description Language), and then is implemented into FPGA-Xilinx (Virtex-II-Pro xc2v1000-4fg456) chip to track the maximal power point (MPP) in a (PV) photovoltaic module. ModelSim-based simulation results confirm the effectiveness of the designed approach in tracking the MPP. In addition, it has been demonstrated that the employed FPGA chip is largely sufficient to implement the designed approach.

14.1 Introduction

The grow of photovoltaic (PV) electricity generation is one of the highest in the field of the renewable energies and as the PV price drops this tendency is expected to increase in the next years (IEA 2010). By 2050, PV will provide 11 % of global electricity production (4,500 TWh per year), corresponding to 3,000 GW of cumulative installed PV capacity.

A typical PV system consists of two main parts: the PV generator which converts irradiation into DC power and the power stage that converts the DC

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current and voltage into sinusoidal AC ones. The efficiency of the most common solar cells is in the range (14–20 %), while excess the 30 % at laboratory level.

The main task of research in power electronics is to guarantee as much of this PV energy as possible to the load. In particular, a good maximal power point (MPP) tracker is fundamental because DC current and voltages are much dependent on weather changes (Mellit et al. 2011). To enhance the conversion efficiency of the electric power generation, a maximum power point tracking (MPPT) module is usually integrated with the PV power installations so that the PV arrays will be able to deliver the maximum power available in a given environmental conditions.

In the last decade, several researches have focused on various MPP algorithms to track the maximum power of the PV array (Salas et al. 2006). These algorithms vary in many aspects, such as simplicity, required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation, and popularity.

Intelligent methods perform better but are generally complicated to implement; they also require relatively high performance processor. Since the functions of various components can be integrated onto the same chip. The employment of FPGAs platform as digital controller for PV systems offers many advantages over others platforms like digital signal processors (DSP), and Microcontroller (Ruelland et al. 2003; Messai et al. 2011a). The most significant FPGA's features are reprogrammability, high speed operation, rapid prototyping, adaptability, low power consumption, large capacity and flexibility in modifying the designed circuit. FPGA can greatly improve system integration, enhance system reliability, and reduce system cost. Furthermore, it has been demonstrated that, FPGA board enables to make easy, fast, and flexible design and implementation, especially in the case of advanced algorithm (Messai et al. 2011a; Zhang and Guo 2009).

Due to their heuristic nature associated with simplicity and effectiveness, for both linear and nonlinear systems, fuzzy logic controller (FLC) methods have showed their salient features in implementations for MPP seeking. Hence, many studies and applications have been proposed, combining MPP tracking and FLC (Godoy and Franceschetti 1999; Mellit and Kalogirou 2008; Messai et al. 2011b).

This chapter aims to present a detailed description of an intelligent approach to track the MPP in a PV module as well as to demonstrate the feasibility of its hardware implementation into a reconfigurable FPGA chip. Genetic Algorithm (GA) is used to choose optimally and simultaneously both membership functions and control rules for the FLC. The procedure followed makes the design of this type of MPP trackers simpler and more efficient.

First, Matlab/Simulink environmental is used to simulate and verify the developed approach. Second, a hardware description language HDL veryhigh-speed integrated circuit (VHSIC) is used to design the different part of the overall system. Finally, the ISE tools of Xilinx and ModelSim software are used to simulate and to check the implementation feasibility of the designed GA-FLC into a FPGA chip (Virtex-II-Pro xc2v1000-4fg456).

14.2 PV Module Modeling

A PV cell generates directly electrical power when illuminated by photons. The P–N junction, which is the core of the PV cells, has the capacity to absorb the solar radiation and make the photon to electron–hole conversion. This occurs when the photon carries an energy exceeding the material band-gap. When a load is connected with the solar cell, the collected separated charges flow through it in a direct current until the light stops (SERI 1982).

Figure 14.1 shows an equivalent electric circuit of the well-known one diode model, it consists of a constant current source, in parallel with a diode, which includes an ideality factor to account for the recombination in the space-charge region, series, and shunt resistances. PV module consists of series connection of solar cells (Markvart 1994).

The I–V equation of PV module is given as:

$$I = I_{\mathrm{ph}} - I_0\left(e^{\frac{V+\mathrm{IR}_s}{n_s V_t}} - 1\right) - \frac{V + \mathrm{IR}_s}{R_{\mathrm{sh}}} \tag{14.1}$$

where $V_t = \frac{n_s \mathrm{AkT}}{q}$ is the module thermal voltage, R_s is the module internal series resistance (Ω), R_{sh} is the module shunt resistance (Ω), I_0 is the dark saturation current (A), n_s is the number of series connected cells in the module, q is the charge of an electron (C), q is the Boltzmann's constant, A is the diode ideality factor, T is the temperature (°K), and I_{ph} is the photo-generated current (A).

For modeling purposes, the Newton–Raphson method is adopted in this work, which relies on parameters given in the panels' datasheet. As example Fig. 14.2

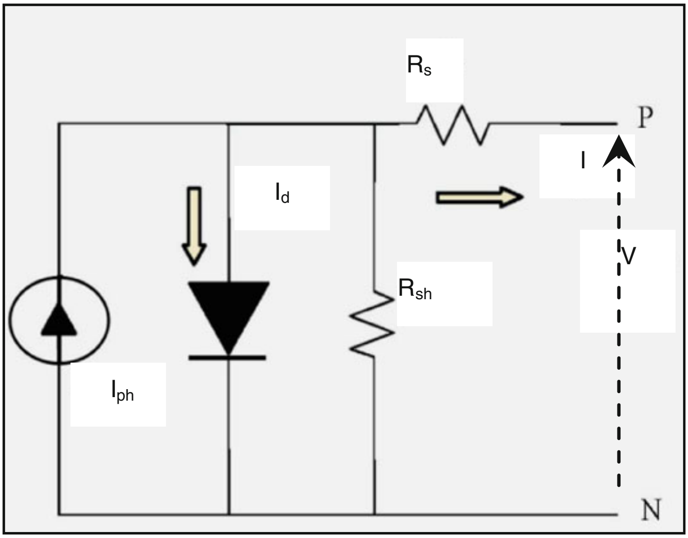


Fig. 14.1 The equivalent electrical circuit of one diode model

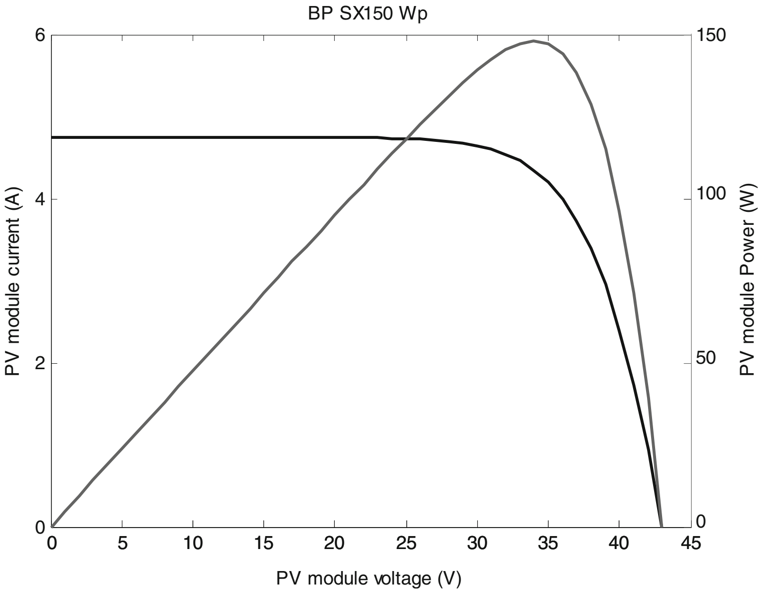


Fig. 14.2 I–V and P–V characteristics of the used PV module (BP SX150)

Table 14.1 PV module specifications

Designation	BP SX150
Maximum power (P_{max})	150 watts
Voltage at Pmax (V_{max})	34.5 volts
Current at Pmax (I_{max})	4.35 amps
Short-circuit current (I_{sc})	4.75 amps
Open-circuit voltage (V_{oc})	43.5 volts

shows, the I–V and P–V characteristics of the employed PV module (BP S × 150). PV module specifications are reported in Table 14.1.

Normally, in an operation of a PV system, there is a single maximum power point (MPP) with the specified temperature and the light intensity (Markvart 1994).

14.3 Fuzzy Logic and Genetic Algorithm

14.3.1 Fuzzy Logic

Fuzzy set (FS) theory is a generalization of conventional set theory and was introduced by Zadeh in 1965. It provides a mathematical tool for dealing with linguistic variables associated with natural languages. Systematic descriptions of

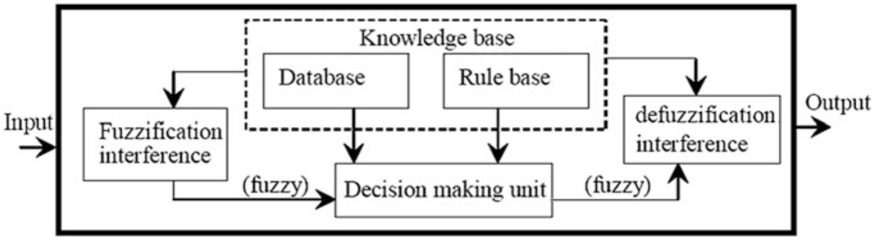


Fig. 14.3 Flow diagram of fuzzy inference system (Lakhmi and Martin 1998)

these topics can be found in several texts (Bellman and Zadeh 1977; Dubois and Prade 1980; Kaufmann and Gupta 1985). A central notion of fuzzy set theory, as described in the following sections, is that it is permissible for elements to be only partial elements of a set rather than full membership. Figure 14.3 shows the flowchart of fuzzy inference system. The development of fuzzy logic was motivated by the need for a conceptual framework which can address the issue of uncertainty and lexical imprecision. Some of the essential characteristics of fuzzy logic relate to the following (Robert 1995; Machado and Rocha 1992):

- In fuzzy logic, exact reasoning is viewed as a limiting case of approximate reasoning;
- In fuzzy logic, everything is a matter of degree;
- In fuzzy logic, knowledge is interpreted as a collection of elastic or, equivalently, fuzzy constraint on a collection of variables;
- Inference is viewed as a process of propagation of elastic constraints;
- Any logical system can be fuzzified.

There are two main characteristics of fuzzy systems that give them better performance for specific applications:

- Fuzzy systems are suitable for uncertain or approximate reasoning, especially for the system with a mathematical model that is difficult to derive;
- Fuzzy logic allows decision making with estimated values under incomplete or uncertain information.

Zadeh stated that the attempts to automate various types of activities from assembling hardware to medical diagnosis have been impeded by the gap between the way human beings reason and the way computers are programmed. Fuzzy logic uses graded statements rather than ones that are strictly true or false. It attempts to incorporate the “rule of thumb” approach generally used by human beings for decision making. Thus, fuzzy logic provides an approximate, but effective way of describing the behavior of systems that are not easy to describe precisely.

FLCs, for example, are extensions of the common expert systems that use production rules like “if–then” statements. With fuzzy controllers, however, linguistic variables like “tall” and “very tall” might be incorporated in a traditional expert system. The result is that fuzzy logic can be used in controllers that are capable of making intelligent control decisions in sometimes volatile and rapidly changing problem environments. Fuzzy logic techniques have been successfully applied in a number of applications like, computer vision, control, decision making and system design including ANN training

14.3.2 Genetic Algorithms

GAs were envisaged by Holland (1975) in the 1970s as an algorithmic concept based on a Darwinian-type survival of the fittest strategy with sexual reproduction, where stronger individuals in the population have a higher chance of creating an offspring. A GA is implemented as a computerized search and optimization procedure that uses the principles of natural genetics and natural selection. The basic approach is to model the possible solutions to the search problem as strings of ones and zeros. Various portions of these bit-strings represent parameters in the search problem. If a problem-solving mechanism can be represented in a reasonably compact form, then GA techniques can be applied using procedures to maintain a population of knowledge structure that represent candidate solutions and then let that population evolve over time through competition (survival of the fittest and controlled variation). The practicality of using a GA to solve complex problems was demonstrated by (Michalewicz 1992; Dejong 1975; Goldberg 1989; Colin and Jonathan 2002). Under this paradigm, a population of chromosomes evolves over a number of generations through the application of genetic operators, like crossover and mutation that mimic those found in nature. The evolution process allows the best chromosomes to survive and mate from one generation to the next. Actually, the GA is an iterative procedure that maintains a population of P candidate members over many simulated generations. The GA will generally include three fundamental genetic operations: selection, crossover, and mutation. These operations are used to modify the chosen solutions and select the most appropriate offspring to pass on to succeeding generations. The life cycle of such populations and the recombination of the parental and mutation are illustrated in Fig. 14.4a and b.

GAs consider many points in the search space simultaneously and have been found to provide a rapid convergence to a near optimum solution in many types of problems; they usually exhibit a reduced chance of converging to local minima. GAs show promise but suffer from the problem of excessive complexity if used on problems that are too large. GAs are an iterative procedure that consists of a constant-sized population of individuals, each one represented by a finite linear string of symbols, known as the genome, encoding a possible solution in a given problem space. This space, referred to as the search space, comprises all possible solutions to the optimization problem at hand. In standard GAs, the initial population of individuals is generated at random. At every evolutionary step, also known as a generation, the individuals in the current population are decoded and evaluated according to a fitness function set for a given problem. The expected number of times an individual is chosen is approximately proportional to its

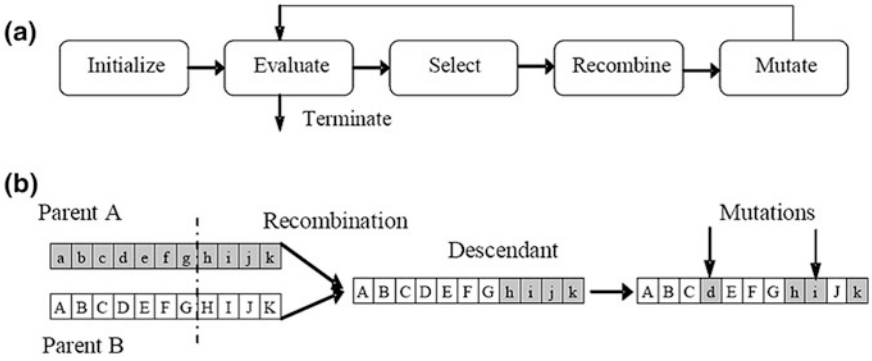


Fig. 14.4 **a** Life cycle of populations. **b** Recombination and mutation (Kalogirou 2003; Mellit and Kalogirou 2008)

relative performance in the population. Crossover is performed between two selected individuals by exchanging part of their genomes to form new individuals. The mutation operator is introduced to prevent premature convergence. Every member of a population has a certain fitness value associated with it, which represents the degree of correctness of that particular solution or the quality of solution it represents. The initial population of strings is randomly chosen. The strings are manipulated by the GA using genetic operators, to finally arrive at a quality solution to the given problem (Kalogirou 2003, 2007).

14.4 Methodology

With reference to Fig. 14.5, the MPPT system scheme includes: a PV module, an Analog–Digital converter, a step-up DC–DC converter, a resistive load and a MPPT control unit (inside the FPGA).

The control circuit allows to follow the MPP by checking the actual PV module voltage V_0 and power P_0 in one switching period and driving a DC–DC boost converter in order to oscillate around the voltage $V_{\max}$ corresponding to the actual MPP. Figure 14.6 depicts the electrical circuit of the step-up DC–DC converter, which is generally used in such PV system setups.

The power MOSFET is usually used as a switching device since it is easy to control and can be operated at high frequencies. The power flow is thus controlled by varying the on/off duty cycle of the switching period. The average output voltage V_0 is determined by the equation (Simoes et al. 1998):

$$\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}} = \frac{1}{1 - D} \tag{14.2}$$

where D is the duty cycle of the switching period.

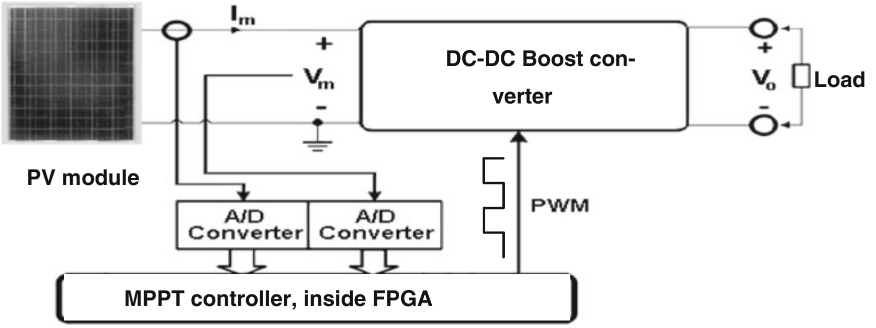
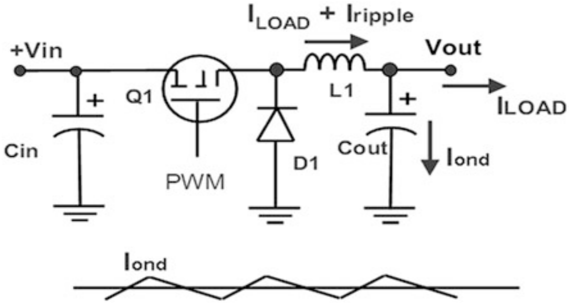


Fig. 14.5 PV system configuration with MPPT control unit (Messai et al. 2011a)

Fig. 14.6 The employed step-up DC–DC converter (Mellit et al. 2011)



14.4.1 MPPT-Based FLC

The MPPT using the (FLC) approach is designed in a manner that the control task try continuously to move the operation point of the solar array as close as possible to the MPP (Khaehintung et al. 2004; Messai et al. 2011b).

$$E(n) = \frac{p(n) - p(n-1)}{V(n) - V(n-1)} \tag{14.3}$$

$$\Delta E(n) = E(n) - E(n-1) \tag{14.4}$$

where E and ΔE are the error and the change in error, respectively, n is the sampling time, while $p(n)$ is the instant power delivered by the PV module, and $V(n)$ is the instant voltage.

The inputs are chosen so that the instant value of $E(n)$ shown the load operation power point's direction. It is possible to know if the operating point stays in a zone where the derivative of the P–V characteristic is positive or negative, while $\Delta E(n)$ shows in which direction the load operation power point moves (Messai et al. 2011b).

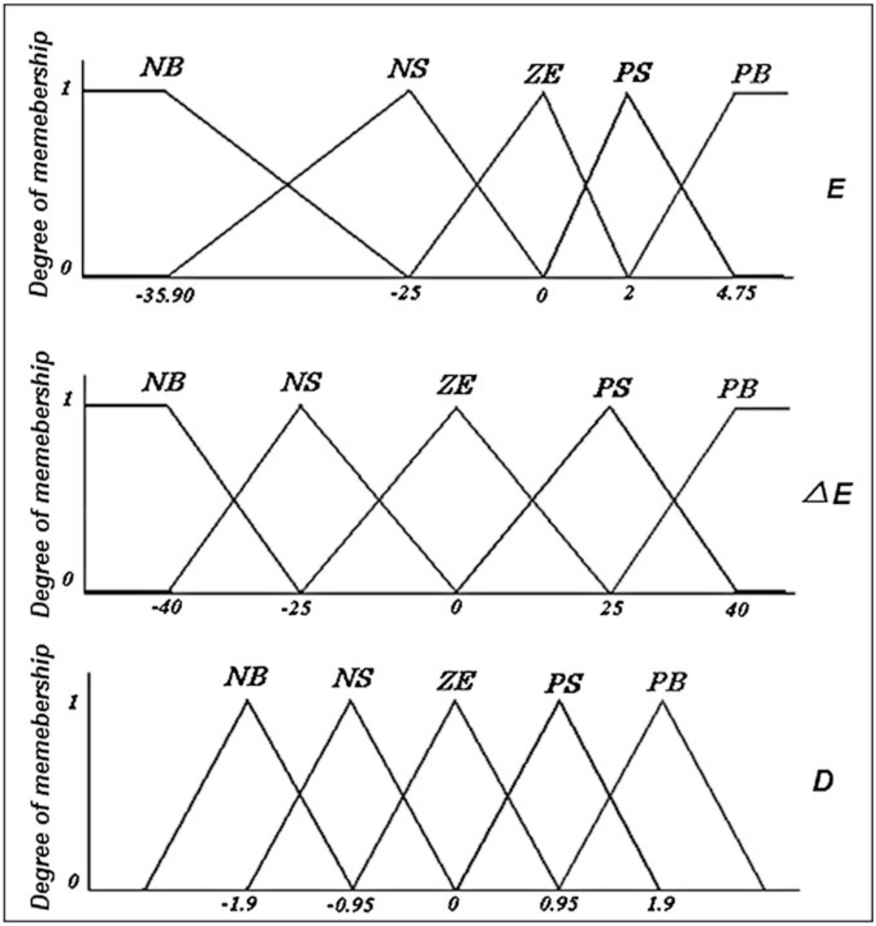


Fig. 14.7 Membership functions for inputs and output of fuzzy logic controller (Messai et al. 2011b)

Rules describing any fuzzy controller operation are expressed as linguistic variables represented by fuzzy sets. The controller output is obtained by applying an inference mechanism defined by (Jiménez et al. 1995):

- the kind of membership functions;
- the connectives used to link the rules antecedents;
- the implication function chosen;
- the rule aggregation operator.

Figure 14.7 shows the membership functions of the input variables (E, ΔE) and the output variable (D) adopted for the design and the implementation of our FLC.

The output variable is the pulse width modulation (PWM) signal so-called the duty cycle D, which is transmitted to the step-up DC–DC converter to drive the load. After the rules have been applied, the center of area as the defuzzication method is used to find the actual value of (D) which is given by the following equation (Messai et al. 2011b; Chekired et al. 2011):

$$D = \frac{\sum_{j=1}^{n} \mu(D_j) - D_j}{\sum_{j=1}^{n} \mu(D_j)} \tag{14.5}$$

Five linguistic variables (NB, NS, ZE, PS, PB) are adopted for each of the three input/output variables. Where NB stands for Negative Big and NS: Negative Small, ZE: Zero, PS: Positive Small, and PB: Positive Big.

The linguistic description of the rules is expressed in terms of a knowledge-base system consisting of "*if* … *then*" linguistic labels and fuzzy logic inference mechanism, such as:

R1: IF E is PB AND ΔE is NB THEN D is NB.
R2: IF E is PS AND ΔE is NB THEN D is NB.

and so forth.

The used rules are collected in Table 14.2 (Rule table of 25 fuzzy rules), they are based on the use of a step-up DC–DC converter in the PV control system.

The basic idea is that if the last change in the duty ratio (D) has caused the power to rise, keep the moving in the same direction; otherwise, if it has caused the power to drop, move it in the opposite direction (Simões and Franceschetti 1999).

In order to test the effectiveness of the designed fuzzy-based MPP tracker, the various parts of the PV system have been modeled by separate blocks using the Matlab-Simulink model shown in Fig. 14.8.

The developed FLC was tested under standard test conditions (Air temperature T = 25° and Solar irradiance G = 1,000 W/m ^{2}), so that only one power-voltage characteristic has been considered. As results, Fig. 14.9 shows the evolution of the simulated PV Voltage, PV current, and PV power versus time. As can be seen, after a short transitional time (0–400 ms), the controller follows very well the expected MPPT with negligible oscillation.

Table 14.2 Fuzzy rule table (Messai et al. 2011b)

E	ΔE	NB	NS	ZE	PS	PB
NB		PB	PB	PS	PB	PB
NS		PB	PS	PS	PS	PB
ZE		NS	NS	ZE	PS	PS
PS		NB	NS	NS	NS	NB
PB		NB	NB	NS	NB	NB

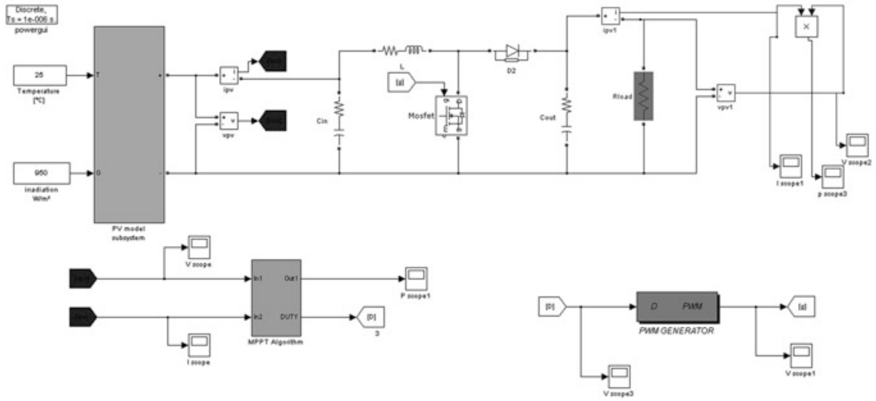


Fig. 14.8 Matlab-Simulink block of the designed FLC with resistive load

The tracking efficiency (η) is an important parameter of an MPPT algorithm. This value is calculated as:

$$\eta = \frac{\int_0^t P_{\mathrm{MPPT}}(t)\mathrm{d}t}{\int_0^t P_{\max}(t)\mathrm{d}t} \tag{14.6}$$

where P_{MPPT} represents the output power of PV system with MPPT, and Pmax is the output power at true MPP (Salas et al. 2006), in our case, the efficiency was estimated at around 78 %.

However, in spite of the good result a drawback which is the design of the FLC used, which was done according to the trial-and-error method rather than a guided approach. In this traditional design, the presence of an expert knowledge is required; conversely, in the absence of such knowledge, their design is usually slow and not optimized (Linkens and Nyongesa 1995). To provide a way of surmounting this shortcoming, Larbes et al. (2009) applied GAs to calculate accurately the base lengths and the peak locations of the membership functions in the FLC for which the rule-base have already been created. The proposed solution leads to a good performance improvement of the MPP tracker addressed. Nevertheless, a literature review in the area of FLC's design (Homaifar and McCormick 1995) reveals that in such a situation, the designed FLC is not yet optimal and still requires the use of an expert's experience to design the control rules.

In the next subsection, we present a more efficient design for a FLC-based MPPT planned to be used in PV systems. The strategy is based on GAs which chooses optimally and simultaneously both membership functions and control rules for the FLC. The procedure followed makes the design of this type of MPP trackers simpler and more efficient.

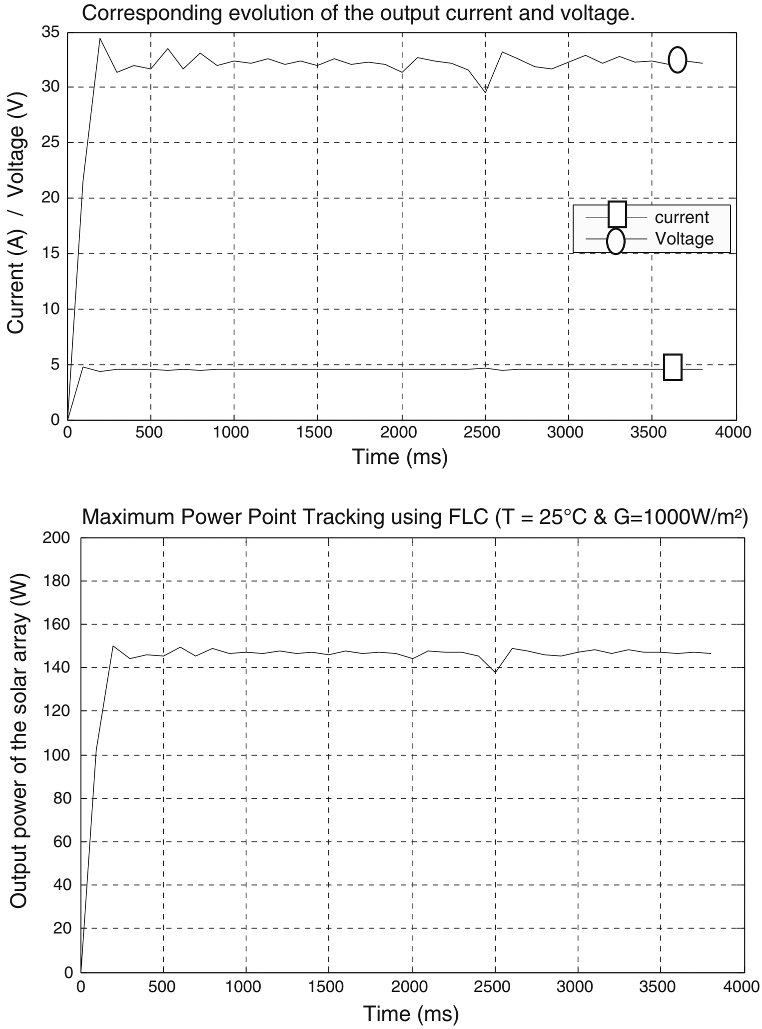


Fig. 14.9 The evolution of the simulated current, voltage and the MPPT during the period 0–4,000 ms (Messai et al. 2011a)

14.4.2 MPPT-Based GA–FL Controller

Generally, designing a FLC involves two major steps; structure identification and parameter identification. Structure identification is the process of choosing a suitable controller structure, such as the size of the fuzzy rule-base. Parameter identification then determines the value of the parameters of a fuzzy controller, such as the shape of the fuzzy membership functions and the contents of the fuzzy rule-base.

In the following subsections, a detailed demonstration is given of how to get over the step of parameter identification by using the GAs optimization approach, in a manner that optimal or near optimal fuzzy rules and membership functions can be designed without a human operator's experience or a control engineer's knowledge. The assumptions used and the constraints introduced to simplify this process are also explained.

14.4.2.1 Coding of the FLC Parameters

By coding the coefficients of the membership functions and the fuzzy logic rule-set, FLC design can be developed and optimized by using GAs. The coded FLC design population can be found by the entire string termed "chromosome," each of which has randomly generated "bits," termed "genes." Then the GA process is used to reproduce and select the "fittest" individual, i.e., the optimal solution of FLC design. To do this, either binary or real-valued coding can be used. In this case, the binary coding is chosen, where each parameter (rule and membership function) is converted into a binary string. These strings are concatenated and the genetic operations are performed on this concatenated string. In the case of the triangular fuzzy sets, used in this work, three characteristic points (center and two widths) are generally used as the parameters to be coded (Timothy 2004). Nevertheless, the number of these parameters can be reduced if certain constraints are imposed on the fuzzy set partition. Most fuzzy systems employ normalized fuzzy sets that require the membership values $\mu_{Ai}(x)$ of all fuzzy sets Ai to sum up to unity:

$$\forall x : \sum_{i}^{N} \mu_{Ai}(x) = 1 \tag{14.7}$$

This can literally be explained as a permission to overlap at most two active rules between adjacent fuzzy sets. It is therefore sufficient to define only the center points C_1, C_2,..., C_N of the normalized triangular membership functions, see Fig. 14.10, in order to specify the entire fuzzy partition of these variables.

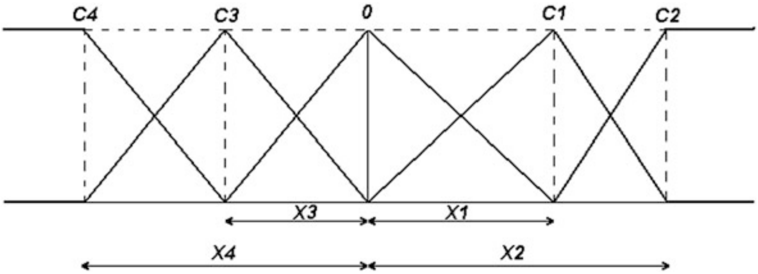


Fig. 14.10 Information which will be coded using binary coding (X_1, X_2, X_3, X_4) (Messai et al. 2011a)

In the present application, the domain intervals for input and output variables are {−35.9, 4.75}, {−40, 40} and {−2, 2}. We note here that these intervals were obtained by calculating the maximum and the minimum value allowed for each used variable in our simulated environment for the considered PV system reported in Fig. 14.5. The four parameters for each input signal are encoded into six binary bits and those related to the output signal are also encoded into six binary bits for each. If we consider that X_i is the abscissa of C_i (the center point of the ith fuzzy set). The decoding mapping (from binary to decimal) is obtained by (Timothy 2004):

$$X_i = X\min_i + \frac{b}{(2^L - 1)}(X\min_i - X\min_i) \tag{14.8}$$

where b is the number in decimal form that is represented in binary form, L is the length of the bit string (i.e., the number of bits in each string), and $X_{\max}$ and $X_{\min}$ are user-defined constants between which X_i vary linearly. These parameters depend on the considered problem.

For the fuzzy rule-set, each fuzzy rule parameter is encoded into 3 binary bits that cover the range from 0 to 7. The rules considered here have 25 parameters that range over 5 fuzzy levels and are coded by: 0 = None (unused), 1 = NB (Negative Big), 2 = NS (Negative Small), 3 = ZE (Zero), 4 = PS (Positive Small), 5 = PB (Positive Big), 6 = None (unused), and 7 = None (unused).

The string produced by concatenating all the encoded parameters forms a genotype of 25 rules × 3bits$)_{25\ \text{rules}}$ + (8 center-point-positions × 6bits$)_{\text{two inputs}}$ + (4 center-point-positions × 4bits$)_{\text{one output}}$ = 139 bits. Each genotype specifies an individual member in the population. Evaluation of each string is based upon a fitness measure that is problem dependent.

14.4.2.2 Steps Followed for the FLC Design

The GA operation starts with a population of randomly generated solutions (chromosomes) and advances toward better solutions by applying the genetic operators. In each generation, relatively good solutions propagate to give offspring that replace the relatively inferior solutions. The fitness function plays the role of the environment in distinguishing between good and bad solutions. In order to find the optimum value for the adjustment factor, we can use the integral absolute error (IAE) performance index as the objective function, which is explained below. This performance index can estimate the dynamic and static characteristics of the control system synthetically. The procedure is as follows:

- *Generating the initial population*: (N = 60) sets of chromosomes are randomly generated before using a GA operation. These chromosomes are called the initial population.
- *Evaluation of the individual fitness*: *For* each individual chromosome (a complete string) in the population, it is necessary to establish a measure of its fitness, *f(x),* that is often used to accurately evaluate the performance of the controller

Table 14.3 Parameters of the used genetic algorithm (Messai et al. 2011a)

Parameter	Value
Representation	Binary
Chromosome size	139 bits
Population size	60
Generations	100
Selection method	Roulette wheel
Rate of crossover	0.8
Mutation method	Gaussian
Rate of mutation	0.03

and will be used to generate a probability according to which the individual in question will be selected for reproduction or not. The task of defining the fitness function is always application specific. In this paper, the objective of the controller is to drive the output to the desired set-point with a minimum overshoot and minimum settling time. Therefore, the fitness function of the GA for each individual is defined as follows:

The optimization done by GA is based on the maximization of IAE given by:

$$\mathrm{IAE} = \int_{0}^{\infty} |e(t)|\mathrm{d}t \tag{14.9}$$

where $e(t) = P(t)_{\mathrm{expect}} - P(t)_{\mathrm{PV}}$

$P(t)_{\mathrm{expect}}$ is the maximal theoretical delivered power at STC, and$P(t)_{\mathrm{PV}}$ is the instant power provided in datasheet of the used PV module.

