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Renewable Energies

Business Outlook 2050

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Preface

This book presents the main advances in renewable energy sources and looks into the Business Outlook of the sector until 2050. Each chapter discusses the key issues expected to influence renewable energy in the forthcoming years. This book integrates analytic principles with business practice in the renewable energy sector. It provides an interface between the main disciplines of economic/engineering/technology and the organisational, administrative and planning abilities of management applied in renewable energy. It is complementary to other subdisciplines such as economics, financial management, marketing, decision-making and risk analysis.

This book is intended for wide use among engineers, economists, strategists, managers, researchers and scientists conducting research or working on renewable energy-related disciplines. The authors of this book describe their original work in the area or provide material for case studies successfully applying engineering management in case studies.

This work provides a comprehensive overview of current renewable energy technologies and their basic principles. It also addresses the financial aspects of renewable energy projects and analyses their profitability, covering the most relevant topics for engineers, economists, managers and scientists who are actively involved in renewable energy research and management. The authors are researchers and professionals active in renewable energy, supplementing the main content with revealing case studies and best-practice examples.

Renewable energy is essential for the world economy and the current and future generations' welfare, contributing in a balanced way to the attainment of the general goal of energy security and environmental protection. However, there are also different technical, economic, societal and financial challenges and limitations for the deployment of renewable energy sources, distribution and consumption which need to be addressed. In order to understand and overcome these challenges and barriers in further promoting renewable energy growth, it is important to model, analyse and assess the cost-effectiveness and societal and environmental impact of various renewable energy solutions systemically. Chapter "Multiple Criteria Performance Modelling and Impact Assessment of Renewable Energy Systems—A

Literature Review" aims to review relevant performance modelling, impact assessment and decision analysis techniques for renewable energy systems.

Chapter "Towards Energy Self-sufficiency in Large Metropolitan Areas: Business Opportunities on Renewable Electricity in Madrid" introduces the paradigm of the large metropolitan areas that are generally associated with high energy demand but low energy production, thus acting as vast energy drains. Reducing energy import levels in this type of region may bring about relevant business opportunities. Given the increasingly significant role of green (low-carbon) energy in current and future energy policies, these opportunities are expected to be closely linked to renewable energy. In this chapter, the energy system model of the region of Madrid (Spain) is used to evaluate novel energy scenarios to 2050 based on alternative electricity import levels. As indigenous electricity supply increases, wider market horizons arise for renewable energy technologies as a plausible option. Overall, through the case study of Madrid, it is shown that the path towards clean energy self-sufficiency has the potential to act as an effective catalyst for business opportunities on renewables in large metropolitan areas.

Chapter "How Do Energy Engineers of the Future Think. Analysis of Master Students' Proposals" considers the projects on renewable energy developed by postgraduate students, as it is significant to know the vision of the new generation of energy engineers. These projects can be used as a source of creativity and innovation. The projects of 168 international students pursuing EIT KIC InnoEnergy masters, more specifically M.Sc. RENE and M.Sc. SELECT, were analysed. The students were gathered in 25 teams and worked on projects and challenges following their own ideas. The students' proposals were listed and classified according to technologies, degree of radical innovation, complexity, scope, TRL and agents that would develop the solutions. The typical proposal is based on solar energy, involves several elements, has, at least initially, a limited scope, uses commercially available technology and is adapted to the case in all other respects. This vision seems to be very promising to spread renewable energy solutions.

Concentrated solar power (CSP) systems use the thermal energy coming from the sun in the form of solar radiation for generating electricity. This renewable energy source will require the use of new technologies in the future to expand further. Chapter "Concentrated Solar Power: Present and Future" describes the main characteristics of CSP systems, their technical issues and maintenance management. The solar thermal industry employs different CSP plant types based on parabolic trough, linear Fresnel, solar towers, dish Stirling and solar chimney technologies. Each of these technologies is analysed compared with the others. The operational expenditure (OPEX) costs of CSP must be reduced further in order to increase its competitiveness in comparison with other power generation sources and increase market penetration prospects. The chapter also presents the main maintenance management approaches, including inspection strategies for ensuring structural integrity during operation.

Big Data is becoming the most powerful tool to analyse the huge amount of data that the condition monitoring and SCADA systems currently collect. Cloud processing is among the benefits offered by Big Data, allowing analysis of data in real time from different parts of the world. The technological advances in mass data processing can be exploited to treat information from thousands of sensors. Chapter "Concentrated Solar Plants Management: Big Data and Neural Network" presents a new approach for optimal condition monitoring and control of CSP Plants spread over different geographical locations. The information from condition monitoring sensors and data for the optimal control of the plants need a cloud platform for joint analysis with forecast data (meteorological, demand of other plants, etc.). The main processing tool used is based on neural networks, responsible for correlating the obtained signals in real time, to determine anomalous results and generate alarms.

Chapter "Wind Energy Power Prospective" deals with wind energy and wind farm operation and maintenance. Wind farms, in contrast to the conventional power plants, are exposed to variable weather conditions. As a result of these variations, wind turbines are subjected to high variable mechanical loads, which require a high level of maintenance to provide cost-effective power production and ensure uninterrupted operation throughout the intended design lifetime. The demand for wind energy has been rising at an exponential rate in recent years, due to the reduction in operating and maintenance costs, as well as increasing reliability of industrial wind turbine models. Wind turbine operators employ condition monitoring systems that collect information regarding the actual condition of the main components of the turbine, enabling maintenance crews to determine anomalous operating situations in time to intervene and correct faults.

Weather conditions have a key role in the amount of energy produced by wind farms. Ice can appear in regions with cold conditions or during winter season. Ice on blades reduces the efficiency of the turbines, increases failures and downtime, causing imbalance of the rotor and resulting in power generation losses and hence reduced profitability. This makes necessary the research and development of new methods for detection, prevention and removal of ice from blades. Chapter "Managing Costs and Review for Icing Problems" presents the current state of the art in dealing with blade icing, including some techniques and methods of detection, anti-icing and de-icing. Finally, an economicotechnic study concerning commercial ice detection systems is carried out.

Chapter "Big Data and Wind Turbines Maintenance Management" focuses on the analysis of the Big Data associated with wind farm maintenance. An analysis of the data collected by Condition Monitoring and Supervisory Control and Data Acquisition Systems is carried out. This analysis is done using two methods whose objectives are to reduce the amount of data and, therefore, to facilitate the data processing. Two case studies are presented in order to clarify how these methods should be applied.

The Icelandic society is conveniently located where the Eurasian and North-American tectonic plates meet. This allows for relatively easy and cheap access to geothermal energy. Icelanders have benefited from this since settlement, first through direct use of the warm water but later on by co-producing electricity. The nation also benefits from large glacial rivers, offering potential for energy harvesting. Chapter "Societal and Environmental Impact of High Energy Return on Investment (EROI) Energy Access" explores the benefits of renewable energy in this region, using Iceland as a case study. It is demonstrated by exploring the energy return on investment (EROI) for the Nesjavellir geothermal and Fljotsdalsstod hydropower plant and the CO_2 mitigation provided by the resources as the Icelandic society no longer needs to rely on fossil fuels for electricity and heating. This chapter demonstrates systematically how societies may benefit ecologically but also energetically from access to renewable energy sources.

Chapter "Future Maintenance Management in Renewable Energies" describes the future of maintenance management in renewable energy industry. The importance of non-destructive testing (NDT) is highlighted. NDT involves the use of a variety of inspection techniques for detecting internal or surface discontinuities in structures, or determining certain properties of materials. The results of NDT processes contribute to the improvement of quality, public safety and prevention of faults. Effective NDT approaches can help reduce the corrective/preventive maintenance requirements of a renewable energy plant as well as increase the operational lifetime of certain components.

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About the Editors

Prof. Fausto Pedro García Márquez obtained his European Doctorate in 2004 at the University of Castilla-La Mancha (UCLM, Spain) with a maximum distinction. He has distinguee with the Runner Prize (2015), Advancement Prize (2013) and Silver Prize (2012) by the International Society of ManagementScience and Engineering Management, or the Advancement Prize in the Third International Conference on Management Science and Engineering Management. He is working at UCLM as senior lecturer (with tenure, accredited as full professor), Spain, Honorary Senior Research Fellow at Birmingham University, UK, lecturer at the Postgraduate European Institute, and he was senior manager in Accenture (2013–2014). Fausto has managed a great number of 253 projects: 5 Europeans as principal investigator (PI), 4 FP7 framework programme and 1 Euroliga+4, being researcher in 3 FP7; he is PI in 2 national projects, and he has participated in 2 as PI and 2 as researcher; 4 regional projects, 1 as PI and 3 as researcher; 3 university projects, 1 as PI and 2 as researcher; and more than 100 with research institutes and industrial companies (98% as director). He has been evaluator in different programs, nationals and internationals. As a result of the research work, he has published more than 150 papers (65% in ISI journals, 30% in JCR journals and 92% internationals), being the main author of 68 publications. Some of these papers have been especially recognised, e.g. by "Renewable Energy" (as "Best Paper Award 2014"); "International Society of Management Science and Engineering Management" (as "excellent"), and by the "International Journal of Automation and Computing" and “IMechE Part F: Journal of Rail and Rapid Transit” (most downloaded). He is the author of 18 books (Elsevier, Springer, Pearson, Mc-GrawHill, Intech, IGI, Marcombo, AlfaOmega, etc), and he is the author of 5 patents. He is the associate editor of the International Journals: Engineering Management Research, Open Journal of Safety Science and Technology, and International Journal of Engineering and Technologies, and he has participated as Committee Member in more than 25 International Conferences and the Director of Ingenium Research Group (www.uclm.es/profesorado/fausto).

Dr. Alexander Karyotakis after graduating in Mechanical Engineering and completing a Ph.D. on the optimisation of offshore wind farm O&M strategies and reliability of wind turbines at University College London (UCL) has been working as a coordinator and business developer on renewable energy projects, while involved as a technical consultant in several international research and development programs in renewables including NIMO, Optimus and SolarFox, having published highly cited journal and conference papers in renewables.

In 2010, he joined TERNA ENERGY (Member of GEK-TERNA Group), where he got involved and coordinated the development, engineering, construction and operation of large onshore wind projects in Europe and the USA, while supervising the first-stage technical design and conceptual development of several offshore wind farms (conventional and floating) in southern Europe.

Dr. Mayorkinos Papaelias (Ph.D. in Metallurgy, Chartered Engineer—Greece) is a senior lecturer in NDT and Condition Monitoring at the School of Metallurgy and Materials at the University of Birmingham. Dr. Papaelias is an expert in NDT and condition monitoring technology. He has been involved as technical coordinator or scientific consultant in several FP6 and FP7 collaborative research projects. He is the author or co-author of more than 70 journal and conference papers in NDT and condition monitoring. He is also a member of the International Society for Condition Monitoring. Dr. Papaelias regularly authors articles for industrial magazines.

Multiple Criteria Performance Modelling and Impact Assessment of Renewable Energy Systems—A Literature Review

Ting Wu, Dong-Ling Xu and Jian-Bo Yang

Renewable energy is essential for the world economy and the current and future generations' welfare, and it contributes in a balanced way to attain the general goal of energy security and environmental protection. However, there are also challenges and barriers to the deployment of renewable energy generation, distribution and consumption, including technical, economic, cultural and financial challenges. In order to understand and overcome the challenges and barriers of promoting the growth of renewable energy, it is important to model, analyse and assess the cost-effectiveness, and societal and environmental impact of various renewable energy solutions systemically. This chapter aims to review relevant performance modelling, impact assessment and decision analysis techniques for renewable energy systems.

1 Introduction

In 2003, the energy white paper released by the British government sets a target of carbon emissions reduced to 60% of 1990 levels by 2050. At the same time, current resources are forecast to be limited in the coming years with apparent destructive consequence to the environment [4]. In order to achieve the objective and solve the energy shortage problem in long term, renewable energy alternatives are widely selected to replace the conventional sources and there is an increase to use electricity which is generated from renewable energy, such as small hydro, solar power, wind power, biomass, biogas, geothermal power, etc. [43]. The major advantages of renewable energy include little pollution and emission, unlimited supply, better energy structure and security. However, relatively low efficiency, high costs for

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power generation and research and development, scattered energy sources and energy acquisition difficulty become the disadvantages of green energy, which hamper their deployment [27, 45].

Therefore, how to evaluate the performance and impact of different sources of renewable energy is a key problem in energy policy making and involves different factors. In order to stride over the challenges and barriers and to support making informed and insightful decisions, there is a great necessity to model and assess the performance, cost-effectiveness, societal and environmental impact of alternative renewable energy system systemically. Renewable energy decision-making problems cannot be analysed by traditional single criteria decision-making approach. It needs to handle various complex issues of current and future energy systems and can be considered as a multiple criteria decision-making problem with correlating criteria.

The next section will introduce the recent development in renewable energy and its related policies. The third section will review criteria, techniques and models for impact assessment of renewable energy systems. The fourth section will focus on the applications of impact assessment of renewable energy systems in policy making. The chapter is concluded in the fifth section.

2 Policy Making Related to Renewable Energy Systems

The development of renewable energy can potentially tackle the climate change, prevent serious environmental pollution and slow down the exhaustion of fossil fuel reserve problem [45, 55]. REN21 report [63] provided an overview on the global renewable energy market and industry across both developed and developing countries. In Europe, the use of renewable energy is seen as a key element in energy policy. Directive 2009/28/EC was issued to promote the use of energy from renewable sources and it established criteria accounting for the 2020 targets on renewable energy sources. As a result, it is observed in the past decade that the use of renewable energy sources has increased significantly. For example, Fig. 1 shows the continuing increase on the share of energy from renewable sources for electricity, and the renewable energy sources account for 27.5% of European energy generation in 2014 [27]. In China, RE100 [62] analysis showed that the government and also private sectors increased investment to renewable energy in 2015 by 32% from the previous year, and a series of policies and regulations were put into effect to encourage domestic renewable energy deployment.

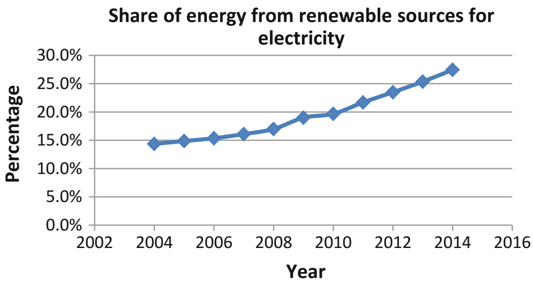

Fig. 1 Share of renewable energy sources for electricity (*Data source* [27])

There are different forms of renewable energy, as complements to traditional energy resources (e.g., oil, coal and natural gas) and nuclear power. The mainstream forms of renewable energy are very briefly introduced below in order to further review relevant criteria, techniques and models for their performance modelling and impact assessment.

(1) Hydropower

Hydropower is derived from the energy or force of fast moving water, and it is regarded as the most flexible and consistent of renewable energy resources. There are different ways of harnessing the waterpower, and hydroelectricity is the most widely used form of renewable energy. According to the key world energy statistics by the international energy agency [35], hydroelectricity contributes 20% of global electricity generation in 2013. However, it is extremely expensive to construct dams for hydropower, which must be operated for decades to be profitable. The natural environment could be changed dramatically from the flooding of large areas of land.

(2) Wind power

Wind power is extracted from airflows, through which wind turbines are run to produce mechanical or electrical power. Wind turbines have been widely installed to offshore and high altitude areas globally where winds are usually strong and constant. Wind power produces an increasing percentage of the global electricity. The wind energy technology is relatively mature and advanced compared with other renewable energy technologies [21], but it also requires a large-scale land use to build wind farms, and noises and visual effect are also obstacles for the wide installation of windmills.

(3) Solar power

A range of ever-evolving technologies have been used to gather solar energy in the forms of radiant light and heat from the sun. Different technologies, such as solar heating, photovoltaics, concentrated solar power (CSP) and solar architecture [34], can be used to capture and convert solar energy in a either active or passive way. However, solar energy is dispersed unevenly around the world and there is no solar energy at night, which makes energy collection discontinuous and unstable, especially with the seasonal and weather effects [55].

(4) Biomass

Biomass uses biological materials usually derived from plants or plant-derived materials. As an alternative renewable energy source, biomass can be used in two different forms: direct combustion to produce heat or indirect conversion to various forms of biofuel, such as methane gas and biodiesel. There is potentially side pollution from the waste processing of biomass energy.

Apart from the mainstream renewable energy sources, there are also some other sources of renewable energy, such as geothermal energy and ocean energy. There are advantages and disadvantages of harvesting each type of renewable energy.

Instead of taking a close look at the various forms of renewable energy, this chapter is mainly concerned with criteria, techniques and models for impact assessment of renewable energy systems, in particular, renewable or decentralised green energy (DGE) systems. In contrast to centralised energy systems, a decentralised energy system relies to a large extent on small-scale and sometimes intermittent generation from the above renewable energy sources [23]. Developing decentralized energy systems can increase the use of renewable energy, so as to reduce carbon emissions, improve energy efficiency, explore new energy generation capacity and improve the security of generation supply [3, 23, 20]. Furthermore, decentralised green energy systems are regarded to be central to the world's future energy and economic strategies. However, there are also barriers and challenges to deploy decentralised renewable energy systems. In addition, the development of the systems is also dependent on national energy legislation and policies. For example, small-scale DGE systems may not as competitive as centralised energy systems without financial subsidies or support. In order to support the decision making process, the performance, cost-effectiveness, social and environmental impact of alternative DGE solutions are reviewed systematically in Sect. 3.

3 Criteria, Techniques and Models for Impact Assessment of DGE Systems

Many researchers have developed a spectrum of different criteria, techniques and models for impact assessment of renewable energy systems [22, 28, 39]. For example, Evans et al. [28] assessed renewable energy technologies in the context of sustainability. The critical sustainability indicators include price of generated electricity, greenhouse gas emission, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts, and they are assumed to have equal importance. The most sustainable energy was ranked as wind power, hydropower and photovoltaics. Elliott [22] looked at the institutional and social obstacles to the development and deployment of renewable energy in the context of sustainable development. Painuly [57] emphasized the importance of providing energy with sustainability to the vast populations in developing countries, and also pointed out the barriers to renewable energy penetration.

3.1 Criteria of Impact Assessment

In the context of impact assessment of renewable energy systems, multiple criteria can be identified and weighted in order to provide a structured way to produce informative assessment results. Multiple criteria performance modelling and impact assessment can provide in-depth understanding of key advantages and inherent impact, and facilitate an informed decision making process. Papadopoulos and

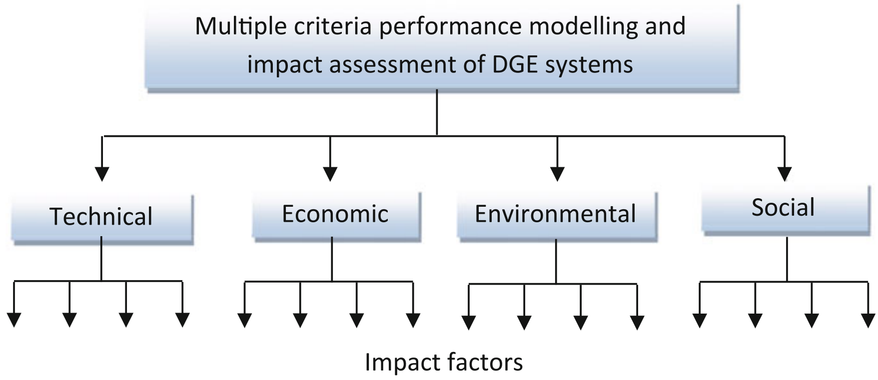

Fig. 2 Multiple criteria performance modelling and impact assessment of DGE systems

Karagiannidis [58] discussed that the implementation of decentralised energy systems has to adopt an interdisciplinary comprehensive approach which analyses technical, financial, environmental and social factors. Wang et al. [69] summarised the criteria of assessing energy supply systems from technical, economic, environmental and social aspects. Similarly, in this chapter, the multiple criteria performance modelling and impact assessment of renewable energy systems can be formulated in a hierarchical structure of having technical, economic, environmental and social categories, as illustrated in Fig. 2.

(1) Technical

The fundamental criterion for performance modelling and impact assessment of renewable energy systems should be attributed to technical feasibility and effectiveness. Thermodynamics can be used to assess how effective and efficient a renewable energy system works. A range of technical factors should be considered, including technical efficiency, safety and reliability.

Efficiency refers to how much useful energy can be produced from raw energy sources [69]. It is one of the most widely used technical criteria to evaluate renewable energy systems, and can be measured by the ratio of output to input energy in a quantitative way [1, 19, 44, 48, 60].

Safety of renewable energy systems is vital to local residents and community. Safety-related issue can be assessed by the fatality rate and the likelihood of occurrence in the context of risk analysis [47, 48, 68, 69].

Reliability is concerned with the capacity of renewable energy systems to perform as designed, and it is also among the essential technical criteria [14, 69].

In addition, some other technical factors, such as technical maturity and availability, should also be considered [13]. To some extent, the degree of maturity also decides how wide the technology can be adopted and its safety level [69].

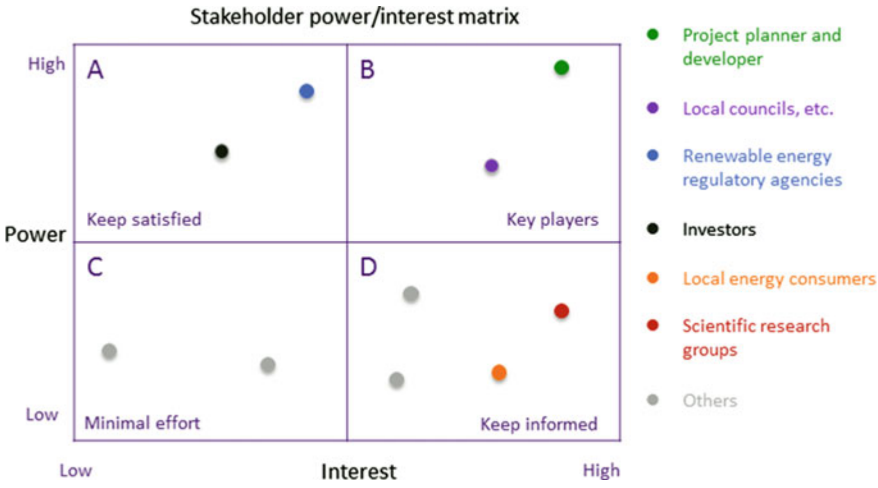

Fig. 3 Stakeholder analysis for environmental impact assessment

(2) Environmental

The environmental impact can be assessed by the formal environmental impact assessment (EIA) method according to the EIA Directives [25, 26, 42]. In the context of conducting a systematic EIA, the stakeholder mapping approach [51] can usually be used to categorise the key stakeholders in terms of their interests and power on expressing environmental concerns, as illustrated in Fig. 3.

In the context of environmental impact, typical factors, such as emissions, land use, noises [31, 46, 69], exposure to electromagnetic field and visual impact, should be considered for each type of renewable energy systems [42, 69].