The fitness values are scaled so as to distinguish the individuals for which the fitness values are calculated. We also use the fitness measure defined by:

$$\text{Fitness } = 1{,}000 -- \text{ IAE} \tag{14.10}$$

It can be seen that since (IAE) is relatively small compared to 1,000, so minimizing IAE maximizes fitness.

- Evaluating of the next generation or stop: The operations of reproduction, crossover, and mutation are used in order to generate the next generation. From generation to generation, the maximum value of the fitness value is achieved. Table 14.3 summarizes the parameters used of the GA.

14.4.2.3 Parameters of the Optimal FLC Obtained

Figure 14.11 shows the evolution of highest and average fitness for generations one to one-hundred. The results show that a better fitness value is achieved from generation to generation. The optimal chromosomes of the FLC were found at approximately generation number 50.

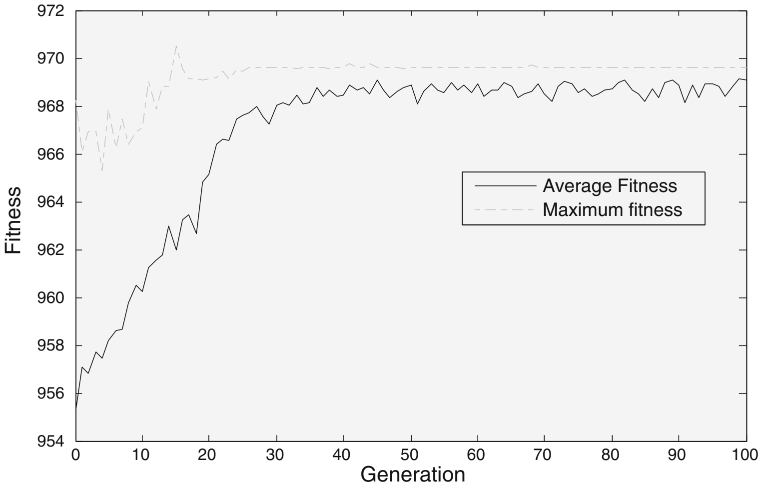


Fig. 14.11 Evolution of GA to evolve the FLC (Average fitness, Maximum fitness)

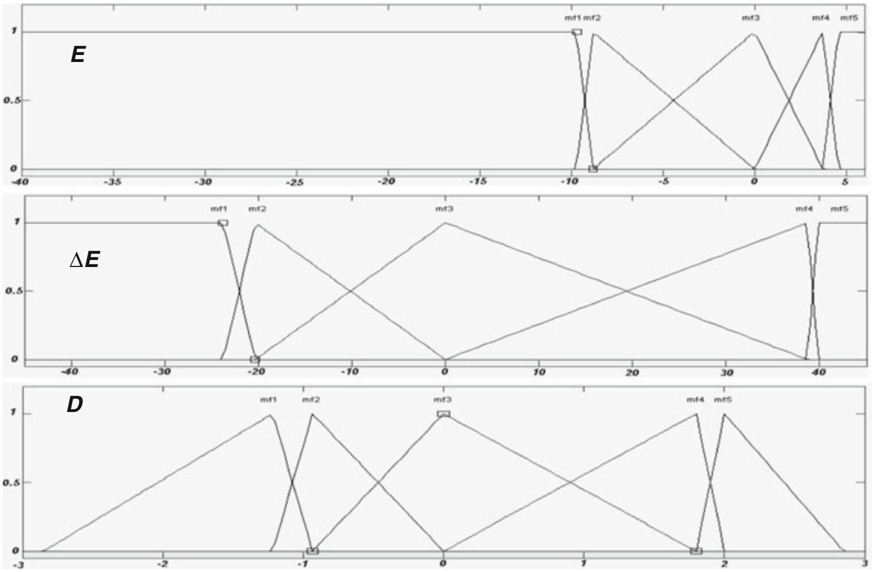


Fig. 14.12 Best membership functions obtained for the system variable (Messai et al. 2011a)

The optimal solution obtained, represented by the chromosome with the highest fitness in the last generation (100th generation), gives the shape of the membership functions as well as the table of the rule-sets shown in Fig. 14.12 and Table 14.4, respectively.

Table 14.4 Control rule table of the designed fuzzy controller (Messai et al. 2011a)

Output (D)		Change in error				
		NB	NS	ZE	PS	PB
Error	NB	PS	PS	PB	PS	PS
	NS	PS	PS	ZE	NS	ZE
	ZE	NS	ZE	ZE	NB	PB
	PS	ZE	ZE	NS	NS	PS
	PB	ZE	PS	NS	NS	PS

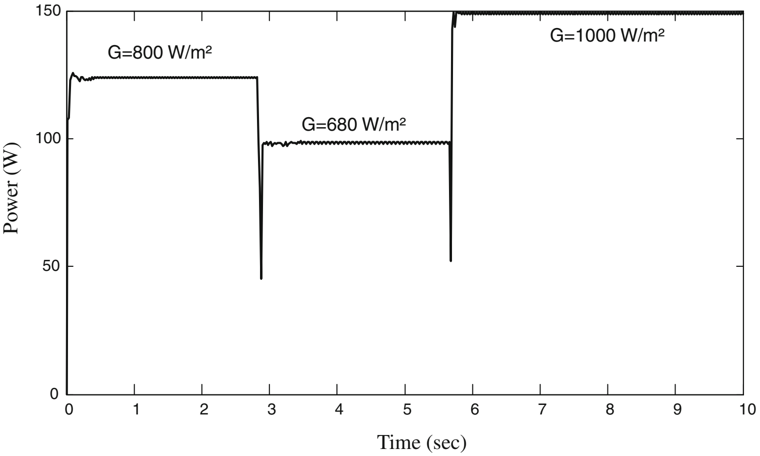


Fig. 14.13 The evolution of the MPP-based optimized FLC for different solar irradiation values: 800, 680 and 1,000 W/m^2, 25 °C (Messai et al. 2011a)

The examination of the implemented controller's robustness with respect to the rapid change of the solar irradiation has been carried out. A sample from the curves obtained at the end of this operation is illustrated in Fig. 14.13, from which it is clearly shown that the controller ensures fast convergence and robust performance against rapid solar irradiation variations. The system stabilizes after a relatively short time and seeks the maximum power transfer in all operating conditions.

The results presented here have shown that the advantages of the system developed are the adaptation of the GA-FLC parameters for fast response, good transient performance, and robustness to variations in external disturbances.

To assess the efficiency of the designed approach, we have also used the system illustrated in Fig. 14.8, in which we have introduced the new parameters of the so optimized MPPT controller. Besides, we have used measured data (real records) as inputs: Solar irradiance and temperature for a given experimental site. The curves shown in Fig. 14.14a and b give an idea on the evolution of these two variables. As can be seen, data are quite nonlinear function versus the time and are highly variable. This situation can validate the effectiveness of the developed MPPT controller.

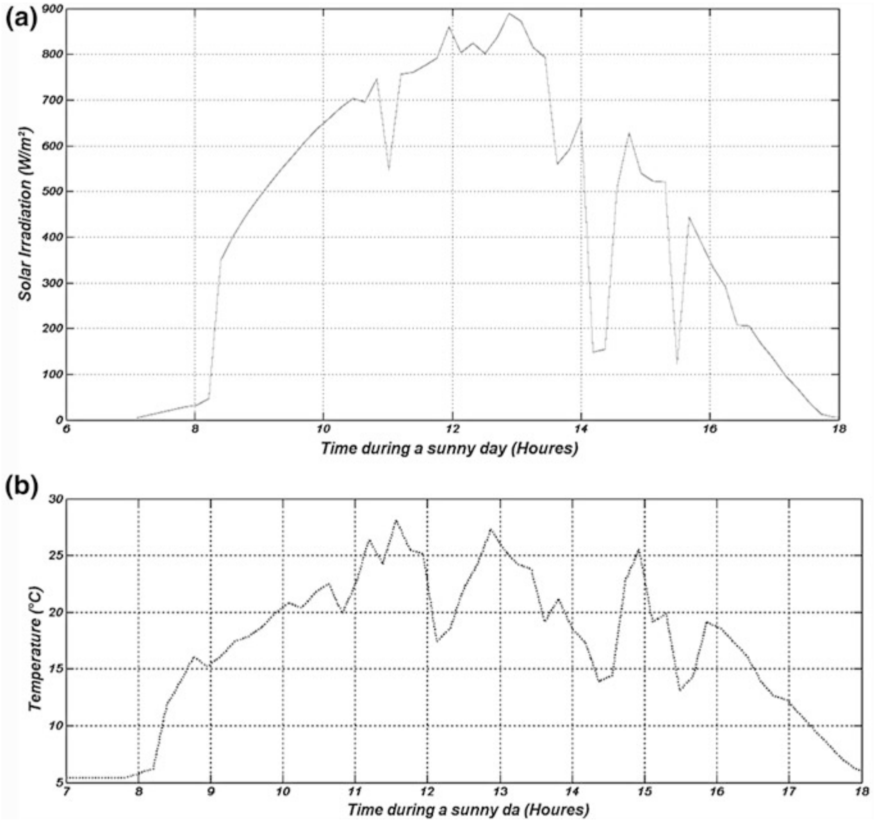


Fig. 14.14 **a** Solar irradiance evolution versus time during a day. **b** Temperature evolution versus time (during one day: from 7:00 to 18:00). **c** Electrical output variables (during one day: from 7:00 to 18:00). **d** System efficiency variation versus time (during one day: from 7:00 to 18:00)

The curves below (Fig. 14.14c and d) show the correspondent input and output electrical variables (PV Voltage, PV current, and PV power) as well as the electrical efficiency of the new system during a day (from 7:00 to 18:00).

At the end of the final simulation step related to the electrical behavior of the whole PV system (PV module, MPPT optimized fuzzy controller, up-step DC/DC converter, and resistive load), we emphasize the fact that we were able to achieve an average energy efficiency of around 92 %.

14.4.3 FPGA Implementation

In the case of the hardware implementation of the optimized FL based GA controller, the shape of the membership functions associated to the FLC linguistic variables are often piece-wise linear functions. Like in any FLC application, the

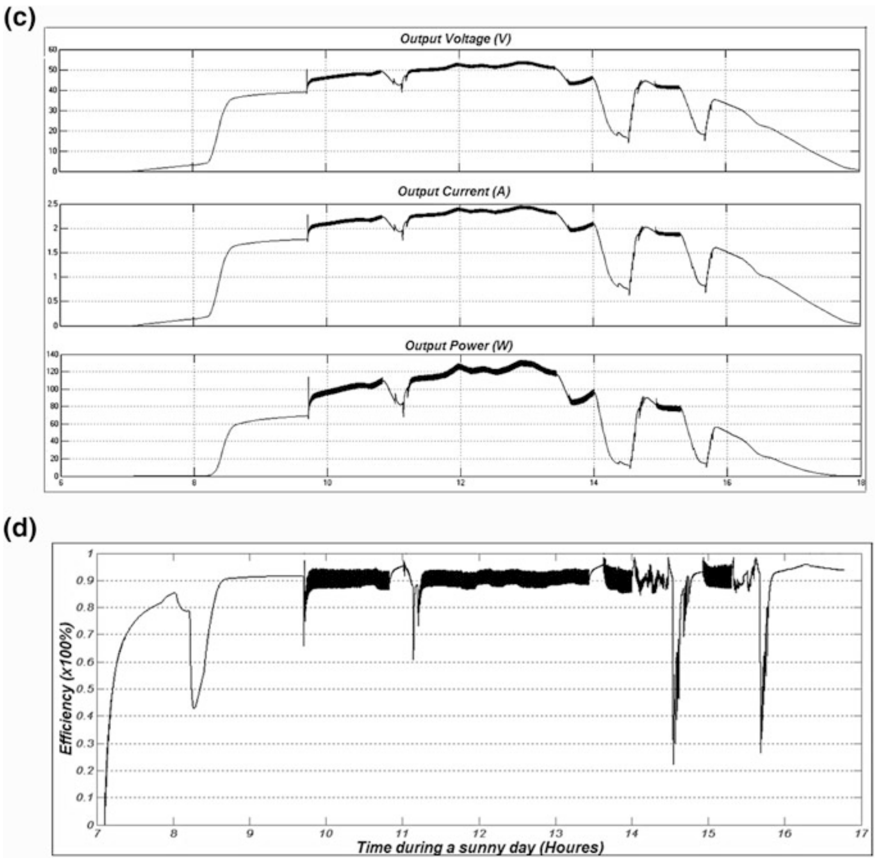


Fig. 14.14 continued

number and the shape of the membership functions of each fuzzy set are selected on the basis of trial-and-error methods, in a manner that the region of interest is covered appropriately by the inputs data.

The FL-based GA controller was designed using a hardware description language integrated with the Xilinx Foundation ISE 10.0 tools. The ModelSim Xilinx Edition-III (MXE-III) v6.0a was also used for the simulation purposes.

Implanting a VHDL code is mainly a two-step process (Ruelland et al. 2003):

- Synthesis: The synthesis involves “compiling” the VHDL code with softwares which are mainly commercially available tools.
- Placement-and-Routing: The result of the “Placement- and-Routing” is the final code to be implanted on the FPGA.

To get the benefits from FPGA solutions for the implementation of FLCs, we have used the well-known functional description approach (Deliparaschos et al. 2006)

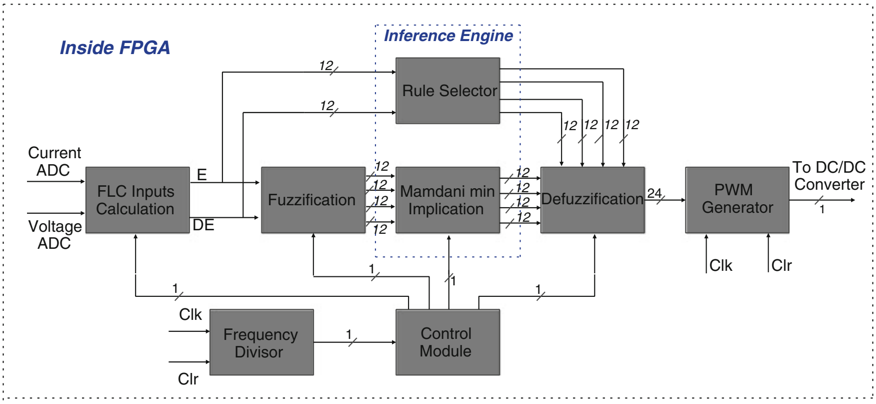


Fig. 14.15 Block diagram of the FPGA implemented MPPT-based FL (Messai et al. 2011a, b)

which increase the fuzzy controller performance as well as the direct access to fuzzy membership, simultaneous rules activation, and implementation of arithmetic functions.

The block diagram of the FPGA implemented MPPT is shown in Fig. 14.15. As can be seen, the MPPT includes four principal units:

- fuzzification unit which converts a crisp input into a fuzzy term set;
- a rule selector unit which stores fuzzy rules describing how the fuzzy system performs;
- an inference engine unit which performs approximate reasoning by associating input variables with fuzzy rules, and finally;
- the defuzzification unit which converts the FLC's fuzzy output to a crisp value representing the control action.

In addition to the standard units shown in Fig. 14.14, we have also used an input precalculation unit, which provides the real inputs to the controller, the error and its change depicted as E and ΔE, respectively. These errors are calculated according to the expressions given by Eqs. (14.3) and (14.4). A sequencer is also used, operating as a manager of the control signals which synchronize the tasks of all units quoted above.

This sequencer, named as control unit in Fig. 14.14, is driven by a frequency divider unit used to adapt the frequency of the FPGA board and the sampling rate for the considered process. The FLC's output, i.e., the crisp value is used to drive a simple PWM generator also implemented on the same chip. Figure 14.16 shows the register transfer level (RTL) view of the designed FL-based GA controller.

The different subunits have been implemented separately on a Virtex II (XC2v1000-4fg456) FPGA chip from Xilinx. Table 14.5 shows the FPGA logic resources used to develop the controller. With reference to Table 14.5, it can be

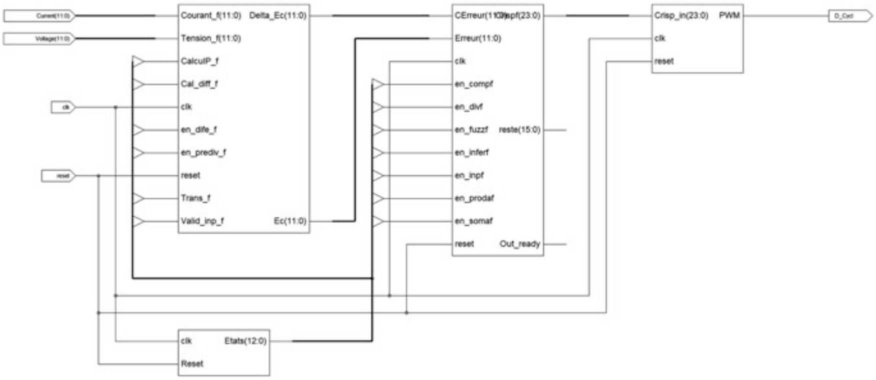


Fig. 14.16 The RTL view of the designed Fuzzy Logic-based GA controller (Messai et al. 2011a)

Table 14.5 Device utilization summary (Messai et al. 2011a)

Selected Device	Xc2v1000
Number of slices	1,964 out of 5,120 38 %
Number of slice flip flops	2,668 out of 10,240 26 %
Number of 4 input LUTs	1,928 out of 10,240 18 %
Number of bonded IOBs	27 out of 324 8 %
Number of MULT18 × 18 s	9 out of 40 22 %
Number of GCLKs	4 out of 16 25 %
Maximum frequency:	97.040 MHz

seen that the used FPGA chip is largely sufficient to implement all the constituents of the MPPT controller addressed in this work as it contains 5,120 slices and 10,240 logic cells as well as 40 18 × 18 multiplier.

14.5 Conclusions

In this chapter, an intelligent approach for tracking the MPP for PV modules has been described and implemented on a reconfigurable FPGA chip. The application of GAs to FLCs design holds a great deal of promise in overcoming two of the major problems in fuzzy controller design; design time and design optimization. As it is shown, they have been successfully used in this chapter, to improve the performance of a fuzzy logic-based MPPT controller by optimizing simultaneously both the membership functions and the fuzzy control rules. It has been shown that the designed GA-FLC performs better than FLC, especially in rapid variation of irradiance since the response time in the transitional state is shortened and the fluctuations in the steady state are considerably reduced. Furthermore, it has been demonstrated that the used FPGA chip is largely sufficient for this application.

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Part III
Simulation Models and Approaches

Chapter 15
Simulation and Renewable Energy Systems

H. Kutay Tinç and C. Erhan Bozdağ

Abstract As technology advances perspectives change, problems shift to reflect the new environment and situations that develop. The same goes for Renewable Energy Systems too. With each new development in a renewable energy system, new problems arise as well and these developments need to be tested before they can be applied safely. These tests can be very expensive if done in real life and that is where simulation comes into the picture. Simulation is widely used for experimentation to understand a system or make decisions about it and is very cost efficient method when compared to real life experimentation as the only requirement for modeling and analyzing complex systems is a good computer. In this chapter, different simulation techniques used in Renewable Energy Systems will be introduced and examples to how they are used will be briefly given.

15.1 Introduction

The energy sector faces serious problems, e.g., oil dependency, reliability, and environmental problems. Large jumps in environmental efficiency may be possible with transition to a new energy system (Verbong and Geels 2007). This transition comes with its own costs and these must be weighed carefully against the costs of the current system. Many challenges exist for both the current system and any proposed system. One of those greatest challenges our industrialized societies face is the protection of our environment. This challenge affects all parts of our daily

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life like politics, economy, citizens, as well as technology and research. A comprehensive and reliable information basis is needed to solve the various problems in environmental protection, environmental planning, research, and engineering. This information basis consists of biological, physical, chemical, geological, meteorological, or social-economic data, which is dependent on time and space and consists of past or current states.

Environmental impacts of energy production and consumption make sustainable development a very important issue to politicians and decision makers. A development plan that both considers the need of the economy and does not have negative impacts on the environment must be established. This plan should take the threats of exhaustion of non-renewable resources, and of global pollution into consideration.

In an energy system that is made up of all these complex relations and processes, devising new strategies, and making decisions is possible via understanding the behaviors of System Dynamics. As devising new strategies for a system that already exists means conducting many experiments, the model used should allow experimentation and should take into consideration that any non-existent condition or component that may be suggested for the system. Simulation is one of the most important tools for modeling dynamic systems and inspecting their behaviors through time with the help of experiments.

Gilbert and Troitzsch (2005) define simulation as a particular type of modeling and a model as a simplification of some other structure or system. They also state that early applications of simulation to the social sciences focused on prediction as other scientific fields. However, social scientists tend to be more concerned with understanding and explanation of the behavior of the system. They also state that, this is due to skepticism about the possibility of making social predictions, based on both inherent difficulty of doing so and also the possibility, peculiar to social and economic forecasting, that the forecast itself will affect the outcome.

Yılmaz and Ören (2009) give three purposes of use of modeling and simulation as:

- Perform experiments for:
  - Decision support: Simulation is used for prediction (of behavior and/or of performance), evaluation of alternatives, sensitivity analysis, and evaluation of engineering design.
  - Understanding: In analysis of mostly natural problems, simulation is a very powerful technique used to understand them. Several models can be tested until the behaviors of the model and the real system match under the same or very similar conditions.
  - Education.
- Provide experience for training (for gaining/enhancing competence) and entertainment.
- Imitation.

The first area of application indicated above is used in social sciences frequently. Simulation models are mostly used for decision support and understanding the basis of the system examined.

Most of the dynamic systems have a complex structure. This complexity of the system derives from components that have nonlinear relations with each other. Emerging properties of these relations cannot be understood by analyzing the simple components or the process of the system. Instead, the system must be analyzed with a holistic point of view. These complex systems cannot usually be treated with an analytical approach, as they are not easily expressed in synthetic general laws and they cannot be decomposed in sub-systems. Also the constant presence of nonlinearity in such systems often makes them analytically untreatable. Hence these systems must be understood through numerical simulation, normally via computer (Dale et al. 2012).

In this chapter, we will be discussing different simulation techniques used to analyze Renewable Energy Systems. The first technique introduced will be Monte Carlo Simulations where computational algorithms rely on random samples. Following Monte Carlo simulations will be System Dynamics which enhances learning in complex systems. The chapter will conclude with Agent Based Simulations.

15.2 Monte Carlo Simulations

15.2.1 Definition

Monte Carlo Simulation is a problem-solving technique that uses a class of computational algorithms which rely on repeated random sampling done on multiple trial runs to compute their results. This kind of simulation tends to be used when it is infeasible to compute an exact result with a deterministic algorithm, which was the situation for its first time use back in 1944, for the research development of the first atomic bomb.

To give a simple example of Monte Carlo simulation we can take the *Birthday Problem* which is a popular probability exercise: Supposing that there are 30 people in a room what is the probability that there are no shared birthdays?

The probabilistic solution is simple yet tedious, we have to calculate the conditional probability that the *nth* person does not share a birthday with the $n-1$ people before him who do not share birthdays for $n \in [1\text{–}30]$ which will give us

$$1 \times \frac{364}{365} \times \frac{363}{365} \times \ldots \times \frac{336}{365} = 0.294$$

The solution with Monte Carlo simulation is simple as well:

1. Pick 30 numbers from a range of [1–365] where each number represents a day of the year.

2. Check to see if any of these 30 numbers are equal.
3. Go back to “step a” and repeat for sufficiently large times. We will take 10,000 for this example.
4. Calculate the percentage of trials that have matching birthdays.

This should, of course, be done on computer as even picking 30 random numbers for the first time would be very time consuming without one. If you are familiar with coding or any mathematical calculation program this simulation is very easy to realize. An example with Python language is:

```
import random
NOFTRIALS = 10000
NOFPEOPLE = 30
Matches = 0
for trial in range(NOFTRIALS):
        taken = {}
        for person in range(NOFPEOPLE):
                day = random.randint(0, 365)
                if day in taken:
                        matches += 1
                        break
                taken[day] = 1
  print float(matches)/NOFTRIALS
```

The result printed from this piece of code is 0.2871 which is close enough to the actual result.

Monte Carlo simulations are especially good at simulating systems with many coupled degrees of freedom. They are used to model phenomena with significant uncertainty in inputs, such as the calculation of risk in business. When Monte Carlo simulations have been applied in space exploration and oil exploration, their predictions of failures, cost overruns, and schedule overruns are most of the time better than human intuition or alternative “soft” methods.

Monte Carlo simulations vary, but usually follow a strict pattern:

1. Define a set of possible inputs.
2. Generate random inputs from a probability distribution defined over the set.
3. Perform a deterministic computation on the inputs.
4. Aggregate the results.

15.2.2 Monte Carlo Simulations and Energy

As Monte Carlo simulations can be applied to many different stochastic problems and Renewable Energy problems are most of the time stochastic, it is easy to deduce that Monte Carlo simulation is used in many different problems regarding

Renewable energy sources including but not limited to: Reliability Evaluation, Green House Gas Emission/Mitigation, Uncertain Power Production Measurements, Economic Effectiveness, Expansion Planning, and Performance of Distributed Generation.

The need for renewable energy sources emerged with the realization of the way we are poisoning our earth with Green House Gases (GHG) which derive from use of fossil fuels and the fact that these fossil fuels will deplete in the future. The GHG emission rate in the last 10 years has become alarmingly increased and starting with the Kyoto Agreement in 2005, countries all around the world have decided to reduce their GHG emissions. Following the Kyoto Agreement was the European Union Directive 2009/28/EC and Cancun Agreement in 2010.

Article 13 of Directive 2009/28/EC of the European Parliament and of the Council states that: “In the light of the positions taken by the European Parliament, the Council and the Commission, it is appropriate to establish mandatory national targets consistent with a 20 % share of energy from renewable sources and a 10 % share of energy from renewable sources in transport in community energy consumption by 2020.” European countries have taken this directive to heart and many studies are being conducted to comply with it.

The Cancun Agreement on the other hand includes 76 countries making voluntary pledges to control their emissions. These countries were responsible for 85 % of the annual global emission at the time of the agreement. If these countries keep their pledges, renewable energy sources will see much more use in the years to come and greenhouse gas emission rates throughout the world will decline.

15.2.2.1 Renewable Energy Sources

The renewable energy sources include solar (photovoltaic), wind, hydro, geothermal, and bioenergies. Solar energy is generated from the rays of the sun via solar panels, wind energy is mostly generated with wind turbines, hydro energy is generated via dams, geothermal energy is generated from hot springs, and bioenergy is generated from biological masses or biogases.

While the renewable energy as sources are increasingly regarded cost-effective, their power outputs are largely dependent on external natural resources such as solar irradiation and wind speed (Li and Zio 2012). Hence costs, outputs, efficiency, and reliability change from energy source to energy source and location to location, but most of the calculations use the same type of parameters for the same type of energy. Table 15.1 shows an example for all kinds of renewable energy costs taken from Hart and Jacobson’s (2011) paper.

Hart and Jacobson (2011) have also setup scenarios for Energy Composition, Carbon Emissions, and Generator output for 2005 and 2050. Data for these scenarios and the actual system used back in 2005 are shown in Table 15.2 below.

Low CO_2 in 2005 meant that the energy generation was done with mostly wind and hydro power with small amounts of solar and geothermal energy generation whereas Low Cost in 2005 meant that the energy generation was done with mostly

Table 15.1 Costs for different types of renewable energy systems

Technology	Capital ($/kW]	Fixed O&M ($/kW-yr)	Variable O&M ($/kW-yr)	Fuel ($/MWh)
Hydroelectric	1,408	13.57	3.41	0
Geothermal	3,300	253.9	0	0
Natural gas	792	14.62	3.05	6.53
Wind	1,675	11.68	7.11	0
Photovoltaic	5,335	74.69	0	0
Solar thermal				
Solar field	1,839	0	0	0
Power plant	2,321	0		0
Storage	22.42	53.35	0	0

Table 15.2 Scenarios for energy composition and carbon emissions of low CO_2 and low cost renewable energy systems

	2005 scenarios		2050 scenarios		Actual 2005 System
	Low CO_2	Low cost	Low CO_2	Low cost	
Delivered energy composition					
CO_2 Free generation (%)	99.8 ± 0.2	39.9 ± 0.1	95.9 ± 0.4	64.6 ± 0.4	49.7
Renewable generation (%)	78.6 ± 0.2	18.8 ± 0.1	82.8 ± 0.4	51.4 ± 0.4	11.8
Carbon emissions					
Annual emissions (× 10 6 tCO_2)	10.2 ± 0.1	58.2 ± 0.1	35.9 ± 0.1	68.9 ± 0.1	54.7
CO_2 intensity (tCO_2/GWh)	43.2 ± 0.1	247 ± 1	94.2 ± 0.1	181 ± 1	273
Generator statistics					
Total capacity (GWh)	174.3 ± 0.1	68.4 ± 0.1	281.7 ± 0.1	182 ± 0.1	66.1
Average capacity factor (%)	16.6 ± 0.1	42.4 ± 0.1	16.5 ± 0.1	25.6 ± 0.1	34.6

natural gas and hydro with small amounts of wind and geothermal energy generation.

Though in 2050 according to Hart and Jacobson, solar power will see much more use than it sees now and in both Low CO_2 and Low Cost cases solar power generation will see an increased usage. Also with its costs getting lower and lower, wind power will become a big part of the Low Cost power generation case.

While the generation data by itself may not be enough to see the big picture, the energy usage table of a typical residence in Greece (Bakos and Tsagos 2003) can be calculated as seen in Table 15.3.

Keeping in mind that a gigawatt is equal to million (10^6) kilowatts it can be seen that the actual system back in 2005 was able to provide for roughly 9,500,000 residences when it was worked at 100 % capacity.

Table 15.3 Yearly energy consumption in a typical Greek residence

Estimated energy usage in a typical residence	
Electrical appliance	Estimated (kWh per year)
Refrigerator	1,140
Electrical kitchen	1,200
Iron	153
Water heater (boiler)	13,000
Washing machine	108
Coffee maker	108
Air conditioning	4,200
Hi-fi	120
Television	504
Lighting	552
Total annual energy consumption	21,088

Wind Power

Definition

Wind turbines use wind power to create electricity and generally several hundreds of wind turbines make up a wind farm. Although wind farms do not produce greenhouse gas emissions and thus are a clean alternative to fossil fuels, the costs are not as cheap as some of the other renewable energy sources. Especially if the wind farm is to be constructed offshore so that it has less visual impact on land. Even though offshore wind farms can produce more energy due to the fact that it can harness stronger and more frequent winds, the construction and operation costs are much more expensive than its onshore counterparts.

Wind power is highly dependent on natural occurrences which are stable on the long run but when analyzed in short terms, problems may transpire when it is used to supply over 20 % of the total demand in an area. A sudden drop in wind speed may result in black outs unless backups like excess capacity storage are in place. Even those would not be enough if the fluctuations are consistent for a long time and the power grid depends mostly on wind power. Despite the drawback of reliability, wind power is dependable when used as a backup and is a popular renewable energy source.

Parameters and Formulas

Although calculating the energy yield of wind power may require the knowledge of many parameters and how they are applied in formulas, there exist some shortcuts for direct input/output formulas, too. The following formulas and parameters are from papers published during the last decade.

Montes et al. (2011) gives a single turbine's piecewise hourly energy generation function of wind speed (U) in terms of megawatt as:

$$P(U)(MW) = \begin{cases} 0.053 \times U - 0.191, & 4 \le U < 7 \\ 0.122 \times U - 0.634, & 7 \le U < 13 \\ 0.0084 \times U + 0.848, & 13 \le U < 18 \\ 1, & 18 \le U < 25 \end{cases}$$

Wind speed is mostly taken as a stochastic variable and it depends on: wind height and roughness length, which is the length at which wind speed is considered to be zero.

Karki (2007) gives Loss of Load Expectation and Expected Fuel Energy Offset, which is the expected energy utilized from the wind sources, as two important indices for evaluation of reliability. These indices can be formulated as:

Loss of Load Expectation ($LOLE$) h/year $= N^{-1}\left(\sum_j^{NH} t_j\right)$

Expected Fuel Energy Offset ($EFEO$) MWh/year $= N^{-1}\left(\sum_j^{NH} WL_j\right)$ where

L_j is the system load in hour j,
C_j is the total capacity available in hour j,
$t_j = 1$ for $L_j > C_j$ and 0 otherwise,
H is the number of hours in the period of interest,
N is the number of Simulation samples,
W_j is the wind power available in hour j,
x is the wind energy penetration constraint
WL_j is the fraction of the MW load served by wind in the hour j, where:

$$WLj = \min(Wj, x(Lj)).$$

Bakos and Tsagos (2003) have set up a Horizontal Axis Wind Turbine in Greece according to Table 15.4.

They have also set up a wind energy conversion system with the following production rates seen in Table 15.5.

Table 15.4 Horizontal axis wind turbine technical characteristics

Parameter	Value
Number of blades	2
Blade diameter (m)	3.5
Tower height (m)	6
Area of rotation (m^2)	9.6
Rotational speed (rpm)	190
Blade material	Wood
Cut-in wind speed (m/s)	4
Cut-out wind speed (m/s)	14–20
Rated power (kW)	2.2

Table 15.5 Production rates for a wind energy conversion system

Monthly useful energy production from WECS	
Month	Useful energy (kWh)
January	204.11
February	192.23
March	101.25
April	86.6
May	85.6
June	91.3
July	171.9
August	115.6
September	111.8
October	155.14
November	191.27
December	210.25
Total annual value	1717.05

Solar Power

Definition and Generation

Solar power is the conversion of sunlight into electricity, which means that it is totally dependent on the amount of sunlight that an installation receives per day. These amounts depend on the geographical situation and weather conditions of the area that the installation would be constructed on. For example, in Turkey where the amount of daylight is on average 7.2 h, the average annual solar energy generation is 1,311 kWh/m^2. Also according to the Ministry of Energy in Turkey, the total potential of solar power generation in Turkey is at 380,000 GWh per year.

Throughout the world most photovoltaic power stations are limited in regards to power generation with range between 50 and 100 MWh for DC peak power. Three exceptions exist: The Agua Caliente Solar Project in USA with 200 + MWh, Charanka Solar Park in India with 214 MWh, and Golmud Solar Park in China with 200 MWh.

On the other hand, concentrating solar thermal power plants (CSPs) have a much wider output range with the current largest generation capacity of 354 MWh of Solar Energy Generating Systems (SEGS) in Mojave Desert, California.

Parameters and Formulas

As solar power is highly dependent on the amount of sunlight, the plant receives choosing a suitable location is probably the most important part for solar plants. This location should be as flat as possible to harness the rays of the sun throughout the day at all times and weather should be as clear as possible in all seasons. From these criteria it is easy to deduce that deserts are the most used regions for solar plants.

Table 15.6 Solar thermal system technical characteristics

Parameter	Value
Solar radiation (W m^{-2})	550
Ambient temperature (C)	32
Aperture width (m)	1.46
Aperture area (m^2)	3.5
Collector optical efficiency	0.655
Slope of collector performance graph (W m^{-2} K^{-1})	0.387
Flash vessel water content (kg)	0.7
Flash vessel outside diameter (mm)	105
Flash vessel inside diameter (mm)	65
Flash vessel wall thickness (mm)	2
Flash vessel height (m)	0.6
UA value of the pipes (W K^{-1})	0.93
Pump body area (m^2)	0.12
Insulation conductivity (W m^{-1} K^{-1})	0.035
Mass flow rate (kg s^{-1})	0.042
Mass of circulated water (kg)	4

Solar radiation (W/m^2) determines the amount generated by plants and the stronger the illumination the higher the radiation becomes. A study by Bakos and Tsagos (2003) shows the characteristics of a solar thermal system they have used in Table 15.6.

Borges CLT (2012) gives the amount of power generation as:

$$P_i(G_{bi}) = \begin{cases} P_{sn}\left(\frac{G_{bi}^2}{G_{std}R_c}\right), 0 < G_{bi} < R_c \\ P_{sn}\left(\frac{G_{bi}}{G_{std}}\right), R_c < G_{bi} < G_{std} \\ P_{sn}, \; G_{std} < G_{bi} \end{cases}$$

where P_i is the power generation (MW), G_{bi} is the estimated solar radiation value (W/m^2), G_{std} is the solar radiation valor at standard environment (usually 10,00)(W/m^2), R_c is the solar radiation conventional valor (usually 150)(W/m^2), and P_{sn} is the generation capacity of solar plant (MW).

Bioenergy

Definition

Oak Ridge National Laboratory defines bioenergy as useful, renewable energy produced from organic matter—the conversion of the complex carbohydrates in organic matter to energy. Organic matter may either be used directly as a fuel, processed into liquids and gasses, or be a residual of processing and conversion.

Bioenergy is generated from materials that are derived from biological sources like wood, wood waste, straw, manure, sugarcane, and many other by-products of agricultural processes.

Table 15.7 GHG values for cattle slurry storage

	Unit	Default value	Range	
			Min	Max
CH_4 emissions from cattle slurry storage	%	10	0.7	13
Direct N_2O emissions from cattle slurry storage	kg $N_2O\text{-}N/N_{\text{total}}$	0.005	0.0025	0.01
N losses due to cattle slurry storage	kg $NH_3\text{-}N/N_{\text{total}}$	0.025	0.016	0.056

Table 15.8 GHG values for conversion of biogene resources to electrical energy

	Unit	Default value	Range	
			Min	Max
Biogas process				
Biogas yield from corn silage	l/Kg_{vs}	575	450	700
Electrical efficiency	%	38	32	40
Power consumption	%	8	5	12
Direct emissions				
Methane leakage and slip	%	0.5	0.004	1
CH_4 emission factor from digestate storage	%	1.5	0.1	8.5

Bioenergy can be categorized in three classes: Biofuels, like ethanol made from corn or biodiesel made from palm oil; Biomass, like wood; and Biogas created from waste products like sewage or manure.

Parameters and Formulas

Meyer-Aurich et al. 2012 gives GHG values of cattle slurry storage and conversion of biogene resources to electrical energy in Tables 15.7 and 15.8.

As can be seen from the tables, biogas production using cattle slurry has lots of parameters and variables: N_2O-N emission factor from all inputs, biogas yield from corn silage, methane leakage and slip, electrical efficiency, N losses by leaching/runoff, N_2O-N emission factor from leaching or runoff, direct N_2O emission cattle slurry storage, N losses due to cattle slurry storage, CH_4 emissions from cattle slurry storage, volatilization for synthetic fertilizer, and CH_4 emission factor from digestate storage.

Yu and Tao (2009) give the total energy coefficient for biofuel energy generation, which is the energy input/output ratio, as:

$$\mathrm{TECff}_i = \frac{\sum_j \left[\mathrm{PF_{ij}Cff}_j\right] + \sum_k \left[\mathrm{EF_{ik}Cff}'_k\right]}{\sum_l \mathrm{EO_{il}}}$$

where PF_{ij} is defined as the consumption of the *jth* process fuel in *ith* lifecycle stage with an energy coefficient Cff_j, EF_{ik} is the consumption of *kth* energy feedstock with an energy coefficient Cff'_k, and EO_{il} is the energy present in the *lth* products of the *ith* life cycle stage.

15.3 System Dynamics

Sterman (2000) defines System Dynamics as a method to enhance learning in complex systems. System dynamics approach is often used to help us learn about dynamic complexity, understand the sources of policy resistance, and design more effective policies. Dynamic complexity is different from combinatorial complexity, where the complexity is caused by the huge number of components and relations in the system or the number of feasible solutions can be astronomical. A system with only two components can exhibit many different behaviors. System dynamics indicates that the underlying reasons for dynamic complexity are:

- the strong relations between the components of the system,
- the feed-back structure of the relations
- the nonlinear structure of the relations

Systems with dynamic complexity can exhibit integral behaviors that cannot be inferred from the analysis of their components individually. Waldrop (1992), states that the very richness of these interactions allows the system to undergo a spontaneous self-organization as a whole. Collective properties such as life, thought, and purpose that might never be possessed individually can be acquired by a series of agents that manage to transcend themselves while seeking mutual accommodation and self-consistency. Self-organizing systems are adaptive; they do not only respond to events but also try to turn whatever happens to their advantage.

Three main tools of System Dynamics are causal loop diagrams, flows diagram, and dynamic equations. Causal loop diagrams can be defined as the qualitative tool of the system. The other two tools are used to model the quantitative structure of the system.

Causal loop diagrams represent the relations between components and their feedback structure. Qualitative analysis of these diagrams can not only yield information about the dynamics of the system, but also can help actors in the system share and understand the mental models that they use. In CLDs, relations between the variables of the system components are shown with arrows. These relations between variables form a cycle that provides the system dynamic. Due to these relations, a change in a variable affects other variables as well. This cycle is called the feedback loop. Relations of the variables in a CLD are assigned either a positive or a negative polarity. Polarity shows how an affected variable reacts to a change on an affecting variable.

System Dynamics has been used in the renewable energy subject for different purposes and areas of application. These areas are:

- Incentives evaluation: Encouraging the use of renewable energy technologies by selecting the best incentive among: reduction in income tax, spending in education, and spending in new energy systems research or subsidies.
- Cost-benefit analysis of long- and short-term investments on energy resources.
- The effects of using biomass as an energy source on the environment and agriculture.

- Analysis of a renewable energy system's evolution through its interaction with other energy systems.

15.3.1 Evaluation of Incentives

Several policy instruments have been developed and implemented in order to support usage of renewable sources. New alternative policies are still developed and put forward to stimulate investment to renewable energy generation. Generation of new incentive policies and selection of most suitable policy among current policies are the main issues in renewable energy.

In SD, Bass Diffusion model is used to describe how a new product or technology gets adopted by the interactions between users and potential users. The adoption of new alternative energy sources might be modeled via Bass Diffusion model. Incentives are considered as advertising effectiveness variable in the standard model.

Trappey et al. (2012) state that the success of the renewable energy is dependent on the sufficient incentives to end-users and cost effectiveness to governments. A formal cost-benefit analysis considering both qualitative and quantitative factors is necessary to evaluate the feasibility of renewable energy policies. Proposed benefit evaluation methodology has three steps: administrative region carbon emissions analysis, the renewable energy policies system dynamics model, and the renewable energy policies benefit analysis. In the first step, the target problem and policy is identified, the current policy is depicted as-is model, and then to-be model is constructed. SD approach is used, in the second step, to estimate the results of the to-be model are beneficial or not. In the last step, detailed policy scenarios are designed and simulated for different system parameters and assumptions. The Simulation results are used to evaluate the costs and effects of carbon reduction. Authors designed four scenarios: base case, promote wind power policies, promote solar application policies, and promote long-term solar applications policies.

Zuluaga and Dyner (2007) also use a simulation model to assess the effects of incentives on new renewable capacity in the electricity market. The model has five submodels: the market, renewable investment, technology diffusion, finance, and environment. In base case scenario, no incentives are in place. Authors present four different promoting scenarios: spending on education and research to reduce the resistance for technology adoption, reduction of income tax (35 % tax and no tax), soft loans with low interest rates and long repayment periods, and direct subsidies. From the analysis of the simulation, the most efficient incentive scheme is found as direct subsidies for production, and the less one is income tax exemption.

15.3.2 Cost-Benefit Analysis

The renewable technologies have some disadvantages. Although capacity costs are decreasing, the majority of renewable energies are still more expensive than conventional fossil fuels. Renewable energy, such as wind and solar, also suffers from intermittence problems and so they cannot be easily integrated into the grid. They also have smaller load capacities compared to incumbent generators (Zuluaga and Dyner 2007). Difficulties in learning and adoption of renewable energy generation restrain the growth of renewable energy investments.

Maalla and Kunsch (2008) used Bass Diffusion model to analyze the potential diffusion of micro-CHP installations as a substitution technology of classical household boilers. Three consumption profiles are considered in the paper for total 16 million households. Authors aimed to present potential market shares of micro-CHP at the end of 20th year. Except base case scenario (no incentives), three incentive scenarios were tested by model: investment subsidy to lower the initial consumers' outlay, the reselling of electricity produced in excess by the micro-CHP, and adapting the price of energy. The later incentive scheme was the best adapted to a sustained and permanent transformation of consumers' needs and attitudes in energy consumption. Authors used market shares of three profiles as performance indicators.

15.3.3 Bioenergy

Energy systems are complex adaptive systems with many factors. The systems approach can be used to analyze comprehensively the factors and interactions between them. Renewable energy sources have good benefits. However, they have also some negative effects on the other components of the system. Therefore, it is urgently required to model the system by means of holistic and systemic analysis method. By analyzing the reason for the negative effects and the threats, one can identifies the controlling and influencing factors and their impact on the system and then determines policies which reduce the negative effects and enhance the positive effects. Influential factors can be tested to insure the feasibility and effectiveness of the improvement policies.

The resources of bioenergy are wood, bioenergy crop, and biomass residues such as straw, wood scrap, and animal dung. Callesen et al. (2010) classified potential bioenergy crops into starch, oil, sugar, grassy, and woody biomass products. Bioenergy is expected to become one of the key energy resources for global sustainable development (Yamamoto et al. 1999). Biomass residues do not occupy land directly, but the others share available land area with biomass production for the required food and materials. Bioenergy production will be limited more strongly when the growths of the population and the economy in the world cause the growth of biomass demand for food and materials in the future

(Yamamoto et al. 1999). The model consists of a land use sub-model and an energy sub-model. Land use sub-model considers a food sector and a wood sector, and represents land use competition among various uses of biomass applications (paper, timber, wood, food, feed, and energy). Energy sub-model includes a module chemical flow, in order to evaluate the energy potential of chemical-products scrap. They point out that a balance must be set between energy biomass production and food biomass production. In a similar manner, even though there will be a significant energy potential for modern fuelwood produced from forest, a severe decline in the mature forest area would be seen in the future.

In rural areas, the use and distribution of energy is an important issue. The rural areas mainly depend biomass energy and other energy available locally and rural energy construction is the basis of ensuring the stable development of local economy (Xiaohua et al. 2006). Energy consumption in rural areas rises from household energy use, agricultural production, and county industrial production. Xiaohua et al. (2006) develop a model with seven sub-models, namely: Living energy production, Farm production subsystem, Afforesting, Investment subsystem, Energy supply subsystem, County industry subsystem, and Rural industry subsystem. They defined three scenarios: improved stoves, popularizing breeding pigs with raw forage, saving energy in township and village enterprises, and developing biogas digester. They used indicators indicating economic and energy benefits.

Li et al. (2012) focus on the ecoagriculture system of a district in China to enhance the sustainable capacity of ecoagriculture system. The System Dynamics model that is used to define potential risk and negative effects of the system and to decide the system improvement policies is composed of three sub-systems: agriculture, effect, and policy. The main subsystem is agriculture which consists of the beef cattle feeding, the methane production and utilization, and the planting of crop, fruit, and vegetable. The operations of agriculture subsystem has some positive effects such as economic growth and yield increase, and some negative effects such as pollution, resource consumption, and greenhouse gas emissions. These effects constitute the effect subsystem. Authors define the policy subsystem for that the decision makers explore improvement policies by simulating the interaction between effect subsystem and agriculture subsystem. In this study, the potential risks and negative effects of the system are identified and then the improvement policies are defined to remove those risks. Authors prove that suggested policies indeed eliminate all the risks, reduce the negative effects, and expand the ecological and economic positive effects.

15.3.4 Limits to Growth

SD approach defines two main feedback loops: positive and negative. Positive reinforcement loops generate variables that continue to grow. Negative loops seek balance or equilibrium. Negative feedback loops bring the state of the system to a desired state. The complex behavior of the system is emerged from the combination of those loops in a system. As infinite growth is not feasible, positive reinforcement loops cannot exist by themselves. Resources that support the state of the system are also a limit to the growth of the system.

The behavior of energy regimes might be characterized by "limits to growth" concepts in System Dynamics. Increasing energy consumption causes overexploitation of the resources, and leads to a steady decrease in carrying capacity of the energy resources and the human activity based on energy.

Podobnik (1999) argued that a third global energy shift, toward a cluster of new energy technologies, is in initial stages of consolidation and can be accelerated in the next century. Since the onset of the industrial revolution, the world has in fact witnessed the full consolidation of two distinct energy regimes. The first, based upon coal, grew to maturity in the 19th century and then entered into relative stagnation in the twentieth century. The second based upon petroleum, underwent global diffusion during the twentieth century but may be reaching maturity (Podobnik 1999).

Verbong and Geels (2007) pointed out the difference between "goverment" and "governance". Governance means that directionality and coordination in a particular domain has an emergent character, arising from interactions between multiple groups. Public authorities may try to influence this emergent directionality, but cannot steer it at will. There will be eventually a limit to the government of public authorities from the groups sharing the same resources.

15.3.5 Technology Sustainability Assessment

Musango et al. (2012) suggest technology sustainability assessment method based on system dynamics approach and apply it to the case of biodiesel developments in South Africa. The assessment of renewable and clean energy technology reveals the future consequences of new technology, the economic, environmental, social effects, and the contribution to sustainable development. Their model has 11 submodels, namely: biodiesel production cost of operation, biodiesel production profitability, gross domestic product, employment from a biodiesel plant, community acceptance, population, land usage, water usage, air emission, and energy demand. System Dynamics structures of the sub-models are described in Musango et al. (2011) in detail. Musango et al. (2012) define ten indicators to evaluate the performance of the system: economic (biodiesel production, biodiesel profitability, GDP), social (employment, the community acceptance to grow biodiesel crops), and environmental (land use, air emission, biodiesel by-product, water use, energy use). Various interesting policies may be tried experimentally by using the model. They define four main scenarios and two combinations of main scenarios. Main scenarios are fertilizer use, subsidies for biodiesel crop, revenue generation from by-product in biodiesel production, and community perception about the biodiesel crops benefits. For example in fertilizer use scenario, model reveals that although there is a reduction in land use, net air emissions increase. They reached the result of no single strategy that is capable of improving the performance of the selected sustainability indicators. To analyze the combined strategies as in the chapter, simulation approaches present convenient models.

15.3.6 Energy Planning and Forecasting

Fan et al. (2007) developed a System Dynamics model to investigate the impact of the investment in mines on the coal system. They also made predictions for the coal production capacities under various scenarios in 2020 and gave some policy recommendations. Important variables in the model are investment in state-owned mines, production capacity of state-owned mines, production of state-owned mines, production of town or village-owned mines, and new available reserves for mine construction, mining reserves. The objective of the study is defined as to confine the productions of town or village-owned mines and to increase production capacity of state-owned mines without getting in over-load production state. They used investment, amount of production, and amount of production capacity as performance indicators.

Dale et al. (2012) proposed a lifetime evolving function for the dynamics of the energy return on investment and incorporate it into a system dynamics model of global energy system. The system has two sectors: the energy and industrial sectors. In the system, the main feedback loop between energy and industrial sectors is that an increase in energy production raises industrial output which in turn may be reinvested back into the energy and industrial sectors. In modeling process, it is necessary to make a number of assumptions for simplifying real system. But to infer about the behavior of the real system via model, assessment of the validity of the assumptions is the most important process in modeling. Authors give detailed validation and verification of the model. In calibration of the model, historic production data for mature technologies was used.

There are significant difficulties with establishing an accurate model to predict natural gas consumption by using forecasting approaches, because many factors such as production strategies, industry policy, GDP growth, infrastructure construction, changing demand patterns, and similar cannot be fully considered (Li et al. 2011). Authors divide the natural gas consumption system into four subsystems, namely: Primary Industry (agriculture), Secondary Industry (chemistry industry, power generation, industrial fuel), Tertiary Industry (transportation sector, catering industry), and Residential Life. They define GDP, population, urbanization, and investment as parameters of scenarios in experiments. The change of natural gas consumption is the performance indicator and is analyzed over the 1997–2029 period.

15.4 Agent-Based Simulation

Agent-based modeling and simulation has the notion that a system is greater than the simple sum of its constituent parts. To manage such systems, the systems must be understood as collections of interacting components with its own rules and responsibilities. Agents are the decision-making components in complex adaptive systems. They have sets of rules or behavior patterns that allow them to take in information, process the inputs, and effect changes in the outside environment (North and Macal 2007).

An energy system has a wide range of actors: government, energy resources, energy utilities, industry, households, environmentalists, agriculture, and environment. The relationships between these actors are inherently complicated and nonlinear. They have beliefs, principles, rules, and goals which are conflicted with each other. For example, industry needs energy to produce the products which serve customer. But use of energy gives rise to pollution which deteriorates the health of peoples and environments. As mentioned above, actors in an energy system can be modeled as agents, but as agent-based simulation is a fairly new technique of simulation when compared to other techniques, there are not many studies of it on the subject of energy systems.

Verbong and Geels (2007) handle the energy transition by means of the multi-level perspective. In micro level, they define niches acting as “incubation rooms,” shielding new technologies from mainstream market selection. The socio-technical regime forms the meso-level and has three interlinked dimensions: (a) network of actors and social groups: in the electricity regime important actors are utilities, large industrial users, households, and related ministry (b) formal, normative, and cognate rules that guides the activities of actors: belief systems, problem agenda’s, guiding principles, and search heuristics (c) material and technical elements: electricity resources, grid, and generation plants. The macro-level is the socio-technical landscape, which forms an exogenous environment that usually changes slowly and influences niches and regime dynamics. The relationship between the three levels in conjunction with actors and elements in each level and the connections between them constitute a complex system.

Mazhari et al. (2011) developed a flexible tool based on hybrid simulation model to obtain optimal production and storage capacities, and an optimal operational decision policy considering the current and future market prices of the electricity. They integrated agent-based model which is used to obtain overall system behavior based on the collection of small individual players with SD model which is used for energy generation and storage segments. In the first scenario, they build a SD model to analyze that only PV-generation system is used to supply electricity consumption of the entire country. In the second scenario, energy generation and consumption of a local region is analyzed by a hybrid simulation model. Each individual household is represented by an agent which has its own electricity consumption. They classified the households into three categories: a single working person, family of a working couple, and family of couple with five children. In the last scenario, a simulation-based optimization model from perspective of a utility company is used for operational decision. Power generation and transmission grid, PV-generation farm, residential network, energy storage, and local transmission grid are main components of the simulation model. They defines several conditions considering future and current prices, energy storage level, production rate to decide sell, store, or buy and sell decisions.

Sensfuss et al. (2008) investigated the impact of renewable electricity generation on the market prices by using a simulation model which simulates reserve markets and the spot market. Five factors which have impact on the volume of the merit-order effect are investigated in sensitivity analysis by simulation models. These factors are fuel prices, the amount of electricity generated by renewable energy sources, scarcity mark-up whose size is depending on the expected ratio of load to be covered and available generation capacity, CO_2 price, and the development of the power plant portfolio. Fuel prices were the main driving factor for the strong growth of the merit-order effect. The gas price is the most important fact with a disproportionately high impact on the result.

In the recent years, the environmental effects of vehicles using oil products have been discussed. Since conventional vehicles is held responsible from global warming and pollution, the global car industries has already begun to research on designing environmentally friendly vehicles. Electric cars are vehicles which solely depend on electricity to work. Many of the large European cities have set ambitious goals concerning the number of EV on the street in the near future (Freund et al. 2012). As the main problem with the electric car is its short traveling time before it needs to be recharged, the installation of charging infrastructure and integration to the grid is an important issue. Freund et al. (2012) developed an event driven, microscopic traffic simulation framework in which the driver is designed as an agent, which is able to act autonomous, reactive, proactive, socially competent, and in communication with its environment. They considered three regulation reserves: home, work, and home and work.

15.5 Results

Renewable energy enjoys the following benefits:

Sustainability: Our society has become dependent on energy which in turn mostly depends on conventional energy resources like oil and coal. As those resources diminish in the future, the need for sustainable energy sources will become greater.
Energy Security: Production of energy inside the borders of the nation will make the production and supply of energy more secure.
Environment: Converting fossil fuels into energy creates greenhouse gases, pollution, and global warming. Increased awareness of environment protection results in more support for renewable energy systems.

Jobs and Economy: Renewable energy plants can be built and operated with a nation's own resources. Those plants are usually built in sparsely populated areas where jobs provided by these plants will improve the area's economy.

The versatile effect of renewable energy systems comes from the fact that they affect and are affected by components like production, economy, population, environment, and many others. In such a complex system, analysis of the components and their relations is of the utmost importance to come up with long-term sustainable energy strategies. Simulation is a technique used to analyze the dynamic behaviors of a complex system and setup experiments to test strategies on that system. Due to those attributes of simulation, it is being used more and more frequently to analyze renewable energy systems. Applications of Monte Carlo simulations can be found in almost any type of renewable energy systems where randomness of external and internal factors widely affect the system. Applications of System Dynamics, which is a macro simulation, are also common in Renewable Energy Systems where behavior analysis and strategy development are prominent. Whereas Agent-Based Simulation, which is a micro simulation, help us understand the overall behavior of the system by analyzing the relations and interactions of its components. Hybrid Simulation models are also expected to become more and more prominent as relations between macro and micro systems like a nation's economy and household behaviors are analyzed together.

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Chapter 16
Combining Mathematical Programming and Monte Carlo Simulation to Deal with Uncertainty in Energy Project Portfolio Selection

George Mavrotas and Olena Pechak

Abstract Mathematical programming (MP) is the most common methodology for modeling and optimization of energy systems. Energy systems' planning and optimization assume the knowledge of future situation, which is usually known with limited certainty. Therefore, the parameters of the model (data which assumed to be known during the modeling process) have usually a degree of uncertainty. Various methods have been proposed for dealing with this uncertainty, the most common ones being fuzzy programming, chance constrained programming, robust programming, and stochastic programming. In this work, we consider the implied uncertainty in the parameters as being of stochastic nature. Each uncertain parameter is characterized by a probability distribution. Subsequently, a Monte Carlo simulation samples the values from these distributions, and the MP models with the sampled values are solved. This process is repeated many times (1,000) in order to have an adequate sample for drawing robust conclusions. Relationships between the values of these parameters (i.e., interdependent parameters) can also be incorporated in the Monte Carlo process. The specific work is focused on the energy project portfolio selection problem where the output of each project as well as other parameters may be uncertain. In the current work, we introduce the iterative trichotomic approach (ITA) that gradually separates projects into green (selected under all circumstances), red (rejected under all circumstances), and gray sets (need further elaboration), combining Monte Carlo simulation and MP. The process output is not only the final portfolio, but also information about the certainty of participation or exclusion of every project in the final portfolio. A case study with real data from clean development mechanism (CDM) projects' database is elaborated in order to illustrate the method.

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16.1 Introduction

In the last two centuries, energy has become one of the most critical issues in mankind's survival and development. Energy is characterized by a variety of sources and conversion technologies. Heavy reliance on fossil energy carriers revealed a multitude of its previously ignored disadvantages, mainly related to the harmful environmental impacts. Especially notable is the impact of energy-related CO_2 emissions on earth's climate. The international effort against the global phenomenon of climate change found its expression in the early 1990s, with the establishment of the United Nation Framework Convention for Climate Change (UNFCCC). In the framework of UNFCCC, Kyoto protocol provides flexible mechanisms in order to reduce GHG emissions. One of them is the CDM which gives the possibility to offset carbon emissions in the shape of environmentally friendly activities. Broadly speaking, they are projects implemented in developing countries using technology and finance assistance from developed countries. The benefit for the funders is that they get "environmental" credits quantified as certified emission reduction units (CERs) in order to reduce their "emission balance." Within variety of CDM activities, energy projects play a major role.

The case study in this paper refers to these types of projects, and it is actually a project portfolio selection problem.

Project selection is defined as the problem of selecting one or a subset from a set of projects (a subset of projects is considered as a "portfolio of projects"). In the latter case, the usual approach is to rank projects using one or more criteria and select the top ranked ones that cumulatively satisfy a budget limitation. However, in real world decision making, there are two concepts that complicate the process: (a) the existence of constraints and limitations imposed by the decision maker (DM) and (b) the uncertainty that accompanies project evaluation, i.e., the future project's performance (output) uncertainty.

Regarding the first issue, the existence of constraints to be satisfied by the final selection destroys the independence of projects, which is one of the main assumptions in multiple criteria decision analysis (MCDA) ranking (see, e.g., Belton and Stewart 2002). In other words, the top ranked projects may only by chance satisfy the imposed constraints. For such cases, MP is an appropriate tool that performs optimization under specific constraints. Furthermore, in case of project selection, the combinatorial character of the problem implies the use of integer programming (IP) with 0–1 (binary) variables expressing the incorporation ($X_i = 1$) or not ($X_i = 0$) of the ith project in the portfolio. The earliest contributions were published under the title of *capital budgeting* (see, e.g., Lorie and Savage 1955; Bernhard 1969), using strictly financial measures to measure the value of projects and portfolios, giving emphasis to the budget constraint. From the early 1960s, the so-called capital budgeting problem was recognized as equivalent to the popular in operational research (OR) knapsack paradigm. The incorporation of multiple criteria can also been found in literature using goal programming (see, e.g., for a review Zanakis et al. 1995; for applications in information systems Badri et al. 2001; Santhanam et al. 1989;

Santhanam and Kyparisis 1996; for university resource allocation Albright 1975; Kwak and Lee 1998; Fandel and Gal 2001; for an industrial application Mukherjee and Bera 1995), combinations of MCDA with IP (see, e.g., Golabi et al. 1981; Abu Taleb and Mareschal 1995; Mavrotas et al. 2003, 2006, 2008), and data envelopment analysis (Cook and Green 2000; Oral et al. 1991, 2001) among others.

The second issue is the implied uncertainty in evaluation of projects and especially in evaluation of their performance (considered as the project output). In his seminal work for portfolio optimization, Markowitz (1952) proposed the modern portfolio theory (MPT) that incorporates portfolio risk in the decision-making process. In MPT, risk is quantified by the co-variance matrix of returns (outputs) as calculated by historical data. The MPT was designed for securities where historical data is not a problem. In relation to projects, the MPT cannot be easily applied as: (a) the decision variables are binary and (b) historical data are scarce. For a more realistic modeling, the uncertainty that characterizes the projects output should be taken into account. In literature, this is done either with the use of scenarios (see, e.g., Georgopoulou et al. 1998) or with fuzzy parameters (see, e.g., Damghani et al. 2011; Cavallaro 2010) or with stochastic parameters (Liesio et al. 2008; Shakhsi-Niaei et al. 2011). A powerful tool for dealing with stochastic uncertainty is Monte Carlo simulation, where sampling from specific probability distributions is performed for the projects' uncertain performance. A great number of iterations are necessary in order to obtain reliable results from the outputs (distribution of output values, etc.).

In the present paper, we combine these two techniques, namely, MP and Monte Carlo simulation in order to deal with project portfolio optimization taking into account multiple constraints and the inherent uncertainty associated with the projects' output. The uncertainty is represented with probability distributions (a stochastic nature is assumed) as it is also done in other methods (Lahdelma et al. 1998; Tervonen and Lahdelma 2007; Hyde et al. 2003).

In the present method, we follow an iterative approach using decision rounds. On each round, a series of Monte Carlo simulations—IP optimizations are performed providing information about the membership of every project in the final portfolio.

This information is aggregated in order to classify projects as green, red, or gray, according to their participation in the final portfolio. From round to round, we reduce the variation (a measure of uncertainty) of gray projects so that the whole process converges to a final portfolio. The output of the process provides important information of the certainty degree associated with every project, which is incorporated in the final portfolio or not. The proposed decision-making process is named ITA because it divides the initial set of projects into three subsets: the green, the red, and the gray sets, and it is implemented in an iterative manner.

The rest of the chapter is organized as follows: Sect. 16.2 contains a detailed description of the trichotomic approach. In Sect. 16.3, details of the case study and the associated model are described. In Sect. 16.4, the trichotomic approach is applied in the case study, and the results are discussed in detail revealing the pros and cons of the method. Finally, in Sect. 16.5, the main concluding remarks are presented with the last two paragraphs devoted to suggestions for future research.

16.2 Iterative Trichotomic Approach

16.2.1 The Basic Idea

The term “trichotomy” refers to the separation of a set into three parts. In this context, the proposed decision-making process is based on the fact that projects are classified in three classes based on their performance and current level of uncertainty. The uncertainty is incorporated using probability distributions for projects’ performance, which is the major driver for the optimization. Monte Carlo simulation is performed using sampling from these distributions. The optimization process with the IP model provides an optimal portfolio. This pair of sampling and optimization is the core of calculations. For example, if the number of Monte Carlo simulations is set to 1,000, then 1,000 sampling and optimizations will be performed.

The output of this process will be 1,000 optimal portfolios based on the sampling of the model’s parameters (in this case—projects’ performance). Eventually, the set of projects is divided into three subsets (classes): green projects that are present in the final portfolio under all circumstances (i.e., in all Monte Carlo simulations), red projects that are absent from the final portfolio under all circumstances, and gray projects that are present in part of the final portfolios. The classification in three subsets is not new in the literature. Liesio et al. (2007) used a similar approach in the framework of robust programming. However, the way the projects are assigned to each set is different. In addition, Mavrotas and Rozakis (2009) used similar concepts in a student selection problem for a postgraduate program.

The term “iterative” indicates that the proposed process is developed in a series of decision rounds (or cycles). A predetermined number of decision rounds may be defined from the beginning and every round feeds its subsequent until a convergence to the final portfolio is attained. From round to round, the uncertainty is reduced for the gray projects, and some of them are forced to become either green or red. The uncertainty reduction can be performed either by inclusion of more information or by an automatic uniform narrowing of gray projects’ probability distributions. The whole process is depicted in Fig. 16.1.

The concept behind the trichotomic approach is that a DM can focus on projects that are really at stake. The “sure” projects (either in or out of the portfolio) are determined and the DM can shift his attention to “ambiguous” projects (e.g., the gray set). The method provides quantitative and qualitative information that cannot be acquired using, e.g., the expected values of distributions.

In the latter case, the DM is provided with a unique optimal portfolio or, in other words, which are “go” and “no go” projects, without any discrimination about the degree of certainty for each one of them. On the contrary, in trichotomic approach, DM is provided with fruitful information about certainty degree of each project in the portfolio. In other words, the DM sees the whole picture with multiple candidate portfolios and has the opportunity to fully control the decision-making process. In the case of “close winners,” the DM is informed about the more or less equivalent solutions. In this way, he can use additional criteria to further discriminate

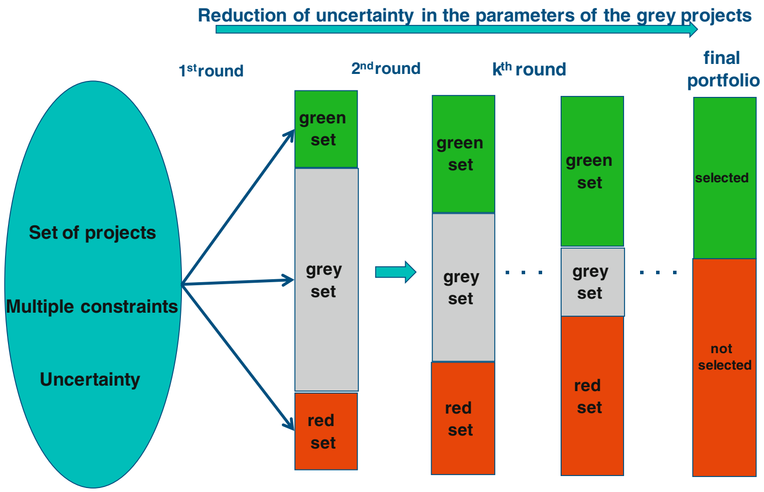


Fig. 16.1 Graphical illustration of the iterative process

"close winners." Hence, the DM is aware of projects prioritization given that he knows in which round a project enters the green set. The earlier the project enters the green set, the more sure he is about its presence in the final portfolio.

An illustrative example will demonstrate, in practice, the above-mentioned issues in the following sections.

16.2.2 The Simulation: Optimization Process

Monte Carlo simulation and optimization with MP is a rather recent development that becomes plausible with the vast improvement in computer power during the past few years. Although it is a computational demanding task, it is still worthwhile as it provides fruitful information regarding the uncertainty of the final solution.

Using Monte Carlo simulation (see, e.g., Vose 1996, 2006) we can consider various probability distributions for uncertain parameters. By sampling from these distributions, we obtain parameters for the MP model that is subsequently optimized. This process is repeated N times (N is a big number, e.g., $N = 1{,}000$), and we receive N optimal portfolios expressing all the possible states of nature (some of these optimal portfolios may be identical).

The MP model on the tth Monte Carlo iteration is following:

$$\begin{aligned}
&\max Z^{(t)} = \sum_{i=1}^{P} c_i^{(t)} X_i \\
&st \\
&X \in S \\
&X_i \in \{0,1\}
\end{aligned} \tag{16.1}$$

where $c_i^{(t)}$ is the objective function coefficient (some type of performance measure or output) of the ith project in the tth Monte Carlo iteration. The value of $c_i^{(t)}$ is assigned by sampling from the corresponding distribution. X_i is the binary decision variable indicating if the ith project from the initial set is selected ($X_i = 1$) or not ($X_i = 0$), and S represents the feasible region formulated by all the imposed constraints. We cannot select only parts of one project; hence the modeling process uses binary variables instead of continuous ones, which is a usual case in stock portfolio selection problem. Apart from the usual budget constraints, segmentation and policy constraints, interactions and interdependencies among projects can be also taken into account in the formulation of the decision space S (Mavrotas et al. 2003; Liesio 2007).