(3) Economic

The affordability and accessibility of renewable energy systems should also be considered in order to maintain economic well-being and opportunities. Initial investment, construction time, operation and maintenance costs, payback time and cycle of service life should be taken into consideration in the economic category [2, 19, 38, 69].

(4) Social

The implementation and use of renewable energy involves every aspect of human participation and activities, and it plays a significant role in shaping the society. For example, launching a renewable energy system requires technicians and creates managerial job positions as well. Social acceptance and benefit should be considered in the introduction of new technologies [14, 52, 69, 73].

It is important that factors are identified to assess the performance and impact of various renewable energy systems in a consistent and systematic way. Furthermore, the relative importance of each category and its impact factors need to be taken into account. For example, the technical feasibility may be among the most important considerations.

3.2 Techniques for Impact Assessment

Menegaki [50] categorised the green energy valuation methods into five main categories, namely revealed preferences techniques, stated preference techniques, portfolio analysis, emergy analysis and various other economic but not welfare-based oriented methods. Conjoint analysis and contingent valuation techniques were adopted to evaluate wind farms and other renewable energy sources [7, 30, 54]. Bergmann et al. [8] applied choice experiments to evaluate renewable energy investments. Yu et al. [72] modelled and valuated the flexibilities on switching tariff for wind energy. Mathematical programming methods were also employed to deal with the optimality and uncertainty of performance assessment and decision analysis. Soroudi et al. [66] used a long-term multiple objective planning model to analyse the pollution emissions and costs. Cai et al. [12] presented an interval chance-constrained programming model to optimise both systematic reliability and cost. Generally, the techniques for impact assessment can be categorised into (1) Quantitative assessment: it refers to the way of quantifying the impact of renewable energy on some of the above criteria. However, it is difficult to quantify some impact factors, especially, some social and environmental impact factors. (2) Qualitative analysis: it is applicable to clarify different features in the formats of descriptive or subjective grades. With the use of both quantitative assessment and qualitative analysis, relationships among impact criteria and their combined impact can be analysed and evaluated in a comprehensive way.

3.3 Models for Impact Assessment

(1) Life cycle assessment

As an ISO standard assessment method, life cycle assessment (LCA) can be implemented to assess the impact of DGE systems [36]. Bhat et al. [9] discussed that LCA can be implemented to assess the impacts of green energy from various aspects, such as pollution, raw material supply and recycle. Ardente et al. [5] argued that LCA is appropriate for the environmental impact assessment of green energy applications. However, LCA-based assessment is only capable of providing a comprehensive assessment of one green energy system at one time [9].

(2) Multiple criteria decision analysis

As discussed in Sect. 3.1, the performance modelling ad impact assessment of renewable energy systems can be formulated as a multiple criteria decision analysis

(MCDA) problem. MCDA can be used to perform multi-criteria performance modelling and impact assessment of alternative renewable energy solutions, where no single attribute can capture and measure the overall [70]. Thus, MCDA models have widely applied to perform energy-related environmental studies [75], sustainable energy planning [61], renewable energy comparison [49], assessment of traditional and renewable energy power plants [15], evaluation of residential heating solutions [11], etc.

Furthermore, Myllyviita et al. [53] discussed that the utilization of multiple criteria decision analysis can incorporate new perspectives into traditional LCA in the context of environmental impact assessment of biomass production chains. Dong et al. [18] pointed out that both LCA and MCDA can be introduced into impact assessment for different kinds of green energy applications.

Among the advances of MCDA models, it worth emphasising that the evidential reasoning (ER) approach has been developed as a generic evidence-based MCDA approach for aggregating both qualitative and quantitative information as well as dealing with various types of uncertainty, including ignorance and randomness [70]. Under a unified belief structure, both quantitative and qualitative criteria can be formulated to a belief decision matrix for further aggregation and analysis. In addition, the weights and reliabilities of assessment information collected from multiple sources can also be taken into account in the generalised ER rule [71].

4 Applications of Impact Assessment of Renewable Energy Systems in Policy Making

4.1 Overview of MCDA Method

Yang [70] stated that MCDA can be used to perform multi-attribute performance assessment among alternatives, where there is no single attribute measuring the overall performance. The development of MCDA helps the comparison in a group of choices under uncertain environment. Also, the evidential reasoning (ER) approach can be used to model and aggregate the decision maker's preference logically into the assessment. Dong et al. [18] points out that both LCA and MCDA can be introduced into assessment, so that the three aspects of energy, environment and economy can be judged together for different types of green energy applications.

The normalized model of MCDA problem is,

$$\max_{A \epsilon A_r} F(A)$$

Here, A is an alternative approach (i.e., decision variable) and it belongs to a set of alternatives $A_r = \{A_1, A_2, \ldots, A_m\}$, in which every element is a controlled variable and has to satisfy certain constraint conditions. $F(A)$ is an attribute vector function $F(A) = [f_1(A), f_2(A), \ldots, f_n(A)]^T$, where $f_j(A)(j = 1, 2, \ldots, n)$ is the attribute value of A approach under the attributes $(C_1, C_2, \ldots, C_n)$. An MCDA problem can also be expressed by a matrix $D = (f_{ij})_{m \times n}$, where f_{ij} is the evaluation value of approach A_i under the j_{th} attribute, $i \in I = \{1, 2, \ldots, m\}$ is the set of alternative indicators, and $j \in J = \{1, 2, \ldots, n\}$ is the set of attribute indicators. The value of f_{ij} can be either quantitative or qualitative (such as good, bad, high, low). Therefore, the row vector $f_i = (f_{i1}, f_{i2}, \ldots, f_{in})$ is the value of approach A_i under every attribute, the column vector $f_j = \left(f_{1j}, f_{2j}, \ldots, f_{mj}\right)$ is the value of every approach on the j_{th} attribute.

Generally speaking, the aim of MCDA is to find the best alternative or rank all alternatives. Since the performance of every alternative is different under different attributes, there is no absolutely best alternative. A preferred structure should be determined by decision makers according to their preferences and decision objectives to comprehensively assess the performance of every alternative under every attribute. The MCDA methodologies have been successfully applied in many real-life problems in engineering, finances, market analysis, management and others. Decision is usually made under uncertain conditions from available alternatives. That is, these alternatives should be compared, ranked or chosen. However, with the development of economy, technology and society, the MCDA problems have become more and more complex. Zhou et al. [75] discussed multiple criteria energy-related environmental studies since 1995. Pohekar and Ramachandran [61] reviewed the applications of multi-criteria decision making to sustainable energy planning. Mendoza and Prabhu [49] used MCDA to compare renewable energy with conventional resources. Chatzimouratidis and Pilavachi [15] applied MCDA to assess different power plants which use both traditional and renewable energy. Browne et al. [11] introduced MCDA to evaluate six types of residential heating solutions and domestic electricity consumption in an Irish city region.

In literature, the typical MCDA methods can be categorised to the following three categories.

(1) The methods based on utility function model. The multi-attribute utility theory is used to give three methods for MCDA problems. In the first approach, the weights are no longer constant but depend on the attribute-values, in the second method, the weights are determined by considering their sensitivity; in the third method, the multiplication of weights and attribute-values are considered as a whole to construct a solution to multi-attribute decision making problems with incomplete information. Relevant approaches in this category include simple weighted average (SWA), weighted product (WP), analytical hierarchy process (AHP) and some other planning methods. SWA is one of the simplest and most popular methods for MCDA problem. The weight of every criterion is determined by actual conditions, and the decision matrix is processed by normalization, then we can get the fusion value of every approach by linear weighted average, and finally, the best approach will be selected according to the order of fusion values. AHP was proposed by T. L. Saaty in 1970s which integrates both quantitative analysis and qualitative analysis. It requires to clearly analyse the essence of the problem, factors and internal relationship. After the identification of these factors and internal relationship of complex decision problems, AHP

divided the alternative approaches into different key elements and classified them to different hierarchies, then formed the multi-hierarchy structure. On every hierarchy, the key elements can be compared one by one according to a special rules and guidelines and built a judgement matrix. The next step is calculating the maximum eigen-value and corresponding eigen-vector, and then getting the weights of the key elements under the rules of this hierarchy, and finally calculating the combined weights of the key elements of every hierarchy for all alternative approaches.

(2) The methods based on outranking relational model, such as ELECTRE [6, 65] and PROMETHEE [10]. ELECTRE method mainly includes two steps. One is building the outranking relation, and the other is ordering all alternative approaches according to the relation. PROMETHEE method uses preference function to discriminate the superiority-inferiority of every approach under a criterion. It starts by normalising the data, so it does not need the pre-procession for original data and avoids the dependence on processing order.

(3) The method based on rough set theory [59]. In this approach, some rules are extracted from the past decision examples by utilizing rough set theory, and then form a warehouse of rules. Finally these rules are used for analysing MCDA problems.

In addition, the evidential reasoning approach has been developed to be a generic evidence-based MCDA approach for dealing with various types of uncertainty, including ignorance and randomness. Simply speaking, it uses a consistent belief structure to represent both quantitative and qualitative criteria, a belief decision matrix to formulate an MCDA problem under uncertainty, and the evidential reasoning algorithm to aggregate multiple criteria to generate the overall distributed assessment. The recently developed evidential reasoning rule further provides a rigorous way of combining multiple pieces of independent evidence conjunctively with weights and reliabilities [70, 71].

In general, MCDA based on additive utility functions consists of four basic steps for making the most effective and rational decisions: (1) Problem structuring, including criteria selection and alternative formation. (2) Display trade-off between criteria and confirm criterion weights. (3) Utilize value judgement on acceptable trade-offs and evaluation. (4) Aggregate information and make the decision [61].

4.2 Multi-criteria Decision Analysis in Renewable Energy Planning and Policy

There are four categories of MCDA application area in renewable energy: renewable energy planning and policy making, renewable energy evaluation and assessment, renewable energy project selection, and environmental impaction assessment [64]. We focus on the first area that refers to the assessment of a feasible energy plan and/or the diffusion of alternative renewable energy option. There are four key factors in this area: adoption to reach a certain national target, decision factors, national planning, and system indicators.

Usually, we focused only on cost minimization when choosing among alternative energy sources. However, it is widely recognized now that energy planning is a much more complicated decision problem involved many factors. Pohekar and Ramachandran [61] have published several papers with a review and analysis on MCDA and its applications on the renewable energy. Wang et al. [69] presented a literature review on sustainable energy decision-making and discussed the applicability of MCDA methods under the multi-dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems. Beccali et al. [6] utilized the ELECTRE method and fuzzy set theory in regional energy problems by analysing actor's reaction and results. Both methods were applied to the development of a renewable energy diffusion strategic plan and described advantages and disadvantages of each methodology. Georgopoulou et al. [29] utilized ELECTRE III to reach a compromise in the choice among alternative energy policies. They defined a set of sustainability indicators and elements that were used in the analysis and assessment of the relationship between an energy system and its environment, and determined the weight of each criterion of each alternative and presented the effect of the priority.

Diakoulaki et al. [17] used MCDA to explore the relative contribution of different factors and characteristics of expected level of energy efficiency and further exploited them in energy policy making. Kowalski et al. [40] had a research on participatory multi-criteria analysis (PMCA) to analyse energy policy making corresponding to public and stakeholder inputs. Lee et al. [43] utilized the fuzzy theory and AHP to determine criteria when they applied MCDA in national energy policy making and analysed the competitiveness of Korea.

Hobbs and Horn [32] used different MCDA methods to develop a set of recommendations in energy planning and policy making through group discussions and interview processes among stakeholders. They concluded that no single method is the best and a reasonable solution is to apply a combination of two or more MCDA methods. Enzensberger et al. [24] considered that all of stakeholder groups are important in the criteria evaluation process and they can help policy makers to anticipate possible problems at an early stage. Afgan and Carvalho [1] presented a process of multi-criteria evaluation of energy systems and compared the hydro power plant option with other renewable energy power plant options. Köne and Büke [41] conducted a multi-criteria analysis using an analytical network process (ANP) to decide the best alternative technology for electricity generation in Turkey. Topcu and Ulengin [67] developed a multi-attribute decision-making tool and supplied an integrated decision aid framework for the selection of the most suitable electricity generation alternative in Turkey. Önüt et al. [56] also utilized ANP to evaluate alternative energy resources for the manufacturing industry in Turkey.

Hamalainen and Karjalainen [33] utilized AHP and value trees to analyse the relative weights of the evaluation criteria of Finland's energy policies. Kablan [37] utilized AHP framework to manage the prioritization process of different energy conservation policies in Jordan. Cristóbal [16] applied a compromise ranking method, also known as the VIKOR method, to the assessment of several renewable energy alternatives to help the Spanish government to reach the target of 12% total renewable energy in 2010. Zhao et al. [74] utilized an AHP model to evaluate alternative power technology according to the criteria of environmental cost and energy security and applied it to a real case study for planning the best choice of power plant in Guangdong province of China.

5 Summary Remarks

In general, the assessment of performances of different renewable energy system is considered as a complex multi-dimensional problem which mainly involves four categories of criteria, namely technical, environmental, economic and social criteria. MCDA frameworks can be used to incorporate objectives other than costs in the decision making process of renewable energy selection and planning, along with their traditional benefit-cost analysis. However, different MCDA methods may provide different solutions even applied to the same problem and the same data, and usually it is difficult to determine which one is the best solution. It may be necessary to study how to choose an appropriate MCDA methodology in alternative energy decision-making. Further research may also be needed to study the optimality of different renewable energy systems when a specific region is under consideration.

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Towards Energy Self-sufficiency in Large Metropolitan Areas: Business Opportunities on Renewable Electricity in Madrid

Diego García-Gusano, Diego Iribarren and Javier Dufour

Abstract Large metropolitan areas are generally associated with high energy demand but low energy production, thus acting as vast energy drains. Reducing energy import levels in this type of region may bring about relevant business opportunities. Given the increasingly significant role of green (low-carbon) energy in current and future energy policies, these opportunities are expected to be closely linked to renewable energy. In this chapter, the energy system model of the region of Madrid (Spain) is used to evaluate novel energy scenarios to 2050 based on alternative electricity import levels. As indigenous electricity supply increases, wider market horizons arise for renewable energy technologies as a plausible option. Overall, through the case study of Madrid, it is shown that the path towards clean energy self-sufficiency has the potential to act as an effective catalyst for business opportunities on renewables in large metropolitan areas.

Keywords Electricity import · Energy systems modelling · Metropolitan area
Power generation · Scenario analysis

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1 Introduction

In contrast to energy-related concerns such as climate change and its environmental, social and economic consequences, other relevant energy issues are often placed on the back burner when energy systems are assessed. That is the case of power self-sufficiency in large metropolitan areas. Globally, urban areas account for 67–76% of energy use and 71–76% of CO_2 emissions from final energy use [1], as well as for high emissions of other pollutants such as sulphur oxides, nitrogen oxides and particulates, all of them causing harmful effects on both humans and ecosystems. Moreover, large cities deal with a critical issue: the origin of the energy they use. In this regard, the present chapter explores in depth key aspects associated with the electricity needs of large metropolitan areas, using Madrid (Spain) as an illustrative case study.

Large cities and the metropolitan areas associated with them generally act as huge energy drains since they consume energy but they do not produce it. All forms of energy fuels and carriers come from neighbouring regions and/or countries (or even further). To face this situation, the corresponding governments develop plans to boost the penetration of renewable technologies as well as to support mitigation measures on the demand side, especially in those sectors where the problems are more marked: transport, residential, and services. Nevertheless, political efforts promoting local power generation are not succeeding in bridging the gap concerning the enormous electricity demand in highly-populated areas. As a result, power self-sufficiency rates are still very low while no new leapfrog policies are expected in the coming years.

Within this context, this work uses the case study of the region of Madrid to evaluate the problem of electricity self-supply in large metropolitan areas, focusing on the identification of business opportunities regarding renewable energy technologies. The installation of this type of technology would reduce the dependence of metropolitan areas on electricity coming from external regions while increasing the efficiency of the electrical system by reducing transmission losses. Furthermore, a solid wager in this direction would mean significant benefits in terms of socio-economic development and welfare.

2 The Energy Model of Madrid

The Community of Madrid (i.e., the region of Madrid) is an 8,030 km^2 region in the centre of Spain. It had 6.45 million inhabitants in 2014, with the capital (Madrid City) accounting for 3.3 million inhabitants. More than 85% of the Madrid inhabitants live in a circle of 25 km radius from Madrid City [2].

The Community of Madrid is one of the most important Spanish regions. Madrid has the highest gross domestic product (GDP) *per capita* in Spain and its service sector represents 77% of the regional economy. The region of Madrid is considered an energy drain because more than 90% of its power demand is satisfied by energy coming from neighbouring regions. Regarding final energy consumption, oil products involve 50–55% of the total consumption, whereas natural gas and electricity involve 20–25% [3].

2.1 The LEAP-Madrid Model

García-Gusano et al. [4] developed the LEAP-Madrid model to represent the energy system of the region of Madrid and discuss long-term future scenarios concerning its evolution in terms of emissions, energy services demands, economic behaviour, technological pathways, etc. This model is in line with others created at the city/region level such as Lazarus et al. [5] for Seattle in the USA and Ahanchian et al. [6] for the Metro Manila metropolitan area in the Philippines. Some adjustments in power capacities and generation have been performed between 2010 (the reference year) and 2014 (last year with full data). The simplified structure of the LEAP-Madrid model is shown in Fig. 1.

LEAP [7] is an accounting framework that operates under the simulation mode unless the optimisation procedure is activated—based on the OSeMOSYS model [8]. In this chapter, the results are obtained by running simulations with 2050 as the modelling horizon.

The main socio-economic drivers assumed are presented in Table 1 according to information retrieved from IE [9] and INE [10]. A conservative constant GDP growth of 2% *per annum* is assumed based on the knowledge of the historical GDP rates of the region of Madrid, usually higher than 3% (on average) except in periods

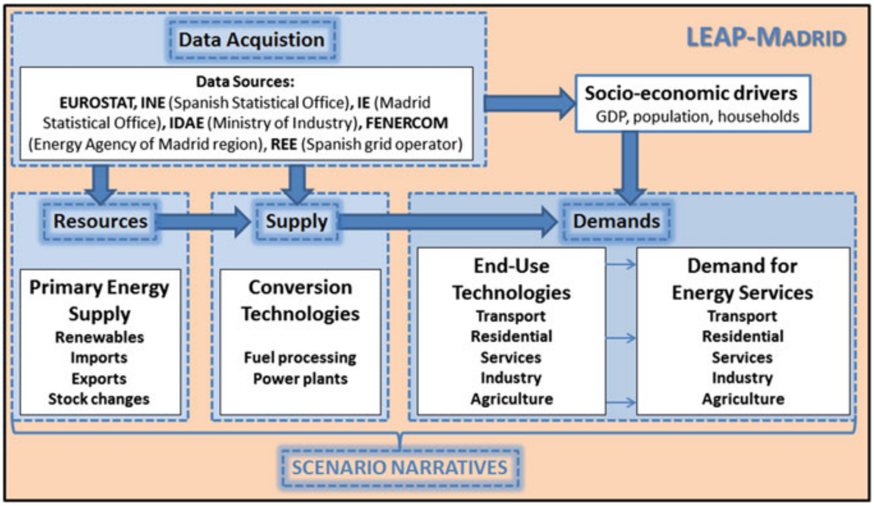

Fig. 1 Conceptual scheme of the LEAP model of the region of Madrid

Table 1 Main socio-economic drivers in the LEAP-Madrid energy model

Driver	Units	Value 2010	Assumption
GDP	Million €	187,393	+2% annual from 2015–2050
Population	Million inhabitants	6.459	6.562 (2029); +0% from 2030–2050
Households	households	2,499,704	2,815,704 (2029); +0.84% annual from 2030–2050

Table 2 Efficiencies (%) of existing and new electricity production technologies in the LEAP-Madrid energy model

Technology	Existing	New (2050)
MSW incineration	23	42
Cogeneration	42	63
Hydropower	80	90
Solar, PV	15	30
Solar, CSP	–	36

of economic shrinkage, e.g. 2008–2012. Population and household growths are based on exogenous models referred to in García-Gusano et al. [4].

Regarding the tree structure designed in LEAP-Madrid, there are branches for the main demand sectors such as transport, residential, services, industry and agriculture. Additionally, the supply side is defined for the transmission system (natural gas and electricity) and the power generation sector.

As an energy drain, the region of Madrid is not characterised by a varied portfolio of existing power supply options. According to regional statistics [9], there were four types of technology feeding electricity to the grid in 2014: incineration plants burning mainly municipal solid waste (MSW), cogeneration (combined heat and power, CHP) plants burning mainly natural gas, hydropower plants (mainly reservoirs from 100 kW to 10 MW), and small solar photovoltaic (PV) systems (1–10 kW). These technologies are listed in Table 2.

Table 2 also shows the evolution of the efficiency of the different technological options (assumed as future installations) by 2050 based on Carlsson [11]. Besides, a 250 MW concentrated solar power (CSP) plant based on parabolic troughs is included for further discussion in Sect. 3.4.

2.2 Scenario Narratives

According to the Energy Agency of Madrid [3], the electricity imported in the region of Madrid meant 2,366 ktoe in 2010 and 2,305 ktoe in 2015. In this chapter, the LEAP-Madrid energy model is used to evaluate novel energy scenarios to 2050 based on alternative considerations about future electricity import levels. Table 3

Table 3 Alternative electricity import scenarios implemented in LEAP-Madrid

Code	Scenario	Description
hi-IMP	High electricity import	Beyond 2015, electricity import grows +1.17% *per annum*
c-IMP	Constant electricity import	Beyond 2015, annual electricity import is kept constant (2,305 ktoe), assuming that electricity comes from the grid
lo-IMP	Low electricity import	This scenario pursues 75% self-sufficiency in electricity consumption by 2050. The 2010 electricity mix disaggregation is modified by assuming hydropower and MSW at their maximum potential by 2050 (24 and 232 ktoe, respectively)

presents the description of the three main scenarios implemented in the LEAP-Madrid model with regard to the behaviour of the electricity imports beyond 2015.

The "hi-IMP scenario" depicts a case in which the import of electricity is almost free. In this scenario, an electricity import growth as the historical electricity balance in Madrid from 2000 to 2014, +1.17% on average, is assumed. On the other hand, the "c-IMP scenario" assumes that the electricity import resulting from 2015 (2,305 ktoe) is kept constant until 2050. Finally, the "lo-IMP scenario" sets a goal of 75% rate of self-sufficiency regarding power demand satisfaction by 2050.

Hydropower generation in Madrid satisfies less than 1% of the total electricity demand, with ranges from 12 to 22 ktoe depending on the hydrological year, the power market and operating conditions. Accordingly, the maximum hydropower potential of the region of Madrid is assumed to be 24 ktoe [12].

The MSW incineration potential is assumed to be 232 ktoe according to the calculations detailed by Castejón and Alonso [13]. If exploited, it could meet 10.1% of the electricity needs of the Madrid region (using 2014 as the reference year).