The output of model (16.1) is the optimal portfolio $\boldsymbol{X}^{(t)}$ with $Z^{(t)}$ the value for the objective function. By exploiting information from N optimal portfolios, we create three sets of projects (thus, the name of the method is known as "trichotomic approach"):

- The *green* set which includes the projects that are present in all N portfolios.
- The *red* set with the projects that are not present in any of N portfolios.
- The *gray* set with the projects that are present in some of N portfolios.

In Table 16.1, we can see an example of green, red, and gray projects in a problem with P projects and $T = 10$ iterations, just for illustrative purposes. The rows contain the values of decision variables for all projects within each Monte Carlo iteration, whereas the columns contain the values of decision variables for each project across Monte Carlo iterations.

It must be noted that especially on first rounds we cannot usually draw conclusions about a portfolio that appears the most (with higher frequency) among the 1,000 iterations, which means that obtained optimal portfolios are rarely the same across the 1,000 iterations. Therefore, since we cannot draw conclusions for the most frequent portfolios, we draw conclusions for the most frequently included

Table 16.1 Example of the results from the initial round

Iteration	X_1	X_2	X_3	X_4	…	X_P
1	1	0	0	1	…	1
2	0	0	1	1	…	1
3	0	0	0	1	…	0
4	1	0	0	1	…	1
5	0	0	0	1	…	1
6	0	0	0	1	…	1
7	0	0	0	1	…	0
8	1	0	0	1	…	1
9	0	0	1	1	…	1
10	1	0	0	1	…	1
	Gray	Red	Gray	Green	…	Gray

projects in portfolios. In the proposed method, we exploit this information and put our focus on the gray set, i.e., the projects that we are not sure about.

To facilitate decision process, we can define membership thresholds for the green and the red set by relaxing the membership requirements. For example, we may set a "green" threshold of 95 % which means that a project is considered to be member of the green set if it is present in the optimal portfolio in at least 95 % of iterations Accordingly, if we set a "red" threshold of 5 %, this means that a project is considered to be member of the red set if present in the optimal portfolio in less than 5 % of iterations. These thresholds are usually symmetric, which means that a green threshold of 99 % implies a red threshold of 1 %. The membership threshold can be used whenever the discrimination ability of the first phase needs to be increased, i.e., when green and red sets are almost empty.

16.2.3 Implementation of the Iterative Process

As it was mentioned, ITA incorporates decision rounds (or cycles). In every round of ITA, a simulation–optimization process takes place, providing the corresponding green, red, and gray sets of projects. The process is quite flexible and can be implemented either with a predetermined, fixed number of rounds, or until sufficient convergence is reached in a less formal way.

16.2.3.1 Predetermined Number of Rounds

The DM initially determines the number R of decision rounds. In the first round, the Monte Carlo sampling is performed using appropriate probability distributions for the uncertain parameters. The results define the *green(1)*, *red(1)*, and *gray(1)* sets (the number in the parenthesis indicates the round from which the corresponding subset emerges). In the second round, projects from the *green(1)* set are considered as "given," those from the *red(1)* set as "discarded" and the variance (quantitative measure of the uncertainty) of the *gray(1)* projects' parameters is reduced by $1/R$. This reduction depends on the form of distribution. For example, for a normal distribution, we reduce by $1/R$ the standard deviation, or, for a uniform distribution, we cut $1/2R$ of the range from both edges. It must be noted that this is performed only for the gray projects, while for the green and red projects probability parameters are kept unchanged from the previous round. The model for the second cycle is the following:

$$\begin{aligned}
&\max Z^{(t)} = \sum_{i=1}^{P} c_i^{(t)} X_i \\
&st \\
&X \in S^{(t)} \\
&X_i \in \{0,1\} \\
&X_i = 1 \quad i \in green(1) \\
&X_i = 0 \quad i \in red(1)
\end{aligned} \tag{16.2}$$

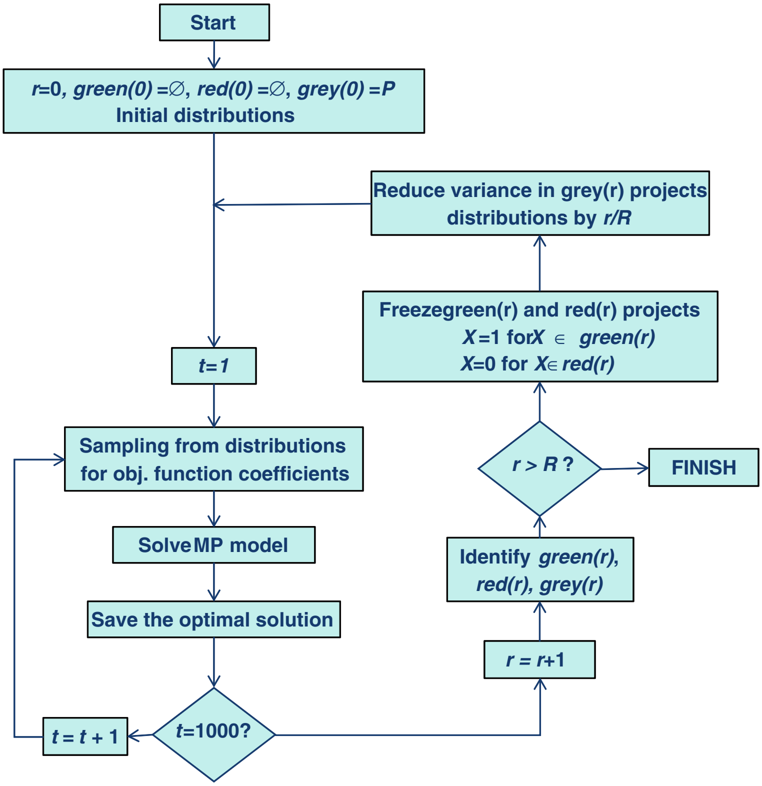


Fig. 16.2 Flowchart of the iterative trichotomic approach (predetermined number of rounds)

After the second round of simulation–optimization process, the output of the process is elaborated. More specifically, green and red sets are enriched by new projects while the gray set shrinks. Subsequently, for the third round, we reduce the variance of gray projects and we consider new green and red sets as given. The flowchart of the decision-making process is depicted in Fig. 16.2.

The variance reduction follows a uniform pattern across the rounds. For example, in case of normal distribution, we reduce the standard deviation by $1/R$ after each round. This means that after round r, the reduction of standard deviation is $sd \times r/R$. Thus, in the final round, gray projects' parameters are considered as deterministic (have no variance at all). The output of the final round is a unique portfolio, because all Monte Carlo simulation–optimization iterations produce the same solution.

16.2.3.2 Not a Priori Number of Rounds

The second option is to avoid the determination of rounds and finish a decision-making process when adequate convergence for the final portfolio has been attained. The whole process is less formal than the previously described one (in Sect. 16.2.3.1). After a simulation–optimization, the DM identifies gray projects (projects in doubt). He gathers additional information about these projects, which is translated in variance reduction in their parameters' distribution. It must be noted that reduction of variance may not be uniform as in the case of previous paragraph. In the next round, gray set obviously shrinks and the DM checks the frequency of each one of optimal portfolios obtained as the output of simulation. If, for example, a specific portfolio occurs in 567 out of 1,000 iterations it actually has 56.7 % probability to be the optimal portfolio under a given uncertainty level. If the DM finds a stochastically dominant portfolio, he can end the decision process. The term "dominant" is flexible. For example, the DM can exit the loops of decision rounds as soon as a portfolio with 60 or 70 % probability emerges. The exit threshold (i.e., the probability of occurrence over which a portfolio is considered as selected) is determined by the DM, according to the specific decision situation. The flowchart of decision-making process is depicted in Fig. 16.3. The darker shading indicates the alterations from the ITA with fixed number of rounds.

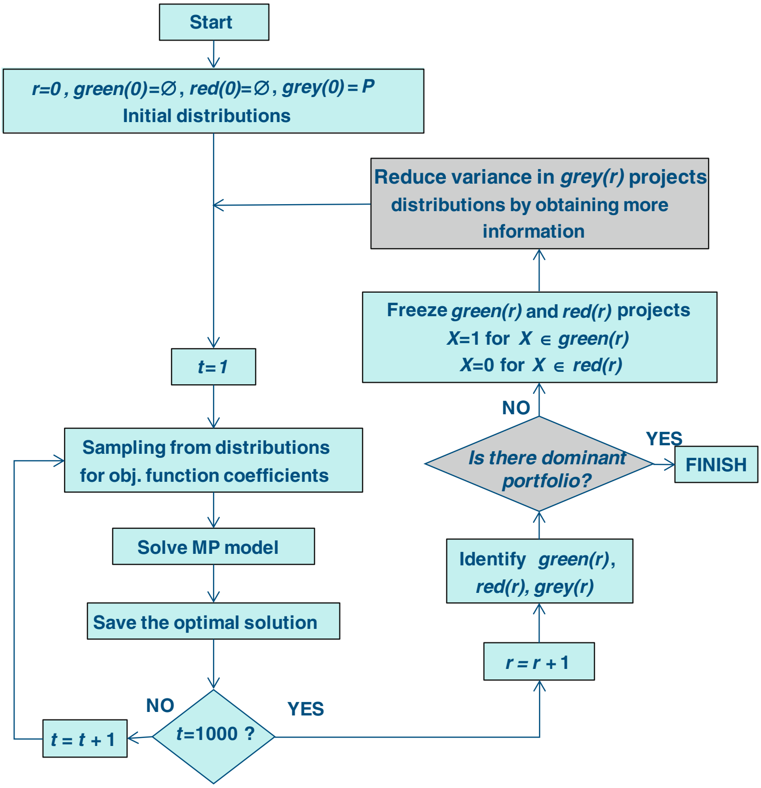


Fig. 16.3 Flowchart of the iterative trichotomic approach (not a priori defined number of rounds)

16.3 Case Study: Selecting a Portfolio of CDM Projects

16.3.1 Description of the Problem

The subject of the specific case study refers to climate related projects. This type of projects is mainly related to energy either from the supply side or from the side of energy efficiency (EE). It is a growing domain of activities with many parties involved, such as governments, that plan and propose different climate friendly activities and address complex objectives of local development and employment, as well as banks and developers, who search for perspective ways of investment. In addition, private companies (both large and small) who care about public perception may also finance and support green activities. Even individual people, interested in a sustainable future, can buy carbon credits to offset their everyday emissions.

Investors always face the problem of choice. Usually, the options for investment are greater than the available budget. That is why we study the case of project selection for a portfolio of activities. One of the main tasks for a DM is to make a balanced selection by taking into account technology, geographical distribution, budget, policy and other constraints that may be imposed. Moreover, the output of projects is rarely known with certainty at the decision level (a priori).

Therefore, in the current case, the problem is stated as: which portfolio of climate-related projects should be selected by an entity, given information about the total budget, the policy and technical conditions that must be met, as well as the inherent uncertainty in projects' output. The "universe" of available options consists of projects under the CDM and the relevant data are drawn from the CDM database (UNEP Risø Centre 2012).

16.3.2 Creating the "Projects' Universe" from the CDM Database

We use a hypothetic set of projects, based on real data from the CDM database. For every activity, before registration a project design document (PDD) is submitted, where its main features are described and calculated. Subsequently, registered projects are subject to performance monitoring and verification according to the adopted schedule. We focus our attention on renewable energy projects, which are represented by the following technologies:

- Wind energy,
- Hydro power plant (HPP),
- Biomass,
- Landfill gas,
- Methane avoidance,
- Energy efficiency in industry (EE).

As wind and hydro electricity generation are dominant technologies, a great number of projects fall in this category. In order to refine the decision process, we further split these projects into small scale projects (with installed capacity up to 15 MW) and large scale (more than 15 MW) ones. We label small scale projects with "S" at the beginning (SWind, SHydro), and the large scale projects—"L" (LWind, LHydro). The remaining projects are not that numerous, and hence, there is no need to create sub-groups.

Wind electricity generation is the largest group of projects with the majority of them situated in China and India. Technology success may be attributed to the strong incentives that these hosting countries have created over the past years (Pechak et al. 2011). Within hydro power generation projects, some are focused on modernisation of already existing facilities, whereas others refer to the construction of a new dam. Hydro power plants face several issues, mainly environmental, both at local and international levels. In cases of international rivers, active construction of dams and hydro power plants in one country may cause water shortages during dry seasons or other relevant problems in the countries that are subsequent in the river flow. This is quite a sensitive issue, particularly in South–East Asia (WWDR4 2012). Biomass covers many sub technologies, mainly related to different types of agricultural wastes. Most of these projects are small scale and possess strong environmental potential, which makes them similar to power generation from landfill gas and to methane avoidance on waste water treatment facilities. The objective of landfill gas projects is to install a highly efficient collection system to capture and destroy methane by flaring at high temperatures and use the generated heat for the community needs. Generally, the avoidance and reduction of methane emissions is very important not only from a public health point view. Methane is characterized by a global warming potential (GWP) 21 times greater of CO_2, and makes a considerable input to the overall greenhouse effect on the planetary scale (UNFCCC 2012). Lastly, great variety is found within the EE projects for own electricity generation from waste heat on industrial facilities such as cement plants, iron and steel production plants, non-ferrous metal production plants and others.

Geographical distribution covers 17 countries (Argentina, Brazil, Chile, China, Ecuador, Egypt, Honduras, India, Indonesia, Malaysia, Mexico, Peru, Philippines, South Africa, South Korea, Thailand, and Vietnam). According to the Kyoto protocol classification, all these countries are considered to be developing. But each of them has many specific characteristics that should be taken into account before the selection process starts. For example, the state support for wind energy projects led China to become a major player in this field and helped to develop a new industry within a few years. On the other side, for many other developing countries, the last technology developments are still not accessible due to lack of funds and knowledge. Without technology transfers, these countries may follow the historical polluting trends of industrialized countries. Instead, CDM demonstrates an effective way to move quickly to environmentally sound and sustainable practices, institutions, and technologies (Karakosta et al. 2010).

Within the evaluation process, big emphasis is put on environmental performance. Actually, the sustainability concept was supposed to be very strong on the stage of CDM development. But reality turned out to be not as "green" as expected. These criteria were very vague and led to strong critics of CDM. Buyers of CERs, in order to ensure that they support real, and not declarative, benefits began to invite external companies to perform sustainability check of the projects, both existing and under development. That is how demand for premium CERs occurred with the gold standard (GS) labeling being best known among them (Gold Standard Foundation 2012). The latter certifies renewable energy and EE carbon offset projects to ensure that they all demonstrate real and permanent greenhouse gas (GHG) reductions as well as sustainable development benefits in local communities that are measured, reported and verified. From a wide CDM database, we consider only registered projects, because they have more rich information. A summary of the input data is presented in Table 16.2.

We selected 300 representative projects with specific technology and geographical characteristics. Solar, geothermal, tidal, and several other types of EE projects are excluded from selection due to lack of initial information (e.g., no investment costs). The portfolio selection has a strong emphasis on environmental performance with the respect to the current situation on CDM map. Since we work with already existing projects, we use available GS labeling for the evaluation of their environmental profile. In the model, the availability of GS certification is expresses by "1," and by "0" if not.

Projects within the model were assigned with an identification number according to technology, i.e., small-scale wind: 1–43; large-scale wind: 44–110; small-scale hydro: 111–155; large scale hydro: 156–204; biomass: 205–235; EE own generation: 236–255; landfill gas: 256–273; and methane avoidance: 274–300.

16.3.3 Model Building

16.3.3.1 The Objective Function

The amount of issued CERs is one of the most critical criteria, if not the most significant, in specific decision situation. When a project is submitted for registration, the expected amount of CERs is declared. However, past experience shows that the declared amount of carbon credits usually differs from the actual amount, which is realized after the implementation of the project. We attempted to quantify this uncertainty by examining past projects' issuance success according to their technology. Issuance success is defined as the ratio between initially expected CERs and actual CERs, and is calculated in the CDM database for the projects that have one or more years of implementation. Because projects may vary in duration, having 10- or 7-year (renewable) crediting periods, we considered the annual amount of CERs to have a common basis. Based on the available historical data, Table 16.3 presents the levels of CERs issuance compared to the expected amounts from PDDs.

Table 16.2 Input data distributed by countries and technologies

	SWind	LWind	SHydro	LHydro	Biomass	Landfill gas	Methane avoidance	EE own generation	GS	Budget MUS$	kCERs/ year	Total projects
China	5	53	21	27	2	6	4	10	40	6,733	2,588	128
India	36	4	10	5	15	1	2	6	10	979	17,050	79
Argentina	0	0	0	0	1	1	0	0	0	42	305	2
Brazil	0	1	4	4	0	2	0	1	0	541	885	12
Chile	0	1	2	3	2	0	0	0	1	490	1,346	8
Ecuador	1	0	0	2	0	0	0	0	0	62	210	3
Egypt	0	1	0	0	0	0	0	1	0	135	359	2
Honduras	0	0	1	0	0	0	1	0	1	10	54	2
Indonesia	0	0	0	0	2	1	3	0	3	52	361	6
Malaysia	0	0	0	0	5	1	4	0	0	44	686	10
Mexico	0	4	0	1	0	3	1	0	0	1,396	2,101	9
Peru	0	0	3	3	0	0	0	0	0	360	879	6
Philippines	0	1	0	0	1	0	1	1	0	104	191	4
South Africa	0	0	0	0	1	2	1	0	0	30	133	4
South Korea	1	1	2	1	0	0	0	0	0	243	501	5
Thailand	0	0	0	0	2	1	10	1	6	161	958	14
Vietnam	0	1	2	3	0	0	0	0	2	119	198	6
Gold standard	3	33	2	2	8	2	12	1	63			
Budget MUS$	436	6,861	400	2,555	389	165	105	593	2,846			
kCERs/year	639	11,059	1,257	6,898	1,794	3,075	1,439	2,644	6,242			
Totals	43	67	45	49	31	18	27	20	63	11,501	28,805	300

Table 16.3 Distribution characteristics of CERs issuance success

	Total projects	Average level of issuance success (avis) (%)	Standard deviation of issuance success (sdis) (%)
Wind	370	89	24
Hydro	465	85	39
Biomass	174	84	35
EE own generation	97	77	25
Landfill	90	52	36
Methane avoidance	122	61	38

In our model, the actual CERs of the portfolio constitute the objective function to be maximized. Given the uncertainty, characterizing the issuance success of each project according to its technology, we draw these values from the corresponding normal distributions with the characteristics given in Table 16.3.

Therefore, the coefficients of the objective function are random parameters sampled from the normal distribution with the following characteristics:

$$c_i^{(t)} = \text{expcer}_i \times \text{normal}(\text{avis}_j,\ \text{sdis}_j) \tag{16.3}$$

where $c_i^{(t)}$ is the objective function coefficient declaring the actual CERs for the ith project according to the tth sampling, expcer_i is the expected CERs declared during the submission of the project, avis_j is the average issuance success for technology j that characterizes project i, and sdis_j is the standard deviation of the issuance success of technology j. The two latter parameters are taken from Table 16.3. The second term of the product indicates that the parameter is sampled from the normal distribution with the specific characteristics. Therefore, the objective function of the problem is:

$$\max Z^{(t)} = \sum_{i=1}^{P} c_i^{(t)} X_i \tag{16.4}$$

where $Z^{(t)}$ is the total number of kCERs achieved by the portfolio $P^{(t)}$ in the iteration t of Monte Carlo simulation, $c_i^{(t)}$ is the number of kCERs from the ith project as it is sampled in the tth iteration of Monte Carlo simulation, and X_i is the binary variable indicating whether the ith project is selected ($X_i = 1$) or not ($X_i = 0$) to the optimal portfolio.

16.3.3.2 The Constraints

The constraints of the problem express policy limitations imposed by the DM. They are related to the desired technology mixture as well as the geographical distribution of the projects in the final portfolio. In present case, the imposed constraints are:

(a) *Budget constraint*
The total investment budget for the selected projects must be less than 2 billion US$ (all 300 projects accumulate to 11.5 billion US$)

$$\sum_{i=1}^{P} \text{budg}_i X_i \leq 2000 \tag{16.5}$$

where budg_i is the budget of the ith project in million US$

(b) *Geographical distribution*
Certain conditions about the geographical distribution of projects are incorporated in the model as it is usually the case in real investment problems. The following conditions are just some examples to illustrate the modeling capabilities.

(b1) *At most 40 % of the allocated funds should be in projects located in China*

$$\sum_{i \in \text{China}} \text{budg}_i X_i \leq 0.4 \sum_{i=1}^{P} \text{budg}_i X_i \tag{16.6}$$

(b2) *At most 30 % of the allocated funds should be in projects located in India*

$$\sum_{i \in \text{China}} \text{budg}_i X_i \leq 0.3 \sum_{i=1}^{P} \text{budg}_i X_i \tag{16.7}$$

(b3) *At least 30 % of the selected projects must be located in Latin America*

$$\sum_{i \in \text{LatAm}} X_i \geq 0.3 \sum_{i=1}^{P} X_i \tag{16.8}$$

(c) *Technology mix*
Certain conditions can be imposed, which affect the technology mix of the final portfolio. This is often required in order to obtain a more or less balanced portfolio avoiding the "all the eggs in one basket" policy. They are usually extracted after some trial and error in the "spontaneous" model (without the technology mix constraints) and are needed to maintain a minimum or a maximum degree of representation of each technology in the final portfolio. In the current model, we have:

(c1) *At least 40 % of the allocated funds should be in wind projects (small and large scale)*

$$\sum_{i \in \text{Wind}} \text{budg}_i X_i \geq 0.4 \sum_{i=1}^{P} \text{budg}_i X_i \tag{16.9}$$

(c2) *At least 30 % of the allocated funds should be in hydro projects (small and large scale)*

$$\sum_{i \in \text{Hydro}} \text{budg}_i X_i \geq 0.3 \sum_{i=1}^{P} \text{budg}_i X_i \tag{16.10}$$

(c3) *The remaining four technologies should not have (separately) more than 10 % of the allocated funds*

$$\sum_{i \in \text{Biomass}} \text{budg}_i X_i \leq 0.1 \sum_{i=1}^{P} \text{budg}_i X_i \tag{16.11}$$

$$\sum_{i \in \text{EEff}} \text{budg}_i X_i \leq 0.1 \sum_{i=1}^{P} \text{budg}_i X_i \tag{16.12}$$

$$\sum_{i \in \text{Landfill}} \text{budg}_i X_i \leq 0.1 \sum_{i=1}^{P} \text{budg}_i X_i \tag{16.13}$$

$$\sum_{i \in \text{MethA}v} \text{budg}_i X_i \leq 0.1 \sum_{i=1}^{P} \text{budg}_i X_i \tag{16.14}$$

(c4) *The GS projects should be at least 30 % of the total projects in the final portfolio*

$$\sum_{i \in \text{GoldStd}} X_i \geq 0.3 \sum_{i=1}^{P} X_i \tag{16.15}$$

The aforementioned constraints are examples of constraints that DM may face in a real case. It must be noted that more conditions can be incorporated in the model with constraints such as mutually exclusive, precedent projects, and other logical conditions. In case that the annual cash flows are available, constraints on the annual expenses can also be incorporated. In general, modeling with IP in project portfolio selection is very flexible.

16.4 Results and Discussion

The required models and the whole solution process is developed in the general algebraic modeling system (GAMS, see, e.g., Brooke et al. 1998) using the mixed integer programming (MIP) solver CPLEX 11.1 for optimizing the MIP models. The number of iterations in the Monte Carlo simulation was set to 1,000.

The ITA method was applied in the specific problem as follows: five rounds of the iterative process are defined a priori (we denote with “0” the initial round, which means that $R = 4$). From round to round, we apply the reduction in the performance variance of gray projects by reducing the distribution variance of a corresponding issuance success. Specifically, in each subsequent round, we reduce the standard deviation of respective probability distribution by 25 %, as shown in Fig. 16.4. Consequently, in the final round, the standard deviation of gray projects is considered zero so that deterministic values of issuance success are assumed for the specific projects.

The membership threshold was set to 99 % for the green set and 1 % for the red set (see Sect. 16.2.2, last paragraph). This means that projects that appear in the final portfolio more than 990 times over 1,000 iterations are considered to be green projects, whereas the projects that appear less than 10 times are considered to be red.

Initially, we run the simulation–optimization process taking into account full uncertainty for the projects' issuance success ($\sigma = \mathrm{sdis}$). Specifically, for the calculation of every objective function coefficient c_i we use Eq. (16.3) and we sample from normal distributions with the characteristics of Table 16.3. It must be noted that among the 1,000 portfolios obtained from the simulation–optimization process, none of them was the same (i.e., we obtain 1,000 different portfolios).

Therefore, no conclusions about a dominant portfolio can be extracted from the first round. The number of projects in the final portfolio varies from 70 to 103 across 1,000 iterations. Eventually, 10 projects are classified as green, 77 as red, and the remaining 213 as gray.

In the second round, according to the flowchart of Fig. 16.2, we fix the values of green projects' decision variables to 1, and those of the red projects to 0. We reduce the standard deviation of gray projects to 0.75 × sdis (the standard deviation of the green and red projects is left at the previous rounds' level). The output of the second round is 16 green projects, 100 red projects, and the rest 184 are gray.

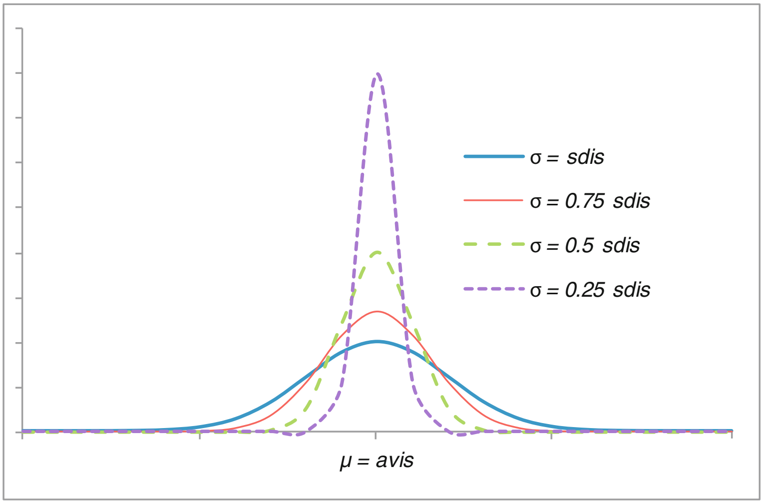
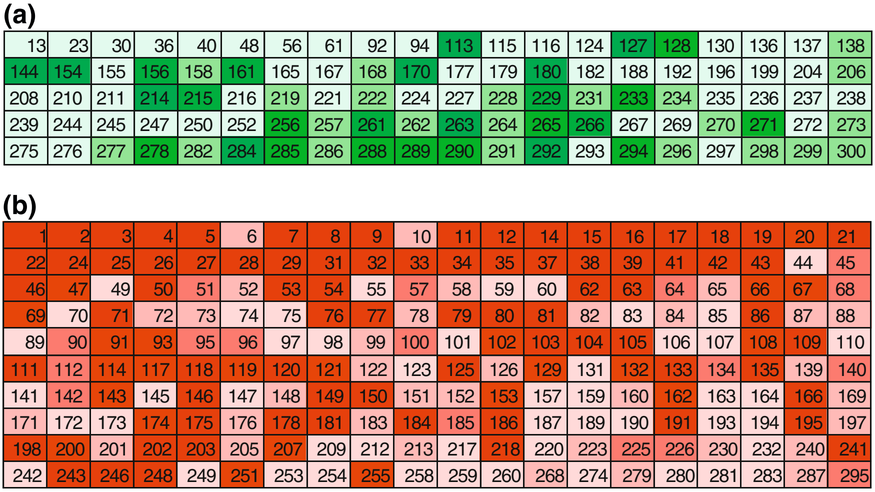


Fig. 16.4 Variance reduction from round to round for the probability distribution of the gray projects

In the third round, we fix again the values of green projects' decision variables to 1 and those of red projects to 0. We reduce the standard deviation of gray projects to 0.5 × sdis. The output of the third round is 27 green projects, 117 red projects, and the remaining 156 are gray projects.

In the fourth round, we fix the values of green projects' decision variables to 1 and those of red projects to 0. We reduce the standard deviation of gray projects to 0.25 × sdis. The output of the fourth round is 49 green projects, 151 red projects, and the remaining 100 are gray projects.

In the fifth and final round, the standard deviation for the last 100 gray projects was set to zero, which means their issuance success was considered as deterministic value taking the average value from Table 16.3. By the end of the round, the last 100 gray projects were fully allocated to green set (51) and red set (49). Conclusively, the whole process ends with 100 green and 200 red projects. In the final round, the CERs obtained from the final portfolio vary from 7,089 to 8,164 with a mean value of 7597 and a standard deviation of 190. The identification numbers (*id*) of projects as well as the decision round of their incorporation (for the green set) or their exclusion (for the red set) from the final portfolio are illustrated graphically in Fig. 16.5. The darker shading of a cell, the earlier round it enters either in the green or red set, i.e., the sooner we come to a conclusion about its status ("go" or "no go") in the selection process. In other words, we are more confident for the darker cells about their inclusion (green set) or their exclusion (red set) from the final portfolio. Therefore, for every project, we do not just obtain the information of "go" or "no go," but also the degree of certainty of this decision.



(a)

13	23	30	36	40	48	56	61	92	94	113	115	116	124	127	128	130	136	137	138
144	154	155	156	158	161	165	167	168	170	177	179	180	182	188	192	196	199	204	206
208	210	211	214	215	216	219	221	222	224	227	228	229	231	233	234	235	236	237	238
239	244	245	247	250	252	256	257	261	262	263	264	265	266	267	269	270	271	272	273
275	276	277	278	282	284	285	286	288	289	290	291	292	293	294	296	297	298	299	300

(b)

1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21
22	24	25	26	27	28	29	31	32	33	34	35	37	38	39	41	42	43	44	45
46	47	49	50	51	52	53	54	55	57	58	59	60	62	63	64	65	66	67	68
69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88
89	90	91	93	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110
111	112	114	117	118	119	120	121	122	123	125	126	129	131	132	133	134	135	139	140
141	142	143	145	146	147	148	149	150	151	152	153	157	159	160	162	163	164	166	169
171	172	173	174	175	176	178	181	183	184	185	186	187	189	190	191	193	194	195	197
198	200	201	202	203	205	207	209	212	213	217	218	220	223	225	226	230	232	240	241
242	243	246	248	249	251	253	254	255	258	259	260	268	274	279	280	281	283	287	295

Fig. 16.5 Final *green* and *red* sets along with the degree of certainty for each project [*darker cells* represent a greater degree of certainty either for inclusion (*green set*) or exclusion (*red set*) from the final portfolio]

This piece of information is very useful for DM s in the presence of the underlying uncertainty on projects' performance.

It is noteworthy that a naïve approach of dealing with uncertainty is to use average (expected) values of issuance success and maximize the average CERs of the final portfolio, ignoring the variance associated with the projects' performance. In this case, the final portfolio that is calculated from a single run (solution of an IP problem) is the same as in our approach. However, we obtain no information about the variance of the final portfolio's performance, or the degree of certainty for each project. In addition, if the probability distributions were not symmetric, the result of the two approaches could differ, which would mean different final portfolios.

Regarding computational effort, although ITA incorporates a Monte Carlo simulation with 1,000 iterations, the whole decision process is not computationally prohibitive. The solution time of one round ranges from 17 to 20 min across the five rounds in an Intel Pentium i5 at 2.53 GHz for 1,000 Monte Carlo simulations–optimizations, which is an affordable computational time.

In Table 16.4, the analysis of the final portfolio is presented. The geographical distribution is determined more or less by the imposed constraints. We can observe that there are still countries that are not present in the final selection (Philippines and South Korea) as it is not explicitly required by the regional constraints (see Sect. 16.3.3.2). Moreover, it was found that projects from Latin America are entering in the final portfolio from the first rounds. On the contrary, most of the wind and hydro projects from China and India are excluded very early in the decision process. It should be also noted that all the available technologies are present in the final portfolio. Because of the restricted available budget (2 billion US$), most of wind projects are excluded due to high initial investment costs. Thus, the share of Chinese projects dropped significantly although there are some projects with GS label among them. It was also observed that the conditions for the HPPs were more favorable than the conditions for wind projects. It was also found that the availability of an already existing dam has a positive effect as it translates to lower investment cost.

Generally, the consideration of minimal share of the GS projects has a positive impact. In the final portfolio, there are 30 % of GS projects while initially, in the project universe, they had the share of 21 %. Aa a matter of fact, all GS-labeled projects for HPPs, landfill gas, methane avoidance, and EE in industry are in the final selection. The proportion of GS projects in the final portfolio may be controlled by the DM.

It is not a surprise that the share of methane-related projects is significant in the final selection (about 1/3). Firstly, these activities provide high emission reductions and thus CERs with moderate investments; one of the reasons is the higher GWP of methane toward CO_2. Secondly, they provide more of direct sustainability benefits such as improved air and water quality, and reduction of dangerous wastes within local communities. Summarizing, we should underline that the final portfolio represents the 17.4 % of the investments that correspond to the project universe (i.e., the initial 300 projects accumulate to 11.5 billion US$) while it accounts for the 35.8 % of the project universe's total CERs (=28,805 kCERs).

Table 16.4 Final selection by countries and technologies

	SWind	LWind	SHydro	LHydro	Biomass	Landfill gas	Methane avoidance	EE own generation	GS	Budget MUS$	kCERs/ year	Total projects
China	0	2	2	7	1	6	3	2	8	799	3,828	23
India	4	1	1	0	10	0	1	5	10	204	1,063	22
Argentina	0	0	0	0	1	1	0	0	0	42	305	2
Brazil	0	0	3	2	0	2	0	1	0	106	1,121	8
Chile	0	0	2	2	1	0	0	0	0	119	278	5
Ecuador	1	0	0	2	0	0	0	0	0	62	210	3
Egypt	0	1	0	0	0	0	0	1	0	135	359	2
Honduras	0	0	1	0	0	0	1	0	1	10	54	2
Indonesia	0	0	0	0	1	0	3	0	3	17	192	4
Malaysia	0	0	0	0	3	0	4	0	0	29	591	7
Mexico	0	1	0	0	0	3	1	0	0	220	751	5
Peru	0	0	3	2	0	0	0	0	0	182	485	5
Philippines	0	0	0	0	0	0	0	0	0	0	0	0
South Africa	0	0	0	0	1	1	0	0	0	16.5	399	2
South Korea	0	0	0	0	0	0	0	0	0	0	0	0
Thailand	0	0	0	0	0	1	7	0	6	33	638	8
Vietnam	0	0	1	1	0	0	0	0	2	24	43	2
Gold standard	3	1	2	2	7	2	12	1	30			
Budget MUS$	33	767	111	595	163	88	68	173	241			
kCERs/year	54	1,634	389	2,255	1,108	2,713	1,181	983	1,287			
Total	5	5	13	16	18	14	20	9	30	1,998.5	10,317	100

16.5 Conclusions

The ITA in project portfolio selection is an attempt to deal with uncertainty in a volatile decision environment. The aim is to provide the DM with as much as possible information before his final choice. The existence of multiple limitations (constraints) denoting projects' interactions and the underlying uncertainty expressed as probability distributions imply the use of a systematic approach. For this reason, a hybrid method combining MP and Monte Carlo simulation is developed. Under these circumstances, the existence of a unique optimal portfolio is almost impossible, so that the trichotomic approach drives the DM to reach the portfolio with greater acceptance.

This approach reduces the information burden by revealing and shifting the focus of the DM only to the ambiguous gray projects. Due to its flexibility, it can be easily adapted to any decision situation and DM.

The absence of a dominating portfolio in the initial round was actually the inspiration to proceed project-wise and create the green, red, and gray sets. Subsequently we proceed iteratively, exploiting the information from previous rounds. In each subsequent round, the variability of results is reduced, and the portfolio(s) of greater acceptance is/are easily recognized. Useful information is obtained from the fact that we don't have just the projects that are eventually selected, but also for discovering how sure we are about their selection or exclusion. In contrast to a single phase decision process that uses only the expected performance values of the projects (naïve approach), the ITA has the advantage of gradually populating the green and red sets, providing information to the DM about the reliability of projects' inclusion/exclusion in/from the final portfolio (according to the round that each project is included in green or red set).

The advantages of ITA over the naïve approach that uses just the expected values were revealed with the illustrative example that we used. From an initial universe of 300 CDM projects, we obtain the final portfolio with 100 projects that satisfy constraints and provide information about the degree of certainty for the adoption or not of each one of them. The utilized modeling language GAMS with the features that provide, proved to be a reliable and appropriate tool for this kind of computational procedures, i.e., combination of Monte Carlo simulation and solution of MP problems.

Within our project selection, the aim was to maximize carbon credits (CERs), even though their final amount is not a certain fixed number. The final portfolio demonstrates how it is possible to make a balanced selection regarding financial as well as technology and geographical constraints. In current case, the modeling of uncertainty in the most uncertain among the project parameters (CERs) was tested.

The model formulation is capable of selecting projects based on their investment return in terms of CERs. In other words, if several projects e.g. A, B and C have cumulative cost less than the cost of a large project D and cumulative CERs more than those of project D, then the combination of projects A, B and C will be preferred to project D. That is why the representation of the increased investment cost projects (wind, hydro) is not very high in the final portfolio, although they are the majority of the examined projects. The effect of the total budget constraint may be further examined through an appropriate sensitivity analysis (e.g., with parametric variation of the total budget constraint). It will also be interesting for future research to test different probability distributions for the CERs (other than normal distribution used in the current case). In addition, if more data are available, we can create probability distributions for more specific categories of projects, a task that will increase the reliability of the final results.

Regarding the future research that will enrich the method and broaden its applicability, two fields are already recognized: The first is that the trichotomic approach can also be implemented in the case that we have multiple objective functions. The only difference is that we will have a set of Pareto optimal solutions instead of a unique optimal solution in the Monte Carlo iterations. Thus, the number of appearances is counted in all the Pareto optimal solutions to draw conclusions about the inclusion of a project in the green, red, or gray set. Instead of reducing uncertainty from round to round (as we did in the present paper) we can narrow the criterion cone of the objective functions by applying either weight intervals or upper and lower bounds. Inevitably, this would mean that the whole process would demand more computational time. The other basic elements of the method remain the same (e.g., the separation into sets of projects and the iterative process in rounds).

The second field is the application of the trichotomic approach in the case of project portfolio selection through group decision making, e.g., when there are multiple DM s, each one expressing his opinion regarding the value of the parameters (especially when these parameters are subjective such as weights of importance, utilities, etc.). In this case, the sampling of the Monte Carlo iterations is replaced by the individual preferences of each one of the DM s.

For example, if we had 10 DM s, we would run 10 optimizations in the initial round and then would proceed as before, with the separation of the projects to “green,” “red,” and “gray” sets. A Delphi-like approach can be formulated in order to aggregate the results in each round and allow the DMs to reconsider their views regarding the decision parameters (e.g., weights of importance, right-hand sides of the constraints) in order to converge to a final portfolio for the next round. In this way, an iterative process gradually enriching the green and red sets can be designed.

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Chapter 17
Value Stream Maps for Industrial Energy Efficiency

Cem Keskin, Umut Asan and Gulgun Kayakutlu

Abstract Lean thinking is an engineering approach to avoid non-value adding tasks or processes in manufacturing. Most of the lean studies in the energy field are focused on savings in manufacturing processes. This paper suggests a future-oriented energy value stream mapping approach that aims to improve energy efficiency in small- and medium-sized manufacturing companies. Energy value stream mapping is a graphical technique that allows identifying the level of energy use and, thereby, discovering saving opportunities at each step of different processes either in production or in facility support. To analyze the possible outcomes of improvement options, future scenarios are developed using Bayesian networks. The suggested model can be used not only for diagnostic purposes but also for energy budgeting and saving measures. An application is given to demonstrate the use of energy value stream maps (E-VSMs).

17.1 Introduction

It is proven that one-third of all the energy consumption is realized by industrial companies all over the world. Energy is used by these companies mainly for direct production processes, space conditioning, and facility support. With all the concerns of global heating and tight energy resources, energy efficiency work has become quite critical. Unfortunately the efficiency concern is still ignored by the majority of manufacturing companies in developing countries due to economic or cultural reasons. Chai and Yeo (2012) have studied all the barriers of energy

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efficiency to suggest a systems approach; the system is composed of motivation, capabilities, implementation, and results. The study shows the opportunities of improvement mainly on the implementation phase. On the contrary, Graus et al. (2011) have predicted very little contribution of industrial efficiency improvements and have seen potential in the hybrid energy usage. These contradicting studies have shown that there is still a lot of efficiency work to be done depending on the business focus.

Energy efficiency studies in manufacturing companies have been concentrated on the technological improvements and mainly focused on the equipments, which consume considerable amounts of energy. For instance, Abdülaziz et al. (2011) provide examples of tools for industrial energy efficiency. Zheng and Reader (2004) have focused on combustion engines used in manufacturing.

Alternatively, a group of researchers have suggested using lean thinking to avoid non-value adding energy consumption in manufacturing processes. Lean thinking in manufacturing management is the way of "putting entire value stream for specific products relentlessly in the foreground and rethinking every aspect of jobs, careers, functions, and firms in order to correctly specify value and make it flow continuously along the whole length of the stream as pulled by the customer in pursuit of perfection" (Womack and Jones 1996). One of the most widely used tools in lean manufacturing is value stream maps. Value stream mapping allows observing the flow of material and information as a product or service that makes its way through the value chain. Once the current state is shown in the value stream map, future state value stream maps can be prepared as a support for new plans and strategies. Although the method has weaknesses in multiple product analysis, it is proven to be effective in determining the bottlenecks of processes (Lasa et al. 2008). Hence, this tool can be used to detect the energy saving potential of any company or industry.

Value stream mapping is a tool that allows to "see the whole" of the manufacturing system, not only equipments. Fraizer (2008) showed that it is possible to use the concept of value and the value stream mapping tool to screen the current state of energy consumption and determine the candidate processes to be improved. Kayakutlu et al. (2007) showed how to use value stream maps in non-linear complex systems by using Bayesian Causal Mapping.

This study suggests a framework to use value stream maps to detect non-value adding energy consumptions and using Bayesian belief networks to establish future state energy value stream maps. This research will contribute to the energy efficiency research field by suggesting a solution for bottleneck handling.

This chapter is so organized that next section introduces the background of the industrial energy efficiency, value stream maps, and Bayesian networks. The suggested framework is discussed in Sect. 17.3 followed by a small case study in Sect. 17.4 and 17.5 is reserved for the conclusion and suggestions.

17.2 Background on Energy Efficiency and Value Stream Maps

17.2.1 Industrial Energy Efficiency

There is immense energy consumption in manufacturing industries because of the high technology usage during the production processes. This means there is a potential for energy saving. Thollander et al. (2007) investigated the methodological, technological, and social aspects of energy efficiency barriers. Bunse et al. (2009) showed the gap between industrial need and scientific literature in the field of energy efficiency. Abdülaziz et al. (2011) listed commonly used tools for industrial energy efficiency as variable speed drivers, waste heat recovery, using high efficient motors, preventing the leaks in air compressors, and also preventing the pressure drop. Nagesha et al. (2008) investigated the role of energy efficiency for sustainable development in small and medium enterprises (SME). Thollander et al. (2007) found out that SMEs do not give priority to the energy efficiency and cannot apply current policies. Kissock and Eger (2009) proposed a method to investigate the limits of energy savings by using the amount of production, outside temperature, and energy bills.

Literature shows samples of efficiency work on technology improvement or instrumentation handling.

17.2.2 Value Stream Maps

The concept of lean thinking (LT) is developed in Toyota Production Systems (TPS) and involves determining the value of any process by distinguishing value-added activities and eliminating wastes (Antony 2011). As Womack and Jones stated (Womack and Jones 1996), five principles of this philosophy lead for the value stream mapping. The first principle is defining the value; it is “capability provided to customer at the right time at an appropriate price, as defined in each case by the customer.” The second principle is value stream and is defined as “specific activities required to design, order, and provide a specific product, from concept to launch, order to delivery, and raw materials into the hands of the customer.” The third principle is creating a value stream, which means “progressive achievement of tasks along the flow so that a product proceeds from design to launch, order to delivery and raw materials into the hands of the customer with no stoppages, scrap or backflows.” The fourth principle is pull system which is defined as “system of cascading production and delivery instructions from downstream to upstream in which nothing is produced by the upstream supplier until the downstream customer signals a need.” Finally, the fifth principle is the target of “complete elimination of waste so that all activities along a value stream create value.”

Pavnaskar et al. (2004) propose a classification scheme to serve as a link between manufacturing waste problems and lean manufacturing tools. To date, lean principles are applied in any industry, including health and service sectors (Shah and Ward 2007). Haque and James-Moore (2004) showed the usage of lean principles even for the new product development.

Value stream mapping conceptualization is initiated by Rother and Shook (1999) in “Learning to See” as “a tool, that helps observing the flow of material and information as a product or service makes its way through the value stream” (Rother and Shook 1999). The procedure for value stream mapping and the calculation of parameters is designed by (Singh and Sharma 2009). It is emphasized by Lasa et al. (2008) that it can only be used by people who know lean manufacturing. Gurumurthy and Kodali (2011) stated the difficulties in using this tool emphasizing that it states the facts at single time slice without any continuation. Abdulmalek and Rajgopal (2007), argued that for the companies which are using traditional manufacturing, it is difficult to observe benefits on future state maps.

One of the main disadvantages of value stream maps is the difficulty of drawing many product flows on the same map. Rother and Shook (1999) suggest drawing a map for each product, whereas Kayakutlu et al. (2007) suggest using cognitive maps to overcome this problem. Abbas et al. (2001) proposes multi product process chart (MPPC) and from-to chart, with a software package for material flow analysis especially for make-to-order production companies. The lean manufacturing concepts mentioned in a variety of studies of manufacturing are defined below.

Value is the precise definition of a specific product from the perspective of the end customer with specific capabilities offered at a specific price and time (Haque and James-Moore 2004).

Value mapping is the process of mapping the material and information flows of all components and subassemblies in a value stream that includes manufacturing (Abbas et al. 2001).

Takt time is the rate at which a company must produce a product to satisfy its customer demand. It is calculated by dividing available working time per day (in minutes or seconds) to customer demand per day (in relevant units) (Singh and Sharma 2009).

Kanban is a signaling system for implementing just in time production (Abdulmalek and Rajgopal 2007).

Visualization is the visual techniques and tools, which are used for managing the process (Gurumurthy 2011).

5S represents procedures for work place organization and standardized work, namely, sorting, stabilizing, sweeping, standardizing, and sustaining (Abdulmalek and Rajgopal 2007).

Standard work is the description of the work in terms of who, when, and how to do it (Pavnakar et al. 2003).

Pull system is the process of designing and providing what the customer wants only when the customer wants it (Haque and James-Moore 2004).

One piece flow means that the parts are moved through operations without work-in-process in between either one piece at a time or a small batch at a time (Haque and James-Moore 2004).

Continuous improvements is continuously improving the work for perfection (Pavnakar et al. 2003).

Process kaizen is a daily process with the purpose productivity improvement based on teamwork, personal discipline, improved morale, quality circles, and suggestions for improvement (Gurumurthy 2011).

Setup time reduction is giving a continuous try to reduce the setup time on a machine (Haque and James-Moore 2004).

Shorter maintenance time is scheduling maintenance time into smaller increments, i.e. it separates the maintenance process into smaller portions that are performed more frequently (Abdulmalek and Rajgopal 2007).

Cellular manufacturing is organizing the entire process for a particular product or similar products into a group (or “cell”), including all the necessary machines, equipments, and operators. Resources within cells are arranged to easily facilitate all operations (Abdulmalek and Rajgopal 2007).

The energy efficiency studies, however, are based on six factors only. Bunse et al. (2009) mention determining *energy intensive processes* by detecting the most intensive energy uses. Kissock and Seryak (2004) emphasizes the *energy bill analysis* is by working on any energy-related bill records of the company. *Theoretical minimum energy usage* is calculated to determine the minimum energy consumption of a plant, which is generally smaller than actual usage.

Important parameters for energy consumption other than bill values are taken as the *key performance indicators* by Bunse et al. (2009). These indicators can be enhanced by working on the *energy efficient technology investments* to improve energy efficiency of a plant (Nagesha 2008). More *energy efficiency improvements* include improving machines or a process in order to get energy savings (Bunse et al. 2009).

These can be combined into the lean energy efficiency as given in Table 17.1 but considering the lean energy influencers accumulated from literature and expert surveys as defined below.

Non value-added energy usage (NVA-EU) is the energy usage by a process which does not add any value to the production process.

Energy of WIP (E-WIP) is the energy used for manufacturing any material on which operations in the plant have already begun but are not yet completed.

Over production (OP) is producing any product more than what customer required (Pavnaskar, 2003).

Faulty production (FP) is the product or WIP which requires correction or reproduction (Pavnaskar, 2003).

Cellular energy usage (CEU)is the amount of energy used by a manufacturing cell.

Energy efficiency kaizens (EEK) are the Kaizens specifically used for energy efficiency improvements.

Table 17.1 Concepts and tools of lean manufacturing and industrial energy efficiency

Lean manufacturing	Lean energy efficiency	Energy efficiency
Value	Non value- added energy usage	Determining energy intensive processes
Value maps	Energy of work-in-process	Energy bill analysis
Takt time	Over production	Theoretical minimum energy usage
Kanban	Faulty production	Key performance indicators
Visualization	Cellular energy usage (Fewer carriage, fewer field)	Energy efficient technology investments
5S	Energy efficiency Kaizens (EEK)	Energy efficiency improvements
Standard work	Total productive maintenance (TPM) (Compressors, Belts, Shafts)	
Pull		
One piece flow		
Continuous improvements		
Process Kaizen		
Changeover reduction		
Shorter maintenance time		
Cellular manufacturing		

Total productive maintenance (TPM) is the maintenance method, which is focused on preventing breakdowns instead of fixing them. The machine operators are closed to the machines, and therefore they are included in maintenance and monitoring activities in order to prevent and provide warning of malfunctions (Abdulmalek and Rajgopal 2007).

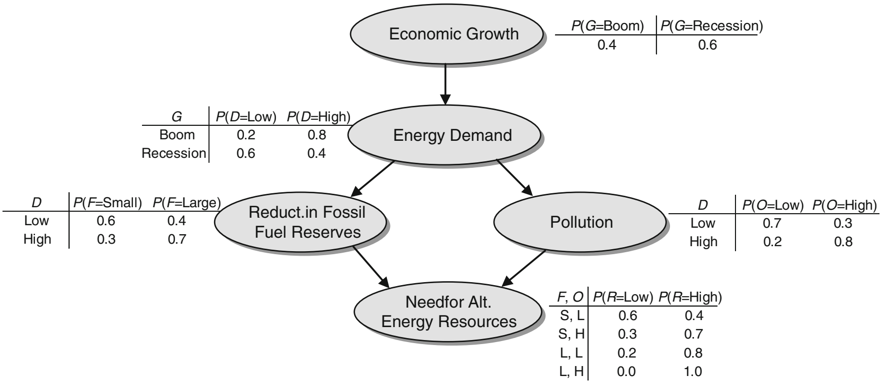
The idea of using value stream maps for industrial energy efficiency improvements is studied for different kinds of facilities. A simple method is advised by U.S. Environmental Protection Agency (2007) in (The Lean and Energy Toolkit). Fraizer (2008) showed the usage of value stream mapping tool for determining energy characteristics of the process. Schmidt et al. (2012) suggested a method that allows a first quick, easy, and comprehensive analysis of energy and material flows within the production processes. Usage of value stream maps in energy efficiency audit is limited to determining current state: developing and using future state energy value stream maps has not been studied yet.

17.2.3 Bayesian Networks

Any improvement of a complex system (e.g. energy efficiency improvements in industry) primarily requires the analysis of its basic elements and the possible relationships between them. In cases where our understanding of the consequences of an improvement is incomplete, it becomes crucial to capture the uncertainty associated with each element in the system. Here, graphical models provide a useful tool for dealing with the complexity and uncertainty of the problem (Jordan 1999).

One of the common probabilistic graphical models specialized in representing and reasoning with uncertain knowledge and/or incomplete data sets is Bayesian networks also known as belief networks. They combine principles from graph theory, probability theory, computer science, and statistics (Ben-Gal 2007). Some advantages of Bayesian networks reported by Jones et al. (2010) and Heckerman (2008) include: (1) providing both a mathematical and visual representation of conditional dependencies (mostly causal relationships), (2) predicting consequences of possible interventions, (3) combining historical data and expert views, and (4) allowing updating the model as new information becomes available.

Bayesian networks are directed acyclic graphs (DAGs), where nodes represent random variables of interest and edges represent informational or causal dependencies among the variables (Charniak 1991; Pearl and Russell 2001). The nodes from which directed edges originate are defined as parent nodes, whereas the nodes where the directed edges point at are defined as child nodes. The dependencies are expressed by conditional probabilities that specify the probability distribution across the states of a child node for each possible combination of states of its parent nodes (Verhoeven et al. 2006). Figure 17.1 illustrates a simple Bayesian network analyzing the need for alternative energy resources. According to the example, growth in energy demand (D) is directly influenced by economic growth (G) and at the same time causes both pollution (O) and reduction in fossil fuel reserves (F), which both in turn affect the need for alternative energy resources (R). The conditional probability functions, in this example, are represented by tables of entries where each entry represents one possible combination of the parents. Unquestionably, in a realistic problem, many more variables would be included and the states of one or more of these variables would be modeled at a finer level of detail.



P(G=Boom)	P(G=Recession)
0.4	0.6

G	P(D=Low)	P(D=High)
Boom	0.2	0.8
Recession	0.6	0.4

D	P(F=Small)	P(F=Large)
Low	0.6	0.4
High	0.3	0.7

D	P(O=Low)	P(O=High)
Low	0.7	0.3
High	0.2	0.8

F, O	P(R=Low)	P(R=High)
S, L	0.6	0.4
S, H	0.3	0.7
L, L	0.2	0.8
L, H	0.0	1.0

Fig. 17.1 A simple Bayesian network representing causal influences

Any complete probabilistic model and hence a Bayesian network has to specify the joint probability distribution of the concerned domain (Pearl and Russell 2001). The joint distribution is considered as the most complete probabilistic description available, since all other probabilistic measures of interest (marginal and conditional) can be computed from it (Russell and Norvig 2002). By this means, a Bayesian network allows making inferences about any subset of variables based on evidence available on any other subset in the network. Note that, in spite of the particular direction of arrows in the network, it is possible to reason and update the model in any direction—both in a deductive and abductive way.

Following the above explanations, a more formal definition of a Bayesian network will be given. Let us consider a directed acyclic graph with n numbered nodes each associated with a random variable $X_i(1 \leq i \leq n)$. The joint probability distribution (JPD) of this network, $p(x_1, x_2,\ldots, x_n)$, is specified by the product of the individual distributions for each random variable

$$\begin{aligned} p(x_1,x_2,\ldots,x_n) &= p(x_1)\cdot p(x_2,\ldots,x_n|x_1) \\ &= p(x_1)\cdot p(x_2|x_1)\cdot p(x_3,\ldots,x_n|x_1,x_2) \\ &\ldots \\ &= p(x_1)\cdot p(x_2|x_1)\ldots p(x_n|x_1,\ldots,x_{n-1}) \end{aligned} \tag{17.1}$$

where x_i denotes some value of the variable X_i. This complete factorization of the distribution, also known as the general chain rule, is true for any set of random variables. Although the joint distribution grows exponentially with the size of the network, the conditional independence property of BNs allows a more compact factorization of the JPDs. This property reduces, sometimes significantly, the number of parameters that are required to characterize the JPD of the network (Ben-Gal 2007). Specified by the (absence of) arcs in a Bayesian network, the independence assumption defines the conditional independence of each variable from any combination of its non-descendants, given its parents (Pearl 1988; Frey 1998). Thus, the JPD for $X = \{X_1, X_2, \ldots, X_n\}$ is given by (Pearl 1988):

$$p(x_1,x_2,\ldots,x_n) = \prod_{i=1}^{n} p(x_i|pa_i) \tag{17.2}$$

where pa_i denotes some set of values for X_i's parents, and $x_i|pa_i$ denotes the conditional distribution for variable X_i given its parents. In our example, by the chain rule, the joint probability of all the nodes is:

$$p(g,d,f,o,r) = p(g)\cdot p(d|g)\cdot p(f|g,d)\cdot p(o|g,d,f)\cdot p(r|g,d,f,o) \tag{17.3}$$

By using conditional independence assumptions, this can be rewritten as:

$$p(g,d,f,o,r) = p(g)\cdot p(d|g)\cdot p(f|d)\cdot p(o|d)\cdot p(r|f,o) \tag{17.4}$$

where, for instance, the third term is simplified because F is independent of G given its parent D. A numerical example for the joint probability that "the need for alternative energy resources in a booming economy with high growth of energy demand and large reduction in fossil fuel reserves along with high pollution is high" can be calculated as follows:

$$\begin{aligned} & p(G=\text{boom}, D=\text{high}, F=\text{large}, O=\text{high}, R=\text{high}) \\ &\quad = p(G=\text{boom}) \cdot p(D=\text{high}|G=\text{boom}) \\ &\quad \cdot p(F=\text{large}|D=\text{high}) \cdot p(O=\text{high}|D=\text{high}) \\ &\quad \cdot p(R=\text{high}|F=\text{large}, O=\text{high}) \end{aligned}$$

$$p(G=\text{boom}, D=\text{high}, F=\text{large}, O=\text{high}, R=\text{high}) = 0.4 \cdot 0.8 \cdot 0.7 \cdot 0.8 \cdot 1.0 = 0.1792$$

A reasonable question to raise here is whether the ordering of the random variables affects the factorization process of a particular joint distribution. The answer is yes. If the order of the variables is chosen carelessly, the process may fail to reveal many conditional independencies among the variables (Heckerman 2008). In the worst case n! different orderings of the variables have to be explored to find the best structure. Therefore, a topological ordering is required by which the variables are ordered such that every variable comes before all its descendants in the graph (Charniak 1991). Next, different approaches for constructing Bayesian networks will be discussed.

17.2.3.1 Construction of a BN

As mentioned before, a Bayesian network consists of a causal and probabilistic semantics (Heckerman 2008). Because of this, in general, the procedure of building a Bayesian network follows two stages: the qualitative stage and the quantitative (probabilistic) stage (Nadkarni and Shenoy 2004). While the qualitative stage is concerned with specifying the structure of the network (the DAG), i.e., the variables of interest including uncertainty and their conditional (in)dependencies, the quantitative stage is concerned with assessing the numerical parameters which encode the strength of linkages between the different variables with conditional probabilities. Speigelhalter et al. (1993) point out that "the inference procedures in a BN are more sensitive to the qualitative structure than the quantitative probabilities associated with the structure."

Few systematic techniques have been suggested in the literature to specify the structure of a Bayesian network model. Among these, two main approaches can be distinguished, namely, the knowledge-based approach and data-based approach. The knowledge-based approaches use expert knowledge in constructing a network. Several of them rely on the following two assumptions: (1) experts can easily specify causal relationships between variables; (2) causal relationships typically provide evidence of conditional dependence (Heckerman 2008). Such approaches practically result in a network structure that satisfies the definition expressed in Eq. (17.2). In a recent study, Nadkarni and Shenoy (2004) suggest a causal mapping approach to the construction of Bayesian networks based on domain knowledge of experts. To address the differences in the two approaches to modeling, they provide a systematic procedure to transform causal maps to Bayesian networks. The steps of generating Bayesian networks from causal maps, as employed in this study, are briefly summarized as follows (for more detail, see Nadkarni and Shenoy 2001, 2004):

- Since a lack of a link between variables does not necessarily imply independence between these variables, to regard a causal map as a Bayesian network, it is necessary to convert the causal map into a perfect map. In a perfect map, lack of links between the concepts in the map certainly denotes independence while the presence of links between concepts certainly denotes dependence. This can be achieved in consultation with experts by critically examining missing and redundant links.
- To obtain accurate directions of linkages, the emphasis in developing Bayesian causal maps should be on the reasoning which requires a distinction between deductive (from cause to effect) and abductive (from effect to cause) reasoning behind the causal linkages.
- A clear distinction between direct and indirect relationships among variables is required, as this distinction influences the encoding of conditional independence assertions. Also, eliminating redundant (direct or indirect) links will help decreasing the complexity of the model (Cinar and Kayakutlu 2010).
- As Bayesian networks are not allowed to contain directed cycles, they are eliminated. Such a condition is of vital importance to the factorization of the joint probability of a collection of variables (Vorobev 1963).

Alternatively, the data-based approaches learn causal relationships and model networks from data using the conditional independence assumption (see for example Heckerman et al. 1995). One common method in this group is constraint-based structural learning that requires no prior knowledge or input from the user. This algorithm search for conditional independence and dependence statements between each pair of variables, and build the model structure based on them (Steck and Tresp 1999). An alternative method is the Bayesian approach, which combines expert knowledge with data to produce improved models. The data is used to find the most likely model structure of a Bayesian network specified by prior knowledge (see for example Cooper and Herskovits 1992). This type of methods can be computationally very expensive (Steck and Tresp 1999).

Once the structure of the Bayesian network is specified, the (conditional) probability functions associated with the variables in the network need to be derived. This starts with identifying the state space of each variable. The probabilities assigned to states may be objective (i.e. physical) or subjective (i.e. Bayesian) in nature. Objective probabilities are learned from data, whereas subjective probabilities are provided by the experts.

17.2.3.2 Inference in BNs

The motivation for developing Bayesian networks is to support reasoning under uncertainty in a given domain (Kjærulff and Madsen 2008). In this context, reasoning under uncertainty is the task of estimating probabilities of any subset of variables by propagating information (evidence) available through the network (Pearl and Russel 2001). As explained above, to do this, the chain rule factorization of the joint probability distribution along with the independence relations assumed by the structure of the network is exploited. The conditional probabilities estimated by the model after evidence are entered to improve the state of knowledge are known as posterior probabilities (Jones et al. 2010).

More formally, the posterior probability of an unobserved variable $X_i \in X$ given a non-empty set of evidence $\varepsilon = \{\varepsilon_1, \ldots, \varepsilon_m\}$ observed so far, is computed as follows:

$$P(X_i|\varepsilon) = \frac{P(\varepsilon|X_i) \cdot P(X_i)}{P(\varepsilon)} = \frac{P(X_i, \varepsilon)}{P(\varepsilon)} \tag{17.5}$$

where $P(X_i|\varepsilon)$ denotes the posterior probability distribution of variable X_i given evidence ε. A Bayesian network can, therefore, be regarded as an extension of Bayes' theorem to more complex problems (Garcia et al. 2007). The following example finds the posterior probability of high pollution, given the evidence that the need for alternative energy resources is high

$$\begin{aligned} p(O = \text{high}|R = \text{high}) &= \frac{p(O = \text{high}, R = \text{high})}{p(R = \text{high})} \\ &= \frac{\sum_{g,d,f} p(g, d, f, O = \text{high}, R = \text{high})}{\sum_{g,d,f,o} p(g, d, f, o, R = \text{high})} \\ &= \frac{\sum_{g,d,f} p(g) \cdot p(d|g) \cdot p(f|d) \cdot p(O = \text{high}|d) \cdot p(R = \text{high}|f, O = \text{high})}{\sum_{g,d,f,o} p(g) \cdot p(d|g) \cdot p(f|d) \cdot p(o|d) \cdot p(R = \text{high}|f, o)} \end{aligned}$$

The normalized probability value for this particular example is 0.675. That means if there is high need for alternative energy resources, this provides convincing evidence of high pollution. Another particular type of probabilistic inference task is to compute the (prior) marginal probability, $P(X_i)$, of a variable X_i in the network. In this case, the above formulation (Eq. 17.5) does not incorporate evidence into the inference task, i.e., it is assumed that $\varepsilon = \varnothing$ (Kjærulff and Madsen 2008). For example, the prior probability of a large reduction in fossil fuel reserves is found as follows:

$$\begin{aligned}
p(F = \text{large}) &= p(F = \text{large}|d) \cdot p(d|g) \cdot p(g) \\
&= p(F = \text{large}|\text{D} = \text{low}) \cdot p(D = \text{low}|G = \text{boom}) \cdot p(G = \text{boom}) \\
&+ p(F = \text{large}|\text{D} = \text{low}) \cdot p(D = \text{low}|G = \text{recession}) \cdot p(G = \text{recession}) \\
&+ p(F = \text{large}|\text{D} = \text{high}) \cdot p(D = \text{high}|G = \text{boom}) \cdot p(G = \text{boom}) \\
&+ p(F = \text{large}|\text{D} = \text{high}) \cdot p(D = \text{high}|G = \text{recession}) \cdot p(G = \text{recession}) \\
&= 0.4 \cdot 0.2 \cdot 0.4 + 0.4 \cdot 0.6 \cdot 0.6 + 0.7 \cdot 0.8 \cdot 0.4 + 0.7 \cdot 0.4 \cdot 0.6 \\
&= 0.568
\end{aligned}$$

17.3 Integrated Framework Proposed

This study integrates value stream mapping and Bayesian network techniques in a framework in order to have a path to follow for the development of future state maps in energy efficiency.

The framework is composed of three steps: lean analysis, energy efficiency analysis for preparing the E-VSM and Bayesian Mapping that will lead for scenarios to construct the future state map.

Step 1: Lean analysis, i.e., lean energy consumption analysis will be performed in a production company so the focus is given only on the energy consumption of value adding activities. This step includes three activities:

Collect data: Collect both quantitative and qualitative data for energy usage of processes and plant. For quantitative data, energy accounting records can be used in addition to necessary measurements taken. For qualitative data, interviews with the workers (like boiler operators, electricity technicians, and so on) and engineers are to be realized.

Prepare VSM: After the data are collected, VSM is prepared just by using the relevant symbols on a paper with a simple pencil during observation of the energy consuming processes.

Determine waste: By analyzing the information (amount of WIP, waiting time, etc.) on process cards and determining unnecessary processes (worker motion, inventory transport, etc.), one can determine wastes on the plant.

Step 2: Apply energy efficiency analysis to design the current state energy value stream map (E-VSM) focusing only on the energy-related activities.

Step 3: Factors and parameters for the Bayesian network are defined with the help of E-VSM. Survey with experts would allow finding conditional probabilities for the bottlenecks. Bayesian network will lead for developing different scenarios for constructing the future state E-VSMs. Figure 17.2 shows the framework in graphical format with details included.

Energy efficiency analysis will be performed through the following activities.

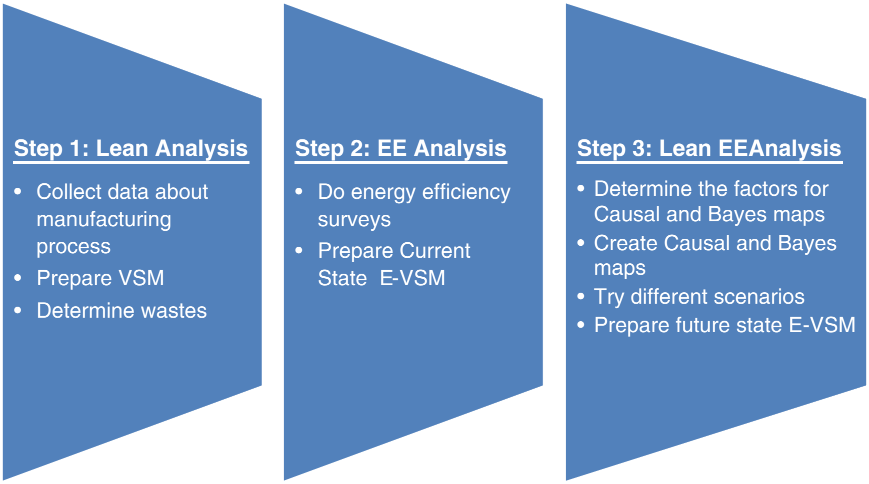


Fig. 17.2 Lean industrial energy efficiency analysis framework

Energy efficiency survey: These parameters can be asked to determine energy efficiency approach of the company: Energy efficiency standard of energy consumers (electric motors, boilers, lamps, etc.), energy saving encouragements, energy-related education level of operators (especially boiler and furnace operators), process performance indicators (machine usage capacities, amount of faulty production, etc.), budget for energy efficiency improvements, awareness for energy consumption of lighting, and HVAC systems of plant.

Current state E-VSM: Using the VSM and results of energy surveys, energy value stream map can be prepared. Here no need to show energy irrelevant items. Also, additional information lines related to amount of energy consumption and energy efficiency improvement potential (harnessed from energy efficiency surveys) can be added to the process cards or to the extra lines in the bottom of the map.

Criteria to be determined: In order to determine effective criteria, besides literature survey, surveys with sector experts and the company staff (managers, engineers, and operators) needed to be performed.

Prepare the Bayesian Map: Probabilistic relations of influential factors on lean energy usage is constructed through the interviews with the operation experts of the enterprise.

Prepare scenarios: In any improvement effort, there are many improvement points to handle but generally companies don't have enough sources for all of them. Some of them should be chosen in terms of their potential and so we have more than one scenario. In order to create scenarios and evaluate their efficiencies, we can use softwares. While considering overall efficiency of a scenario, we should consider specific efficiency of each parameter and also the interaction between parameters.

Future state E-VSM: Analysis of alternative scenarios for the solution of energy consumption bottlenecks allows the choice of most realistic approach to prepare the future state E-VSM. It shows the points to focus on and also the specific target values for energy savings.