The solar PV technology, which accounts for 4–9 ktoe (2010–2014), is still unimportant and it plays a minor role in the indigenous supply. However, solar PV potential is high in Madrid. Victoria [14] concluded that, taking into account a list of restrictions mostly linked to the availability of roofs, solar PV could generate up to 886 ktoe in the region of Madrid at 15% efficiency. Furthermore, it should be noted that solar CSP technology is considered afterwards in an additional scenario where renewables are intensified (see Sect. 3.4).

Finally, wind power generation is discarded in this study. This is based on several facts: areas with good wind conditions are scarce in the region of Madrid; there are barriers to wind power deployment such as social acceptance and environmental conservation plans; and energy planning policies do not favour the use of micro wind turbines. Nevertheless, according to Gallego [15], wind power generation could reach up to 86 ktoe, assuming a maximum capacity of 500 MW and 2,000 h of annual operation.

3 Identification of Business Opportunities Through Energy Systems Modelling

The government of Madrid City has recently approved an action plan against air pollution and climate change (*City of Madrid Plan for the Sustainable Use of Energy and Climate Change Prevention—Horizon 2020*) with the aim of implementing measures on energy efficiency, greenhouse gas emission reductions and climate change adaptation [16]. In the plan, there is a set of measures concerning renewable energy and cogeneration in buildings and facilities. Among them, there is a specific measure entitled "Initiative 'Madrid Solar' to facilitate projects on solar energy in the residential sector". The description of this measure includes the role of the Madrid government in supporting politically and legally (in terms of cooperation and bureaucracy) the development of power generation from renewable sources, with emphasis on solar PV and the promotion of self-consumption. However, almost nothing has been done in this respect since the plan was approved.

Looking at the long term, the expected growth of the economy and, to some extent, increases in population and number of households—key drivers in Table 1—would lead to a general increase in the energy demand of Madrid. Figure 2 shows the evolution of the electricity demand considering these socio-economic drivers and their evolution along with the specific activities at the sectoral level.

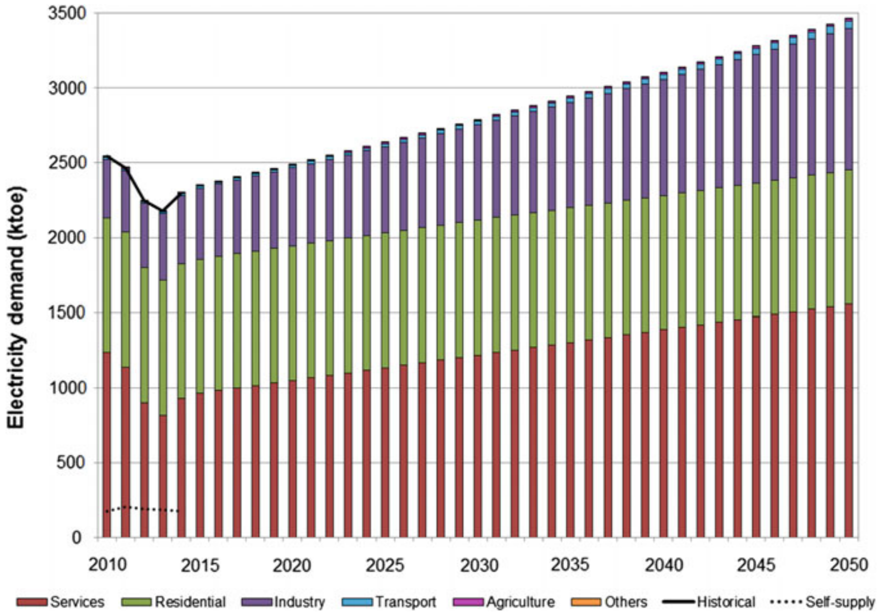

Fig. 2 Electricity demand of the Community of Madrid in the "c-IMP scenario". Historical demand and generation (self-supply) in the period 2010–2014 are both included

Figure 2 shows the evolution of the electricity demand in the Community of Madrid disaggregated by sector. It is significant that, under a business-as-usual type scenario, services is the most consuming sector followed by residential and industry. The contribution of transport to the electricity demand is very low because no future penetration of electric vehicles is assumed herein. The evolution of the electricity demand goes from 2,176 ktoe in 2013 (historical data) to 3,460 ktoe in 2050, i.e. a 59% increase.

In the following sections, business opportunities on renewable electricity in Madrid are identified through energy systems modelling, i.e. using the LEAP-Madrid energy model with alternative scenarios based on different electricity import levels.

3.1 Electricity Production in the "hi-IMP Scenario"

The import of electricity from neighbouring regions poses a significant problem in terms of energy self-sufficiency in large metropolitan areas such as the region of Madrid. Electricity self-production–within the limits of the consuming region–leads to self-government advantages as well as to economic and security improvements.

Regarding country divisions, Spain presents not only a national government ruling the country and a parliament approving laws, but also seventeen regions (called "autonomous communities") with a significant capacity to design regional laws, manage budgets and perform regional policies and plans. Within this context, the Spanish electricity grid is operated by *Red Eléctrica de España* (REE), a public-private company founded on a trans-regional approach of solidarity between regions. In this way, there are no preferences and/or vetoes due to regional/political disagreements. However, the regional nature of the plans designed to face climate change, avoid emissions, increase energy efficiency, boost economy, etc. makes necessary to strengthen electricity self-supply in the autonomous communities, especially in regions acting as energy sinks (i.e., regions such as Madrid).

The "hi-IMP scenario" is designed to discuss the situation faced by Madrid due to high electricity dependence. Figure 3 shows the evolution of electricity production when a year-on-year 1.17% growth of the electricity import is assumed beyond 2015, based on historical electricity balances of Madrid. It can be observed that, under a high electricity import scenario, electricity production in the Community of Madrid remains approximately at 2010–2015 levels (*ca.* 200 ktoe) for the whole period. This means that electricity self-sufficiency decreases from *ca.* 8% in the initial years to 5% by 2050 due to the increasing electricity demand. Furthermore, Fig. 3 shows the retirement profile of the existing electricity production technologies after their useful life and the penetration of new options (area with vertical arrows in Fig. 3), with a leading contribution from new natural gas cogeneration plants.

In this scenario of high electricity import–moving from 2,305 ktoe in 2015 to 3,463 ktoe in 2050–, business opportunities hardly arise, both generally and

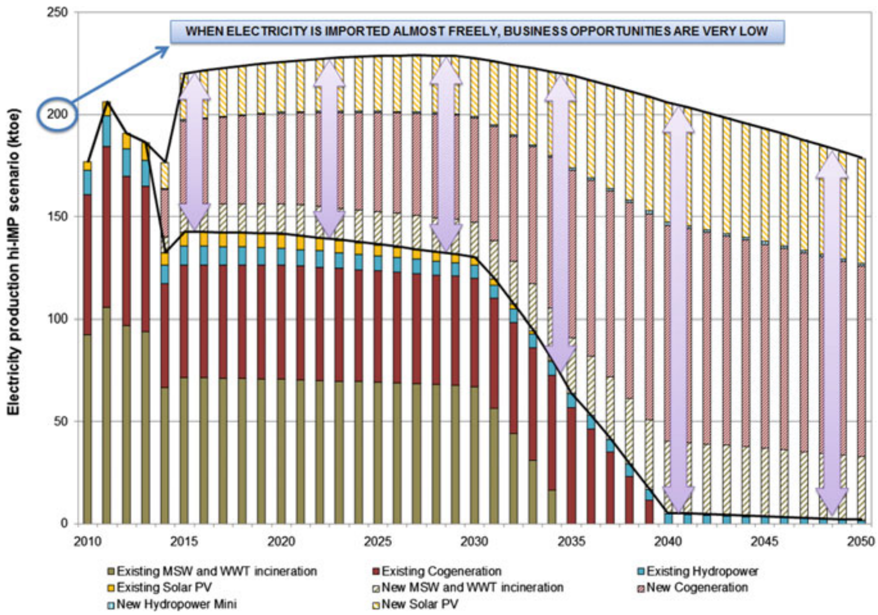

Fig. 3 Electricity production in the Community of Madrid in the "hi-IMP scenario". Low business opportunities are found in the area with *arrows*

specifically to renewables. Hence, in this case, the challenge of reducing electricity imports from neighbouring regions remains as a decisive mid-, long-term goal from an economic viewpoint.

3.2 Electricity Production in the "c-IMP Scenario"

Taking into consideration that Fig. 3 is based on an extreme scenario where the importation of electricity from surrounding regions is practically unlimited, a market niche should appear when pursuing a trade-off between electricity imports and the increasing electricity demand. Accordingly, the "c-IMP scenario" is implemented following a more realistic—even conservative—approach. This scenario keeps the electricity import constant for the entire analysis. Figure 4 shows the evolution of power generation under this scenario.

In Fig. 4, it can be observed that, if electricity imports remain constant, electricity self-production grows significantly, moving from 177 ktoe in 2014 to 1,337 ktoe in 2050. This means that the ratio of electricity self-production to electricity demand in Madrid increases from 8% in 2014 to 38% in 2050. Among the new production technologies (area with vertical arrows in Fig. 4), natural gas cogeneration plants play the leading role, with 695 ktoe in 2050, followed by solar PV options (385 ktoe).

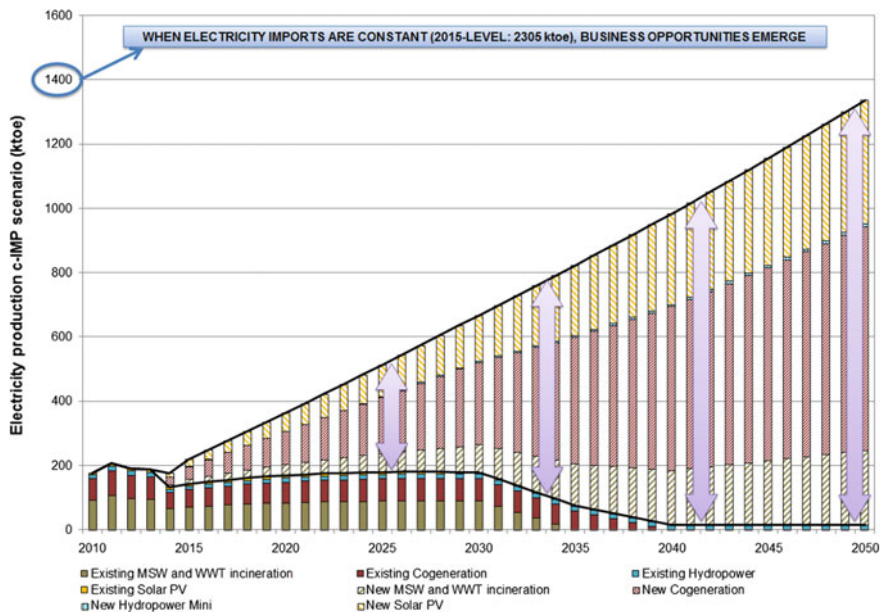

Fig. 4 Electricity production in the Community of Madrid in the "c-IMP scenario". Emerging business opportunities are found in the area with *arrows*

It is seen that forcing the electrical system to not import electricity above current import levels arises as a strategic decision that should be understood by policy-makers in Madrid as a potential mid-term target. This would help mitigate issues related to the security and sustainability of the grid mix (the Spanish mix is still significantly based on nuclear, coal and gas power) while providing interesting opportunities to invest in new (potentially low-carbon) power generation facilities.

3.3 Electricity Production in the "lo-IMP Scenario"

Results from Fig. 4 suggest that the electricity self-sufficiency rate of Madrid could increase up to 38% in 2050 by keeping the current import levels constant, i.e. investing in local electricity production from now on. In this section, a novel scenario of low electricity import—the "lo-IMP scenario"—is implemented to explore a more ambitious target: 75% self-sufficiency in Madrid by 2050. In this case, electricity self-production would reach 2,595 ktoe by 2050, more than ten times the present value. This behaviour is depicted in Fig. 5.

This scenario of low electricity import is designed based on some restrictions. According to the generation potentials described in Sect. 2.2, hydropower and waste incineration potentials are assumed to be exploited completely by 2050. This gives freedom to solar PV and cogeneration when it comes to increasing their

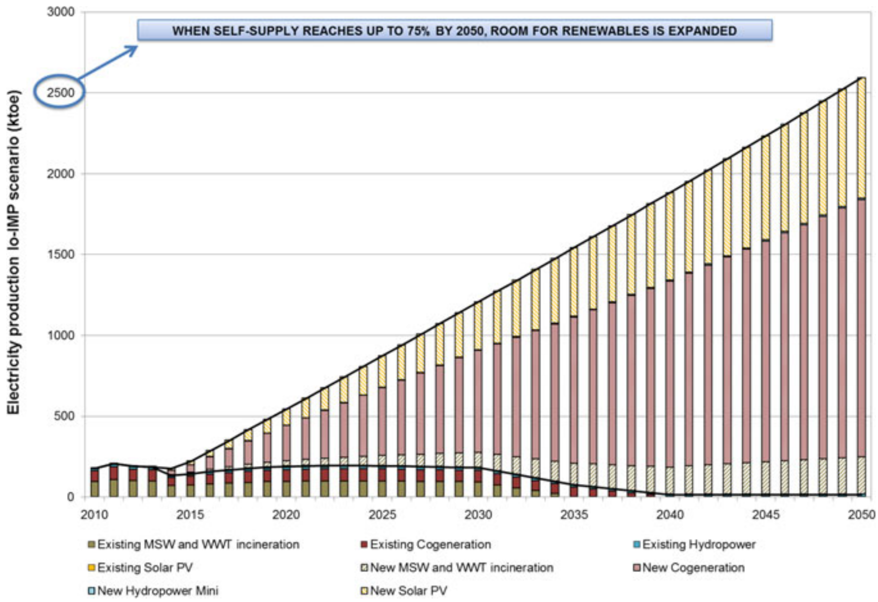

Fig. 5 Electricity production in the Community of Madrid in the "lo-IMP scenario"

contribution to the future mix. Thus, new natural gas cogeneration plants reach 1,591 ktoe in 2050 and new solar PV installations provide 748 ktoe (Fig. 5).

Even though the results from Fig. 5 are good enough to open the door to new business opportunities in the field of renewables, new natural gas cogeneration plants would actually play the leading role in the Madrid mix for several reasons. First, cogeneration plants are mostly associated with industry and, to some extent, tertiary sector applications, which entails lower dispersal and easier management than options such as solar PV. Moreover, efficiencies and knowledge of cogeneration plants are significantly high. Finally, the Spanish system is being progressively "gasified", with a robust natural gas pipeline network. Therefore, in this scenario, the use of natural gas appears as a priority when promoting self-supply despite the fact that the solar potential in Madrid is high and the levelised costs of PV electricity present a promising horizon.

From an environmental perspective, although natural gas facilities generally perform better than other facilities based on different fossil fuels, the penetration of new fossil-based cogeneration plants would cause (among other impacts) significant direct non-biogenic CO_2 emissions. This could create a serious problem if they were prioritised as a self-supply option. Hence, an alternative scenario assuming that solar PV reaches its maximum potential while diminishing cogeneration with natural gas is explored in Sect. 3.4.

3.4 Electricity Production in the "REN Scenario"

As seen in Sects. 3.2 and 3.3, power self-supply in Madrid could generate fruitful business opportunities for new technologies, including renewables. New cogeneration plants could dominate the competition between new technologies because of the benefits currently associated with CHP plants used in industries to retrofit some manufacturing processes. However, this would involve negative effects in terms of sustainability: burning large amounts of natural gas releases large CO_2 emissions, among other pollutants. Accordingly, the "REN scenario" is implemented as an additional case to explore how renewables could contribute to a more suitable electricity self-supply profile. As described in Table 4, the "REN scenario" adopts the same assumptions as the "lo-IMP scenario" but considering a maximal exploitation of the solar PV potential according to Victoria [14].

In contrast to the exclusion of wind power, this scenario also considers a single, large CSP plant to be installed in Madrid given the appropriate solar radiation conditions in this region and taking into account that Spain is at the forefront in CSP deployment. A CSP plant using parabolic troughs with storage (6 h) is considered because it is currently the most common type in Spain and there is enough land in Madrid to build this type of facility. In particular, a 250 MW plant is assumed, based on the one existing in Arizona ("Solana"), which reaches 280 MW and takes up 780 ha [17]. In the case of Madrid, there is a potential restriction that avoids installing more than 50 MW of this technology in a single plant since it is included within the "*special regime*" of technologies [18]. In this exercise, this legal restriction is omitted [19] since this is a long-term assessment and no technical barriers exist.

Figure 6 shows the evolution of the electricity production in Madrid under the "REN scenario". Regarding total electricity self-production, Fig. 6 presents the same performance as Fig. 5, reaching 2,595 ktoe in 2050. However, the enforcement to use more solar PV potential and the 250 MW CSP plant involves an increase in the share of renewables to the detriment of natural gas cogeneration plants. In this respect, the fossil contribution decreases to 48% of the local electricity production in 2050 in the "REN scenario" whereas this share is 61% in the

Table 4 Description of the electricity import scenarios oriented towards emerging business opportunities in the field of renewables

Code	Scenario	Description
lo-IMP	Low electricity import	This scenario pursues 75% self-sufficiency in electricity consumption by 2050. The 2010 electricity mix disaggregation is modified by assuming hydropower and MSW at their maximum potential by 2050 (24 and 232 ktoe, respectively)
REN	Renewable intensification	This scenarios involves the same description as the "lo-IMP scenario" but adding more renewables. The exploitation of solar PV reaches its maximum potential (1,014 ktoe) by 2050. Penetration of solar CSP is assumed, with a single plant (250 MW, 6 h storage) generating up to 51 ktoe by 2050

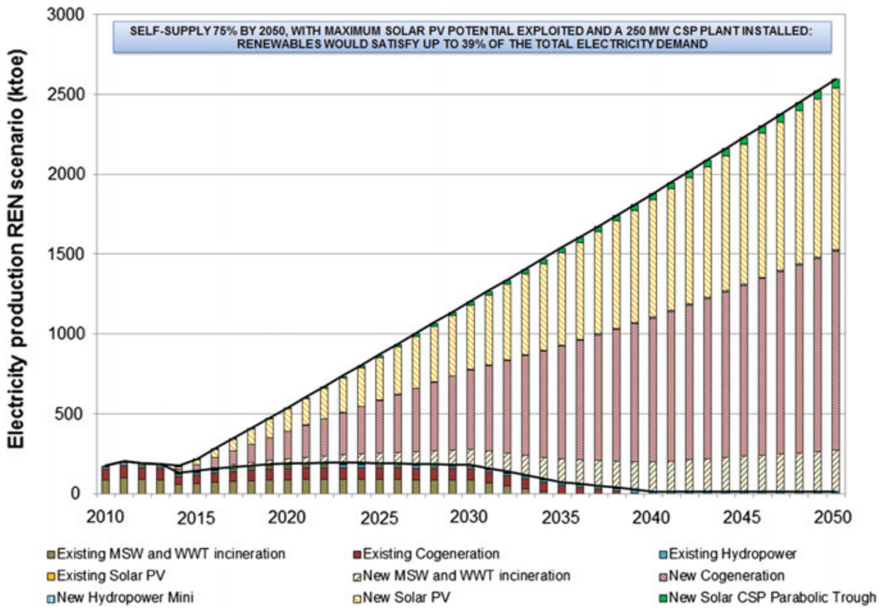

Fig. 6 Electricity production in the Community of Madrid in the "REN scenario"

"lo-IMP scenario". Thus, under a challenging scenario with 75% power self-sufficiency, business opportunities on renewables could mean half of the electricity production. In particular, solar PV could satisfy 39% of the electricity production in Madrid by 2050.

From an environmental standpoint, Fig. 7 further supports the bet on investments in renewable technology to increase electricity self-supply. As discussed above, high contribution of new cogeneration plants would bring about increased CO_2 emissions. In this respect, Fig. 7 shows the comparison of the direct CO_2 emissions resulting from the "lo-IMP" and "REN" scenarios. The partial avoidance of new cogeneration plants in the "REN scenario" would lead to significantly reduce the CO_2 emissions (*ca.* 1 Mt of carbon dioxide by 2050) by strengthening the role of renewables in the electricity self-production profile.

In summary, measures oriented towards electricity self-sufficiency in Madrid should focus on attracting investments in renewable energy technology, mainly solar PV due to its high potential, as well as on raising awareness of the sustainability concerns linked to relying excessively on natural gas cogeneration as the main long-term option.

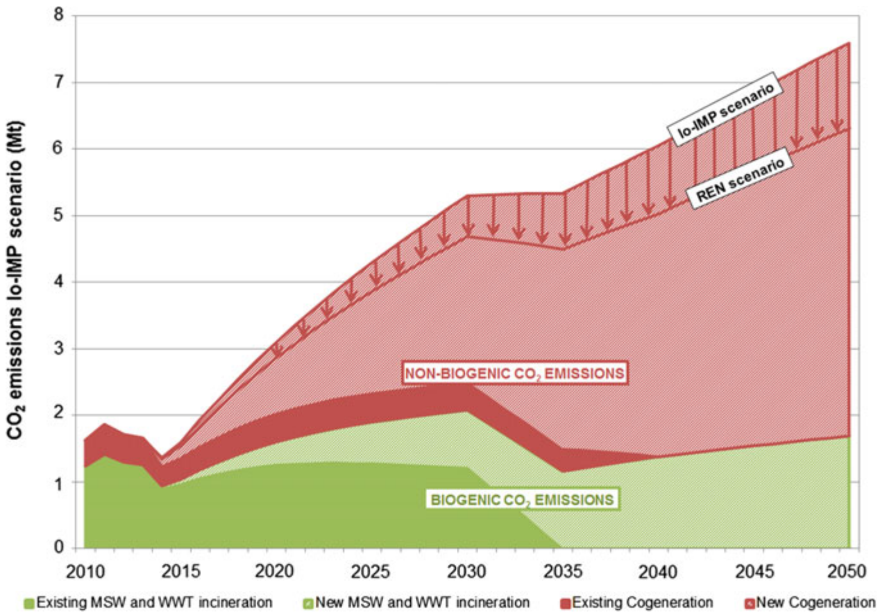

Fig. 7 Direct CO_2 emissions from electricity production in the Community of Madrid: "lo-IMP" versus "REN"

4 Conclusions

This chapter identified business opportunities on power generation technologies by assessing alternative strategies to increase power self-sufficiency in large metropolitan areas, traditionally considered as vast energy drains since they consume electricity but they do not produce it. The region of Madrid was used as an illustrative case study of large metropolitan areas.

Four prospective energy scenarios were explored for the region of Madrid based on alternative electricity import levels from neighbouring regions in Spain. On the one hand, when imports grow almost freely, no business opportunities arise for new power generation technologies. On the other hand, when considering a more convenient scenario in which the electricity imports remain constant from 2015 to 2050, the need for additional power generation emerges, thus opening the door to new investments in power technology in Madrid. In this scenario, new installed technologies could satisfy up to 38% of the electricity demand in 2050. Furthermore, when exploring the consequences of a higher degree of electricity self-sufficiency (75% of the demand satisfaction), new business opportunities were found to be dominated by new natural gas cogeneration plants, accounting for more than 60% of the local electricity production despite environmental concerns such as CO_2 emissions. However, in a final scenario with 75% self-sufficiency and prioritisation of renewable electricity, business opportunities on renewables (mainly solar PV) could mean half of the local electricity production by 2050 as well as significant CO_2 emission reductions.