17.4 Sample Application

A sample application is performed to demonstrate the three steps of the suggested framework. The case is an SME producing shaped and covered chipboard (SCC). The manufacturing processes of SCC include chopping, drying, gluing, pre-forming, and hot-press processes, which can be briefly defined as follows:

- Chopping: Huge wood blocks are cut into pieces and then chopped as chips.
- Drying Chips: In order to take the humidity of chips, they are dried in a big cylindrical turning furnace.
- Gluing: Dried chips are glued in a simple mixing machine.
- Pre-forming: By using cold hydraulic presses, chips are wedged in the shape of different products.
- Hot-pressing: Pre-shaped boards are cooked and covered with decorative papers using hot hydraulic press.

17.4.1 First Step: Manufacturing VSM Construction

The analysis started with questioning the manufacturing engineers, who planned and controlled the production in the plant. Data on operations, employees, and inventories are collected. Since the company has not previously realized any lean manufacturing analysis, the missing data is completed by new measurements.

To follow up, value stream map rules are applied and current value stream map is constructed to show the material and information flow as in Fig. 17.3. Value-related information for each process is shown on shapes and cards. For example, "1 × Month" label on a truck means one shipping per month. C/O is changeover time which is a non-value adding time required in changing the setup of different product lines. The timeline shows value adding times (Cycle Times) and non-value adding (wait) times, which are used to calculate lead time and total cycle time. This is the basic form of (current state) value stream map and doesn't contain any information about energy usage.

Semi-automatic machines are used in this plant for all the processes and characteristics of the process allow lean applications naturally. Production is run in a small area, the communication between work stations can be done by human

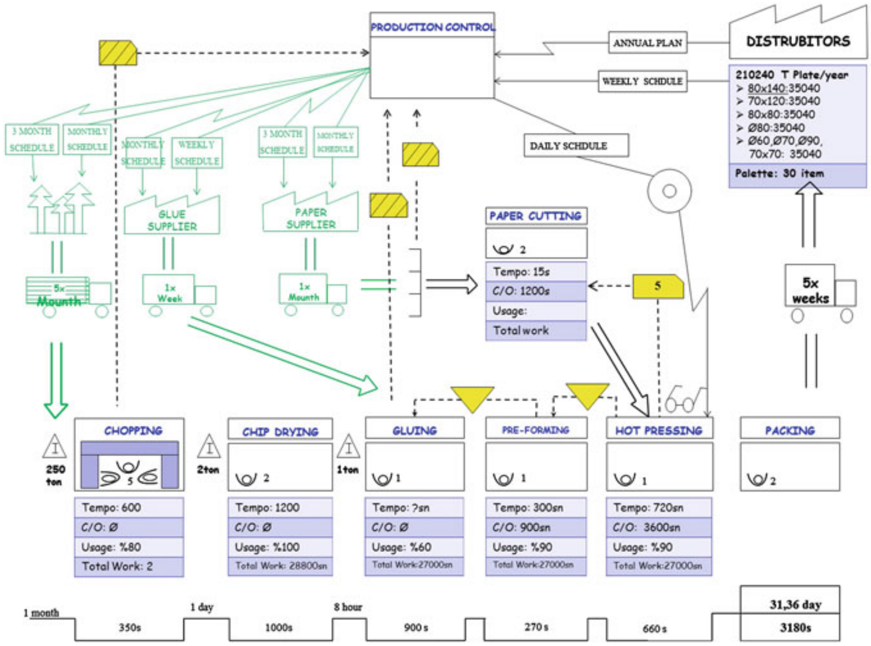


Fig. 17.3 Current state VSM

voice, and a simple pull system exists. There is an important waste in a critical point.

The boards are thicker than required even though the size is standardized by the Turkish Standards Institute according to fragility. It makes products heavier and requires more drying and cooking times where energy is used intensively. The chopping process is performed in three steps, which needs a technological change because it is possible to complete the process in a single step. The company has just started mass production and therefore, machine settings are to be improved and employees need to have more experience.

17.4.2 Second Step: E-VSM Construction

This step starts by collecting data about the energy utilization during each manufacturing process. Recordings on electricity consumption are analyzed, and necessary measurements are realized. Technological specialties about the energy utilization of machines, boilers, and ovens are reviewed; observations of the process operators are questioned. After combining and analyzing all the data and information accumulated, Current state VSM is redesigned to include energy-related components. Energy intensity points are shown by red lines and energy

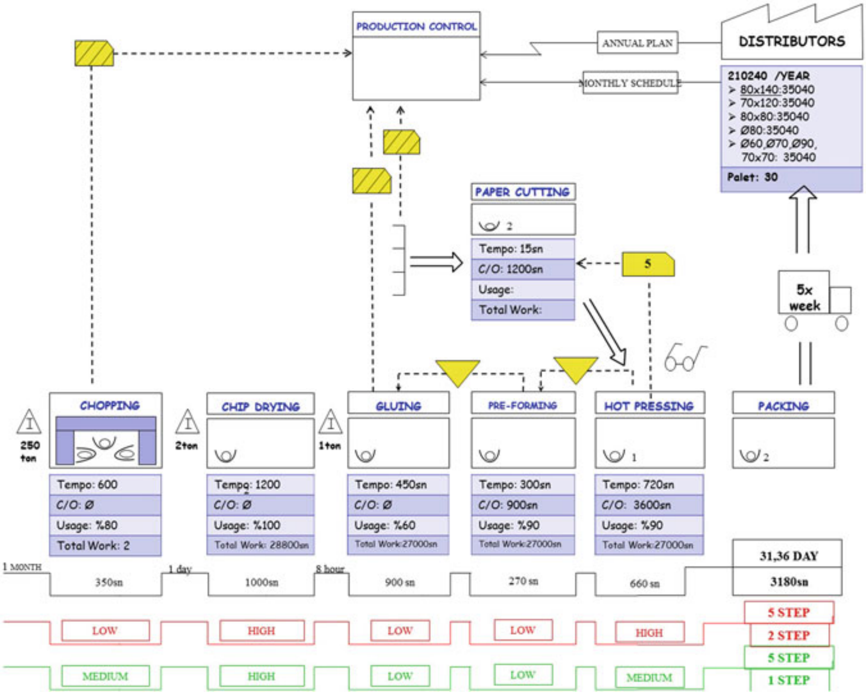


Fig. 17.4 Current state E-VSM

efficiency improvement potentials are marked by using the green lines. The new current state VSM diagram will be called current state e-VSM, which works specific to energy usage as shown in Fig. 17.4. Such a special diagram will allow managers focus on the energy efficiency improvement points. Red and green lines give detailed information about energy leanness in all manufacturing processes as well as helping to detect energy efficiency bottlenecks.

Current state E-VSM of the case operations showed that during the processes of chip drying and hot press non-value-adding energy usage (NVA-EU) is high. Therefore, the scenarios will be developed in the third step in order to avoid this high usage.

17.4.3 Third Step: Scenario Construction for the Future E-VSM

Scenario construction starts by preparing a causal map. Causal maps are composed of three major parts: causal concept, causal connection, and causal value. A causal concept can be an attribute, an issue, a factor or a variable and represented by a node. Causal connection is presented by an arrow that heads the connection target.

The nodes and arrows are used to create a cause effect relation between two concepts (Kayakutlu et al. 2007). The causal map is used to collect the beliefs of the experts on the relation of the criteria. The seven criteria combined to make lean energy efficiency given in Table 17.1 are used in constructing the causal map in relation with energy efficiency as the eight factor. Hence the questionnaires included Non value-added energy usage (NVA-EU), energy of work-in-process (E-WIP), over production (OP), faulty production (FP), cellular energy usage (CEU), energy efficiency Kaizens (EEK), total productive maintenance (TPM), and energy efficiency (EE).

The survey is run with the technical employees and the engineers of the company as well as the managers. In total, nine responses are collected and combined to show the criteria having the positive relation (shown by +1), negative relation (−1) and no relation (0). The mode is taken for the nine responses, and the result is given in Table 17.2. It is observed that non-value adding energy usage affects energy of works in process and energy efficiency Kaizens positively, hence as NVA-EU increases both E-WIP and EEK increase but energy efficiency decreases. Increase in energy for works in process increases the non-value-added energy usage and the cellular energy usage. Overproduction is not seen effective on energy efficiency in this company, whereas faulty production causes decreases in energy efficiency.

Cellular energy usage, energy efficiency kaizen, and total productive maintenance are accepted as energy efficiency increasing tools. Energy Efficiency is observed to have a negative relation with all the non-value adding operations excluding the faulty production and cellular production, which are dependent on the process flow handling.

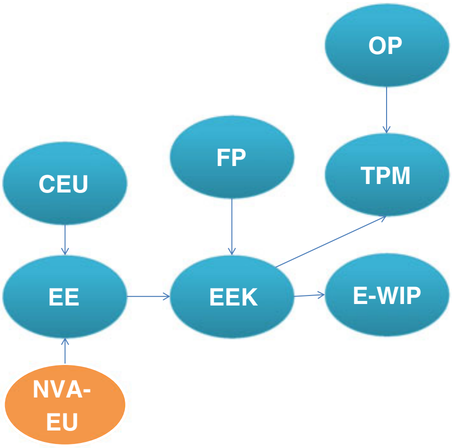
After having studied the relations through the causal map, the Bayesian map is constructed. The bottleneck factor, in our case Chip Drying operation is chosen as the decision node of the Bayesian Map for which scenarios will be constructed.

The conversion of the causal map into the Bayesian Map is performed by (1) eliminating branches connecting where the relation is decided to be zero (not related) (2) eliminating the direct links or links that connect two factors via another factor (indirect link); (3) combining the similar links; and (4) eliminating the deterministic factors on the causal map (Cinar and Kayakutlu 2010). In our case

Table 17.2 Criteria relations as experts believe

	NVA-EU	E-WIP	OP	FP	CEU	EEK	TPM	EE
NVA-EU	0	+1	0	0	0	+1	0	−1
E-WIP	+1	0	0	0	+1	0	0	0
OP	+1	+1	0	+1	+1	0	+1	0
FP	+1	0	0	0	+1	+1	0	−1
CEU	−1	0	0	−1	0	0	0	+1
EEK	−1	−1	0	−1	0	0	+1	+1
TPM	−1	−1	0	−1	−1	−1	0	+1
EE	−1	−1	0	0	0	−1	0	0

Fig. 17.5 Bayesian network



study, only indirect links are eliminated since there were limited numbers of factors in relation with at least one other factor. Figure 17.5 shows the Bayesian network with decision mode as the non-value adding energy usage as decision node and all the rest of the factors with relations indicated.

Bayesian network is then transferred to NETICA software in order to create scenarios that will lead to the future state map. Figure 17.6 shows initial Bayesian network which is a simple one with a single decision variable of non-value adding

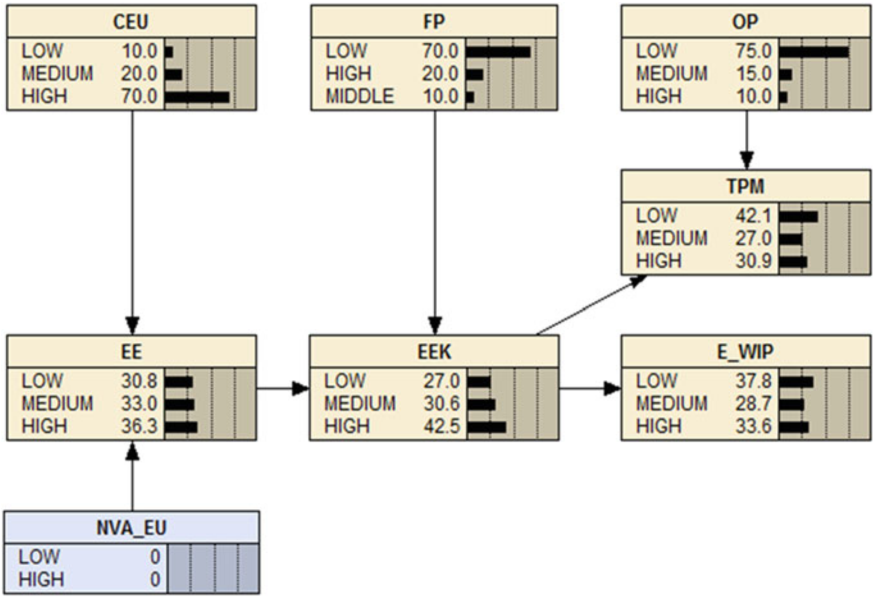


Fig. 17.6 Initial Bayesian network

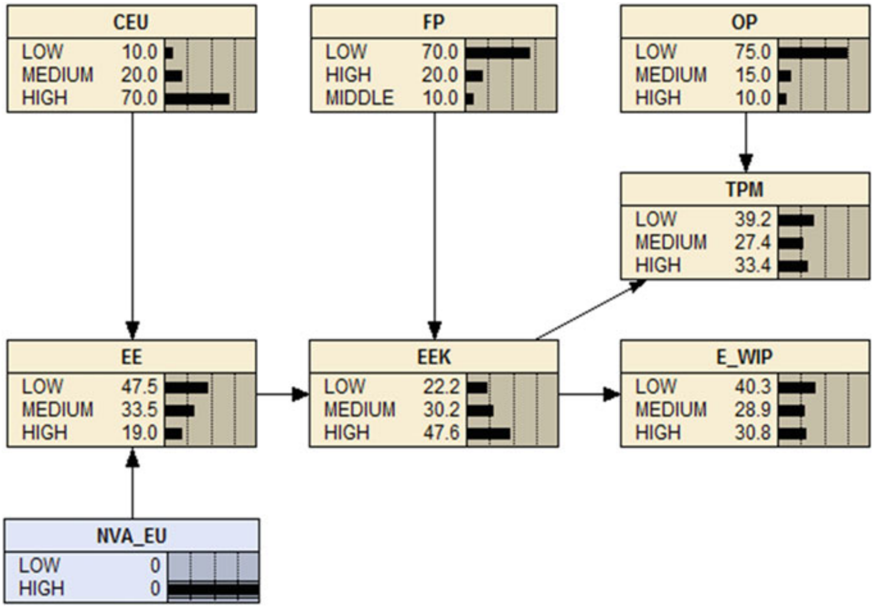


Fig. 17.7 High NVA-EU case

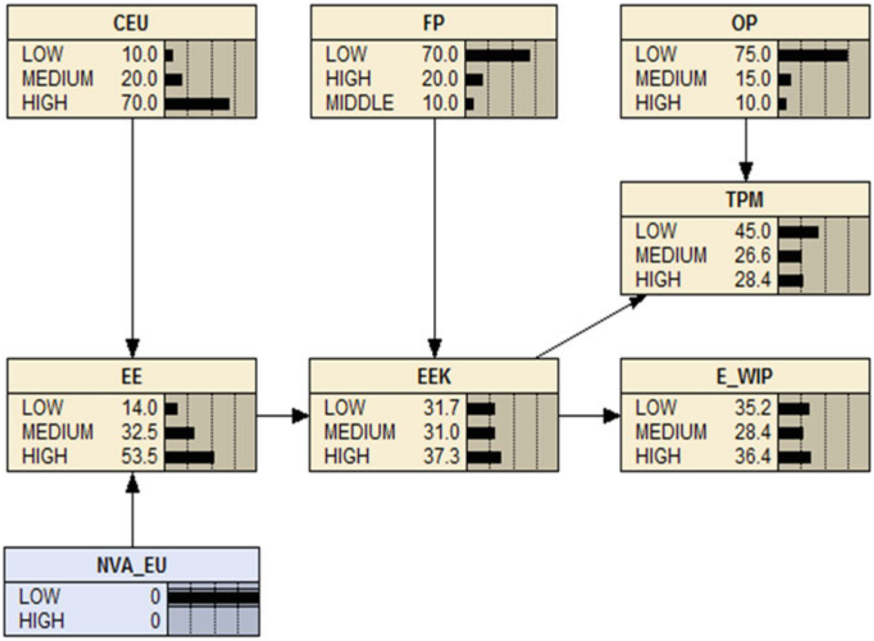


Fig. 17.8 Low NVA-EU case

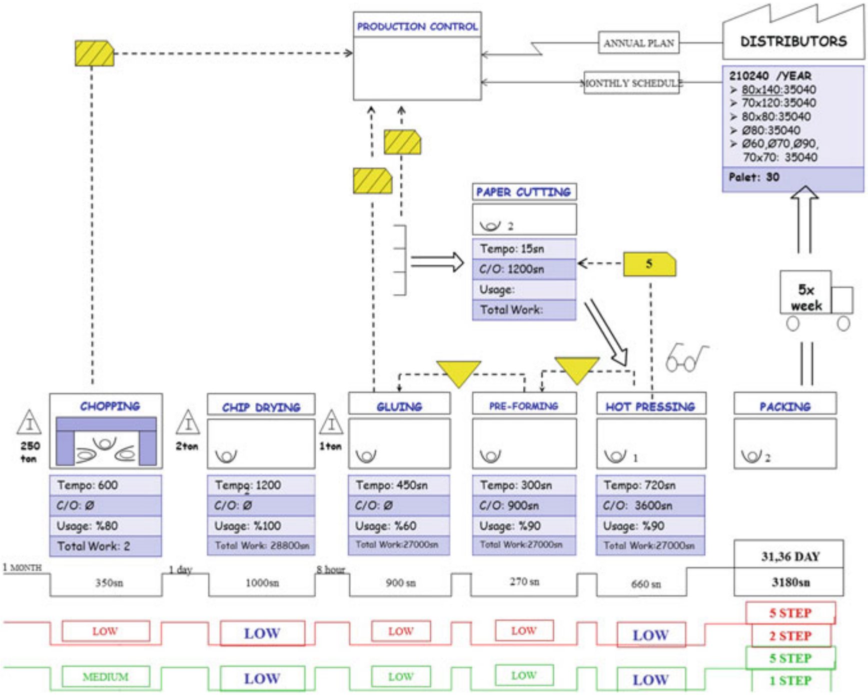


Fig. 17.9 Future state E-VSM

energy usage: NVA-EU in the current case. The probabilities used in the current case are calculated according to the operation survey. During this second survey, manufacturing experts have indicated the probability of each factor being low, medium, or high according to their experiences in the last 5 years.

Two scenarios are created. The first scenario is a precaution case, where we try to observe in which case of factorial changes the non-value adding energy usage gets even higher (Fig. 17.7). The second scenario is to observe how effective factors are to be changed in order to reduce non-value adding energy usage toward low, which is our main objective (Fig. 17.8).

After having completed all the scenario creation, the future state map can be constructed based on the objectives of reducing the non-value adding energy usage to the minimum, or maximizing the efficient energy usage. Figure 17.9 shows the future state map in detail where the focus is given to the low energy usage in chip drying.

This new map indicates a few roadmaps for the manufacturing strategies. Either the technology or the process or the operators of the focused process are to be modified. In our case, the process depends highly on technology, hence the managers are warned to renew the technology for the most current ones in order to reduce the energy consumption. It is observed that only 5-year-old technology is used but the ecological concern of the producers are reflected in the newest model which only came into the market 2 years ago. When the economical comparison is made, it is also observed that the reduction of energy utilization costs will compensate the technology costs only in a couple of years.

17.5 Conclusion

In this study, a framework for using VSMs for energy efficiency improvements is proposed. In order to create future state E-VSMs, Bayesian networks are used. It is observed with a sample application that the proposed framework is applicable and useful. Especially for the situations where there is not enough quantitative data, and using expert beliefs is inevitable, combining E-VSMs and Bayesian networks is proven to be beneficial in order to determine improvement areas. SMEs are commonly faced these kinds of situations, and proposed framework is not difficult to be used. Yet, in order to construct detailed scenarios, more parameters are to be used in Bayesian networks. These can be driven both from production and other energy-related concepts like energy consumption, energy intensity, etc.

A numerical evaluation is obligatory. Further work will be done to measure the performance. It is only possible to minimize the energy usage after observing the performances. Changes in the amount of production related to the outside temperature and energy bills will be observed (Kissock and Eger 2009). Inferences and benefits of Bayesian nets will be more beneficial with the scenarios created in line with the performances.

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Chapter 18
Assessment of Energy Efficiency in Lean Transformation: A Simulation Based Improvement Methodology

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Abstract The philosophy of Lean Manufacturing is to do more with less by eliminating non-value-added activities from production process. Lean manufacturing has several tools to improve lead time, cost, and quality performance as well as flexibility of systems. Therefore, the application level of Lean Manufacturing has gone through a significant evolution from shop floor to supply chain. Furthermore, Lean Manufacturing tools lead to significant effect on energy efficiency which is a vital factor for competitive advantage and environment preservation. In this chapter, a simulation-based generic framework is provided for the assessment of energy efficiency in Lean Manufacturing systems with the aim of providing contribution to the theoretical and practical studies addressing both sustainable energy and performance in manufacturing systems. Reflecting hierarchical nature of manufacturing systems, the proposed framework is illustrated in detail.

18.1 Introduction

Lean Manufacturing is originally derived by Toyota Production System and classifies all activities as value-adding or non-value-adding. Value-adding activities transform materials and information into products and services that customers want. However, non-value-adding activities do not directly contribute to create products and services in spite of the fact that they consume resources. Companies

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applying Lean Manufacturing tools ultimately want to meet customer demands with fewer resources and less waste. Succeeding a cultural as well as people-oriented transformation, Lean Manufacturers use many process-improvement tools to achieve and sustain effectiveness, flexibility, and profitability (Kiss 2009).

As the expected results of Lean Manufacturing, shorter lead times, reduction in inventory, space requirement, machine breakdowns, and improvement in delivery performance and cost management provide competitive advantage to lean companies.

On the other hand, energy becomes one of the costliest and most volatile inputs. What is more, there is a widespread societal demand for energy conservation to preserve the environment (Kiss 2009).

Conventionally, energy consumption has not been regarded in lean value streams, since Lean Manufacturing focuses on other resources like machines and materials. The energy costs have been a small portion of the total cost. Recent energy price spikes and fluctuations have made energy a central resource in supply chains as far as current cost-effective market conditions are concerned (Johansson et al. 2009).

The debate on energy consumption of manufacturing systems has been known to promote retroactive actions such as limiting the energy input for existing systems. It is demonstrated that the application of Lean Manufacturing tools results in reduced energy consumption (Khalaf et al. 2011). Therefore, energy efficiency should be considered as a performance measure in Lean Manufacturing Systems. By integrating Lean Manufacturing and Energy Efficiency, Lean participants cannot only significantly enhance competitiveness by lowering costs and improving their robustness to energy price increases and fluctuations, but also proactively estimate the environmental and climate impacts of energy consumption (Sciortino et al. 2009). Examples of Lean Manufacturing applications and their related benefits with respect to energy efficiency are given in Table 18.1.

Table 18.1 Energy efficient benefits of lean manufacturing applications (U.S. Environmental Protection Agency—EPA 2007)

Company	Strategy/tool	Energy cost saving
Steelcase Inc. (California)	Lean manufacturing	60 %
General Electric	Lean manufacturing	$70,000,000 (2005–2007)
Baxter International	Lean six sigma	$300,000/year
Toyota Motor Manufacturing	Lean manufacturing	19 % since 2000
Cummins, Inc.	Visual cues	$1,200,000
Eastman Kodak Company	Kaizen	$15,000,000 (1999–2006)
Howard Plating (Michigan)	Lean manufacturing	25 %
Lasco Bathware (Washington)	Lean manufacturing	$99,000
Naugatuck Glass (Connecticut)	Lean manufacturing	19 %
Mission Rubber	Value and energy stream mapping	$40,000/year
Packaging Plus LLC	Value and energy stream mapping	$61,000/year
Trojan Battery Company	Value and energy stream mapping	$100,000/year
UPS	Fleet optimization	4.7 %

In order to evaluate the energy efficiency of the manufacturing systems, three main techniques were employed. These are the Sustainable VSM (Faulkner et al. 2012), Life-cycle assessment (LCA), and discrete event simulation (DES) (Paju et al. 2010). These different techniques have some strengths and weaknesses that will be discussed through the chapter.

The purpose of this chapter is to introduce various aspects of discrete event simulation as a tool for measuring energy efficiency of the manufacturing systems in cases of different lean techniques at different application levels. A superior proactive approach which performs the assessment of energy efficiency is developed for the design of the eco-conscious lean manufacturing systems. Proposed approach is illustrated on a hypothetical case.

The rest of this chapter is organized as follows. In Sect. 18.2, relevant literature is reviewed. In Sect. 18.3, background information about the integration of Lean Manufacturing tools and energy efficiency is given. Proposed discrete event simulation-based approach is included in Sect. 18.4. Finally, conclusions are provided in Sect. 18.5.

18.2 Literature Review

Some attempts have been made to analyze the effect of Lean Manufacturing on energy efficiency. In a conceptual study, U.S. Environmental Protection Agency—EPA (2007) expressed practical strategies and techniques to improve energy and environmental performance by applying Lean Manufacturing techniques. Numerical energy cost savings from successful Lean Manufacturers are also included. Sciortino and Watson (2009) performed a pilot program, namely the U.S. Environmental Protection agency (EPA) and the U.S. Department of Commerce (DOC)'s Manufacturing extension partnership (MEP) program. According to the program, unnecessary energy consumption should be regarded as an additional waste type in Lean Manufacturing. Seryak et al. (2006) reviewed several existing energy efficiency programs that promote manufacturing productivity. In addition, several widely excepted energy saving calculation method is reviewed and a detailed discussion is provided.

Developing Regression models, Khalaf et al. (2011) revealed that implementing both the Human Resources Management and Total Quality Management-related modules of Lean Manufacturing applications have significant effects on labor efficiency and capacity utilization, respectively. Then, the authors claimed that lean manufacturing implementation significantly influence energy efficiency by the argument that higher labor efficiency as well as higher capacity utilization leads to higher energy efficiency.

As an important Lean Manufacturing tool to determine wastes, Value Stream Mapping has been modified and utilized as sustainable value stream mapping (Sus-VSM) to show energy usage and environmental effects of manufacturing processes. Faulkner et al. (2012) proposed initial results of an effort to develop a methodology for Sus-VSM. The application of the methodology in a local manufacturer of satellite television dishes indicated the Sus-VSM approach was able to capture the economic, environmental, and societal sustainability of the line studied. Gogula et al. (2011) used VSM so as to emphasize the contribution of lean implementation in energy saving. An application of the methodology in a cylinder valve regulator manufacturing company demonstrated that implementing lean principles can result in significant energy reduction, and different lean tools can help in energy savings in different types of operations. Moreover, Li et al. (2012) proposed an improved VSM technique where the carbon emissions are also mapped. Besides, the authors suggested measuring the carbon efficiency of the products and processes. The processes that have higher efficiency improvement potential could be identified based on the Sensitivity analysis employed by the authors. This methodology was implemented for a printed circuit board assembly system.

Kara and Ibbotson (2011) addressed the embodied energy of a product life cycle that is manufactured under different manufacturing supply chains using LCA technique. A roofing system is chosen as a case study, in which its current supply chains have been assessed and compared with 10 different supply chain scenarios. Winkler (2011) stated that many negative environmental impacts, such as waste, energy consumption, transport processes, and packaging can be avoided if companies establish closed-loop production systems. Developing a generic methodology that allows comparability across the supply chain of products, supply chains, and countries, Rizet et al. (2012) compared the energy consumption and CO_2 emissions of supply chains in Belgium, France, and UK.

When the assessment of energy efficiency is concerned, in Giacone and Mancò (2012), mathematical process modeling, through statistical analysis of energy consumption data, is used to quantify the specific energy consumption as a function of the output. Application in cast iron melting process showed that this structured approach is relevant for energy benchmarking and suitable for energy management system standard (e.g., EN 16001, ISO 50001) or LCA standard (e.g., ISO 14044). Seow and Rahimifard (2011) proposed a novel approach to model energy flows within a manufacturing system and processes the energy consumption data at ‘plant’ and ‘process’ levels to provide a breakdown of energy used during production. Tanaka (2011) presented foundation for policy analysis for enhancing energy efficiency and conservation in industry, by surveying more than 300 policies with respect to 570 measures in IEA countries, Brazil, China, India, Mexico, Russia, and South Africa. The study not only outlined the measures’ main features, their incidence of use, and their connections with specific technical actions and key stakeholders, but also examined the key features underlying the measures’ success.

To sum up, among the three techniques, VSM has been frequently used for the assessment of the energy efficiency of the manufacturing systems, probably because it is user friendly and a good visual communication tool. LCA is also another technique employed for the same purpose that is formally more standardized where the required public data is available. As Paju et al. (2010) stated, VSM and LCA are appropriate for deterministic cases, and cannot reflect the dynamic nature of the manufacturing systems. However, DES is able to represent the dynamic event relationships and probabilistic parameters of the manufacturing systems (Paju et al. 2010). Despite its advantages, DES has not been employed frequently yet for energy efficiency and environmental assessment, because more sophisticated modeling skills and software are needed. However, these three methods can complement each other as Paju et al. (2010) recommended.

18.3 Lean Manufacturing and Energy Efficiency

Lean Manufacturing is a business system for organizing and managing product development, operations, suppliers, and customer relations that requires less human effort, less space, less capital, and less time to make products with fewer defects to precise customer desires, compared with the previous system of mass production (LEI 2012a). Lean Philosophy provides effectiveness in performance by maintaining the continuous flow of products, materials, or services through the value stream. To achieve this, the different types of waste, step, or process that does not add value for the customer, must be identified and eliminated. Wastes are classified into seven types as given below:

- Overproduction: This type of waste can be described as producing more than required.
- Transportation: Multiple handling or movement of products.
- Motion: It should be regarded as the motion of the workers, machines, and handling.
- Waiting: Waiting for a machine to finish a cycle, waiting for a supervisor to answer a question, or waiting for information or materials result in an interruption of flow.
- Processing: Overprocessing a part, a work order, or a project.
- Inventory: Work in process (WIP) is a result of large lot production or processes with long cycle times. This type of waste leads to increase in lead time.
- Defects: The occurrence of defects should be eliminated instead of scrapping or repairing.

To eliminate waste and achieve flow, basic principles of Lean philosophy are developed and these principles are realized by the implementation of the lean techniques.

- Identify value: Specify value from the standpoint of the end customer by product family.
- Map the Value Stream: Identify all the steps in the value stream for each product family, eliminating whenever possible those steps that do not add value.
- Create Flow: Make the value-creating steps occur in tight sequence so the product will flow smoothly toward the customer.

- Establish Pull: As flow is introduced, let customers pull value from the next upstream activity.
- Seek Perfection: As value is specified, value streams are identified, wasted steps are removed, and flow and pull are introduced, begin the process again and continue it until a state of perfection is reached in which perfect value is created with no waste.

Lean Manufacturing can be considered as an employee-oriented philosophy that has proved its worthiness in industrial environments over a long period of time. The determination and elimination of such wastes provides cost effectiveness, higher quality, and customer responsiveness to manufacturing and service systems. It is obvious that companies should realize effectiveness in energy efficiency from adopting Lean Manufacturing, since energy and environmental wastes are hidden in the wastes.

The waste categories and associated tools to reveal and eliminate them are given in Table 18.2.

Coordinating Lean Manufacturing with energy efficiency assessments improves the persistence of savings. Reduced changeover time, reduced failure time, increased throughput rate and increased quality, and other benefits associated with lean manufacturing has a positive effect on energy savings.

In detail, most important lean techniques are given below.

- *Pull System*: In Lean Manufacturing, production is pulled by costumer demand in terms of amount, time, and location. Pull system practices are designed to provide the right materials at the right time to support manufacturing needs. This

Table 18.2 Waste types examples and lean techniques as countermeasures

Waste category	Example	Countermeasure/lean technique
	(Energy hidden in…)	(To reveal and eliminate…)
Defects	Defective products	Promote first time through (FTT)
		Performance criteria
	Space for repair and rework	Utilize standard work
Transportation	Labor that handles items	Layout kaizen
	Transportation equipment	Cellular manufacturing
Motion	Unnecessary movements, steps	Work study
		5S
Waiting	Space for queues	Line Balancing
	Production of obsolete products	Kanban (pull production) SMED (single minute exchange of die)
Inventory	Storage space	Kanban (pull production)
	Warehouse up-keeping	One-piece flow
	Warehouse staff	
Unnecessary processing	Over sensitive measurement or control	Relocation/redesign of tools and equipment
	Counting parts	5S
Overproduction	Operations to produce the unnecessary products	Kanban (pull production) SMED (single minute exchange of die)

concept focuses on reducing excess inventories of raw or work in process materials which cannot be consumed immediately by the production cycle. The most widely known pull system tool is Kanban which is a small card or signboard (or any authorizing device) attached to boxes of specific parts in the production line signifying the delivery of a given quantity. Energy reduction due to inventory takes place in form of lighting and cooling of warehouses or storage areas. What is more, pull systems decreases transportation activities in parallel with inventory levels. The opposite of pull system is the push system, where the preceding process does not consider the production speed or availability status of the subsequent one. This may result in accumulation of excess inventory/work-in process, long manufacturing lead times, and consumption of excess energy.

- *Manufacturing Cell*: Improving the flow of product and process inputs can significantly reduce the amount of energy required to support a production process. Lean Manufacturers arrange equipment and workstations in a sequence that supports a smooth flow of materials and components through the process, with minimal transport or delay (U.S. Environmental Protection Agency—EPA 2007). Manufacturing cells are frequently adopted as facility layout alternative in Lean Manufacturing Systems. In manufacturing cells, parts with similar operations and/or raw materials are manufactured on dedicated set of closely positioned machines (Hyer and Wemmerlöv 2002). The alternative of the cellular configuration is the functional layout where excess material handling, long lead times and high work in process occur. All these lead to a large amount of energy consumption.
- *Single Minute Exchange of Die* (SMED): SMED is a procedure to reduce the setup and changeover time for a process. This tool reduces the time the production is down. It also reduces the energy and labor used to make the changeover, i.e., for transportation of dies, tools, and equipment. Moreover, during the setup activities, some trial and error production is made where unqualified parts are produced and have to be scrapped. By means of the SMED technique, this kind of production is reduced and hence both the energy and the raw material consumption through the setup activities can be decreased.
- *Total Productive Maintenance* (TPM): Involving all employees, TPM is a company-wide team-based effort to build quality into equipment and to improve overall equipment effectiveness. Systematic care and maintenance of the equipment increases the life of machines and reduces machining downtime. It especially decreases machine breakdown sourced waiting wastes. Some activities that should be made to integrate energy efficiency into TPM are listed below (Gogula et al. 2011):
  - Integrate energy reduction opportunities into autonomous maintenance activities.
  - Train employees on how to identify energy wastes and how to increase equipment efficiency through maintenance and operations.
  - Conduct energy kaizen (continuous improvement) events to make equipment more efficient.

  - Build energy efficiency best practices into systems for management of safety, health, and environmental issues.