It is concluded that electricity self-sufficiency in large metropolitan areas involves a crucial challenge that requires high support to renewable energy technology and increased awareness of energy-related sustainability concerns. The progressive achievement of high power self-sufficiency rates in this type of region would result not only in an enhanced environmental performance of regions such as Madrid, but also in a socio-economic enhancement in terms of e.g. job creation as the driving force behind regional development.

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How Do Energy Engineers of the Future Think. Analysis of Master Students' Proposals

Jordi Olivella, Josep Bordonau, Gema Calleja and Enrique Velo

Abstract The future of energy largely depends on the creativity and innovation capacity of energy engineers. Projects on renewable energy developed by master's students can be significant to know the vision of the new generation of energy engineers. The projects of 168 international students pursuing EIT KIC InnoEnergy masters, more specifically MSc RENE and MSc SELECT, were analysed. The students were gathered in 25 teams and worked on projects and challenges following their own ideas. The students' proposals were listed and classified according to technologies, degree of radical innovation, complexity, scope, TRL and agents that would develop the solutions. The typical proposal is based on solar energy, involves several elements, has, at least initially, a limited scope, uses commercially available technology, and is adapted to the case in all other respects. This vision seems to be very promising to spread renewable energy solutions.

1 Introduction

Today's energy engineering students will be major influencers on the future state of the environment. These future leaders are currently being trained and shaped within the world's higher education system, which highlights the relevance of incorporating greener energy-oriented curricula [1, 2]. In this context, we think that analysing the students' proposals to address sustainability challenges is vital to better understand where the environment is heading.

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Among sustainability issues, energy is probably the most important one. The recent study International Energy Outlook 2016 found that, if there are no changes in our current practices, total world consumption of marketed energy in 2040 will be 48% higher than in 2012 [3]. Such ever-increasing demand could place significant pressure on the current energy infrastructure and potentially damage world environmental health, not only because of gas emissions and global warming, but also because of other serious problems such as air pollution, ozone depletion, emission of radioactive particles, deforestation and biodiversity destruction [4]. These problems need to be addressed if we want to pass on a sustainable heritage to future generations. In this context, renewable energy resources are considered to be the best solution to meet future demands while protecting the environment [5, 6].

There is a growing global awareness that increased deployment of renewable energy is essential for mitigating climate change while creating new business opportunities and providing energy access to billions of people still living without modern energy [7, 8]. At the same time, there is a wide recognition of universities raising environmental awareness among students and contributing to the development of society [9, 10]. Over the last few years, some of the most widely renowned universities have created energy-focused programs and sustainability centres to encourage active participation in joint projects with local companies, research institutes and other universities [11].

The Universitat Politècnica de Catalunya (UPC) in Spain offers innovative teaching and learning programs aimed at fostering entrepreneurship among students in the field of renewable energy, namely MSc SELECT (Environomical Pathways for Sustainable Energy Systems) and MSc RENE (Renewable Energy), in the framework of the EIT KIC InnoEnergy partnership.[1] Both programs nurture teaching and learning about engineering, innovation and entrepreneurship towards a future sustainable energy system based on university-business collaboration.

Given the failure of past strategies to prevent environmental degradation, it has been suggested that it is now time to pay attention to the role that entrepreneurs can play to achieve a more sustainable environment [12]. Environmental entrepreneurs, also called ecopreneurs, are increasingly considered as having the innovative potential to encourage start-ups to develop technologies which bring about a transformation to sustainable products and processes [13–15].

The concept of ecopreneurship has been defined as the entrepreneurial action that has an overall positive effect on the natural environment [16]. Ecopreneurship is distinguished from social entrepreneurship, which focuses on making a difference in society and is bounded by context [17]. It is also different from sustainability entrepreneurship, which integrates a triple objective: social, environmental and economic (the so-called "triple bottom line").

Traditionally, most corporate and sustainability literature had focused on how existing companies can become greener and how this affects competitive advantage

[1]EIT is the European Institute of Innovation and Technology. KIC stands for Knowledge and Innovation Community.

[18–20]. However, a survey about pays-to-be-green literature identifies unique opportunities for increasing revenues from sustainability investments [21].

Some authors have explored sustainability from an ecopreneurial perspective. A number of papers apply the Schumpeterian concept of "creative destruction" [22], by which global sustainability pressures allow entrepreneurs to create new, more environmentally sustainable products (see, for example, [15, 19]). However, the risk of the so-called "panacea hypothesis", i.e. the supposition that ecopreneurship is the solution to all environmental problems, has also been highlighted [14, 23].

With regard to student role, the importance of analysing their attitudes is emphasised by the so-called "impressionable years hypothesis", which argues that attitudes, beliefs and values crystallise during adolescence and early adulthood, and that these core orientations are unlikely to change thereafter [24].

Several published studies examine environmental attitudes held by university students [25, 26]. Other papers explore the general association between education and environmental concern [27]. Finally, some studies focus on ecopreneurial education at university [28]. According to the literature, it seems clear that environmental education is essential to develop a positive attitude towards the environment. In turn, ecopreneurship has been recognised as a major conduit for sustainable products and processes and as a panacea for social and environmental problems.

However, there is still little understanding of how energy engineering students (i.e. possible future ecopreneurs) think and where attention should be focused to nurture sustainable entrepreneurship. The objectives of this chapter are to analyse how energy engineering students think when proposing a solution for an environmental challenge and to gain valuable insight into how they perceive renewable energy utilisation.

The rest of the chapter is structured as follows. Section 2 describes the master's programs in sustainable energy where students develop projects combining engineering and entrepreneurship. Section 3 outlines the methodology used to investigate the students' proposals on environmental challenges, and analyses and discusses the results. Finally, Sect. 4 ends with conclusions.

2 Teaching Context

2.1 Master's Degrees Involved

The innovative MSc programs considered in this work are offered by the European Institute of Innovation and Technology (EIT), funded by the EU through KIC InnoEnergy, an alliance of top actors in the European energy sector including companies, research centres, business schools and technical universities. The Universitat Politècnica de Catalunya (UPC) is one of these partners, fully committed to the vision of EIT and KIC InnoEnergy, responsible for the coordination of MSc RENE and very active in MSc SELECT.

EIT's mission, like KIC InnoEnergy's and that of the rest of partners, is the creation of a new generation of so-called "game changers", capable of creating new, sustainable and affordable solutions for the energy challenges of today and tomorrow and of generating a positive socio-economic impact in Europe. These game changers are selected among the best candidates worldwide and are trained in a new spirit.

MSc RENE and MSc SELECT are two-year comprehensive training programs (120 ECTS) encompassing

- Strong technological background in the fields of renewable and sustainable energy
- Training oriented to a specialisation in these fields
- Understanding of the implication of the business side of technological development, including concepts such as market analysis, cost analysis, value proposition, etc.
- Fostering of the entrepreneurship spirit among students

The first three points are relatively conventional in the sense of being related to the transfer of knowledge to students. However, the last one is a real challenge because it does not rely on knowledge transfer entirely but rather on raising student ambition to develop their career from a very different perspective.

The ultimate objective is that students develop their own ideas from all critical points of view: (i) identifying a technological innovation; (ii) looking for funding to develop the idea; (iii) starting a venture to commercialise the idea.

MSc RENE and MSc SELECT have designed activities and experiences to foster the entrepreneurship spirit among students. Thus, their curricula include the development of projects. The projects considered here are RENE Project, RENE Project/EDPR University Challenge and SELECT Project of the Year. Their characteristics are presented below.

2.2 Project Requirements

Projects in educational settings have been classified into three types [29], as can be seen in Table 1. The projects considered in this chapter fall into type 2, where students have the opportunity of defining the problem and the instructor/supervisor manages the learning process. Table 1 shows the specific characteristics of these projects.

Table 1 Types of projects in educational settings (based on [29])

Type		Problem and discipline	Instructor/supervisor
(1)	Case/task-based project	Discipline, problems and methods are decided in advance	The instructor/supervisor plans and controls the projects
(2)	Discipline-based project	Students can choose/define the problem while the discipline and methods are decided in advance	The instructor/supervisor manages the learning process
(3)	Problem-based project	The problem is the point of departure and will guide students towards appropriate disciplines and methods	Students must take responsibility for their own learning and the instructor/supervisor has a less active role

2.2.1 MSc RENE—RENE Project

The "RENE Project" is specially designed for MSc RENE students at UPC and is in the process to be extended to the rest of universities of the consortium (IST, KTH and École Polytechnique). It is integrated into a complete learning activity, the so-called "Engineering and Business Case", which combines a set of training activities with industry experts and in business schools with projects at the technical universities of the consortium. The projects presented in this publication are previous to this integration.

The modern society needs to drastically change its view towards a more sustainable behaviour in a global environment. On the way towards a sustainable energy system, the concept of heat and power generation from renewable energy resources becomes essential. In order to make the most of the concept, many innovations are still required. The UPC RENE Project is about addressing some specific needs/challenges for change by working on technically sound engineering designs, in combination with a thorough business feasibility discussion of the proposed product/service.

The overall objective of the RENE Project is a pre-design and in-depth business feasibility discussion on the innovative energy conversion schemes needed in the respective sub-projects. Proposals made by students at the beginning of the semester aim for a "product or service" that can be brought to the market, and work teams prepare the technical approach and the business feasibility discussion such that a business plan can naturally follow as the "next step". Teams are made up of 3–4 students sharing an interest in a particular challenge.

2.2.2 RENE Project/EDPR University Challenge

The "EDPR University Challenge" is an initiative of EDP Renewables in collaboration with PremiValor Consulting whose mission is to contribute to the development of academic excellence of undergraduate, graduate and master's students. Its aim is to promote interconnection between universities and the business world. Students are challenged (in a yearly contest) to show that they can change the world by putting into practice their knowledge and developing a project in the areas of engineering, strategy and/or marketing in the field of renewable energy.

The projects are carried out by 2–5 student teams (depending on the complexity of the project) and a university supervisor. They are evaluated by an independent jury composed of specialists in the areas covered by the competition, with representatives of faculty and staff of EDP Renewables and PremiValor Consulting. Finally, monetary prizes are awarded for the best projects within several categories.

This experience has been addressed by KIC InnoEnergy students, especially MSc RENE students following the RENE project 1.

2.2.3 MSc SELECT Project of the Year

Teams of 6–10 MSc SELECT students work from different cities on the development of a "Product or Service" that makes a significant impact in the field of sustainable energy for one year. A project manager is chosen among the students in each team. Since the subject area is very broad, i.e. sustainable energy, projects can be proposed on a variety of levels (e.g. from the specificity of small-scale fundamental innovations in the field of heat transfer to comprehensive regional/global system studies) as long as the scale is motivated based on the intended product or service that provides a solution to an identified problem or fulfils the need addressed. The project is supervised by academic advisors and industry experts.

3 Analysis of Projects

3.1 General Approach

A set of MSc RENE and MSc SELECT projects is analysed to characterise the solution proposed by them and, by extension, the way future energy engineers think. The following factors are taken into account:

(a) Technologies. Involved technologies classified according to IPC (International Patent Classification) Classifications for Renewable Energy Generation Technologies [30]. Consideration of an ICT (Information and Communication Technologies) solution is also mentioned.
(b) Degree of radical innovation. This factor is measured by the three-dimensional (business model) innovation scale proposed by Taran et al. [31].The degree of radical innovation can be low, medium or high.

(c) Complexity. The number of elements involved in the proposal are considered indicators of complexity. For example, if two elements, such as a solar panel and an energy storage device, are involved, the level of complexity is 2. When a market is considered it is also mentioned.
(d) Scope. Area to which the proposal refers (local market, specific market or industry).
(e) TRL (Technology Readiness Level). The TRL scale is used to reflect the readiness of the technology proposed [32]. In some cases, no technology is directly involved.
(f) Agent. The agent of the change proposed can be an existing company, a new company, a public initiative developed by a public authority, a social initiative run by an NGO (Non-Governmental Organization) or users themselves.

3.2 Example

An example of one of the projects is presented. The title of the project is "Renewable desalination plants in Sal Island of Cabo Verde", within the RENE Project/EDPR University Challenge. A short summary of the project is also given in the general list of projects as project number 4, Table 3.

Water and Energy are the two most important aspects of life as they ensure not only survival but also human population growth for a much better future. With the world moving towards sustainability in order to preserve the planet, it is imperative to shift the focus towards renewable resources to meet these two basic needs. Local renewable resources also promote self-dependency, which, from the perspective of a remote island such as Sal Island in Cabo Verde, turns out to be the fundamental feature.

The proposal consists in retrofitting the existing desalination plants in Sal Island of Cabo Verde with a hybrid renewable energy park to fulfil the 100% electricity demands of the plants. Any extra energy generated would be supplied to the grid. Furthermore, the resulting waste brine solution would be used as an extra revenue source.

Technologically, the concept decentralised renewable energy-powered desalination plant is applied. All energy requirements are covered by solar energy exclusively and total brine elimination is foreseen. A Hydropower Pumped Storage Plant is proposed to store energy.

With the implementation of this proposal, a public service business would be created to supply cheap water and electricity to residents while boosting the image of renewable energy as a sustainable path towards a better future.

As for the analysis factors, the technologies involved are Light radiation directly converted into electrical energy and Desalination; the degree of radical innovation is high, as the solution is original and totally different from the present one; complexity is 2, as solar energy and a desalinisation process are involved; TRL is 9, as the technology is already commercialised and the agent is public, as it is proposed that the project is developed as a public initiative.

3.3 Analysis Development

This section presents details of 25 projects, developed by 25 teams composed of a total of 168 international students. Projects 1–3 correspond to the RENE Project and are included in Table 2; projects 4–7 belong to the RENE Project/EDPR University Challenge and are included in Table 3; and projects 8–25 were carried out as part of the MSc SELECT PoY and are presented in Table 4. The projects were developed between 2013 and 2015. The information includes a short summary of the projects followed by the values of the factors considered, see Sect. 3.1.

3.4 Discussion

This subsection presents the values of factors obtained from the analysis of the projects. The technologies are summarised in Fig. 1. Solar solutions are by far the technology most often proposed. It seems that the idea that "the future is solar" is widely shared by students. This is probably because of expectations of cost reductions of these solutions with the subsequent potential for applicability in affordable and sustainable energy supply.

The results on the degree of radical innovation, complexity and scope of the 25 projects are given in Table 5. No clear trend can be observed regarding the first factor. This is an interesting result that requires a more detailed analysis. Ultimately, it means that students are open to the solution that seems more appropriate in each case, be it a game changer concept or a relatively conventional (usually business) solution.

On the other hand, students have a strong preference for complex solutions considering several elements. Solutions are often combined to create sustainable and, when possible, stand-alone systems. Furthermore, the scope of the solution tends to be limited. Most of the solutions could, however, be generalised.

Finally, the results on TRL and agents are presented in Table 6. The TRL of the proposals is very high; that is, commercially available technologies are preferred. Edge technologies are generally discarded. This can be interpreted as the orientation to obtain short-term results with an immediate impact on the market. The students' background (mostly from engineering) and the training on business/innovation/entrepreneurship that the students receive in EIT KIC InnoEnergy masters can account for these results.

With regard to the agents that would develop the solution proposed, students have no clear preference between an existing company implementing new practices, a new company or a cooperative solution. The selected option seems to depend on

Table 2 Projects RENE Project 1

Num.	**Description**	Technologies	Degree of radical innovation	Complexity	Scope	TRL	Agent
(1)	Replacing a conventional diesel-powered water supply system with a photovoltaic-powered water pumping system in a rural area	2.1. Devices for producing mechanical power from solar energy	Medium	2	Local market	TRL 9	Existing company
(2)	Biodiesel obtained from oil collected from restaurants	6.1. Solid fuels essentially based on materials of non-mineral origin	Medium	2	Local market	TRL 4	New company
(3)	Generating renewable energy from different sources and storing it to make a city energy autonomous	2.5. Light radiation directly converted into electrical energy	High	2	Local market	TRL 9	New company

Table 3 Projects RENE Project/EDP University Challenge

Num.	Description	Technologies	Degree of radical innovation	Complexity	Scope	TRL	Agent
(4)	Desalination plants for an island with a hybrid renewable energy park to fulfil the 100% electricity demand	2.5. Light radiation directly converted into electrical energy + Desalination	High	2	Local market	TRL 9	Public initiative
(5)	Example of sustainable energy on the beach	1.2. Wind motors; 2.5. Solar	Low	2	Local market	TRL 9	Existing company
(6)	Card game where different responsibilities are given to players and environmental commitment is promoted	None	Low	1	Local market	–	Existing company
(7)	PV panel enhanced by a PV cooling system and a high precision monitoring system	2.5. Light radiation directly converted into electrical energy	Medium	3	Industry	TRL 7	New company

Table 4 Projects MSc SELECT PoY (Project of the Year)

Num.	Description	Technologies.	Degree of radical innovation	Complexity	Scope	TRL	Agent
(8)	Contained unit of solar PV panels, biomass and battery storage to generate electricity coupled with ultrafiltration for water purification in a rural community	2.5. Photovoltaic system 6.1. Solid fuels essentially based on materials of non-mineral origin	Low	3	Local market	TRL 9	Social
(9)	Integrated solution for school classrooms providing the room structure, clean water and electricity using renewable sources	2.5. Photovoltaic system 1.2. Wind motor	Low	4	Local market	TRL 9	Social
(10)	Lowering carbon dioxide emissions by retrofitting of coal-fired power plants in Europe to work with biomass and converting CO_2 emissions into a fuel	6.1. Solid fuels of non-mineral origin 2.2. Solar heat 1.2. Wind motors	Medium/ High	3	Industry	TRL 9	Social
(11)	Integration of a thermoacoustic engine (TAe) into a vehicle to capture waste heat and generate electric power	6.4. Engine using waste heat from internal-combustion engines	High	1	Industry	TRL 7	Existing company
(12)	Stand-alone module to provide clean water and electricity to poor areas	2.3. Light-sensitive semiconductor components	Low	3	Local market	TRL 9	Social
(13)	Consultancy services in the field of shore-side power generation to address particle emissions from ships docked at ports and an innovative hub to implement innovative projects in the naval sector	6.3. Gaseous or liquid fuels 2.6. PV solar roofing system	High	2	Industry	TRL 9	New company

(continued)

Table 4 (continued)

Num.	Description	Technologies.	Degree of radical innovation	Complexity	Scope	TRL	Agent
(14)	Power source based on microbial fuel cell technology to charge cell phones and power LED lamps	6.1. Solid fuel based on material of non-mineral (microbial) origin	High	1	Industry	TRL 7	Social
(15)	Consultancy company specialising in providing holistic energy concepts/solutions to urban eco-communities to make a transition into more sustainable ways of living	ICT technologies	Low	Market	Local market	–	Social
(16)	Integrated photovoltaic-thermal (PVT) and membrane distillation (MD) system to produce "green" electricity and provide ultra-pure water in a sustainable way	2.2. Solar heat collector 2.3. Semiconductor devices to convert light radiation into electricity	High	3	Local market	TRL 9	Social
(17)	Power to Gas (P2G) system to convert excess electricity into gas fuel which can be efficiently stored and ultimately used in the regeneration of electricity for isolated locations	6.3. Gaseous fuels	High	3	Industry	TRL 9	Social
(18)	50-house community on an island powered by fuel cells	1.2. Wind motors 2.3. PV panels 6.3. Gaseous fuels	Low	3	Local market	TRL 9	New company
(19)	Modular solar system that can be attached on top of cargo containers while these are on-board to satisfy part of the auxiliary demand with renewable energies	2.3. PV (SMT: Sustainable Maritime Transport Modules) panels	Low	1	Local market	TRL 9	New company
(20)	Solar PV blind combining solar PV cells with traditional roller blinds to provide an easy-to-install renewable energy device for almost any home	2.3. PV panels	High	2	Specific market	TRL 9	Existing company

(continued)

Table 4 (continued)

Num.	Description	Technologies.	Degree of radical innovation	Complexity	Scope	TRL	Agent
(21)	Modular solution (PV panels and eventually a wind turbine) for electrification of a rural area by charging a central battery bank and a series of individual portable batteries to transport electricity to households and charge their lanterns or mobiles	1.2. Wind motors 2.3. PV panels	Low	1	Local market	TRL 9	Social
(22)	Simple off-grid electrical power system for lighting and small battery recharging for rural areas called FIREFLY	2.3. PV panels	Medium	3	Specific market	TRL 9	Existing company
(23)	Feasible expansion proposal for Smart Rural Grid IDPR technology, with short and long-term goals dictated by market needs	ICT technologies	Medium/ High	Market	Specific market	–	Existing company
(24)	Suggestions of actions that the government of an island can take to achieve a reliable, environmentally-friendly and economically sustainable energy system by 2030	2.2. Domestic heating with thermal storage 2.3. PV panels for household use	Low	Market	Specific market	TRL 9	Existing company
(25)	Finding an affordable, reliable solution for electricity supply for an island community based on 100% renewable resources and with minimal impact on local wildlife	1.2. Wind motors 2.2. Solar collector 2.3 PV panels	Low	Market	Specific market	TRL 9	Existing company

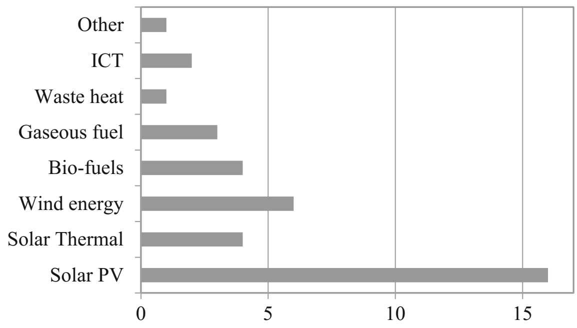

Fig. 1 Analysis of the technologies selected by students to address the challenges

Table 5 Occurrences of degree of radical innovation, complexity and scope

Factor	Value	Number of occurrences
Degree of radical innovation	Low	11
	Medium	4
	Medium/High	2
	High	8
Complexity	1 element	5
	2 elements	7
	3 elements	8
	4 elements	1
	Market	4
Scope	Industry	6
	Local market	14
	Specific market	5

Table 6 Occurrences of TRL and agent

Factor	Value	Number of occurrences
TRL (Technology Readiness Level)	No technology	3
	TRL 4	1
	TRL 7	3
	TRL 9	18
Agent (of the change proposed)	Existing company	9
	New company	6
	Public initiative	1
	Social	9

the circumstances. When a similar solution is offered by a company, some students propose sometimes the adoption of the new solution by the company and others the creation of a new company. Other options are also considered according to the circumstances. In none of the cases is expected profit their main motivation.

In general, the students' approaches are very strongly focused on solutions rather than on edge technologies, or market or organisational aspects. Their main concern is the development of environmental and economically sustainable solutions. This is consistent with their engineering background and the focus of the master's programs that they are pursuing.

4 Conclusions

This chapter presented a field research analysis on how international energy engineering students face our current societal and technological challenges for sustainability. The boundary conditions are given by the fact that students are following EIT KIC InnoEnergy's MSc RENE or MSc SELECT master's programs. The vision and mission of these programs was summarised.

The proposals made by 168 international students gathered in 25 teams were analysed. Students worked on these proposals in the framework of several projects (RENE Project, RENE Project 1/EDP University Challenge and SELECT Project of the Year). The main characteristics of the projects were summarised and categorised to better understand the boundary conditions under which students work.

A systematic analysis of technologies, degree of radical innovation, complexity, scope, TRL and agents that would develop the solutions showed interesting results. According to this analysis, the typical proposal is based on solar energy, involves several elements, has, at least initially, a limited scope, uses commercially available technology, and is adapted to the case in all other respects. From the authors' point of view, this vision is very promising to spread available and future renewable solutions.

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Concentrated Solar Power: Present and Future

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Abstract Concentrated Solar Power (CSP) plants exploit the thermal energy coming from the sun in the form of solar radiation in order to generate electricity. This chapter describes the different types of CSP systems currently in use, the technological issues associated with them and possible maintenance management methods. The solar thermal industry makes use of parabolic trough, linear Fresnel, solar towers, dish Stirling CSP plants and solar chimney CSP plants. In this chapter a comparison between the different technologies is also presented. The energy production cost of CSP plant needs to be reduced further in order to increase the competitiveness of solar thermal energy in comparison with other power generation technologies. Effective inspection can help increase maintenance efficiency, increase reliability and reduce downtime, resulting in improved profitability of CSP plants.

1 Introduction

Concentrated Solar Power (CSP) is a rapidly growing renewable energy source with excellent predictability and dispatchability [1]. Despite financial problems experienced by certain CSP plant operators associated with recently commissioned large-scale projects, investment in renewable energy and CSP in particular, is expected to continue to surge in the forthcoming years. Investments in CSP technology are expected to be encouraged as governments across the world realise the

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rising cost of their dependence on fossil fuels [2]. In 2012, CSP plants in Europe generated 11 TWh, a noteworthy contribution to the overall energy mix of the continent [3].

As of 2016, more than thirty-six CSP plants of various sizes producing a total of 2.6 GW of power had been installed in the EU. This represented approximately 55% of the 5.1 GW total global CSP capacity produced by seventy-four CSP plants built worldwide. Outside Europe, there were eighteen CSP plants in the U.S. with four of the biggest ones having been completed in 2014. There were also five CSP plants in China and more than sixteen in the Middle East and North Africa (MENA) region and the rest of the world. More than twenty-five new CSP plants had been reported to be under construction worldwide, adding 3 GW (265 MW in Europe) of new capacity. Several more CSP projects had been announced with sixteen new projects (the equivalent of 1 GW) planned in Spain alone. If all announced projects materialised they would result in further 10 GW of CSP capacity being connected to the grid by 2020.

CSP has clearly the potential to cover up to 25% of the global energy demand by 2050 if growth trends continue at the same pace. The investment in new CSP projects increased from €1.65 billion in 2009 to €10 billion in 2015. At this rate by 2050 the total annual investment in CSP could exceed an estimated €175 billion. The annual turnover of the global solar thermal power industry is estimated to reach €8 billion for 2020. The Operational and Maintenance (O&M) costs were estimated to be 13–25% of the overall CSP market or €0.9–2 billion by 2020. Moderate estimates predict that the global CSP market will reach 22 GW of installed capacity worth €100 billion by 2025.

2 CSP as Part of the Modern Energy Mix

Among the solar electric technologies, CSP has the lowest Levelised Cost of Electricity (LCOE) when a 35-year operational lifetime is considered. Hence, in the context of continuously growing energy demand, supply constraints, environmental degradation and climate change concerns, CSP has the ability to offer a realistic renewable and sustainable energy alternative to conventional power generation sources based on burning of fossil fuels.

However, to guarantee the financial viability of large-scale CSP projects and stimulate further their widespread implementation it is of utmost importance that the technical challenges associated with the efficiency, operational reliability and maintenance of critical CSP plant components are addressed promptly. The potential financial failure of a number of large utility-scale solar thermal projects to achieve their targeted power output has made apparent the investment risks associated with CSP production [4]. As a result, the need to address the technical challenges CSP industry is currently facing in measurable, tangible, definite and timely manner have been clearly highlighted.

3 CSP Technologies

Parabolic and Linear Fresnel are the most common technologies in use for utility-scale CSP production, followed in more recent years by solar towers. Parabolic trough (Fig. 1) and Linear Fresnel (Fig. 2) plants consist of several tens of kilometres of solar absorber tubes and insulated pipes. The solar absorber tubes are spread as parallel arrays across the solar field where the working fluid (usually oil, less often molten salts) gets heated during circulation. The heat from the working fluid is then used to generate steam through a heat exchanger. The pressurised steam generated at the heat exchanger drives a steam turbine generating electricity. The cycle repeats itself continuously as solar radiation keeps heating up the working fluid flowing through the solar field.

Modern CSP plants are able to continue their operation by storing the excess heat in storage tanks (Fig. 3). Therefore, after the sun has set CSP plants with storage facilities can maintain operation until the stored thermal energy has been exhausted. The duration for which a CSP plant can maintain operation after the sun has set depends on the size of the storage facilities and their capacity to store the excess heat made available during daytime operation. Most modern CSP plants do make use of storage facilities in order to increase their output potential and increase the profit margin for the operator. Storage facilities offer significant advantages. Although, they do add considerably to the overall construction cost of a CSP project, their implementation is relatively simple and does not require fundamental changes in the original design of the plant.

Fig. 1 Example of parabolic trough CSP technology at Plataforma Solar De Almeria (PSA) facility, Tabernas Desert, Spain

Fig. 2 Example of linear Fresnel CSP technology at Plataforma Solar De Almeria (PSA) facility, Tabernas Desert, Spain

Fig. 3 Molten salt thermal energy storage facility at Plataforma Solar De Almeria (PSA), Tabernas Desert, Spain

Solar towers in their simplest form, make use of a single closed circuit solar absorber vessel installed on the top of a tall tower (Fig. 4). Heliostat mirror arrays, installed strategically in the form of concentric circles around the solar tower, track the sun and reflect the solar rays towards the solar absorber vessel where they are focused. The cold working fluid enters the solar absorber vessel from the bottom, heats up and exits from another pipe. A heat exchanger removes the excess heat from the hot working fluid generating the necessary steam to drive the steam turbine and produce electricity.

Modern solar tower designs make use of volumetric solar absorbers. Volumetric solar absorbers are made of ceramic or metallic porous mesh and capture the solar ray energy in order to heat ambient (open volumetric receiver) or pressurised (pressurised volumetric receiver) air. Air, being the working fluid in this case, enters from the front of the receiver and heated up through convection. Then, the pressurised hot air is fed to a gas turbine producing electricity whilst the excess heat is used to drive the steam cycle and produce additional electricity. In the case of open volumetric receivers, the entire electricity production is based on the steam cycle since hot air does not have sufficient pressure to drive a gas turbine.

Dish Stirling CSP plants have begun attracting additional interest over the last few years. Dish Stirling solar thermal device have very high efficiencies when compared with other solar renewable energy systems. They comprise of a dish mirror, which concentrates solar rays on the heating element in the front of the device driving a Stirling engine. The concept is very similar to a satellite dish only in this case the device collects the solar ray energy to heat up air and drive the piston in the Stirling engine (Fig. 5). The reciprocating motion of the piston as air heats up and cools down drives the rotating component of the engine to generate electricity. In some cases, a steam cycle may be built-in the system instead.

Solar chimneys are a cheap and simple method of generating solar thermal energy. However, they require a vast amount of land to enable production of

Fig. 4 Example of solar tower at Plataforma Solar de Almeria, PSA facility, Tabernas Desert, Spain. The heliostats are visible in the foreground

Fig. 5 Example stirling energy systems—Dish Stirling Engine [11]

electricity at utility scale. In addition, they have very low efficiency. The concept of solar chimneys is fairly simple. They consist of a tall chimney which is open at both ends (top and bottom). Around the solar chimney land is surrounded by a large greenhouse structure with unobstructed entrance in all directions. The air pressure at the top of the chimney is measurably lower than the air pressure at ground level. Therefore, air is able to flow from the edges of the greenhouse structure towards the centre of the plant where the chimney is located. As the air flows towards the centre of the plant it heats up due to the greenhouse effect. As it arrives at the central point where the chimney is located, it drives gas turbines generating electricity. The hot air then travels up the chimney where it is released out in the atmosphere. This simple CSP plant design have very low maintenance cost but its construction is expensive whilst capacity factor is very low.

4 Technical Challenges

Each of the above CSP technologies has its own technical challenges to address. So far parabolic trough CSP technology has been used most widely. Linear Fresnel plants are similar in concept with parabolic trough ones, making use of simpler mirror design to reduce complexity and cost. However, they also have lower efficiency than parabolic trough CSP plants. Solar towers despite a slow start have been picking up pace in terms of their exploitation, particularly since volumetric receivers begun to enter the market. Dish Stirling CSP plants are also seeing gradually further development, particularly in the Middle East where a number of large scale projects based on this technology have been under development or announced [9].

The inspection of CSP tubing and piping in parabolic trough and Linear Fresnel plants is very challenging. In the case of solar absorbers, the tubes are inside a glass envelope under vacuum. The substrate material which is normally an austenitic stainless steel grade such as 304L is covered with a black cermet coating. The cermet coating enables a high amount of solar energy to be absorbed and very little to be reflected and emitted as radiation, thus maximising heat gain and minimising heat loss. However, this means that the stainless steel tube itself is not visible to inspection engineers and no traditional inspection technique can be applied to assess its structural integrity due to the presence of the external glass envelope that shields the solar absorber tube from the open atmosphere (Fig. 6).

Thermographic inspection has been proposed as a possible method of identifying overheating or tube thinning [5]. However, due to the presence of the glass envelope and cermet coating the thermograms obtained with infrared cameras are unreliable. Thus, the inspection of solar receivers is currently impossible with traditional means.

The remaining pipes of the plant forming the rest of the primary coolant system as well as the secondary coolant system are insulated to avoid any collateral heat losses, hence assisting in maximising operational efficiency and capacity factor of the plant. Fibreglass, mineral wool or a combination of mineral wool with ceramic

Fig. 6 Standard solar absorber tube and connection between two solar absorbed tubes

fibre are usually employed as insulation materials. To inspect insulated pipes using conventional Non-destructive Evaluation (NDE) methods such as Magnetic Flux Leakage (MFL), Eddy Current Testing (ECT), Ultrasonic Testing (UT), etc. the insulation needs to be removed. The removal of pipe insulation is time-consuming and can potentially result in damage to both pipes and insulation. Moreover, removal of the insulation is only safe during plant shutdown since corroded or cracked pipelines may rupture during the removal process while they are still in-service posing an unacceptable risk to the safety of maintenance engineers.

Tangential radiography can be applied for the detection of corrosion in in-service pipelines without the need of removing the insulation. However, its use involves health and safety considerations and therefore exclusion zones need to be imposed before radiographic inspection can begin. It is also impossible to inspect every single section of insulated piping.

Conventional Long Range Ultrasonic Testing (LRUT) or guided waves based on piezoelectric transducers on the other hand can be employed for the inspection of long section of insulated pipes but only during a planned outage [6]. The installation of the inflatable ring containing the piezoelectric transducers also requires the removal of the insulation in the area that the ring is mounted on. Since there is always a risk of pipe rupture, the ring can only be safely installed when the pipe is out of service. Even if the pipe is known to be defect free, the piezoelectric elements (typically lead zirconate titanate or PZT crystals) and inflatable ring are not designed to operate at temperatures above 120 °C which is much lower than the operational temperatures of in-service CSP pipelines.

LRUT based on Electromagnetic Acoustic Transducers (EMATs) can be applied without the need of physical contact of the sensors with the inspected tube or surface. EMATs apart from being capable of operating from a distance can also be designed with a cooling circuit in order to maintain their temperature constant at all times. EMAT design is simple consisting of a rare earth magnet or DC electromagnet and a coil excited by an alternating current fed at ultrasonic frequencies. EMATs are inexpensive to build, extremely robust and do not require any maintenance once they have been installed [7, 8]. EMATs do not suffer any appreciable degradation over time. In contrast, piezoelectric transducers are much more expensive (>€300/unit) and their performance deteriorates with time particularly when operating at adverse environmental conditions. The quality of the piezoelectric elements also needs to be assessed to ensure an acceptable level of consistency from batch to batch. The quality control of EMATs is far easier. Identical sensors with exactly the same performance and characteristics can readily be manufactured very easily. EMAT rings can be permanently attached in the area of interest to continuously monitor a section of the solar receiver tubing or insulated piping regardless of the operational temperature at very low cost and without the need for ever carrying any maintenance on the inspection unit after installation.

In the case of solar thermal towers, apart from the inspection issues of insulated pipes, there is additional complexity related to the geometrical characteristics of the volumetric receivers as well as the types of materials employed still pose significant manufacturing challenges. An additional consideration is the performance of the heliostat field. Since heliostats need to continuously track the sun to reflect and focus the solar rays to the volumetric receiver, problems with their tracking system and motion controllers and mechanisms can result in reduced plant efficiency.

Structural defects found in solar receivers and insulated pipes can be classified either as critical or non-critical. Non-critical defects are those which do not compromise imminently the structural integrity of the solar receivers and insulated piping or the safety of CSP plant operations. Critical defects are those which can unexpectedly result in failure of the solar receiver and pipes, potentially compromising the power generation process.

5 Future Prospects of CSP Technology

The reduced output that has been observed in certain recently completed commercial CSP plants has made clearly evident that there is an urgent need to increase the reliability of CSP infrastructure and optimise maintenance procedures by using efficient and cost-effective inspection methods. The long-term development projection of CSP plants carries a noticeable risk due to the technology advances needed in the fields of solar absorber efficiency, structural reliability of key plant components, thermal storage, selection of optimum working fluid and structural health assessment to enable the safe operation of the plant at high operational temperatures above 400 °C.

Existing parabolic trough plants suffer at least one week of forced outages per year whilst solar receiver tube failure rates alone can be as high as 0.09 per tube per year [10]. There is currently no available methodology for online SHM of in-service solar receivers and insulated pipes and therefore CSP plant maintenance procedures are based on corrective rather than preventive approach. Offline inspection of the solar receivers is also impossible. Although, offline inspection of insulated piping can be carried out using traditional inspection techniques, this requires the removal of the insulation which is a time consuming and expensive process. Furthermore, the removal of the insulation and its installation anew can result in damage being incurred on the plant's coolant infrastructure during either of these processes.

Reducing the cost of maintenance without compromising operational reliability would improve the value for money for the European CSP industry aiming to reduce LCOE by 2030. It would also release substantial capital for new investments contributing to the further rapid expansion of CSP and renewable energy in general worldwide.

The main challenge for the CSP industry is to increase its operational reliability, cost-effectiveness and profitability by minimising Operational Expenditure (OPEX) to render it more competitive against conventional fossil fuel energy sources. CSP production needs to be efficient and reliable with a high level of asset availability. Improved CSP utility operations will increase competitiveness of solar thermal power, making it an attractive renewable energy source which contributes decisively towards keeping environmental impact of the power generation sector to a minimum. To enable this, the CSP industry must adopt the technologies which will enable it to achieve optimum operational capability and contribute to a noteworthy reduction of OPEX.

6 Conclusions

CSP has all the credentials required to contribute profoundly in the sustainable and environmentally friendly energy production on a large scale. For the next ten years, CSP is expected to experience almost double the annual growth rate than wind energy industry, making it the strongest performer in the energy market overall. Nonetheless, there are still certain technical problems which need to be addressed quickly so as the long-term prospects of CSP industry are not adversely affected from excessive O&M costs and reliability issues already causing output issues in some of the most important CSP projects currently in operation. Further effort is required in order to implement appropriate inspection technology for the reliable assessment of critical CSP components, particularly solar absorbers and insulated pipes. Also a better understanding of the materials used and damage mechanisms as well as factors influencing efficiency of the CSP plants is required. The use of storage facilities offers significant advantages to operators increasing the prospects of successfully achieving a timely return of the original investment made for the construction of the plant. However, the cost of the project is also significantly higher when storage facilities are included and this needs to be taken into account in future operational planning based on the anticipated availability and capacity factor of the plant.

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Concentrated Solar Plants Management: Big Data and Neural Network

Alfredo Arcos Jiménez, Carlos Q. Gómez and Fausto Pedro García Márquez

Abstract Big Data is becoming the most powerful tool for analysing the huge amount of data around us. Cloud Processing is among the benefits offered by the Big Data, which allows analysis of data in real time from different parts of the world. These technological advances in mass data processing can be exploited to treat information from thousands of sensors. A new approach for optimal condition monitoring and control of Concentrating Solar Plants spread over different geographical locations is proposed. The information from the condition monitoring sensors (in this instance ultrasonic guided waves) and the data for the optimal control of the plants need a cloud platform in order to be analysed jointly with forecast data (meteorological, demand of other plants, etc.). The main processing tool used is based on neural networks, responsible for correlating the obtained signals in real time, to determine anomalous results and generate alarms.

1 Introduction

An IBM manager once said that "Data is the new oil" and that message sum-marises in a few words the importance of data around us. Technological advances have allowed storage of a large amount of data coming from a wide variety of sen-sors. But now it presents a new problem, related to the processing of that immense amount of data when conventional computers are not adapted for it.

We talk about *Big Data* when the volumes of data exceed the capability of available software to handle and manage them. This concept is in continuous movement because technological advances allow greater volume treatments. For example, this

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allows the analysis of the *logs*, which so far they are not used because the technology does not allow processing within a reasonable time. The concept of volume is highly variable but analysis becomes inherently more challenging when we consider large volumes of data.

Variety concept refers to the inclusion of other types of different data sources, for example, the information obtained from various sensors, each with a completely different type of information, sample rate, duration, acquisition frequency, etc. This information can be semi-structured or may not have any structuring. The management of this unstructured information requires different technology and allows decision-making based on information with a significant degree of inaccuracy. Many of these algorithms are related to the treatment of advanced fuzzy logic.

The velocity concept refers to the speed with which the data is received, processed and decisions are made. In most traditional systems it is impossible to analyze immediately the large volumes of data, however, the incorporation of the concept of real time processing is essential for a wide range of applications.

The veracity concept alludes to the data reliability, selecting the quality data and excluding those data which do not add value or potentially unpredictable.

Finally, the value concept fives importance to data, knowing what data that should be analysed is critical. At this point, experts are particularly important, who can select and provide value to each data type.

There are two main categories depending on the structuration of the information.

- *Structured data*: They are those having length and format and can be stored in tables (relational databases).
- *Unstructured data*: They are lacking a certain format and cannot be sorted in a table. Within this category, it can be added the semi-structured data, which are not relational databases and are not limited to certain field, although they have internal organisation or markers that facilitates the processing of its elements.

1.1 Cloud Computing

The term cloud computing refers to a technological concept and a business model that meets different ideas such as data storage, communication between computers, provision of service or methodologies of application development, all under the same concept: everything happens in the cloud. Cloud, defined in a simplistic way, is a set of computers, spread across the world and united by a dense communications mesh, offering spaces for information [1].

Three basic types of services can be considered to constitute the business model of the cloud computing and it is called the generation "As a service" (IaaS, PaaS, SaaS). Generally, cloud computing is divided into three categories according to their purpose.

- Infrastructure as a service (IaaS): It offers customers storage space or processing power on their servers. This service is based on access to the use of hardware based on cloud.
- *Platform as a service (PaaS)*: It provides users the tools for carrying out IT development. The developer has not to acquire the expensive licenses for developing of tools.
- *Software as a service (SaaS)*: It provides finished products that offer specific services for which they were developed. The applications are located on servers in the cloud provider and they have a billing mechanism (pay per use) or they can be a free service.

2 Cloud Computing for Concentrated Solar Power

In the current era, where the satisfaction of the energy demands of the growing world population reaches very high limits, it becomes imperative to develop alternative sources of energy [2, 3]. The alternative sources must be economic, non-polluting, inexhaustible and technologically applicable to satisfy the demand of society [4].

Solar energy is one of the most important alternatives for use as an alternative energy source and it can be technologically exploited by photothermic conversion. Significant growth and development of new Concentrated Solar Power (CSP) has been exhibited as a result in recent years [5]. There are a large number of power generation plants using this technology (Fig. 1). The parabolic through solar receivers transform the incident solar radiation into thermal energy. This is achieved by heating aw working fluid in the form of oil, molten salt or steam which can reach up to 550 °C.

Nonetheless CSP plants need to improve the operational efficiency and maintainability because a failure in the system can halt production of an entire power plant [6–10]. Therefore, the need for implementing a condition monitoring system to analyse the actual condition of critical elements of the plant, such as the absorber tubes and insulated pipes increases [11–14].

One of the major advantages of cloud computing is the introduction of the ‘elastic resources’ concept which expand and contract according to the system load dynamics. In this way it is possible to reduce the latency by the shared across applications. The great penetration of Internet throughout all industrial sectors, the increasing power of computational systems and advances in software have made possible that this new computing architecture emerges as a real solution.

In this chapter a new system for condition monitoring and control for CSPs is proposed based on cloud computing. The main objective is to jointly benefit data processing, cooperative work between different power plants, optimisation of resources, and increasing the performance of CSP plants.

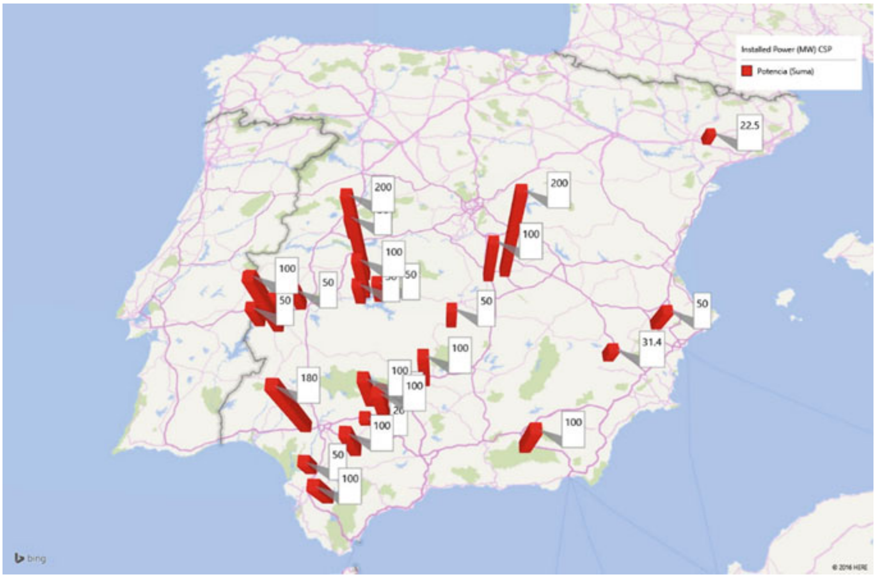


Fig. 1 Storage of the CSP power plants in Spain. The Spanish Association of Solar Thermal Power Industry (PROTERMOSOLAR)

For this purpose, there are two mainly groups of input data to the system:

- *Endogenous Data*: This group encompasses all those variables and parameters that are intrinsic to each CSP plant. On the one hand, there are the fixed parameters. These parameters are not modifiable values of the characteristics of the CSP plant. These parameters are, for example, the collection surface, the reflectivity of the mirrors, the storage limit, etc. These parameters will be considered for later compare performance of different plants to obtain conclusions which are more efficient. On the other hand, there are the endogenous variable data, which have to be continuously optimised. They are all those values that are generated from CSP plant sensors. Examples of endogenous variables are the temperature on the absorber tubes, the ultrasonic signals and the generated MW. It is crucial to analyse all these variables, in order to optimise the operational performance of the CSP plant. All these sensors will be connected to the central station of the CSP plant, sending signals so the provider of online cloud services (Table 1).
- *Exogenous Data*: This group includes all the parameters which are independent of the CSP plant. The Exogenous data are part of an indirect way in the las purpose of the CSP plant, the energy generation. Although they are not directly involved they have an important role. They are, for example, the meteorology, cloud cover, market demand and company strategies (Table 2).