- *Standard Work*: Standard work is a set of work procedures that establish the best and most reliable method of performing a task or operation. Each operator performing the same task follows the same procedure. This enhances variability reduction through the processing times, thus the energy consumption. Work procedures maintained at each work station incorporating energy reduction best practices can reduce the energy waste.
- *5S*: It is a five-stage method to improve and sustain workplace organization. It has the principle of "Each item should be in its appropriate place in workplace." It eliminates searching activities because it provides continuous cleanliness and order in systems. When 5S is not implemented, the manufacturing system is disorganized, hard to clean, and becomes a chaotic work environment. This kind of workplace is likely to require more labor to carry out the manufacturing processes.
- *Visual Control*: It consists of visual indicators so that goals and current status of the workplace or production can be easily identified. These indicators can include energy usage goals, which can help workers and managers to be conscious. (Color-code pipes to quickly identify and report key information (e.g., leaks), a sign over on/off switches or power outlets to remind operators to turn off or unplug equipment that is not in use, etc.)
- *Mistake-Proofing* (Poka Yoke): These are the mechanisms that are used to prevent errors from occurring or to immediately point out a defect as it occurs. Mistake-proofing devices such as occupancy sensors and lock-out/tag-out de-energizing steps are a simple, low-cost means to power down equipment that is not in use. By mistake-proofing equipment, a facility can waste less energy, time, raw material and resources, as well as prevent rework (U.S. Environmental Protection Agency—EPA 2007).
- *Jidoka*: It means providing machines and operators the ability to detect when an abnormal condition has occurred and immediately stop work. This enables operations to build-in quality at each process and to separate men and machines for more efficient work (LEI 2012b). One simple energy-efficient action is to automatically power down energy-consuming equipment when not in use, since process equipment and lighting do not always need to be on.
- *Milk-run*: Lean logistics can be regarded as the logistics dimension of the Lean Manufacturing (Baudin 2005), and milk-run is a practice of lean logistics. In traditional supply chains, deliveries are made in large quantities where a full-truck load or minimum order quantity is tried to be reached. This incurs order of goods more than or earlier than required. However, in Milk-run systems parts supply is performed with small lots and frequent cyclic tours of vehicles either from the warehouses to the manufacturing lines/cells or from to supplier companies to the customer. That being the case, it will be appropriate to state that Milk-run systems may increase energy consumption of vehicles due to the frequent deliveries, while increasing delivery performance of the suppliers. Table 18.3 gives Lean Tools with their correspondent waste types and application levels.

Table 18.3 Lean tools and associated application levels

Lean tool	Related waste type(s)	Application level
Pull system	Overproduction, inventory, transportation	Supply chain level, plant level, manufacturing cell/line level
Manufacturing cells	Transportation	Plant level
SMED	Waiting, motion, inventory, transportation, overproduction	Plant level, manufacturing cell/line level
TPM	Waiting	Plant level, manufacturing cell/line level
Standard work	Defects	Manufacturing cell/line level
5S	Motion, defects, inventory	Plant level, manufacturing cell/line level
Visual control	Defects	Manufacturing cell/line level
Mistake-proofing	Defects	Manufacturing cell/line level
Jidoka	Defects, waiting	Manufacturing cell/line level
Milk-run	Inventory, (it has a negative effect on transportation costs)	Supply chain level, plant level

18.4 Methodology

A discrete event simulation-based methodology is proposed for energy assessment of manufacturing systems. This methodology serves two purposes; (1) It can be used by manufacturing system executives to evaluate the energy consumption associated with a given lean manufacturing technique and (2) it can also be regarded as a higher level road map for energy consumption analysis by researchers and demonstrates several distinguished research paths.

18.4.1 Value-Based Energy Taxonomy

An energy taxonomy adapted from (Seryak et al. 2006) and (Seow and Rahimifard 2011) is proposed to provide the foundation of the methodology. Basically, in plant level, energy consumption is divided in two categories as (1) Direct Energy and (2) Indirect Energy.

Indirect Energy Consumption is a measure of energy requirement of auxiliary services such as lighting or air conditioning. Day-to-day routine office operations may also be regarded in this category. These activities or services are not strongly correlated with the daily throughput but a drastic reduction on lead time or WIP may significantly reduce the indirect energy consumption. On the other hand, Direct Energy Consumption category is linked directly to throughput or operating hours.

The main relation between Direct and Indirect consumption can also be stated by means of Little's Law (Hopp and Spearman 2011). Little's law states that the ration of Lead Time to Work in Process equals to Throughput rate as given in Eq. 18.1.

$$\text{Throughput} = \frac{\text{Lead Time}}{\text{Work in Process}} \tag{18.1}$$

A further analysis of Little's Law reveals that same throughput level can be reached either with short lead time and low WIP or with long lead time and high WIP. This is critical in the sense of direct and indirect energy consumption. If we restate the little's law in terms of proposed energy taxonomy; same direct energy consumption can be attributed to either high or low indirect energy consumption.

This is why it is crucial to first set the distinction on plant level between direct and indirect energy consumption.

Furthermore, Direct Energy consumption, on process level, divided into (1) value-added and (2) non-value-added energy consumption. Non-value-added consumption is a result of previously mentioned waste categories. Each category of waste results in additional energy requirement in the system. Here, we suppose that the previously discussed waste categories do not only increase the energy consumption in terms of indirect energy but also in terms of direct energy consumption.

18.4.2 Steps and Cycles

Proposed methodology involves energy consumption calculation steps and associated improvement cycles as given in Fig. 18.1. Proposed methodology has a dual branch structure, for (1) direct energy and (2) indirect energy. Regardless of the system and the products, these two classes are investigated simultaneously. For direct energy consumption, a "process analysis" approach is applied via value streams and for indirect energy consumption a feature and characteristic-based assignment approach is applied.

This methodology may be applied to the whole manufacturing system at once but to avoid the obstacles associated with oversized implementation project, a pilot study concerning one or several product groups are favorable. A product family or a set of families first selected. In other words, a value stream or a set of value streams are picked first. Identifying "definition of value" and "elements of value stream" will provide the roots for further steps of the methodology. Beginning with this point on, a two parallel branches of the methodology may function for direct and indirect energy consumption simultaneously.

A process analysis approach is followed for direct energy consumption. Therefore, first the processes of the value stream is identified and then unit production energy is measured for each process. For example for a drilling process,

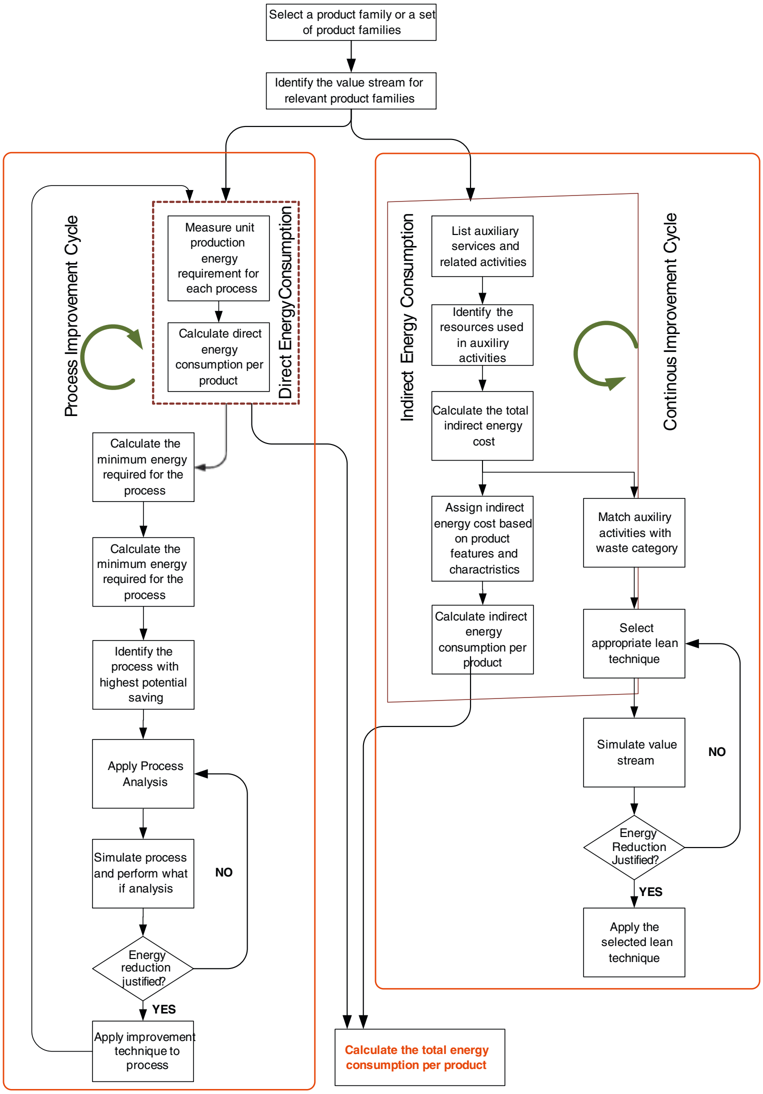

Fig. 18.1 Simulation-based energy efficiency assessment methodology

energy requirement for performing a single drill operation varies by technological parameters, but still a simple energy measurement device may be employed or the vendor may be advised with a certain confidence level. At this point measuring every single task may be overwhelming but energy consumption for a certain task may be assumed to be accurately generated based on others. For example, for the same drill operation, a three hole drill may be assumed to consume three times the energy consumed with a previously measured one-hole drill. Or a change in the technological parameters, such as the material of the work piece can be compensated by multiplying the measured value with a coefficient that reflects the characteristic of the material. Two points of caution are that; (1) measurements should include throughput information; that is both the duration and number produced for that duration should be well noted. Also, (2) so called "unaccepted" events should also be noted and measured. For example, if a certain resource tends to fail on average in every 1,000 h and average time to repair is 20 h; the resources required to perform the repair should also be measured. Otherwise, for this example, real effect of maintenance policies on energy consumption can never be considered.

Indirect energy consumption requires a close examination of these auxiliary services, such as maintenance, repair, services that sustain the plant (heating, lighting, etc.), and all office operations. The challenge concerning these activities is that at first sight these cannot be downgraded to a unit product, therefore even if we can measure precisely the energy consumption by relevant resources an extra step is required to assign the indirect energy consumption to each product. At this point, methodology employs an assignment approach based on Features and Characteristics. This approach is adapted from Features and Characteristic Costing (Maskell and Baggaley 2003).

Assume that indirect energy consumption is already measured for lighting appliances of a warehouse. Lighting is correlated with the depth and surface area of an item, therefore the volume is the key to assign energy consumption. So volume characteristic is used to distribute the total value of this auxiliary service to each product type. Then, indirect energy consumption per product is calculated as sum of all these activities.

Both branches have dedicated improvement cycles and both of these cycles are supported by simulation. The underlying motive of this methodology is to justify improvement efforts and demonstrate the gains solidly. Similar to any big scale transformation project, executive buy-in is a crucial element of success. Here, simulation serves the purpose of a justification tool based on what-if scenario analysis by illustrating the benefits of improvement acts on energy efficiency.

For energy savings, there are two apparent opportunities which are (1) savings on direct energy consumption and (2) savings on indirect energy consumption. As previously stated in proposed energy taxonomy, savings from direct energy can be realized by differentiating value-added and non-value-added parts of an activity through process analysis. Indirect energy savings, on the other hand, are much simpler to realize. Potential indirect energy savings can be linked to various waste categories.

However, proposed change cannot be easy to grasp for everyone. For example for indirect energy consumption; air condition and lighting, energy costs can be reduced by utilizing less space which can be accomplished through a layout change, in particular, transforming from functional layout to cellular layout. Also, applying a pull system to reduce WIP would lead to energy savings. Both of these strategies require intensive planning and evaluation of several scenarios. Therefore at this point of the methodology simulation will be used to illustrate the benefits and to evaluate what if scenarios.

Also in direct energy consumption, simulation is required on the process level. For example on lathe machine, a better estimate of tool life, or change in technological parameters may alter the energy consumption of the machine. But first this idea should be evaluated through simulation analysis. What-if scenarios and trade off analysis will also help to illustrate the potential gains.

18.5 Conclusion

This chapter introduces an energy consumption assessment methodology for lean manufacturing implementation. Underlying value taxonomy stems from lean thinking and focusses on non-value-added activities for energy reduction. Both for indirect and direct energy, an energy requirement calculation procedure and an energy reduction and performance improvement cycle is defined.

This chapter's contribution to the current practise is twofold. First, a novel methodology is introduced to the academic literature for lean manufacturing implementation that focuses on the energy requirement aspect of the manufacturing system and second, that methodology may serve as a readily available assessment tool for the manufacturing industry. On both cases the focus of the overall technical requirement to realize these objectives is simulation.

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Chapter 19
Socio-Effective Value of Bio-Diesel Production

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Abstract Increasing air pollution in urban areas has accelerated the interest in biodiesel and vehicles that consume biodiesel. As a caution, majority of the developed countries have started using biodiesel in transportation or determined goals and targets for the near future. Brazil has been a pioneer in the field, whereas the European Union has set the objective of utilizing 10 % of all vehicles using biodiesel by 2020. While the utilization and implementation of biodiesel-based systems severely contribute to economical and environmental savings, the antecedent production process has its own adverse effects such as the demolishment of agricultural sites. This chapter aims to analyze these effects as well as to propose a model for balancing the trade-offs by minimizing the negative consequences and maximizing the positive ones. The related model involves nonlinear constraints and objectives which are dependent of different uncertain scenarios and expectations. A particle swarm optimization (PSO) and self-organizing maps (SOMs) approach are implemented to attain appropriate solutions of the model. This proposition will also provide a new perspective for both academia and investors in the biodiesel field.

19.1 Introduction

Energy is considered as the backbone of human survival and growth activities involving industrial activities (Mofijur et al. 2012). Together with the increasing energy demands, in order to extricate any potential energy shortages, the search for alternative sources of energy has been accelerated. One of these sources of

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renewable energy is biomass, known as organic material including gases and liquids obtained from biological plants or animals (Basu 2010). Biofuel and biogas are two most important products extracted and processed from biomass. These products have different sources such as different feedstock or animals (Padula et al. 2012). Biodiesel sources can be listed as rapeseed, jatropha, soybean, sunflower, and palm, whereas biogas sources can be vegetal or animal. Since these resources are mostly determined by geographical conditions, for a specific region, they are mostly unchangeable (Pate et al. 2011). However, other biodiesel and biogas production remain dynamic and require constant optimization depending on changing technologies, economic, or social conditions. In all conditions, production amount is a decision that should be optimized.

Biodiesel and biogas production volumes used to be considered as solely dependent on the sources and the feedstock (Souza-Santos 1999). However, social, environmental, technical, and economic aspects are also recently included in calculating production amounts or making other significant decisions (Gwavuya et al. 2012). In this study, a socioeconomic evaluation and determination of production amounts have been achieved for one type of biodiesel and two types of biogas. The biodiesel in the context of this study is a hybrid of rapeseed oil and sugar beet. Sources for biogases are molasses and cattle manure. Each of these energy and fuel sources has its own employment, CO_2 emission, operation cost, and land use rates as its objectives under economic, environmental, and social constraints.

Furthermore, all constraints, contributions, and drawback parameters are not certain, because these values are sensitive to geographical and societal conditions (Kowsari and Zerrifi 2008). A sensitivity analysis under a multiobjective linear model is proposed for different cases in order to produce the right amount. According to the literature review, the most volatile parameters are observed to be the employment rate of biogas obtained from cattle manure and the operation costs for biogas based on molasses. Hence, this study aims to obtain the efficient front of the objectives in cases that two parameters are high, average, and low. For creating the efficient front, particle swarm optimization (PSO) algorithm is used. In consideration of understanding the efficient fronts and effects of the changing parameters, a clustering analysis is applied using self-organizing maps (SOM). The model also offers alternative production schemes for different scenarios.

This chapter is so organized that the next section will give a brief overview of the biomass literature in order to clarify the motivation of the study. The methodologies will be presented in the Sect. 19.3. The proposed optimization model will be clarified in Sect. 19.4 and an application of the model is explained with the results obtained in Sect. 19.5. The Sect. 19.6 is reserved for concluding remarks and further suggestions.

19.2 Literature Review

The increasing need for clean, sustainable, and renewable energy allows biomass technologies improve as a response to the needs, along with other resources. As a result of these improvements, investigations on biodiesel and biogas production have been a prominent area for research. Earlier studies have mostly analyzed establishment related and technical issues of the biomass technologies such as feasibility (Souza-Santos 1999; Hammad et al. 1999), potentials (Sudha and Ravindranath 1999; Kuwahara et al. 1999), and primal technologies (Chanakya et al. 1999) in terms of technicalities and economics. As a result of further developments in the field variety of studies are performed in terms of measuring the impacts of different technologies (Ping et al. 2012; Yang et al. 2011) or offering novel and more complicated methods for production (Kovács et al. 2004; Phukingngam et al. 2011).

In the literature, the impacts of biodiesel and biogas production have been examined socially, technically, economically, and ecologically. In the environmental or ecological context, different production methods or raw material sources have been observed to produce various amounts of greenhouse gasses (Emery and Moiser 2012; Wicke et al. 2008). Moreover, conversion of arable lands into biomass production sites has been analyzed as in either ecological or economic impacts of biomass production (Elauria et al. 2003; Murphy and Power 2009).

Under the social context of biomass production, employment generation is the most exploited and significant concern (Gwavuya et al. 2012; Silalertruksa et al. 2012). Working conditions, health, and safety of employees constitute the other aspects of social context, together with another vital social debate, that is, whether to use crops as food or energy feedstock (Actionaid Tanzania 2009). The economic context stands for the productivity, feasibility, and all costs related to biomass production from investments such as crop production or purchase of feedstocks to operation costs and trade prices (Arora and Singh 2003; Huang et al. 2009). Lastly, technical concepts involve evaluations of design and analysis of configurations (Kempegowda et al. 2011). Depending on these aspects, sensitivity analyses and scenario evaluations have been achieved in biomass production.

The literature involves different feedstock for biodiesel or biogas production analyzed with various analyses. For the production of biodiesel, the type of feedstock changes according to geographical regions. Cornstarch in USA, sugar cane in Brazil, rapeseed in Europe, and jatropha in Africa and southern Asia have been the main feedstock for biodiesel which have made the feedstock selection a challenge (Solomon 2010; Findlater and Kandlikar 2011). Hence, different studies from various countries favor different feedstock. Thamsiriroj and Murphy (2009) analyze technical and environmental aspects of biodiesel produced from palm oil and rapeseed oil for Ireland and find out that palm oil is more efficient than rapeseed oil. Different feedstock as castor, palm, jatropha, sunflower, soybean, and rapeseed have been evaluated related to the economic and technical aspects by Padula et al. in Brazil (2012). Unlike the study of Thamsiriroj and Murphy (2009), their results point out that soybean is more efficient to be used. Rodrigues et al. 2007 discusses that rapeseed is preferable since it grows faster and is more efficient even in winter conditions, contributes to bee feeding, and contains an abundance of nutrients. Rapeseed also has been found a suitable alternative regarding food versus energy debates, since it cannot be eaten (Actionaid Tanzania 2009).

Apart from feedstock evaluation, distinct investment alternatives for biodiesel are also evaluated in the literature. Quintero et al. (2012) conduct a social, technologic, and economic analysis of biodiesel produced from palm oil and jatropha under the scenarios of two partnership alternatives: associated small-holder or commercial producers. Stanojević et al. (2006) have described economic aspects in four dimensions: microeconomic, macroeconomic, demand, and supply. Another investment related study is conducted with a technical approach by Kiss et al. (2010) who analyze biodiesel produced from vegetable oil from the economic and ecological aspects in terms of different catalysts. These analyses also invite the question of sustainability of the investment. Rodrigues et al. (2007) have examined the challenge by carrying out a comparison between the ecological and socioenvironmental performance of biofuel production, concluding that the customer respect, employment, income, health, management, and administration are the main criteria that affect the social-environmental performance. Land availability is another criterion for sustainable production defined by Solomon (2010).

In terms of biogas, the sources are animal manure, animal fat, and various crop residues. Gwavuya et al. (2012) have analyzed the costs and benefits of biogas produced from the cattle manure to be used in rural areas for heating purposes. In that study, biogas is assessed through an economic approach considering the investment, labor costs, and maintenance costs together with time saving value and energy saving value in the study. Wang and Calderon (2012) calculate the net present value (NPV) on treating water hyacinth for biogas production under two different production schemes. The reverse interaction between socioeconomic factors and biogas production, that is the relation with the socioeconomic situation of the region and biogas production methods is analyzed by Mwirigi et al. (2009) and it is implied that socioeconomic demographics such as education level, income, farm size, and farming system do not have an impact on the adoption and sustainability of the biogas production. Moreover, Meang et al. (1999) state that the research structure and the taxation are critical factors affecting biogas production.

The main social issue for both biodiesel and biogas energies is generally accepted as employment generation. Silalertruksa et al. (2012) has investigated employment effects of biofuel where cassava, molasses, sugarcane, ethanol, and palm have been considered as feedstock. Employment definition is held broad as people working in agriculture to cultivate the feedstock and to harvest, and working in processing them to obtain biofuel. The assessments have been divided into two parts such as direct employment and indirect employment. Peters (2009) has analyzed the relation of working conditions and leisure activities people experience while working in biodiesel production. Majdalawi et al. (2012) have discussed the impact on employment and other social aspects by concluding that research and awareness should be raised in Arabic regions.

The literature also offers sensitivity and scenario analyses. Quintero et al. (2012) have implemented different scenarios that are about productivity levels and being smallholder or commercial producers. Gwavuya et al. (2012) apply a sensitivity analysis for biodiesel production with different scenarios based under changing costs and savings. Likely, Kiss et al. (2010) apply a sensitivity analysis on unitary cost which has fluctuated 25 % up or down where the objective has been determined as the investment cost. Wang and Calderon (2012) presented a NPV that relies on the sensitivity analysis of discount rate, prices, or quantities of biogas, price or quality of GHG emission reduction, value of water quality improvement, cost of collection, and cost of initial investment. This study concluded that the present value does not fluctuate more than 1 %. Silalertruksa et al. (2012) bases four scenarios on different production methods, feedstocks, and government policies which yield that the utilization of ethanol should be encouraged for biodiesel.

When it comes to the methodology, most of these studies implement statistical (Cornejo and Wilkie 2010) or empirical analyses. Peters (2009) utilize a regression analysis between working and leisure times of workers. Gwavuya et al. (2012) also implement regression analysis to measure the correlation between several parameters together with a cost-benefit analysis that includes the internal rate of return. Silalertruksa et al. (2012) use an input–output model for measuring direct or indirect employment factors. Majdalawi et al. (2012) carry out an empirical analysis based on observations; whereas Maeng et al. (2009) apply another empirical analysis by the web analysis and the Diamond-E analysis. Mwirigi et al. (2009) employ an ex-post facto research design by assigning socioeconomic status as an independent variable using a 7-Likert scale. Lastly, Thamsiriroj and Murphy (2009) employ a life cycle assessment for comparing different feedstocks.

In this study, socioeconomic factors that affect biodiesel and biogas product scheme are evaluated. Biodiesel production from canola, biogas production from molasses (which will be referred as biogas 1), and biogas production from cattle manure (which will be referred as biogas 2) are evaluated with a sensitivity analysis. A multiobjective linear model is established aiming to maximize employment, minimize CO_2 emission, minimize operation costs, and maximize valuation of the infertile land. For the multiobjective model, the PSO algorithm is run in order to observe the non-dominated solution sets. Additionally, a sensitivity analysis in two parameters are used to generate scenarios due to the uncertainties in both the literature and real-life applications. The two parameters are determined as employment rate of biogas production from cattle manure, operation cost rate of biogas production from molasses. Since the non-dominated sets of the scenarios have yielded more than 2,000 solutions, an SOM approach is applied for better and further comprehension of the solutions.

19.3 Methodology

19.3.1 Multi Objective Particle Swarm Optimization Algorithm

PSO is an optimization algorithm proposed by Kennedy and Eberhart (1995). The algorithm imitates behaviors of natural swarms such as bird flocking or fish schooling. It is a stochastic and population-based algorithm where each solution is presented by a particle. Each particle position is denoted by x_i and each particle velocity is denoted by v_i. Steps of the algorithm are presented below:

1. Initial solution set is randomly generated as in

$$x_{ij} = x_{\min} + r(x_{\max} - x_{\min}), \quad i = 1, \ldots, n; j = 1, \ldots, N \tag{19.1}$$

$$v_{ij} = \alpha(x_{\min} + r(x_{\max} - x_{\min})), \quad i = 1, \ldots, n; j = 1, \ldots, N \tag{19.2}$$

where i represents the particle number, j represents the related dimension of the particle. n is the total number of particles and N is the dimension number. $x_{\min}$ stands for the lower limit of the variables, $x_{\max}$ stands for the upper limit of the variables, r is a uniformly distributed random number in the interval [0,1], and α is either a random number or a predetermined coefficient. x is the particle position and v is the particle velocity.

2. Objective value for each particle is calculated.
3. Position with the best value of the current iteration is assigned to be the particle best.
4. Best position up to the related iteration is determined as the swarm best.
5. Particle velocities are updated according to the formula:

$$v_{ij} = wv_{ij} + c_1 r_1 \left(x_{ij}^{\text{pb}} - x_{ij}\right) + c_2 r_2 \left(x_j^{\text{sb}} - x_{ij}\right), \quad i = 1, \ldots, n; j = 1, \ldots, N \tag{19.3}$$

where w is the inertia coefficient, c_1 is the cognitive coefficient, c_2 is the social coefficient, r_1 and r_2 are uniformly distributed random numbers in the interval [0,1], x_{ij}^{pb} is the particle best position and x_j^{sb} is the swarm best position.

6. Positions of all particles are updated such that:

$$x_{ij} = x_{ij} + v_{ij} \quad i = 1, \ldots, n; j = 1, \ldots, N \tag{19.4}$$

7. Steps 2–6 are repeated until finishing criteria is reached.

According to the algorithm, after velocity updates on the swarm best and the particle best, if the objective value of a newly found solution is better than the predecessors, then it is assigned as the best value. However, in case of more than one objective, the newly found solution may result in improvement for a number of objectives, yet, cause deterioration in others. In this case, the algorithm saves the non-dominated best solution of all swarms as well as for each particle in the external archive (Reyes-Sierra and Coello–Coello 2006). In literature, numerous methods are offered for selection of the swarm member from the external archive. In this study, Moore and Chapman's method (1999) is used, that is, for particle best and swarm best positions a random non-dominated solution is chosen and assigned as particle or swarm best. In this method, the particle or swarm best to be used in the formula is selected randomly from the external archive.

19.3.2 Clustering

Clustering is the process of uncovering groups for a given data set (Aboyni and Feil 2000). Most real-world problems include an overwhelming number of data or patterns that are difficult to be conceived and prone to be misinterpreted; hence, clustering is an assistant for dividing data into meaningful groups according to their similarities or diversities (Wong and Li 2008). In the literature, abundant number of methods are available for clustering. In this study, clustering of the data is achieved by SOMs which have been proven to be powerful tools for clustering and discovering the patterns in data sets (Herbert and Yao 2007).

19.3.2.1 Self-Organizing Maps

SOM is a clustering technique derived from Artificial Neural Network where the unsupervised learning algorithm compare and calculate the error function without an actual output; i.e., the learning is actualized without the existence of a supervisor.

The aim of SOM is to convert a high dimensional data set of inputs into a lower-dimensional space. Two dimensional spaces are preferable as a result of providing easier comprehension of data (Leopold et al. 2004). Each node of the map represents a cluster whose characteristics are homogenous within but heterogeneous between. The most known type of SOM is called Kohonen Map, named after Teuvo Kohonen who first proposed the mapping in 1982. The main steps of SOM are listed as competition, cooperation, and adaptation (Haykin 1999). SOM is based on competitive learning that the output nodes strive to be the winner node, which is called the competition step. In order to select the winner node, the differences between input vectors and weight vectors are calculated. Then, the neighbors of the winner node are activated with the neighborhood effect (Larose 2005). After the competition step, the weight vectors of the winner node and its neighbors are updated in the adaptation step (Haykin 1999). The steps of the algorithm are given below:

1. The weights of the neurons (the weight vectors—$\underline{w_j}$) are initialized randomly.
2. The winning neuron is found, having the below property.

$$j^* = \arg\min \left\| \underline{x(k)} - \underline{w_j} \right\| \quad \text{where } k = 1, 2, \ldots, m \times n \tag{19.5}$$

where, $\underline{x(k)}$ is the input vector and mxn is the total number of neurons which means the winning neuron is the neuron that has the vector whose Euclidean distance of difference with the weight vector, makes the minimum angle between the x axis.

3. The weights of the winning neuron and its neighborhood are adjusted with the below formula:

$$\underline{w_j}(k+1) = \underline{w_j}(k) + \eta(k) N_{j*}(k) \left(\underline{x}(k) - \underline{w_j}(k) \right) \tag{19.6}$$

where $\eta(k)$ is the learning rate at the kth iteration, $N_{j*}(k)$ is the topological neighborhood of the winning neuron at kth iteration. It can be observed that the algorithm is dependent on $\eta(k)$ (learning rate) and $N_{j*}(k)$ (neighborhood of the winning neuron).

4. Steps 2 and 3 are repeated until the elements in clusters remain still.
5. Once the clusters are obtained, the results are to be tested in order to check the validity and robustness of the method.

There are a variety of topologies with different structures, yet, the literature generally agrees on that square-type topologies tend to perform better (Kiang 2001). SOMs are known to be powerful tools for clustering with the advantage of optimized number of clusters determined by the topology of the map and unnecessary clusters are not assigned any elements (Abbas 2008).

19.3.2.2 Cluster Validity

There is no rigid formula for the optimum number of clusters for a given data set in any clustering method. Besides, robustness of the clusters has to be measured in order to understand the quality of the clustering. For measuring robustness or finding the optimum number of clusters, numerous statistical methods have been developed (Arbelaitz et al. 2013; Halkidi et al. 2002). In this study, the C Index proposed by Hubert and Levin (1976) is used.

The C Index is defined as in equation:

$$C = \frac{d - d_{\min}}{d_{\max} - d_{\min}} \tag{19.7}$$

where $d_{\max}$ is the maximum intracluster distance, $d_{\min}$ is the minimum intercluster distance, and d is the average intracluster distance. This index only requires minimum intracluster distances, meaning as small clusters as possible. A smaller value of the C Index indicates a better clustering (Milligan and Cooper 1985).

19.4 SocioEconomic Modeling of Biodiesel and Biogas

19.4.1 Decision Variables

The decision variables in this study are the amounts of biodiesel and biogas amounts to be produced given the objectives and constraints. The feedstock and sources of biodiesel and biogas are given in Fig. 19.1 which displays the types of related biodiesel and biogas types. The biodiesel that is in the context of this study is produced from canola or rapeseed with a hint of sugar beet and results in glycerin as a by-product.

Two types of biogas are taken into consideration: biogas 1 produced from molasses which is in turn produced from sugar beet and biogas 2 produced from cattle manure (Fig. 19.1). The production unit of biodiesel is liters and the production unit of biogas is kilowatt-hours (kWh).

For the PSO model of the problem, each particle is formed with three dimensions, each dimension denoting a variable. The first variable is the production amount of biodiesel, the second variable is the production amount of biogas 1 and lastly, the last variable is the production amount of biogas 2. All variables are assumed to be continuous, that is, fractional values can be produced in terms of liters and kilowatt-hours. Each infeasible solution obtained by the PSO algorithm is handled with penalty values according to their types. Minimization objectives are increased by a very large number of times than their actual values. Likely, maximization objectives are decreased in the same manner.

19.4.2 Objective and Constraints

In the literature review part, it has been aforementioned that in socioeconomic context, the most important criterion is employment generation which is also the

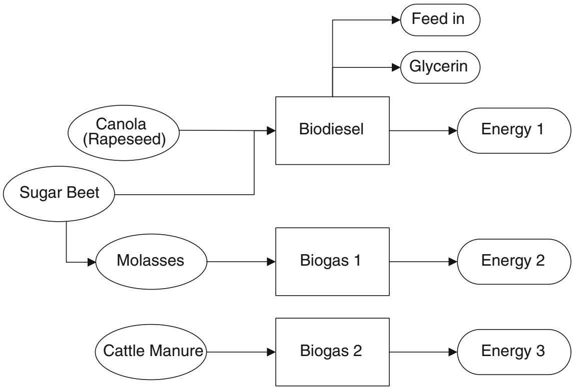

Fig. 19.1 The feedstock and sources of biodiesel and biogas

first maximization objective of the model. Second, CO_2 emissions are the main environmental criterion of the biomass production, yet, in turn, this criterion also affects the quality of life. The third objective is minimizing the operational costs which include the production or purchase of the feedstock, production of biodiesel or biogas, maintenance and insurance costs. Lastly, land use constitutes another objective of this study. Since, the land is essential for production in terms of crops, animals, and facilities and the land is either infertile or arable; infertile land usage is maximized.

The constraints of the model have been derived from restrictions in environmental and economic characteristics. The first two constraints are determined by European Union policies such that the reduction in CO_2 emission is aimed to be 20 % by 2020 (Capros et al. 2012). One of the assumptions of the model is that biodiesel is the main substitute for conventional diesel and biogas is the substitute for other energy needs. Hence, the first constraint measures the emission amount of biodiesel against the conventional diesel and the emission amount of biogas compared to other energy sources. The total contribution to the decrease in CO_2 emission is taken as at least 20 %. Capros et al. (2012) also state that the 20 % decrease is the 2020 goal for all greenhouse gases; hence, for the NO_x emissions, the total amount of allowable emission is taken as the 80 % of the actual and recent amount of NO_x emission.

Another challenge is the land usage which is analyzed in two parts. It has been aforementioned that the maximization of the usage of the infertile land is one of the objectives. The total land required depends on the production amounts of biodiesel and biogas. For a specific amount of biodiesel and biogas, the required land is constant. Maximization of infertile land usage directly signifies the minimization of the arable land usage. Therefore, one of the land usage constraints involves that the sum of total infertile and arable land used is equal to the required land. Second land usage constraint involves that the arable land used should be less than 10 % of the infertile land used for the worst case which is another assumption of the model.

The investment cost and demand cause new restrictions for the model. The model requires an upper limit for total investments. Additionally, the production should be more than a predetermined amount. In this model, 10 % of the total required amount is assumed as the lower limit of production.