Table 1 Endogenous data of the CSP plant

Endogenous data CSP plant (Parameters and variables)			
Solar collection	Collection surface	Tilt angle relative to the horizontal plane	CSP orientation relative to the geographic plane
	Optic efficiency	Mirror width	Mirror reflectivity
Storage	Current storage	Storage limit	Heat loses rate
Circulation	Pump head HP	Liters per minute	Mass flow rate
	Re-circulation index	Heat loses rate	Internal and external diameter
Performance	Generated MW	Installed MW	Steam turbine
Condition monitoring	Ultrasonic signals	Temperature sensors	

Table 2 Exogenous data of the CSP plant

Exogenous data			
Meteorology	Anemometer	Pluviometer	Hygrometer
	Thermometer	Barometer	Pyrometer
	Cloud cover	Radiance index	
Performance forecast	Power demand of CSP (MW)	Power demand of others CSPs	Storage Forecast
Decision making	Energetic strategy	Condition monitoring strategy	Performance strategy
Market demand	Watt current price	Watt price forecast	

Figure 2 shows a schematic of the information flux proposed in this chapter for a condition monitoring and management of a CSP plant. Where the inputs are the variables and parameters mentioned above and outputs are the optimal maintenance and CSP plant control. The optimal maintenance comprises a proper condition monitoring of the plant within a specific maintenance strategy. The CSP plant control will manage the production as a function of the power production strategy, which comprises the current energy demand and the status of other CSPs.

Specifically, if we focus on inspecting the absorber tubes, according to National Laboratory of the U.S. Department of Energy (NREL), a common 50 MW power plant has 22,464 concentrating solar receiver pipes. The Spanish Association of Solar Thermal Power Industry (PROTERMOSOLAR) would comprise a total of 1.035.000 absorber pipes.

The European project ‘Intersolar’ [15] proposes to inspect the absorber receiver tubes employing ultrasonic guided waves in order to detect defects such as cracks or corrosion in solar receivers and insulated pipes [15–17]. This project proposes to inspect the pipes employing 4 ultrasonic transducers. A unique ultrasonic signal is

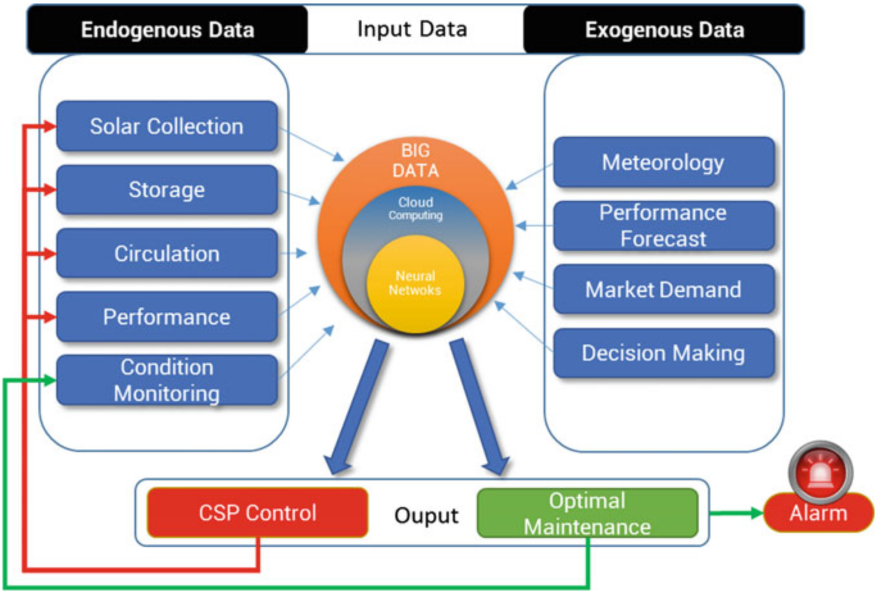


Fig. 2 Flux data scheme of the proposed processing data system based on Cloud Computing

approximately 100 kb, therefore it multiplied by all installed sensors would generate 41 PB after each sweep. By sweeping hourly, 1 EB of data would be generated daily. This is only information from ultrasonic signals for condition monitoring, so this should be added the signals from all other sensors that may be present.

2.1 Proposed Infrastructure for Cloud Computing

A node controls the information collected by the sensors with the metadata, and organizes them in packages to send them through the network. The above estimations of the amount of data collected by the sensors will determine the characteristics of the hardware employed. This will define the optimal choice of the Infrastructure as a Service (IaaS). Then the data will be transmitted to the computing center. The standard HTML5 is the proposed technology to carry out this process due to its integration to work in a web browser (Fig. 3).

The most appropriate data transmission technology will be selected depending on the granularity of the data and the responsiveness of the system. For the granularity it is necessary to balance the trade-off between small and big queries. The responsiveness is a strong requirement for the condition monitoring.

In order to avoid the system collapse at demand picks, the system should be designed to scale and balance the resources as need. It is recommendable to split the load of work by processing some tasks ‘in the background’ and others ‘in the main thread'. It depends on several factors, like the volume of data, request frequency and computing cost of each request. High scalability of the system is necessary, where the processes of each task are dynamically replicated according to the system load.

The processing algorithms executed during these tasks depend on the concrete application. In CSP plants, condition monitoring using ultrasonic sensors will make use of a reduced amount of data by extracting the characteristic features of the signal. Then the following methods are proposed to process the data and to determine the structural health of the absorber tubes.

3 Neural Networks Techniques and Fuzzy Logic Controllers

Prognosis and prediction of solar radiation are stochastic processes due to the variability of solar resources. As a consequence, numerous mathematical techniques have been developed to model these processes. Among these techniques, Artificial Neural Networks (ANN), Fuzzy Logic (FL), Genetic Algorithms (GA) and hybrid

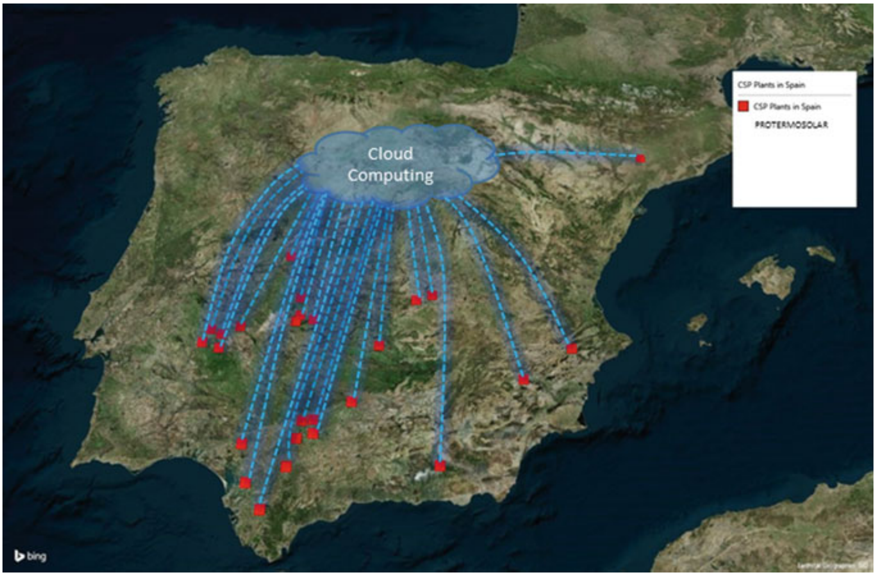


Fig. 3 Proposed Cloud Computing platform to jointly analyze and control a group of CSP plants. The example shows the Spanish Association of Solar Thermal Power Industry (PROTERMOSOLAR)

systems (GA/ANN ANN-FL) are widely employed. Further information about these techniques can be found in references [18–28].

Figure 2 shows some parameters (Solar Collection, Storage, Circulation, etc.) which are considered as inputs of the system to obtain useful information for establishing maintenance and control schedules of the plant. In this chapter, show an example of a condition monitoring application based on ultrasonic inspection employing neural networks is discussed.

3.1 Ultrasonic Inspection

Inspection using guided waves consists of the excitation of an ultrasonic transducer, which generates ultrasonic waves that propagate along the pipe walls [27]. The main advantage offered by this technique, compared with traditional ultrasonic methods, is the ability to inspect structures, such as plates or pipes, over significant distance several metres or more. This technique allows knowledge to be gained regarding the state of the pipe at a particular location. In some cases, tens of metres can be inspected without the relocation of the transducer. Novel methodologies in signal processing for these applications are being published [29], such as online predictive analysis to be employed in structural health monitoring.

An unsupervised neural network Selft-Organizing Feature Maps (SOFM) [30, 31] which will serve as a tool of grouping patterns for ultrasonic signal and data mining [32]. It will also serve as a tool for process monitoring and data mining.

Initially the focus is to remove unwanted noise in the ultrasonic signals using wavelet transforms. Then the filtered signals are inputted to the neural network. The architecture of this model consists of two layers: an input or sensory layer consisting of m neurons (a neuron for each signal), distributing the information to the second layer. The processing is done in the second layer with a linear structure. Firstly, each neuron calculates the similarity between the input vector x(t) (ultrasonic signal) and reference vector (vector of synaptic weights) according to established criteria. The winner neuron is called best matching unit (BMU), whose weight vector is more similar to the input. Therefore, each winning neuron (BMU) indicates the pattern detected in the input vector. In the learning phase the winning neuron modifies its weights to make it more similar to the input vector. On the other hand, the neighborhood function causes neurons belonging to the environment of the winning neuron modify their weights similarly. This implies nearby neurons tune in with similar patterns. After a sufficient number of iterations, the network adapts to the form of data or input distribution. The neural network has an associated cost function that the map attempts to minimise during their learning. This function in our case is the root mean square error (MSE).

$$MSE = \frac{\sum_{i=1}^{M} \|x_i - BMU(x_i)\|^2}{M} \quad (1)$$

where:

$\{x_i\}_{i=1,\ldots M}$ *input data*
M *number of inputs or samples*

We can summarise the operation of the network in three stages [32].

Initialization of the weight neurons vectors.

Learning of the Neural Network.

Presentation of a pattern x(t) taken in accordance with the distribution function p (x) of sensory input space.

Calculation of the similarity of each neuron with their synaptic weights vector w_{ijk} and the current input vector using the method of the Euclidean distance:

$$d^2(w_{ij}, x) = \sum_{k=1}^{n} (w_{ijk} - x_k)^2 \quad (2)$$

Determination of the BMU neuron.

Updating of the synaptic weights (w_{ijk}) of the winner neuron (g) and its neighboring neurons using the rule.

$$w_{ijk}(t+1) = w_{ijk}(t) + \alpha(t).h(|i-g|, t).(x_k(t) - w_{ijk}(t)) \quad (3)$$

where:

$\alpha(t)$ *learning rate parameter*
$h(.)$ *function neighborly*

Evaluation of the MSE function.

In the section 'Detection of cracks and corrosion in absorber tubes' it is shown the results obtained by this technique.

3.2 Temperature

When corrosion occurs in the tubes, for example near welds, hot spots are generated. The hot spots may not be detected by temperature sensors if they are far from the hot spot. A solution employing guided waves to sweep the total pipe and obtain the pipe's temperature has been considered. The guided waves are sensitive to changes not only in the material but also in temperature. Knowing the temperature using guided waves can be very useful avoiding sensor redundancy.

Fig. 4 Process flow ANN

To explore the idea of the condition monitoring in a CSP plant establishing a relationship between temperature of the pipes and the guided waves, tests have been performed on a platform simulating the operation of a CSP plant. The results are shown in Sect. 4.2.

This section deals with the establishment of a hybrid control system (ANN-FL) using as main parameters the temperature of solar absorber tubes. The ultrasonic transducers will be used to determine the temperature of solar absorber tubes by analysing the guided waves generated. Short ultrasonic pulses were emitted at different temperatures, and acquired signals were processed to train a neural network. The output of this neural network allows us to evaluate the actual temperature of the pipe. The Fig. 4 shows the process flow.

Once the temperature has been obtained by the neural network, a fuzzy logic controller provides the state of the CSP plant with respect to temperature.

3.2.1 De-noising and Feature Extraction from Ultrasonic Signal

The signal obtained must be conditioned in order to properly train the neural network. For this purpose, wavelet transforms have been used to perform the signal de-noising. Wavelet transforms have been shown to be a powerful tool in removing noise and extract the relevant information within the acquired signal [8–10]. The Daubechies family of Wavelets was chosen to perform signal denoising.

It is necessary to use a technique that allows reducing the number of inputs while maintaining the characteristic signal information. The characteristic coefficients of each ultrasonic signal were extracted by using the autoregressive model AR, by employing the Yule-Walker equations.

The method autoregressive (AR) of Yule-Walker are an example of parametric approach. They calculate the power spectral density estimating the linear coefficients of a hypothetical system that generates the first signal. These methods tend to produce better results than conventional techniques, when the length of the available signal is relatively short.

Pattern Recognition by Neural Network (Multilayer Perceptron).

For pattern recognition it has been used a Neural Network Unidirectional supervised through a Multilayer Perceptron (MLP) with training by

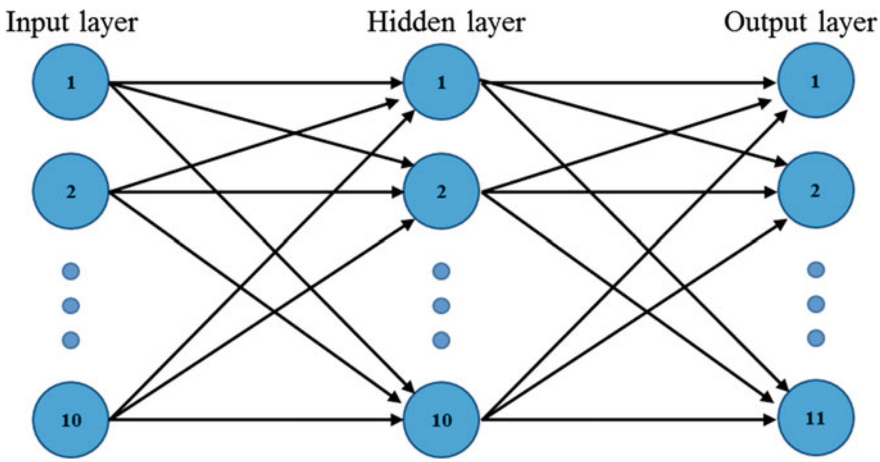


Fig. 5 Multilayer perceptron scheme, where the inputs are the AR parameters, and the outputs are the temperature

backpropagation algorithm [33]. The inputs of the ANN are the AR coefficients of the ultrasonic signal and the outputs are the temperature ranges of the experiments.

The structure is three layers of processing units as it can be seen in Fig. 5.

The steps used to achieve the results with the neuronal network are described.

- Set of samples: In the input of the neural network the extracted characteristics of the signal are introduced. The architecture of the neural network, and configuration of the hidden layer, depending on the structure of the input data. Herewith, the input parameter of the signal that has been tested is the AR-10.
- Extraction of the training set, test and validation: Samples the set of signals processed in order to generalise the network (cross validation) apart in sets:
- Training: 70%; Validation: 15%; Test: 15%
- On the other hand, we have selected another set of signals (15%) to perform a check on the external network to test modes.
- Learning process: It was used a training modes back-propagation algorithm: Scaled conjugate gradient and performance Cross Entropy [29, 34] with 'Early Stopping' to avoid overfitting [35].

3.2.2 Fuzzy Logic Controller (FLC)

Data interconnected from different sensors (temperature, oil flow, etc.) are often disordered. Therefore, it is necessary to establish a relationship which allows the acquisition of an output, for example, an alarm. Fuzzy logic controller emerges as a solution to this problem and has been used in many fields. The structure of a FLC is formed by three blocks: Fuzzifier, Fuzzy Inference System, Defuzzier.

The Fuzzifier converts the numerical values of the input variables into linguistic variables (fuzzy sets). In this case a Singleton Fuzzifier has been used.

The Fuzzy Inference System interprets the type of rules 'IF-THEN' of a set of rules, in order to obtain the output values. These values are based on the current values of the linguistic variables which are the inputs of the system.

Defuzzifier is the function that transforms a fuzzy set, which is the typical output of a Fuzzy Inferring System in a non-Fuzzy value. It is usually converted into a continuous signal.

The advantage of this system is the computational efficiency and ease of adaptation.

In this case an FLC with triangular functions has been used including, Fuzzifier of Singleton type and Defuzzifier by mean centers successfully.

The FLC operation can be summarized as:

- Outputs of different neural networks will be FLC inputs. Each neural network will be interpreted by different signals from multiple sensors.
- The FLC expert system will establish the status of the plant according to the input, and if necessary, it will activate the corresponding alarms.

4 Case Study: Results

Two applications were studied to test the efficiency of the NN for two purposes. The first is the condition monitoring of the pipe based on the detection of cracks employing guided waves. The second is the determination of temperature employing ultrasonic waves in order to find hot spots such as corrosion.

4.1 Detection of Cracks and Corrosion in Absorber Tubes

The aim of the experiment is to develop a technique able to detect changes in the thickness of the pipe, to locate them and to determine the size of the damage. Lamb waves were generated in a 316L austenitic stainless steel pipe.

An experimental platform for ultrasonic inspections has been developed to carry out the experiments. Figure 6 consists of a device that is able to read and generate signals up to 4 MS/s. The device is connected to a PC for condition monitoring. The high frequency amplifier is used to enhance the signal to noise ratio. The actuator is driven by the computer and different input signals can be generated.

The frequency used to generate the guided waves were 200 kHz and 6 cycles pulses (to find a compromise between the excitation of this frequency and avoid the overlapping of the echoes), and the guided waves were received by three sensors. To perform the identification, location and size determination of defects a cut was made as shown in Fig. 7.

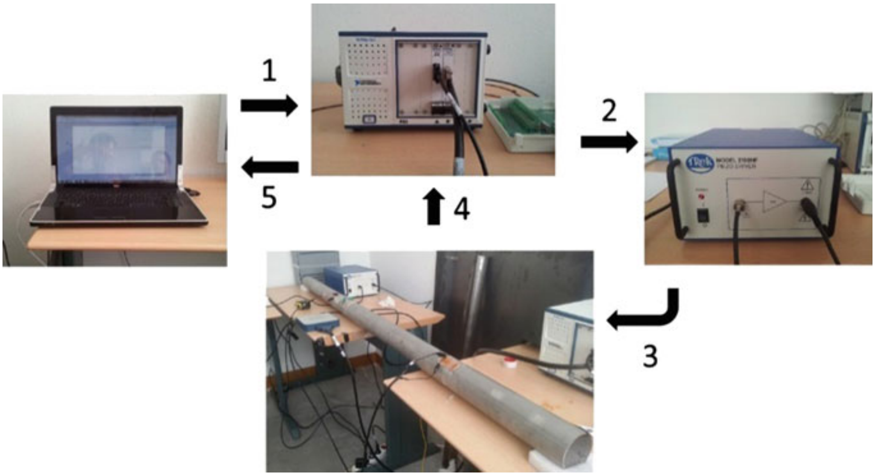


Fig. 6 Experimental platform for ultrasonic inspections

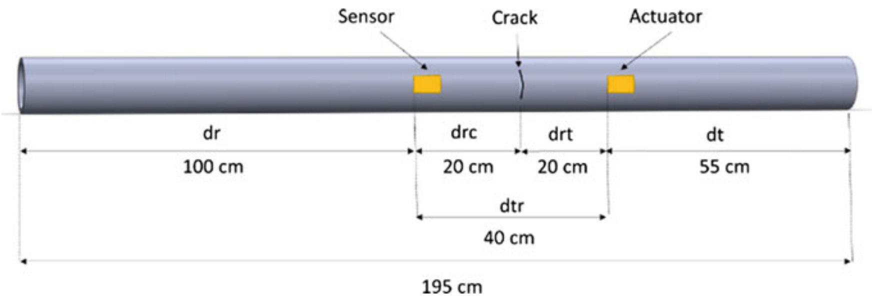
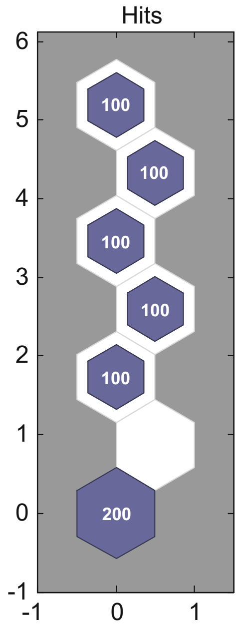


Fig. 7 Location of the crack in the pipe

Fig. 8 Location of the crack in the pipe and location of the transducers

Fig. 9 Results clustering



The first experiments were carried out in the pipe without any defect in order to have benchmarking signals. Subsequently, measurements were performed by making a cut with six different depths. The increment of each cut is 0.5 mm (Fig. 8).

Ultrasonic signals obtained are processed in a neural network SOFM order to classify them into six groups. Each pattern will reflect the status of damage. The process followed is collected in the previous section. In Fig. 9 clustering results it is shown in six groups. It can be appreciated that there are a group samples twice in the rest. This is because the healthy tube and first damage is barely noticeable grouped.

4.2 *Structural Health Monitoring Based on Temperature*

The objective of this experiment is to establish a series of patterns to register different temperatures in the oil pipe.

The experiment was carried out in a test rig (Fig. 10) consisting in 316L austenitic stainless steel tubes, four meters long, similar to those used in CSP, whereby oil is circulated at high temperature.

Two Macro Fiber Composite (MFC) transducers were placed on the test rig, where one acts as a transmitter and the other as receiver (pitch and catch). The transmitter transducer generates short pulses (6 cycles) of 250 kHz. The receiver

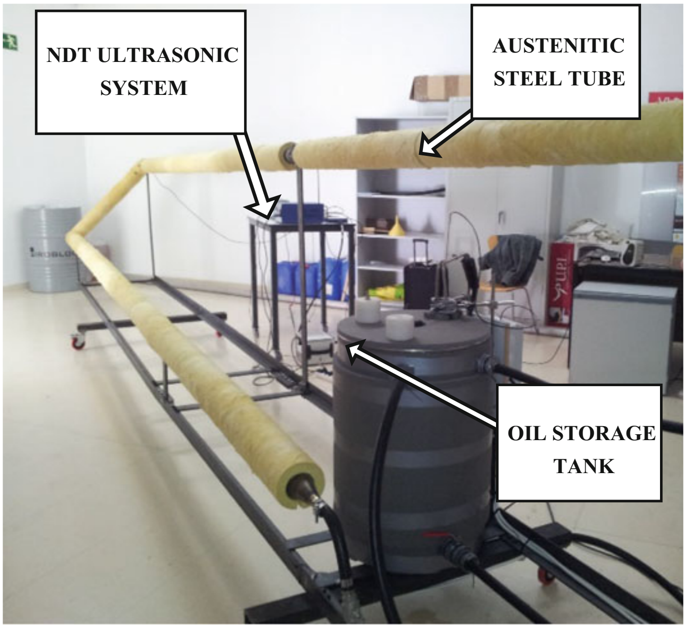


Fig. 10 Test rig: austenitic stainless steel pipes

collects the ultrasonic wave, by converting the mechanical movement of the wave into electrical signal [36]. Also the temperature is collected by using a thermocouple on the pipe, in order to train the neuronal network.

The oil that circulates inside the pipes was heated from 25 to 75 °C and the external surface of the pipe reached 55 °C. During the heating of the experimental platform were collected 1100 ultrasonic signals with their respective temperatures.

During the design of the architecture of neural network, it has been determined the following parameters:

1. Number of inputs to define the neural input layer. The number of inputs is significantly reduced after extracting the characteristics of the signal through the method of autoregression (AR). Network has been tested with different inputs as can be seen in Fig. 11, and the AR-10 method provides better results.
2. Numbers of outputs. A neuronal network with fewer outputs have better results that with more outputs. It was decided to have more outputs for the range of temperature range were lower. Thus, each range has a range of 2.7 °C, corresponding to eleven outputs elected.
3. The number of neurons in the hidden layer is considered by many authors. There is a criterion based on the number of inputs and training patterns. This is one of the main problems of MLP. For the calculation of the hidden neurons we've had on one hand the network performance through the mean square error and on the other the number of patterns to train. In this study we have trained, validated and

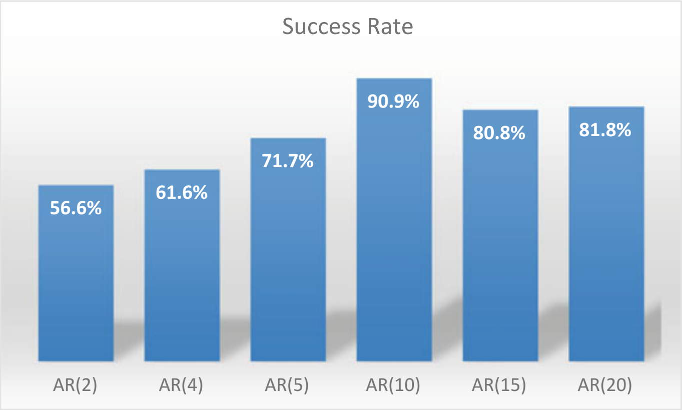


Fig. 11 Success rate of the AR employed

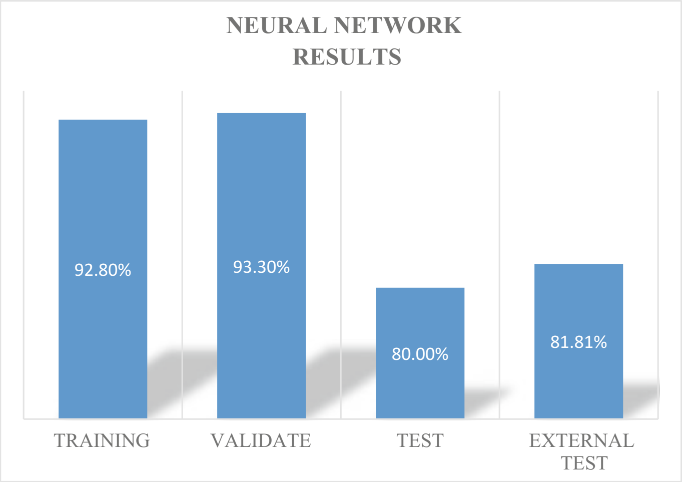


Fig. 12 Success rate of the neural network to determine the temperature range

tested 990 signals, leaving 110 signals for further test in order to generalise the neural network.

4. Scaled conjugate gradient and performance Cross Entropy has been training mode chosen as the best performance.

The established neural network architecture has been trained with the following results (Fig. 12).

5 Conclusions

A new system for condition monitoring and control for CSP plants is proposed based on the cloud computing. The main objective is to jointly benefit data processing, cooperative work between different power plants, optimization of resources, and increasing the performance of CSP plants.

In this chapter it has been studied the application and implementation of Big Data techniques for monitoring a CSP plant. The proposed technique for processing the data is a hybrid system which consists in Artificial Neural Network and Fuzzy Logic Controller, also known as Neuro-Fuzzy (ANNS-FLC). It has been shown that, based on data obtained through ultrasonic signals in the solar absorber pipes, it is possible to obtain parameters such as the temperature or the structural state of the pipe. A fuzzy logic expert system employ processing with 'SOFM' and 'MLP' neural networks in real time to determine the state of the plant and sets alarm.

The idea presented in this work proposed autonomous and optimal management of CSP plants. It is possible thanks to recent advances in hardware and software which are based on Big Data and Cloud Computing techniques. By using these resources, it is possible to intelligently manage and control a large number of similar CSP plants dispersed around the world.

Acknowledgements The work reported herewith has been financially supported by the Spanish Ministerio de Economía y Competitividad, under Research Grants DPI2015-67264-P and RTC-2016-5694-3.

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Wind Energy Power Prospective

Carlos Quiterio Gómez Muñoz and Fausto Pedro García Márquez

Abstract Wind energy and its perspective is introduced and described in this chapter. Wind farms, in contrast to conventional power plants, are exposed to the inclement and variability of weather. As a result of these variations, wind turbines are subjected to high mechanical loads, which require a high level of maintenance to provide a cost-effective power output and care the life cycle of the equipment. The demand for wind energy continues to rise at an exponential rate, due to the reduction in operating and maintenance costs and increasing reliability of wind turbines. Wind turbines make use of condition monitoring systems that allow information to be gathered regarding the condition of the main components, and determine anomalous operating situations. The power generation plants have incorporated a basic online monitoring control system. This system generally includes sensors for monitoring key machine parameters, such as temperature, speed, fluid levels, unbalance in the rotor, etc.

1 Introduction

The renewable energy industry is in a constant improvement in order to cover current demand. Wind farms, in contrast to conventional power plants, are exposed to the inclement and variability of weather. As a result of these variations, wind turbines are subjected to high mechanical loads, which require a high degree of maintenance in order to provide a cost-effective power output and maximise the lifetime of the equipment [1–3]. The demand for wind energy continues to grow at an exponential rate, due to the reduction in operating and maintenance costs and increasing reliability of wind turbines [4, 5].

Wind turbines make use of certain monitoring systems that allow evaluation of the status of critical components, as well as to determine anomalous operating

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situations. Power generation plants have incorporated a basic online monitoring control system. This system generally includes sensors for monitoring key machine parameters, such as temperature, speed, fluid levels, unbalance in the rotor, etc. [6].

Condition Based Maintenance (CBM) is an advanced maintenance strategy based on ascertaining the machine status using monitoring data. It is based on obtaining condition monitoring measurements from key wind turbine components [7–11]. The main objective of CBM is to optimise maintenance activities and reduce costs [12, 13].

The challenge for the future is to get a cheap source of energy, non-polluting, renewable and accessible to all countries in the world, allowing to reduce dependence on fuels to households, industries and transportation. Current data on wind power places it as the main renewable energy source globally. Its importance in the energy market is essential and all indicators show that this trend will continue in the near future.

This industry requires therefore of significant improvements in reliability, lifetime or availability that it is done by an efficient maintenance based on condition monitoring systems. Modern wind turbines need also an autonomous condition monitoring system because of the associated repair costs, especially for offshore plants, where any repair actions can extend several weeks due to the difficult working conditions [14].

2 Wind Turbines

Wind energy is gradually becoming more competitive in comparison with other energy sources [15]. Significant improvements in reliability, lifetime and availability can be expected from efficient maintenance and repair strategies on the basis of condition monitoring systems (CMS) [16]. The new wind turbines require of CMS in order to reduce the maintenance and operations costs, especially in offshore machines, where any corrective/preventive maintenance task can require several weeks before it can take place due to the deployment difficulties arising from weather and sea conditions as well as availability of appropriate vessels [17].

The evolution of wind energy over the past 15 years suggest that its importance will continue to grow in the future and will remain in a relevant position within renewable energy in the global energy scene [18].

Figure 1 shows the annual installed wind power capacity in the world from 1997 to 2014.

Wind Turbines (WT) are typically subject to high and varying loads, as well as extreme weather conditions. Consequently, the operational unavailability of Wind turbines reaches 3% of the lifetime of a Wind turbine. The operation and maintenance costs can account for 10–20% of the total Levelised Cost of Electricity (LCOE) and can reach 35% towards the end of the wind turbine lifetime.

A high degree of maintenance is necessary to provide safe, cost-effective, and reliable wind power generation [20]. This is even more critical for offshore wind farms (Fig. 2), where turbines cannot be reached during adverse weather conditions.

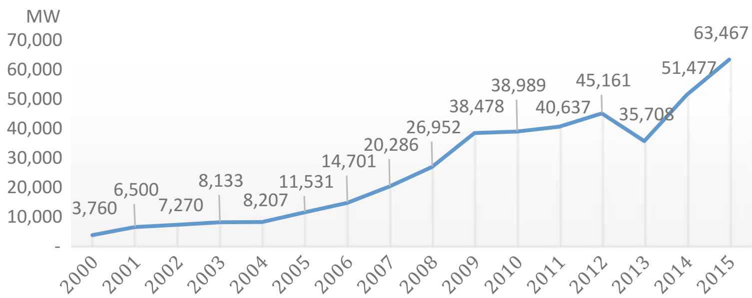

Fig. 1 Annual installed wind power capacity in the world [19]

Fig. 2 Offshore wind turbine in the wadden sea

Condition monitoring (CM) is defined as the process of determining the condition of system using various sensor measurements [9, 10, 22]. The main propose of CM is to identify a significant change in the condition of the system or its subcomponents which is indicative of a developing fault. It is usually considered as part of a predictive maintenance strategy, in which maintenance actions, and therefore preventive maintenance tasks, are scheduled to prevent failure and avoid its consequences [13, 23, 24]. The objective is to extend the life cycle of the system analysed, and to avoid major failures, resulting in considerable cost and associated downtime reduction.

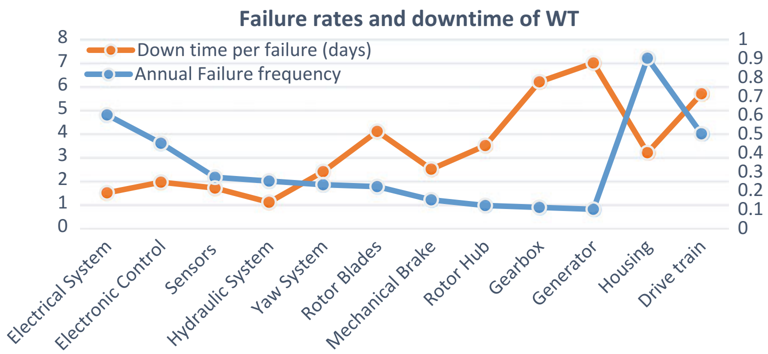

Fig. 3 Failure rates and downtime from two large surveys of European WTs over 13 years

Approximately 75% of the annual downtime in wind turbines is caused by only 15% of the failures [25]. It is more relevant to increase the condition monitoring in those parts that cause downtime bigger, not those having more failure rate [26].

The results published by Haln et al. [27] presents the average failure rate and average downtime per component. Figure 3 shows the three groups that cause the majority of downtime, i.e. the blades, gearbox and drive-train. Condition monitoring efforts should focus on these parts.

In the field of wind turbine, condition-monitoring is used to determine the optimum point between corrective and scheduled maintenance strategies [25, 28–30]. Maintenance approaches in the wind energy industry can be classified into three main groups:

- Corrective maintenance: The reaction is initiated after the failure occurs.
- Preventive maintenance: The operative period of a wind turbine is around 20 years [27, 31] and most of the failures are predictable using time-based strategies.
- Predictive maintenance. This strategy is based on the condition of the wind turbine. By knowing the structural condition of the parts of the machine it is possible to detect defect in an early stage.

There are several non-destructive testing (NDT) methods for structural health monitoring of wind turbine blades, such as acoustic emission [12, 32, 33] or conventional ultrasonic inspection [32, 34–37].

2.1 Wind Turbines' Blade Failures

Some Wind turbine blades are made from composite materials based on glass fibres. Normally a spar made also of composite materials which can also be based on tape wound fibre glass or in larger blades of carbon fibre, supports the outside glass fibre composite skin of the blade and provides structural stiffness. The need to manufacture blades with a complicated geometry due to the aerodynamic efficiency requirements, low weight and satisfactory mechanical properties has led to the use of composite materials by default. One of the important factors is the resistance of such materials to fatigue damage initiation and propagation. Also these materials have low thermal expansion and low thermal conductivity.

A composite material is formed by long and straight fibers impregnated within a polymeric matrix that surrounds, binds and protects fibres. Laminates are made by superimposed layers of fibres in the thickness direction. The material properties depend on orientation, stacking sequence and physical properties of fibres as well as the choice of matrix material. Sandwich structures are composed of two outer skins covering a material that is lightweight called core. The set results in a material of high rigidity and light weight. The core is thick compared to the outer skins and has a much lower density. The core function is to prevent relative movement of the skin. To lower production cost E-glass fibres are most widely used in combination with epoxy resins. Icingblade Failures. Wind farms are located in areas with suitable wind characteristics.

Icingblades has become a problem in regions where climatic conditions can lead to icing almost throughout the entire year. The ice affects the aerodynamic efficiency increasing the surface roughness and reducing power output efficiency of wind turbines. It also causes imbalance of the rotor, leading to higher stresses being applied on both the blades and the drive-train. The wind turbines require to be stopped until de-icing has been completed causing significant production losses and associated costs.

A study conducted during the *IcingBlades* research project [38] revealed that 517 wind turbines, with a total installed power output of 682 MW, failed to produce 18,966 MWh over a 29 month period solely due to ice on the blades in Spain. This energy loss is practically equivalent to the sum of all major incidents: gearbox replacement, generator replacement, etc. [39]. Extrapolating these figures to Spain, with more than 21,000 MW installed, this would be equivalent to a production loss of 550 GWh and, therefore, 45 million € every 29 months. The avoidance of these production losses would be equivalent to the consumption of 200,000 homes and 658,682 tonnes of CO_2.

Onshore wind farms are usually located in elevated areas in order to get the maximum wind velocity [40]. Suchg locations are often exposed to freezing temperatures, presenting multiple problems due to icing of blades and resulting power generation losses and costs [41]. The WECO (Wind Energy in Cold Climate) project analysed the ice effects, energy generation and icing in wind turbines. It is estimated that 20% of the wind farms are installed in areas with high probability of icing [42].

2.1.1 Ice Formation

Parameters such as temperature, wind speed, relative humidity or air density, among others, condition the ice appearance (see Fig. 4). A classification of different types of icing is presented in reference [43], discerning between in-cloud icing and precipitation and hoar frost. In-cloud icing appears when the atmospheric temperature is below 0 °C and the humidity is high. Super-cooled water droplets hit the surface of the structure and freeze at the time of impact. The major problem is the accumulation of different layers of this kind of ice.

Frost is the most common cause of ice appearance in wind turbines. It grows in all parts of the wind turbine but the onset occurs in the leading edge of the blades, owing the incident velocity [44, 45].

2.1.2 Wind Turbine Phases During Ice Accretion

Wind turbines do not operate properly when ice accumulation is considerable. Consequently, the machines need to be stopped. In the first stage, prior toicing, the wind turbine is working in optimal conditions. In a second stage, icing starts but the wind turbine can operate until it reaches the icing limit alarm. In the third stage, the ice accumulation continues and the turbine needs to be stopped to prevent possible damage from occurring [46]. In the last stage, post-icing, the turbine continues to be stopped until the ice is completely removed.

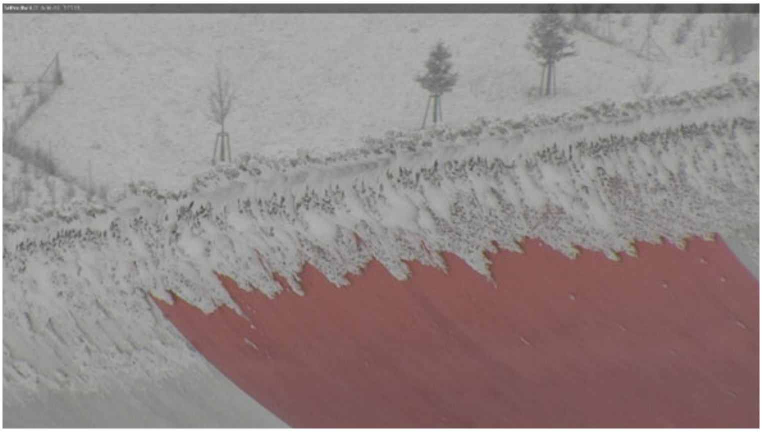

Fig. 4 Ice at rotor blade of a wind turbine

The objective for the ice prevention or removal systems is the reduction of the wind turbine downtime. The mitigated wind turbines are those with a system incorporated in order to deal with ice accretion. During the icing stage, the ice growth is controlled by the system installed in order to avoid the alarm, reducing the necessary downtime to remove the ice from the turbine. When the accumulation is significant, the alarm appears and the wind turbine is stopped until the ice is removed. Downtime is lower than those in the non-mitigated machines. During post-icing the wind turbine can operate [47].

2.1.3 Failures due to Icing and Cold Climate in Wind Turbines

The main problems due to icingblades can be summarised as [48]:

- *Power loss by the reduction of aerodynamic efficiency*. The presence of ice modifies the aerodynamics of the blades by increasing the coefficient of friction and making turbulences, vibrations and noise, as well as a reduction of revolutions.
- *Loads on turbines*. The icing on blades makes loads on the turbine. Icing causes an increase in mass, drag coefficient, imbalance of the rotor and vibrations.
- *Influence in the lifetime of the components*. The fatigue due to loads reduces the life expectancy of the components of the wind turbine, e.g. blades, hub, gearbox, shafts, etc.
- *Increased noise generated by blades*. The drag coefficient of the blades increases due to icingblades.
- *Changes in blade surfaces by ice accretion*. The frozen layer modifies the thickness of the boundary layer, and therefore the air transition characteristics on the blade.
- *Safety hazards*. A problem arises owing to that the ice fragments can break off of the blades and can impact against the ground or other objects.
- *Measurement errors*. During the icing process, the anemometers, temperature sensors and wind vanes are exposed to icing conditions, showing measurement errors higher than 40% [49].

Wind farms located in these areas present problems related to icing such as energy losses, mechanical failures, downtimes, problems to access for human resources, measurement errors or safety hazards among others (see Fig. 5). An analysis carried out by the authors, as part of the research project *IcingBlades* [38], showed that 18,966 MWh were lost over a period of 29 months as a sole consequence of blades icing up in a set of 517 wind turbines with a total installed power of 682 MW. This waste is practically equivalent to all the other major stoppages together (change of multiplier, turbine change, and so on). Extrapolating this to a national (Spanish State) level, with more than 21,000 MW installed, this phenomenon would be equivalent to a loss larger than 550 GWh of power production and, thereby, to about 45 million € over every 29 months. Avoiding these

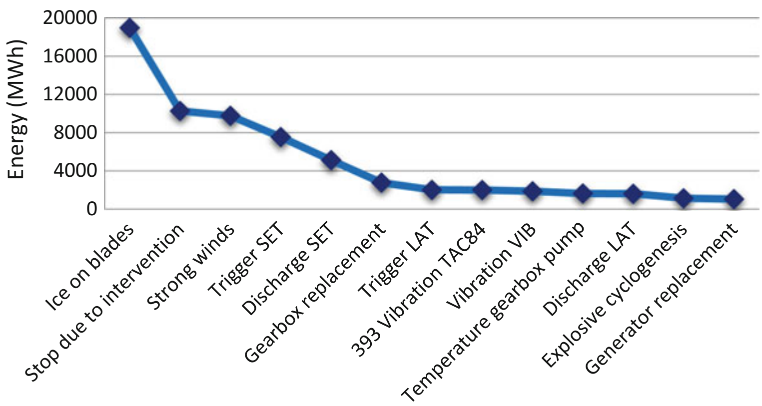

Fig. 5 Power losses due to different alarms in icing blades

production losses would be equivalent to the energy consumption of 200,000 households and savings of 658,682 tons of CO_2. Figure 5 shows the main causes of the production energy losses. Note that ice on blades is the principal one. These energy losses involve an increment of the operation and maintenance (O&M) costs.

2.2 *The Soiling and Erosion Failures*

Often, the wind farms are in areas difficult to access, making it difficult to evaluate and clean the blades. The accumulation of dirt and mud on wind turbine blades represents a decrease in the performance of power generation. Stall on the blade is occurred due to changes in aerodynamic performance.

Wind turbine soiling is a leading edge surface contamination problem characterized by accumulation of foreign objects on the leading edge [50]. Examples of foreign objects are: insects, mud, dust, salt which collide with the blade when it rotates. The soiling of the blades may be due to factors such as flying insect population, intermittent rain, low humidity and farming activities. The geographical situation and the season also affect the severity of soiling. The accumulation of the foreign objects on the leading edge reduces the blade performance and the energy production, and it increases the noise emitted by the wind turbines (Fig. 6).

Soiling produces disturbances in the air flow, concretely in the layers near the surface, generating a turbulent regime in the air flow and favouring the emergence of the 'stall' phenomenon. The kinetic energy is decreased and therefore, the mechanical rotation energy is diminished. Finally, the amount of electricity generated is reduced. Soiling can also reduce the aerodynamic efficiency of the blade which increases noise emissions [51]. In addition, it can be produced false alarms due to the reduction of performance of the wind turbine.

Fig. 6 Soiling of the surface of a WT blade

Other effects of soiling include additional costs associated with the cleaning of the blades. Cleaning WT blades is an expensive operation that requires a special equipment such as cranes, qualified staff, etc. It is necessary also to stop the wind turbine, with the consequent loss of power generation. Some of the efforts to mitigate the soiling problem are shown in references [52–57].