19.4.3 Proposed Model

Decision Variables

- x_{can}: amount of biodiesel that is produced from canola (rapeseed)
- x_{mol}: amount of energy produced from biogas 1 that is produced from molasses
- x_{man}: amount of energy produced from biogas 2 that is produced from cattle manure

- x_{ift}: infertile land used (ha)
- x_{arb}: arable land used (ha)

Objectives

Employment generation with employment parameters (EP):

$$\max \mathrm{EP}_{\mathrm{can}} x_{\mathrm{can}} + \mathrm{EP}_{\mathrm{mol}} x_{\mathrm{mol}} + \mathrm{EP}_{\mathrm{man}} x_{\mathrm{man}} \tag{19.8}$$

CO_2 Emissions with parameters CO:

$$\min \mathrm{CO}_{\mathrm{can}} x_{\mathrm{can}} + \mathrm{CO}_{\mathrm{mol}} x_{\mathrm{mol}} + \mathrm{CO}_{\mathrm{man}} x_{\mathrm{man}} \tag{19.9}$$

Operation cost with operation parameters (OP):

$$\min \mathrm{OP}_{\mathrm{can}} x_{\mathrm{can}} + \mathrm{OP}_{\mathrm{mol}} x_{\mathrm{mol}} + \mathrm{OP}_{\mathrm{man}} x_{\mathrm{man}} \tag{19.10}$$

Infertile land use:

$$\max x_{\mathrm{ift}} \tag{19.11}$$

Constraints

CO_2 Reduction compared to diesel oil:

$$\frac{\mathrm{COR}_{\mathrm{can}} x_{\mathrm{can}}}{\mathrm{total}_{\mathrm{oil}}} + \frac{\mathrm{COR}_{\mathrm{mol}} x_{\mathrm{mol}} + \mathrm{COR}_{\mathrm{man}} x_{\mathrm{man}}}{\mathrm{total}_{\mathrm{energy}}} \geq \mathrm{Percentage} \tag{19.12}$$

NO_x Emissions:

$$\mathrm{NO}_{\mathrm{can}} x_{\mathrm{can}} + \mathrm{NO}_{\mathrm{mol}} x_{\mathrm{mol}} + \mathrm{NO}_{\mathrm{man}} x_{\mathrm{man}} \leq \text{Total allowable } \mathrm{NO}_x \text{ emission} \tag{19.13}$$

Land use:

$$\mathrm{LU}_{\mathrm{can}} x_{\mathrm{can}} + \mathrm{LU}_{\mathrm{mol}} x_{\mathrm{mol}} + \mathrm{LU}_{\mathrm{man}} x_{\mathrm{man}} = x_{\mathrm{ift}} + x_{\mathrm{arb}} \tag{19.14}$$

$$x_{\mathrm{arb}} \leq 0.10 x_{\mathrm{ift}} \tag{19.15}$$

Investment cost with parameters IC

$$\mathrm{IC}_{\mathrm{can}} x_{\mathrm{can}} + \mathrm{IC}_{\mathrm{mol}} x_{\mathrm{mol}} + \mathrm{IC}_{\mathrm{man}} x_{\mathrm{man}} \leq \text{Budget for investment} \tag{19.16}$$

Demand:

$$x_{\mathrm{can}} \geq 0.10\, \mathrm{total}_{\mathrm{oil}} \tag{19.17}$$

$$x_{\mathrm{mol}} + x_{\mathrm{man}} \geq 0.10\, \mathrm{total}_{\mathrm{energy}} \tag{19.18}$$

19.5 Model Application

19.5.1 Parameters of the Model and Scenarios

Values of the parameters for the proposed model have been collected through the literature on biodiesel and biogas. These values are shown in Tables 19.1 and 19.2.

19.5.1.1 Employment Rate of Biodiesel (EP_{can})

For biodiesel production, there are different employee numbers which vary from 0.14 employees (Actionaid Tanzania 2009) to 0.17 employees (Peters 2009) per hectare. An average value of 0.155 employees per hectare has been used in this study.

1 L of biodiesel contains 87 % oil and 12 % alcohol. Canola is cultivated for oil and sugar beet is cultivated for alcohol. Moreover, one hectare of land consists of 1.5–2 tons of canola (rapeseed). Since 42 % of canola is oil, the expected range of oil amount per hectare is between $1.5 \times 0.42 = 0.63$ ton and $2 \times 0.42 = 0.84$, 0.735 ton. The density of canola oil is 0.92 kg/L or 92×10^{-5} ton/L (Friedman and Friedman 2011). Then 0.735 ton of oil indicates approximately 800 L of oil. Because 800 L of oil is extracted from one hectare, 0.87 L oil requires 0.001088 ha of land.

Four ton sugar beet can be cultivated from one hectare of land. Since 6.22 kg sugar beet contains 1 kg alcohol (ethanol) and one hectare land provides (4,000 kg)/(6.22) = 643 kg alcohol. The density of ethanol is 0.789 g/cm^3 (Ethanol 2012) or 0.789 kg/L. Then, 643 kg alcohol means approximately 815 L alcohol. Since 815 L alcohol is extracted from one hectare, 0.12 L alcohol requires 0.00015 ha of land.

According to the above calculations, one liter of biodiesel produced from canola requires 0.001238 ha as a total land.

One liter of biodiesel needs 0.001238 ha of land. Since 1 hectare requires 0.155 employees, 0.001238 ha requires 0.000192 emp/L. Therefore:

$EP_{can} = 0.000192$ emp/L.

Table 19.1 Parameters for objectives

	Employment	CO_2 emission	Operation cost
Biodiesel	0.000192 emp/L	2057.092 g/L	66.5 €-cent/L
Biogas (molasses)	0.019 emp/kWh	94.586 g/kWh	141.35 €-cent/kWh
Biogas (manure)	0.0065 emp/kWh	93.629 g/kWh	1.145 €-cent/kWh

Table 19.2 The parameters for the constraints

	CO_2 (%)	NO_x	Land use	Investment cost
Biodiesel	10.6	55.949 g/L	0.001238 ha/L	0.0001642 €/L
Biogas (molasses)	62.2	1.944 g/kWh	0.0026 ha/kWh	0.07 €/kWh
Biogas (manure)	62.5	0.302 g/kWh	0.0864 ha/kWh	1.02 €/kWh

19.5.1.2 Employment Rate of Biogas 1 (EP_{mol})

Direct employment requires 0.5 employees, indirect employment requires 4.8 employees per TJ, and totally 5.3 employees are required for biogas production from molasses (Silalertruksa et al. 2012). Since 1 TJ equals to 278 kWh, employment generation value is calculated as the following: (5.3 emp/TJ)/(278 kWh/TJ) = 0.019 emp/kWh. Therefore: $EP_{mol} = 0.019$ emp/kWh.

19.5.1.3 Employment Rate of Biogas 3 (EP_{man})

Number of employees who work for biogas production is calculated with a lower limit of 4.9 (Aldas and Gildart 2005) and an upper limit of 7.8 (Pettenella et al. 2009–2010) per MW. Approximately, 0.005–0.008 employees per kWh have been considered as the first scenario set parameters. The average employee number of biogas produced from manure is 0.0065 emp/kWh. Therefore:

$EP_{mol} = 0.0065$ emp/kWh.

19.5.1.4 CO_2 Emission Amount of Biodiesel (CO_{can})

CO_2 emission of biodiesel is cited as 62.16 kg/GJ (Thamsiriroj and Murphy 2009). In order to convert the unit of kg/GJ into g/L, the following steps are executed.

1 GJ = 278 kWh ⇒ 1 kWh = 0.00359712 × (62.16 kg/GJ) × (1,000 g/kg) × (0.00359712 GJ/kWh) = 223.597 g/kWh.

Since one liter of biodiesel produced from canola provides 9.2 kWh energy (Fossdal et al. 2007), the CO_2 emission of biodiesel per liter is calculated 223.597 g/kWh = (223.597 g/kWh) × (9.2 kWh/L) = 2,057.092 g/L. Hence, $CO_{can} = 2057.092$ g/L.

19.5.1.5 CO_2 Emission Amount of Biogas 1 (CO_{mol})

CO_2 emission of biogas produced from molasses is 0.66 kg/m^3 (Stucki et al. 2011). Since 1 m^3 of biogas provides 0.73 m^3 of CH_4, and 1 m^3 of CH_4 has energy of 34,384 kJ, (0.73 × 34,384) = 25,100 kJ energy is obtained from 1 m^3 of biogas. After the following calculations, CO_2 emission is obtained in terms of g/kWh.

[(0.66 kg/m^3) × (1,000 g/kg)]/[(25,100 kJ/m^3) × (2.78 × 10^{-4} kWh/kJ)] = 94.586 g/kWh. Hence, CO_{mol} = 94.586 g/kWh.

19.5.1.6 CO_2 Emission Amount of Biogas 2 (CO_{man})

Direct CO_2 emission from deposited manure is 1717.07 Gg per and indirect CO_2 emission from deposited manure is 171.71 Gg per 4,354 × 10^3 cattle (Cornejo and Wilkie 2010). It can be seen that the total emission is 1,888.78 Gg per 4,354 × 10^3 cattle. It is known that 1,500 cattle make 30 m^3 manure, and then 750 m^3 methane is extracted:

1 m^3 CH_4 = 34,384 kJ → 750 m^3 CH_4 = 25,000,000 kJ

1 kJ = 2.78 × 10^{-4} kWh → 25,000,000 kJ = 6,950 kWh

Since 6,950 kWh energy is produced from 1,500 cattle, one of them provides 4.63 kWh and 4354 × 10^3 cattle provide (6,950 kWh/1,500 cattle) × (4,354 × 10^3 cattle) = 20.17 × 10^6 kWh energy. (1,888.78 x 10^6 g)/(20.17 × 10^6 kWh) = 93.629 g/kWh. Therefore: CO_{man} = 93.629 g/kWh.

19.5.1.7 Operation Cost Rate of Biodiesel (OP_{can})

Operation cost of biodiesel produced from canola is $ 0.8588/L (Canola Biodiesel Production Costs—Farm Fuel 2012). After the conversion of Dollar into Euro-cent, the unit operation cost is obtained as 66.5 €-cent/L. Therefore:

OP_{can} = 66.5 €-cent/L.

19.5.1.8 Operation Cost Rate of Biogas 1 (OP_{mol})

Operation cost of biogas produced from molasses has different values from 10 to 17 €/m^3 (Sajbrt et al. 2010). Since one m^3 contains 34,384 kJ energy and 1 kJ energy equals 2.78 × 10^{-4} kWh energy, the lower and upper value for operation cost are calculated as in the following:

(10 €/m^3) × (1/34,384 m^3/kJ) × (1/2.78 × 10^{-4} kJ/kWh) × (100 €-cent/€) = 104.7 €-cent/kWh

(17 €/m^3) × (1/34,384 m^3/kJ) × (1/2.78 × 10^{-4} kJ/kWh) × (100 €-cent/€) = 178.0 €-cent/kWh.

These values, 104.7 €-cent/kWh for lower and 178.0 €-cent/kWh for upper, have been used as the second scenario set parameters. The average operation cost of biogas produced from molasses is 41.35 €-cent/kWh. Therefore:

OP_{mol} = 41.35 €-cent/kWh.

19.5.1.9 Operation Cost Rate of Biogas 2 ($\mathbf{OP_{man}}$)

Operation cost of biogas produced from manure is \$ 0.015/kWh (Martin 2003). After the conversion of Dollar into Euro-cent, the unit operation cost is obtained as 1.145 €-cent/kWh. Therefore: $OP_{man} = 1.145$ €-cent/kWh.

19.5.1.10 Total Oil and Total Energy Amounts

European Union has targeted to reduce to CO_2 emission by 20 %. Therefore, emission caused by current diesel and energy consumption is claimed to reduce through biodiesel and biogas at least 20 %.

Petroleum consumption in Turkey is 706.07 thousand barrels per day according to Energy Information Administration (EIA) statistics (EIA 2010). The metric conversion of the value into the liter denotes 112,256.16 L per day. Hence, $total_{oil} = 4{,}677.34$ L per hour.

Heat and electricity consumption are considered as total energy in order to benchmark with biogas. Electricity consumption has a lower value of 155.19 billion kWh yearly (EIA 2010) which is 17.9×10^6 kWh per hour and an upper value of 198,085 GWh/year (Electric energy consumption 2012) which is 22.9×10^6 kWh per hour. Then, an average electricity consumption value 20.4×10^6 kWh has been considered in this study. Besides, the heat consumption has an average value of 484.234×10^9 kWh/year (TCMB 2011); which means 56×10^6 kWh per h, with the total energy becoming the sum of heat and electricity consumption. Therefore: $total_{energy} = 76.4 \times 10^6$ kWh.

19.5.1.11 $\mathbf{CO_2}$ Emission Rate of Biodiesel ($\mathbf{COR_{can}}$)

CO_2 emission of diesel is stated as 0.25 kg/kWh (Guidelines for Company Reporting on Greenhouse Gas Emissions 2005)

(0.25 kg/kWh) × (1,000 g/kg) = 250 g/kWh.

Since CO_2 emission of biodiesel is calculated as 223.597 g/kWh CO_2 reduction of biodiesel compared to diesel oil. Hence, $COR_{can} = 1 - (223.597/250) = 0.106 = 10.6\ \%$.

19.5.1.12 $\mathbf{CO_2}$ Emission Rate of Biogas 1 ($\mathbf{COR_{mol}}$)

Since CO_2 emission of biogas produced from molasses is 94.586 g/kWh and CO_2 emission of diesel is 250 g/kWh, CO_2 reduction of biogas produced from molasses compared to diesel oil. Hence, $COR_{mol} = 1 - (94.586/250) = 0.622 = 62.2\ \%$.

19.5.1.13 CO_2 Emission Rate of Biogas 2 (COR_{man})

Since CO_2 emission of biogas produced from cattle manure is 93.629 g/kWh and CO_2 emission of diesel is 250 g/kWh, CO_2 reduction of biogas produced from cattle manure compared to diesel oil. Hence, $COR_{man} = 1 - (93.629/250) = 0.625 = 62.5\ \%$.

19.5.1.14 Allowable NO_x Emission Amount of Biodiesel

The literature provides the values for NO_x emissions country by country, which enables further to use different values in their calculations and sensitivity analyses. Total NO_x emission in Turkey is given as 932 Gg per year (Vestreng et al. 2009). Since there are approximately 8,640 h in a year, the expected emission in an hour is calculated as in the following:

$(932\ \text{Gg/year}) \times (10^9\ \text{g/Gg}) \times (0.25656\ \text{year/h}) \sim 107.8 \times 10^6\ \text{g/h}\ NO_x$.

European Union target is a 20 % reduction in NO_x emission as in CO_2 emission. Therefore, the allowable maximum NO_x emission has been taken into consider as 80 % of total emission: $(107.8 \times 10^6\ \text{g}) \times (0.80) = 86.24 \times 10^6\ \text{g}$.

19.5.1.15 NO_x Emission Amount of Biodiesel (NO_{can})

NO_x emission of biodiesel is known as 6.0814 g/kWh (TBK-BioDiesel KTI Engine Analysis of the Full Load Test Procedure 2010). Since the one liter of biodiesel produced from canola is 9.2 kWh of energy (Fossdal et al. 2007), the NO_x emission of biodiesel per liter is calculated as following:

$(6.0814\ \text{g/kWh}) \times (9.2\ \text{kWh/L}) = 55.949\ \text{g/L}$.

Hence, $NO_{can} = 55.949$ g/L.

19.5.1.16 NO_x Emission Amount of Biogas 1 (NO_{mol})

NO_x emission of biogas produced from molasses is 540 g/GJ (Kristensen et al. 2001). The value per GJ is needed to be converted to a value per kWh:

$(540\ \text{g/GJ}) \times (1/277.77\ \text{GJ/kWh}) = 1.944\ \text{g/kWh}$.

Hence, $NO_{mol} = 1.944$ g/kWh.

19.5.1.17 NO_x Emission Amount of Biogas 1 (NO_{man})

Direct N_2O emission from deposited manure is 5.54 Gg and indirect N_2O emission from deposited manure is 0.55 Gg per $4{,}354 \times 10^3$ cattle (Cornejo and Wilkie 2010). It is obvious that the total emission is 6.09 Gg per $4{,}354 \times 10^3$ cattle. As calculated in CO_2 emission parameter, $4{,}354 \times 10^3$ cattles provide 20.17×10^6 kWh energy.

$(6.09 \times 10^6$ g)/$(20.17 \times 10^6$ kWh) = 0.302 g/kWh.
Hence, $NO_{man} = 0.302$ g/kWh.

19.5.1.18 Land Use of Biodiesel (LU_{can})

As calculated in employment generation parameter, one liter of biodiesel produced from canola requires 0.001238 ha as a total land. Hence, $LU_{can} = 0.001238$ ha/L.

19.5.1.19 Land Use of Biogas 1 (LU_{mol})

425 m^3 of biogas is produced by per ton of molasses approximately. Since 60 % of biogas is CH_4, 1 ton molasses releases 255 m^3 of CH_4.
1 m^3 CH_4 = 34,384 kJ → 255 m^3 CH_4 = 8,767,920 kJ
1 kJ = 2.78×10^{-4} kWh → 8,767,920 kJ = 2,440 kWh

One hectare land gives 4 ton sugar beet and 160 kg molasses comes out as by-product. Thus, one ton molasses requires 6.25 ha. 2,440 kWh energy requires 6.25 ha, and then 0.0026 ha is required per kWh. Hence, $LU_{mol} = 0.0026$ ha/kWh.

19.5.1.20 Land Use of Biogas 2 (LU_{man})

The farm with 90 cattle comprise 36 ha land for biogas production (Biogas plant "Bioterm d.o.o." 2008). By proportion, it is seen that 0.4 ha is required per one cattle. Since one cattle provides 4.63 and 4.63 kWh of energy requires 0.4, 0.0864 ha is required per kWh. Hence, $LU_{man} = 0.0864$ ha/kWh.

19.5.1.21 Budget for Investment Cost

Investment cost generally consists of building, machinery, equipment, land etc. The maximum budget for the investment is assumed as nearly 12,000,000 € (Redubar 2009).

19.5.1.22 Investment Cost Rate of Biodiesel (IC_{can})

Investment cost is $245 per mt of annual capacity of biodiesel production (Kiss et al. 2010). Since the density of biodiesel is 0.88 kg/L (Oil yields and characteristics n.d.) and one mega ton means 10^6 kg, $0.000216 per L. After the conversion of Dollar into Euro, the unit investment cost is obtained as 0.0001642 €/L. Hence, $IC_{can} = 0.0001642$ €/L.

19.5.1.23 Investment Cost Rate of Biogas 1 (IC_{mol})

Investment cost of biogas produced from molasses is 5.14 INR/kWh (DNV 2012). After the conversion of Indian rupee into Euro, the unit investment cost is obtained as 0.07 €/kWh. Hence, $IC_{mol} = 0.07$ €/kWh.

19.5.1.24 Investment Cost Rate of Biogas 2 (IC_{man})

Investment cost of biogas produced from manure takes different values changing in 0.65 and 1.39 €/kWh (Gebrezgabher et al. 2010). In this study, an average value of 1.02 €/kWh is used as the unit investment cost. Hence, $IC_{man} = 1.02$ €/kWh.

19.5.2 Scenario Analysis

For the application of the PSO algorithm, the generation of random solutions involves 4 variables: the amount of biodiesel produced, the amount of biogas 1 produced, the amount of biogas 2 produced, and the arable landfill. The infertile land use is calculated via the constraints. Algorithm parameters are 100 as the swarm size, 0.9 as the inertia coefficient, 1.5 as the cognitive coefficient, and 2.5 as the social coefficient. The algorithm is stopped when any new non-dominated solution have not been added to the external archive for 20 iterations.

The PSO application has produced 2,456 feasible and pareto optimal solutions for 9 scenarios, which contains the combinations of 2 parameters that the employment rate of biogas2 and operation cost rate, which are held at 3 different levels: low, average, and high. The low levels of values are assigned by the lowest number or rate that are found through the related literature or interviews as well as the highest number or rate. The average rate is taken as the median of the lowest and the highest values. These scenarios are selected to observe the sensitivity of the biogas and biodiesel production as well as the changes in the objective values.

The excessive number of non-dominated solutions provided by the PSO algorithm necessitates a further method for analyzing and comprehending the effects of the scenarios in terms of sensitivities. In this study, the efficient fronts are attempted to be examined with a clustering approach. SOM is used for clustering and the results are validated with the C Index.

In order to find the optimal cluster numbers, first, a hierarchical approach is applied and a dendogram is obtained. Observations on the dendogram has yielded that the optimum number of clusters was between 19 and 25. Hence, using SOMs all number of clusters from 19 to 25 were evaluated. The square-type structures have been tried for different number of clusters. In order to determine the best cluster structure, the trials have been validated with C index. For a better clustering, the C Index requires to have lower values. The C Index values relative to the number of clusters are provided in the Table 19.2. It can be observed from the table that the best number of clusters is 21, with a 7 × 3 structure. The average values for each character of the clusters are given in Tables 19.3 and 19.4.

19.5.3 Results

According to the clustering results in Tables 19.4 and 19.5, the range of production are [59,710, 789,340] with a mean of 331,668 L for biodiesel, [1,863,364, 36,266,758] with a mean of 19.6 million kWh for biogas 1, and [202,374, 10,105,668] with a mean of 2,849,768 kWh for biogas 2. In most of the scenarios, biogas 1 is preferred over biogas 2 due to its employment rate coefficient despite its relatively high operation cost.

The sensitivity analysis based on the clustering results also offer that very low values of employment rate of biogas 2 has very little effect on the outcome, and is absorbed during the clustering phase by other scenarios where employment rate is assigned relatively low values. Similar results are obtained in cases where operation cost of biogas 1 is low. Low values do not have a significant result-altering effect and these values are absorbed by very low values of clustering.

If the employment rate of biogas 2 production is closer to its lower limits and operation cost of biogas 1 is at its average levels, different levels of production favor different objectives. For favoring the employment objective, the production amount of biodiesel should be at around 450,000 L, the production amount of biogas 1 should be at around 23 million kWh, and the production amount of biogas 2 should be at around 275,000 kWh. Compared to other scenarios, these results offer an average amount of production for biodiesel, a moderately high amount for biogas 1 but a very low value for biogas 2. Yet, for this scenario, this option aggravates the operation and implementation cost objective of the problem and does not offer a compromise solution. In order to favor the operation cost and land use objectives, the production amount of biodiesel should be at around 450,000 L, the production amount of biogas 1 should be at around 10 million kWh, and the production amount of biogas 2 should be at around 9 million kWh. Compared to other scenarios, these results offer a moderately high amount of production for biodiesel, a moderately low amount for biogas 1 but a very high value for biogas 2.

Table 19.3 C index values

Number of clusters	Topologic structure	C index value
25	5 × 5	0.3456
24	6 × 4	0.3338
23	23 × 1	0.3215
22	11 × 2	0.2984
21	7 × 3	0.2940
20	5 × 4	0.3249
19	19 × 1	0.3203

Table 19.4 Average values for each objective functions of the clusters

Cluster	Employment	CO_2 emission	Operation cost	Infertile land use	Employment_ manure	Operation_cost_ molasses
1	121,939.13	1,927,077,885.79	531,464,506.89	841,272.59	0.0067	171.97
2	115,121.76	2,449,013,855.25	321,555,906.01	828,456.82	0.0079	143.07
3	257,407.74	2,568,286,199.43	1,100,348,587.10	765,784.24	0.0079	106.83
4	235,861.96	2,223,550,358.91	1,852,819,963.70	385,352.26	0.0073	174.63
5	438,226.02	3,360,596,534.01	3,444,782,032.58	662,301.16	0.0075	169.66
6	247,179.44	3,443,493,509.02	1,537,301,033.51	763,012.36	0.0055	142.85
7	221,158.73	1,852,828,473.78	2,044,622,857.57	51,099.17	0.0074	174.62
8	289,342.13	2,758,983,399.84	2,553,332,093.37	63,644.44	0.0067	165.90
9	273,825.69	2,991,447,808.91	2,070,593,022.51	67,943.99	0.0058	141.98
10	350,349.17	2,108,567,770.86	3,188,810,235.33	59,701.36	0.0075	170.46
11	449,322.50	2,565,237,254.45	4,177,673,423.67	75,407.88	0.0064	175.05
12	444,173.48	3,173,136,212.93	3,431,275,568.57	70,129.72	0.0058	144.97
13	505,428.87	2,880,951,179.93	4,553,006,969.87	100,107.17	0.0077	170.26
14	580,853.02	3,051,193,735.30	4,942,389,901.71	89,654.86	0.0071	157.57
15	668,138.32	3,495,714,969.47	5,796,383,297.30	147,437.02	0.0059	163.95
16	308,903.55	2,503,103,119.69	2,294,791,948.57	74,263.02	0.0080	141.35
17	594,147.81	3,179,997,605.51	4,390,293,024.96	126,283.72	0.0080	141.35
18	655,240.10	3,446,867,781.04	4,862,283,079.04	106,752.04	0.0065	140.97
19	275,554.17	2,272,694,852.79	1,503,096,407.07	92,241.66	0.0078	104.70
20	523,480.74	2,941,597,849.63	2,837,028,637.94	173,571.66	0.0079	104.70
21	694,931.16	3,668,344,397.54	3,803,346,793.89	154,631.17	0.0073	104.70

Table 19.5 Average values for each decision variables of the clusters

Cluster	Biodiesel	Biogas 1	Biogas 2	Arable land use	Employment_ manure	Operation_cost_ molasses
1	346,450.43	2,835,661.04	10,105,668.66	39,658.81	0.0067	171.97
2	646,478.55	1,863,364.02	10,070,596.13	40,773.25	0.0079	143.07
3	387,730.44	9,820,769.66	8,990,608.70	37,018.36	0.0079	106.83
4	360,329.05	10,346,954.00	5,379,138.49	41,894.55	0.0073	174.63
5	367,627.71	20,042,622.12	7,568,179.20	40,101.02	0.0075	169.66
6	789,340.52	10,429,042.71	8,900,084.41	34,047.64	0.0055	142.85
7	358,190.78	11,532,426.80	269,050,95	2,574.58	0.0074	174.62
8	621,145.51	14,954,920.66	712,426.79	18,129.19	0.0067	165.90
9	768,873.91	14,158,738.58	753,879.63	41,876.28	0.0058	141.98
10	171,425.48	18,351,233.01	215,318.58	3,015.65	0.0075	170.46
11	153,693.60	23,577,772.98	202,374.76	3,569.78	0.0064	175.05
12	459,310.68	23,285,701.47	275,454.40	17,251.06	0.0058	144.97
13	153,186.09	26,215,336.44	920,969.79	16,589.27	0.0077	170.26
14	71,502.92	30,476,676.03	228,975.69	7,234.18	0.0071	157.57
15	59,710.34	34,935,304.42	731,553.30	6,674.89	0.0059	163.95
16	454,741.45	16,016,319.04	563,271.72	4,003.90	0.0080	141.35
17	92,001.98	31,011,473.96	614,017.02	7,511.08	0.0080	141.35
18	82,161.78	34,396,106.93	261,278.68	5,354.03	0.0065	140.97
19	412,253.59	14,083,570.47	988,397.76	5,929.59	0.0078	104.70
20	128,907.22	27,000,550.45	1,308,887.00	8,831.20	0.0079	104.70
21	79,975.64	36,266,758.16	785,008.53	7,586.15	0.0073	104.70

As a result, for lower values of biodiesel employment rate and average biogas 1 operation cost rate, if the intended objective is employment, the production is accumulated over biogas 1. If the model is intended to opt for operation cost and land use, the production is shifted to biogas 2 from biogas 1. For decreasing CO_2 emission, the production amount of biodiesel from canola should be at around 750,000 L, the production amount of biogas from molasses should be at around 14 million kWh, and the production amount of biogas from manure should be at around 750,000 kWh. Compared to other scenarios, these results offer a very high amount of production for biodiesel, a moderately low amount for biogas 1, and a low value for biogas 2. Hence, this objective favors the production of biodiesel. The trade-offs between the objective functions also indicate that the biogas 1 production is more price-sensitive than biogas 2.

In cases of employment rate of biogas 2 being between its lower limit and average (around 0.006) and operation cost of biogas from molasses being high, the only solution obtained produces a relatively high employment rate (around 670,000 workers), yet with the highest operation and implementation cost. The solution involves the production of biodiesel being very low, around 60,000 L and production of biogas 2 being very low at around 750,000 kWh but very high levels of biogas 1 (around 35 million kWh). The CO_2 emission in this scenario is either the same or slightly higher than other scenarios. The results have not changed significantly when both employment rate of biogas 2 and operation cost of biogas 1 are at their average values. In these two scenarios, the operation cost objective is observed to be more volatile than the changes in the employment objective, that is, a small improvement on the employment objective leads to a large setback in the operation cost objective. However, a small improvement on the operation cost objective yields a very small setback in the employment objective. When the operation cost of biogas 1 is increased slightly higher than its average value, the model no longer encourages the production 1 and tends to increase the value of the production of biodiesel from canola which results in an increase in the CO_2 emission and decrease in employment.

If the employment rate of biogas 2 is between its lower limit and average (around 0.006) and operation cost of biogas 1 is very high, the model offers two options in terms of favoring different objective functions. For employment, the production amount of biodiesel should be at around 150,000 L (relatively moderately low compared to other scenarios), the production amount of biogas 1 should be moderately high at around 23 million kWh, and the production amount of biogas 2 should be at around 200,000 kWh. The other option favors the CO_2 emission, operation cost, and land use objectives. According to this option, the production amount of biodiesel from canola should be at around 350,000 L (an average value compared to other scenarios), the production amount of biogas 1 should be at around 2 million kWh (very low compared to other scenarios), and the production amount of biogas 2 should be at around 10 million kWh which is one of the highest values for biogas 2 production.

In cases of slightly higher levels of employment rate of biogas 2 production from canola and high operation costs of producing biogas from molasses, the model favors one option. The production amount of biodiesel from canola should be at around 70,000 L (relatively very low compared to other scenarios), the production amount of biogas from molasses should be at around 30 million kWh, and the production amount of biogas from manure should be at around 230,000 kWh. This yields a slightly high value of employment, CO_2 emission and operation cost, and a very low level of land usage.

In case of relatively high employment rate of biogas 2 production from canola and very low levels of operation costs of producing biogas 1, the model favors one option. The production amount of biodiesel should be very low at around 80,000 L, the production amount of biogas 1 should be very high at around 36 million kWh and the production amount of biogas 2 should be moderately low at around 780,000 kWh. This yields a very high value of employment and CO_2 emission; a high value of operation cost, and a low-to-average level of land usage.

In case of relatively high employment rate of biogas 2 production and very high levels of operation costs of producing biogas from molasses, the model favors four options. For favoring employment and land use objectives, the production amount of biodiesel should be at an average value at around 370,000 L, the production amount of biogas 1 should be slightly high at around 20 million kWh, and the production amount of biogas 2 should be high at around 7.5 million kWh. On the other hand, for favoring the CO_2 emission objective, the production amount of biodiesel should be at an average value at around 360,000 L, the production amount of biogas 1 should be moderately low at around 11 million kWh, and the production amount of biogas 2 should be very low at around 270,000 kWh. For favoring the operation cost objective, the production amount of biodiesel should be at an average value at around 360,000 L, the production amount of biogas 1 should be moderately low at around 10 million kWh, and the production amount of biogas 2 should be moderately high at around 5.4 million kWh. Yet, this scenario offers another compromise solution for all objective functions which determines the amount of biodiesel production as moderately low at around 170,000 L, the amount of biogas 1 production as average at around 18 million, and the amount of biogas 2 production as very low at around 215,000 kWh. In this scenario, an important remark involves that the biodiesel production is almost table at a moderately low level regardless of the objective function.

If the employment rate of biogas 2 is closer to its upper limits and operation cost of biogas 1 is closer to its lower limits, three production options are available. In order to favor the employment objective, the production amount of biodiesel should be moderately low at around 130,000 L, the production amount of biogas 1 should be high at around 27 million kWh, and the production amount of biogas 2 should be moderately low high at around 1.3 million kWh. In order to favor the operation cost and land use objectives, the production amount of biodiesel should be slightly high at around 390,000 L, the production amount of biogas 1 should be moderately low at around 10 million kWh, and the production amount of biogas 2 should be very high at around 10 million kWh. Lastly, for favoring the CO_2 emission objective, the production amount of biodiesel should be moderately high at around 412,000 L, the production amount of biogas 1 should be slightly low at around 14 million kWh, and the production amount of biogas 2 should be moderately low at around 1 million kWh.

When the employment rate of biogas 2 is held almost constant at its upper limit and the operation cost of biogas 1 are increased to its average values, three options are available. In favor of the employment objective, the production amount of biodiesel should be low at around 92,000 L, the production amount of biogas 1 should be high at around 31 million kWh, and the production amount of biogas 2 should be low high at around 650,000 kWh. The other three objectives are optimized by producing biodiesel at a high level at around 650,000 L, biogas 1 at very low levels at around 1.8 million kWh, and biogas 2 at very high levels at around 10 million kWh. There is also a compromise solution that produces biodiesel at a slightly high level at around 450,000, biogas 1 at slightly low level at around 16 million kWh, and biogas 2 at a slightly low level at around 560,000 kWh. The most important remark of this scenario involves that the second option minimizes the operation cost at more than 85 % of its nearest opponent in this scenario.

When both the employment rate of biogas 2 and operation cost rate of biogas 1 are very high, one option is provided. The production amount of biodiesel should be low at around 150,000 L, the production amount of biogas 1 should be high at around 26 million kWh, and the production amount of biogas 2 should be moderately low at around 920,000 kWh. This yields a slightly high value of employment and operation cost, an average value of CO_2 emission and a very low level of land usage.

19.6 Conclusions and Further Studies

Biomass is an alternative and renewable energy source with production amount depending on the geographical and socioeconomic conditions. The geographical conditions limit the feedstock, which can be easily constrained in a decision model. Conversely, the uncertainties of socioeconomic parameters avert easy investment decisions. Additionally, production of biodiesel and biogas have socioeconomic and environmental effects such as employment generation, implementation costs, gas emissions, and land use, resulting in a dependency on strategic and environmental limitations. The efficient front can only be computed with the analysis for each individual case.

In this study, PSO algorithm is used for generating efficient front for the biodiesel and biogas for 9 scenarios that are combinations of two changing parameters: employment rate for biodiesel and operation cost rate for biogas obtained from molasses. Since the PSO algorithm has produced more than 2,400 non-dominating solutions, in order to make the solution sets and efficient fronts more comprehensible, SOMs are applied to the solutions. The optimum number of clusters is determined as 21 and the clustering results are determined by the C Index.

The obtained results show that the most volatile parameter state of the proposed model is the employment rate of biogas 2 being high, that is, when the employment rate of biogas 2 is high, a small change in other parameters cause big changes in the objective values. Besides, the operation cost rate of the biogas obtained from molasses is only effective when there are significant changes in the cost. The clustered solutions highlight different production schemes that can be applied under each scenario with the efficient alternatives.

Further studies may involve addition of other objectives and constraints. More scenarios can be created by considering uncertainties in all the parameters. More advanced clustering analyses leading to different scenarios can be performed with a variety of indices for further comprehension of the behavior of the decision schemes relative to the changes in other parameters. These analyses could utilize and compare other conventional or novel clustering methods.

In this study, for a given scenario, the favorable option depends on the decision makers' choice on the objective to be optimized. On the other hand, for a compromise solution, methods such as Goal Programming can further be applied.

This study brings a new vision in the biomass energy field by introducing models on scenario analysis of uncertain parameters. The proposed model can be used both by the researchers and the investors in the field.

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Index

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