3 Outlook 2050

An important objective of the Wind Energy Roadmap given by the European Commission is: "*improve the reliability of the wind turbine components through the use of new materials, advanced rotor designs, control and monitoring systems*", we propose this PhD research training programme. The key objectives are:

It addresses the needs to design and develop the new technologies essential in overcoming the challenging condition monitoring and control problems currently acting as a barrier to improved wind turbine reliability and reductions in the cost of energy from offshore wind power generation.

Energy security and global warming have led to wind energy becoming one of the fastest growing renewable energy sources (RES) in the world, aforementioned. In the EU, a significant number of offshore wind farms have already been constructed or are being planned; large wind turbines with rotor sizes up to 180 m in diameter (e.g. Vestas 8 MW V-164 with rotor size 164 m) have been or will be manufactured and installed to effectively exploit wind resources in remote offshore areas. Wind energy was a key energy priority of the EU Framework Programme 7, and is one of the main technologies to be further promoted to provide low cost and low carbon electricity in Horizon 2020. The market and technological objectives of the EU wind energy industry are ambitious. In the "Energy Roadmap 2050", the European Commission (EC) expects that by 2050, the share of RES in electricity consumption will reach up to 97% in a high renewables scenario, and the wind power will provide more electricity than any other technologies. In addition, according to “European Wind Initiative: Wind Power Research and Development to 2020”, the European wind industry and the EC plan to make onshore wind the most competitive energy source by 2020, with offshore following by 2030, and achieve a 20% share of wind energy in EU total electricity consumption creating 250,000 new skilled jobs by 2020. These give the wind energy industry huge potential for growth both in Europe and globally.

Offshore wind turbines benefit from more favourable wind conditions present in the open sea, as compared to onshore conditions. However, their installation in a remote and harsh marine environment places much greater demand on reliable and sustained operation in order to minimise the need for costly repair and maintenance activities. This poses a major challenge to almost all wind energy related technologies. In order to meet these challenges and satisfy the ambitious demand for wind energy over next two decades, the EC published the Wind Energy Roadmap on 7 October 2009. Following the roadmap, a series of actions were planned to address research, development, and demonstration challenges in the technological areas associated with the widespread implementation of wind energy. A key objective of these actions was to “*improve the reliability of the wind turbine components through the use of new materials, advanced rotor designs, control and monitoring systems*”.

4 Conclusions

This chapter book has showed the reasons that justified the development and use of the wind energy in the worldwide from the technical and economic point of view. This industry requires of complex and advanced condition monitoring system in order to increase the reliability, availability, maintainability and safety of the system. It will also reduce the cost and increase the probability.

The main failures are presented, where they are analysed in details for the blades, due mainly by icingblades, and soiling and erosion.

Finally, he main objectives of the wind energy roadmap for 2050 given by the European Commission are analysed and presented.

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Managing Costs and Review for Icing Problems

Jesús María Pinar-Pérez and Fausto Pedro García Márquez

Abstract The weather conditions have a key role in energy production of wind farms. Ice can appear in regions with cold conditions or during winter season. Ice on blades reduces the efficiency of the turbines, increases failures and downtime and causes imbalance of the rotor. This results in power losses which can be translating in operational costs that can reach millions of euros. Therefore, it is necessary to research and develop new methods for detection, prevention and removal of ice from blades. This chapter presents the current state of the art on ice detection and mitigation. Various techniques of detection, anti-icing and de-icing tare considered. Finally, an economic analysis of a selection of commercial ice detection systems is carried out.

Keywords Wind turbines · Icing blades · Maintenance management

1 Introduction

The appearance of ice on wind turbine blades has adverse effects including production losses, unbalanced rotor loads, effect on expected lifetime of components, uncertainties in production forecasts, increase noise generated from the rotor, and safety implications since ice can become detached and thrown away several hundred metres away from the wind turbine [1].

Blades are critical components of wind turbines [2]. The formation of ice changes the aerodynamic performance of the blade and causes mass imbalance of the rotor resulting in excessive vibrations and losses in power generation [3]. Some components of the wind turbine can be damaged, e.g. a known failure caused by

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icing is the yaw system [1]. The drive-train can also become damaged due to the imbalance effects arising from the rotational movement of the rotor.

The accumulation of ice on wind turbines can force machines to be stopped in order to prevent possible damage from occurring. Associated downtime is unavoidable until icing-related problems have been addressed (repair or remove the components damaged, wait for de-icing, etc.).

In 2003, a study was published, which reported 880 ice throwing incidents between 1990 and 2003 in Germany [4]. The safety of both maintenance staff and people living near wind farms must be taken into account due to the risk of ice throwing.

An analysis of wind turbine failure statistics in Finland between 1996 and 2008 is presented in reference [5]. This study shows that icing (4% of total downtime) is not the main problem concerning downtime but must be taken into account for safety reasons. Reference [6] shows another Finnish downtime analysis of wind turbines. It suggests that icing varies from 4 to 28% of total downtime recorded depending of the location of the wind farm.

The research project ICINGBLADES analysed more than 500 wind turbines with 682 MW of installed power. This analysis found that ice on blades were the largest alarm with 18,966 MWh lost during the analysis (see Fig. 1) [7].

The effect of ice in wind turbines leads to operational costs in the range of several millions of euros due to power production lost. Therefore, the reduction of O&M costs and improvement of RAMS (reliability, availability, maintainability and safety) can be achieved if icing problems associated with wind turbine blades can be mitigated to avoid loss of energy production and associated costs. Currently, wind energy industry is focused on the development and installation of condition monitoring systems (CMSs) and SCADA systems to detect, predict or remove ice on the blades and reduce such effects. Different techniques and methods of CMS for wind turbines are described in reference [8].

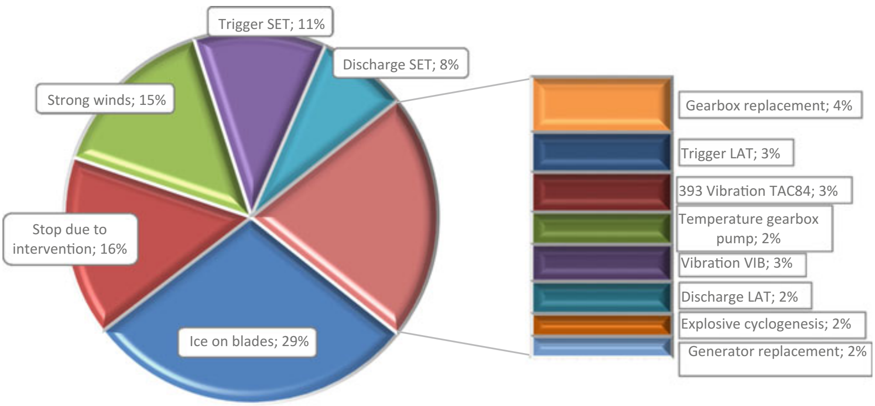


Fig. 1 Percentage of losses due to different alarms in ICINGBLADES project

In this work the icing blades problem is described, the methods for ice detection, prevention and removal are shown and finally an economic analysis for some detection systems is carried out.

2 Icing Problem

Mountains or hill tops are typical locations for onshore wind farms but these areas are often exposed to freezing conditions. The height of wind turbines is another parameter to take into account for icing. The increasing height of new wind turbines raises the icing risk [1].

Different parameters such as temperature, wind speed and humidity plays a key role in ice accretion or ice development. The normative of atmospheric icing of structures (ISO 12494, 2001) makes a classification of different types of icing: In-cloud icing, precipitation, and hoar frost [9]. The most prominent form of ice growth is the frost that occurs when the temperature is below 0 °C, with a certain speed and humidity. It has been observed that this growth starts at the tips of the blades. The WECO study (Wind Energy in Cold Climates) [10] shows that fusion occurs when the temperature rises. The ice accumulated in the rotor may cause malfunction of the sensors producing stops for safety operations. The least desirable form of ice growth is the formation of ice in clouds.

When wind turbines operate under the ice conditions, the occurrence of icing is usually at the tips and front edges of the blades as Fig. 2 shows.

The most important problems arising from ice on blades are collected in reference [11]:

- Power losses by the reduction of aerodynamic efficiency. Reference [12] presents a wind speed—power graph for icing and normal conditions showing losses when icing accretion occurs.

Fig. 2 Ice on the rotor of wind turbines

- Loads on the rotor of wind turbines. The stochastic nature of icing accretion on the different blades makes the imbalance of the rotor resulting in poor power production capabilities and increased blade and rotor vibrations.
- Mechanical and electrical failures and the influence in the lifetime of the components. Fatigue due to loads reduces the life expectancy of the components of the wind turbine such as blades, hub, gearbox, shafts, etc. [11].
- Increased noise generated by iced blades,
- Changes in blade surface. Ice modifies the thickness of the boundary layer of the blades and thus the air transition characteristics [13].
- Ice throwing. The fragments of ice located on blades can break off making a non-safety area.
- Measurements errors by anemometers or temperature sensors.

3 Detection, Prevention and Removal of Ice Methods

If there is ice on the blades the wind turbine will stop. The most important issue for the maintenance of blades is the detection of ice. Then, the operator of the wind farm can schedule maintenance task and/or intervene to avoid ice. Anti-icing prevents the formation of ice and de-icing removes the ice when a predetermined amount has accumulated [1]. Therefore, sensors, thermocouples or heaters were installed on blades as Fig. 3 shows.

Table 1 shows the different methods or techniques to detect, prevent and remove ice from blades. Detection methods can be divided in two: direct techniques and

Fig. 3 Installation of sensors on a blade in the laboratory

Table 1 Methods for detect, prevent and remove ice from blades

Detection	Anti-icing	De-icing
Direct techniques • Damping of ultrasonic waves [20] • Measurement of frequency in resonance [15] • Vibration measurement of a diaphragm [21] • Measurements of temperature change • Measurement of electric properties [16–18, 22] • Measurement of ice loads [23] • Optical measurements: Direct measurement of the reflected light [24] Infrared spectroscopy [14, 23] Reflection from inside of surface	• Heating blades or air layers [25, 26] • Ice-repellent coating [27, 25] • Microwaves [28, 29] • Black paint [30, 31] • Chemical products [32]	• Heating resistance [33] • Warm air and radiators [33] • Electro impulsive/expulsive. (Electromagnetic vibration) [25] • Mechanical removal by pneumatic elements [34, 35] • Flexible blades • Active Pitching
Indirect techniques • Difference in expected and real power output [10] • Heated anemometers [1] • Dew point and temperature [17] • Direct measurement of liquid water content and mean volume of raindrops • Video Monitoring • Noise measurements [1] • Probability frost maps [23] • Ultrasonic techniques		

indirect techniques. Infrared spectroscopic through fiber optic cables [14], resonant frequencies [15], capacitance [16], inductance [17] or impedance-based sensors [18] are the techniques that reach the best quality results. Other methods compare normal operating curves for a specific wind speed and temperature [19], the variation of the forces that appear on the blades, the variation of electrical energy output or noise.

Anti-icing and de-icing techniques are introduced and classified into active and passive approaches. The passive procedure consists of physical properties of the wind turbine blades to prevent and de-ice such as special coatings, black paint and chemical products. Some European operators coated blades with different materials and special paint. They concluded quite early that these methods are not sufficient to prevent icing [36].

The active approach consists of external equipment consuming power. The systems usedare divided in anti-icing and de-icing ones. Thermal [26], air layers [25] and microwaves [28, 29] are used for anti-icing., Heating resistance [33], warm air and radiators [33], electro impulsive/expulsive [25] and pneumatic flexible boots [34] are used for de-icing, e.g. based on boots which blow up to break up the ice.

The boot fits over the blade. When ice increases from 6 to 13 mm the system is activated and breaks up the ice. The boots blow compressed air. When the ice is thrown away by centrifuge and aerodynamic forces, the boot comes back to his original position by vacuum eliminating the imperfection on the surface. Some of these techniques have been tested in laboratories but not yet on wind turbines [37].

4 Sensors for Ice Detection Methods

Detection of ice on blades capability has been implemented in several wind farms. De-icing and anti-icing systems are not taken into account for the following study due to the focus on CM system.

Table 2 shows some ice detection sensors (commercial sensors) that can be implemented in condition monitoring system of wind turbines. This table describes the main characteristics and the techniques employed by each sensor. More information about these sensors can be found in reference [37].

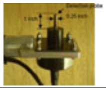
5 Costs Analysis for the Implementation of a Selected Detection Sensors in CM System

This chapter analyses the costs of a selection of ice detection methods implemented in wind turbines. This work takes into account the costs of investment, operation and maintenance and energy losses of the different detection systems. For this purpose, a Life cycle cost (LCC) analysis has been performed. The main objective of the LCC study is to determine whether the ice detection system recovers their investment costs and provides certain economic benefits throughout its lifetime. The LCC model described in references [38] is the base of the model of this research including direct and indirect initial costs plus any periodic or continuing costs for operation and maintenance [39]. The following expression was taken into account for this purpose:

$$Y = \sum_{i=1}^{n} y_{\mathrm{i}} = \lambda \sum_{\mathrm{i}=1}^{\mathrm{n}} a_{\mathrm{i}} c_{\mathrm{i}}^{\mathrm{T}}$$

where **Y** is the total cost, $Y = [Y_1, \ldots, Y_{\mathrm{t}}, \ldots, Y_{\mathrm{T}}]$; Y_{t} denotes the cumulative cost in year t; the subscript T is the total number of years; y_{i} indicates the cost of breakdown in category I; and λ is the net present value vector. All the costs are usually discounted, and the total to a present day value is known as the net present value (NPV) as shown from the following equation:

Table 2 Some ice detection sensors to implement in CM system of wind turbines

	Ice detection system	Manufacturer	Condition	Operating Temp. (ºC)	Power Supply	Power Consumption (W)	Technique
	LID-3300IP	Labkotech	Normal	[− 30º:60º]	230 V VAC, 50/60 Hz	7	Vibration measurement of a diaphragm
			Heating			350	
	0871LH1 Freezing Rain Sensor	Goodrich	Normal	[− 55:71]	[22:29.5]	15	Measurement of frequency in resonance
			Heating			50	
	Ice Load Surveillance Sensor	Combitech	Normal	[− 40:50]	[11:26]	100	Measurement of ice loads
			Heating			2000	
	Ice Meister Model 9734	New Avionics Corporation	Normal	max 50 °C	[12:36]	2	Optical Measurement of the reflected light
			Heating			50	
	HoloOptics Series T40 Sensor	HoloOptics	Normal	–	[12:48]	1.5	Optical Measurement
			Heating			60	
	WXT-520	Vaisala	Normal	[−52:60]	[5:32]	42341	Measurement of various climate parameters
			Heating		[5:32]	50	
	WAA252 Anemometer	Vaisala.	Normal	[−55:55]	24	72	Measurement of Wind Speed
			Heating			1	
	WAV252 Vane	Vaisala.	Normal	[−55:55]	12	50	Measurement of wind direction
			Heating		24	1	

(continued)

Table 2 (continued)

	Ice detection system	Manufacturer	Condition	Operating Temp. (ºC)	Power Supply	Power Consumption (W)	Technique
	IceFree3 Anemometer	NRG Systems	Normal	[−40:60]	–	–	Measurement of wind speed
			Heating		24 CC/CA		
	IceFree3 Wind Vane	NRG Systems	Normal	[−40:80]	1–25 DC	–	Measurement of wind direction
			Heating		24 CC/CA		
	DSC111	Vaisala	Normal	[−40:60]	9–30 CC	1.9	Infrared spectroscopy (Optical measurement)
			Heating			4	
	Blade Control	Rexroth (Bosch Group)	Normal				Measurement of frequency in resonance
			Heating				

$$NPV = -I_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+k)^{t-1}}$$

being I_0 the initial investment, CF_t the cash flow in t and k the annual rate of return on investment. Additionally, assuming that the previous costs remains constant throughout the lifetime of the project, $CF_1 = CF_2 = \cdots = CF_T = CF$, the NPV factor λ is given as follows:

$$\lambda = \sum_{t=1}^{T} \frac{1_t}{(1+k)^{t-1}} = \frac{1}{k}\left[1 - (1+k)^{-T}\right]$$

Considering the above expressions, the NPV value can be calculated as

$$NPV = -I_0 + CF \cdot \lambda = -I_0 + \frac{CF}{k}\left[1 - (1+k)^{-T}\right]$$

The LCC analysis is carried out with data acquired from the IcingBlades project. A total of 517 turbines with 682 MW of power are analysed in 29 months finding 227,146 downtimes registered [7].

This work assumes that n = 4 being:

- i = 1, the investment cost. is related to the costs of capital. These costs include the general investment costs, the installations costs and other costs such as regulatory approval or initial testing.
- i = 2, the operation cost is related to the costs incurred by the technical operation process in a period of time.
- i = 3, energy production and energy losses by ice detection systems. The cost due to production losses is given by the difference of production losses employing and not employing the ice detection system
- i = 4 the maintenance and maintenance reductions reached by ice detection systems. It is the difference between the total maintenance costs with and without ice detection system.

Failure rates and downtime were used in this research work to calculate the costs described above. Reference [40] shows failure rates and downtimes for different components of different types of wind turbines (Fig. 4).

Three different scenarios have been established to compare the results with different characteristics (Fig. 5):

- *Generic scenario*: In this scenario, ice detection systems have the same probability values of reduction of energy losses and reduction of maintenance. The investment costs of the different ice condition monitoring systems can be compared in this scenario.
- *Favourable scenario*: In this case, wind turbines are operating in favourable climate conditions. In this case, the percentage of downtimes due to ice

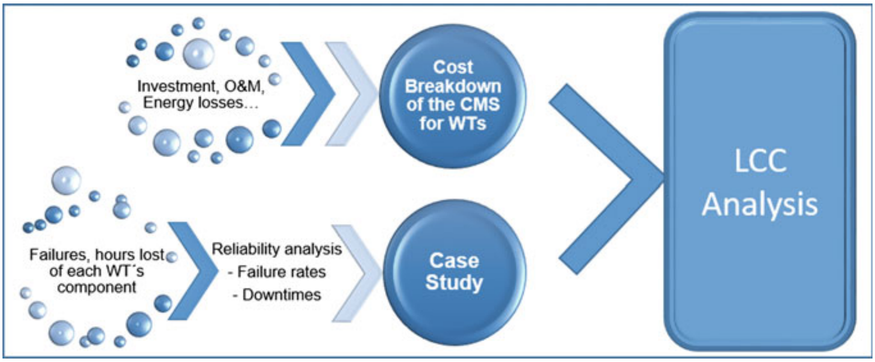
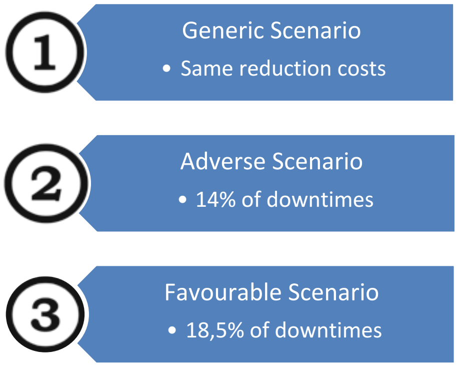


Fig. 4 Life cycle cost scheme

Fig. 5 Characteristics of the scenarios employed



accretion is assumed to be a 14.05% of the total wind turbine downtimes [7]. The values for the probability of reduction of energy losses depend on the type and the technique used by each ice detection system.

- *Adverse scenario*: In this case, wind turbines are operating in adverse climate conditions. The percentage of downtimes due to ice accretion is now assumed to be 18.49% of the total wind turbine downtime [7].

Finally, the LCC model described above has been applied to the following ice detection systems: Ice Load Surveillance Sensor, NRG IceFree3, BladeControl, 0871LH Goodrich and HoloOpticics.

Table 3 shows the results of the LCC for the above sensors through the different scenarios stablished before and for rates of return of 1 and 10%. BladeControl sensor system requires the largest investment and the recovery will be complex before ten years. Although Ice Load Surveillance Sensor has a high investment, it will be recovery until 10th year with profits in all scenarios. The investment on NRG IceFree3 will be the first to recover in all scenarios following by 0871LH Goodrich sensor which will reach the best profits until 10th year. HoloOptics sensor

Table 3 LCC's results for the ice detection CMS and scenarios using a rate of return of k = 1% and k = 10%

Device (Investment)		Scenario 1: Generic		Scenario 2: Favourable conditions		Scenario 3: Adverse conditions	
		k = 1%	k = 10%	k = 1%	k = 10%	k = 1%	k = 10%
ILSS	Recovery	4 years and 2 months	3 years and 6 months	3 years and 1 month	2 years and 6 months	4 years and 2 months	3 years and 7 months
(-12507,5)	Value 10th year	11,200 €	24,000 €	18,500 €	35,200 €	9,200 €	21,000 €
NRG IceFree3	Recovery	11 months	10 months	1 year and 5 months	1 year and 3 months	2 years and 1 month	1 year and 9 months
(-5216)	Value 10th year	32,400 €	52,700 €	21,500 €	36,000 €	23,000 €	13,100 €
BladeControl	Recovery	7 years and 6 months	5 years and 3 months	No recovery	7 years and 3 months	No recovery	No recovery
(-15480)	Value 10th year	3,100 €	13,200 €	**−1,900 €**	**5,500 €**	**−9,600 €**	**−6,400 €**
0871LH Goodrich	Recovery	2 years and 11 months	2 years and 5 months	1 year and 11 months	1 year and 8 months	2 years and 7 months	2 years and 2 months
(-10661)	Value 10th year	16,200 €	30,800 €	29,600 €	51,500 €	19,700 €	36,200 €
HoloOptics	Recovery	2 years and 3 months	1 year and 11 months	1 year and 10 months	1 year and 7 months	2 years and 7 months	2 years and 3 months
(-8950)	Value 10th year	19,800 €	35,400 €	25,100 €	43,500 €	16,200 €	29,800 €

has better results than 0871LH for scenarios 1 and 2 but the opposite occurs for the scenario with adverse conditions. The results of this study could change due to other variables such as weather, life time of the components, wear and type of wind turbine.

6 Conclusions

A significant economic problem for operators of wind turbines appears with icing blades. Ice can reduce the aerodynamic efficiency of the blades, generating failures, downtimes, and contributing to unscheduled maintenance requirements.

In this research work, a state of the art of the ice problem together with some techniques and methods of detection, anti-icing and de-icing has been presented describing solutions that have been or can be implemented. To date neither active nor passive systems are completely effective against initial ice formation and subsequent ice build-up on the turbine blades. Future research focused on the blade coatings and the continued development of new compounds may constitute satisfactory solutions to the problem of de-icing.

Finally, an economic study of a selection of commercial ice detection systems has been carried out, finding that not all sensors are capable to recover the initial investment before the 10th year.

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Big Data and Wind Turbines Maintenance Management

Alberto Pliego, Raúl Ruiz de la Hermosa and Fausto Pedro García Márquez

Abstract Nowadays, the modern technologies and processes demand a big amount of information in order to be optimised. As the consequence, a huge amount of data is being generated. This is the main cause of the current boom for the so called Big Data. There are a lot of systems and sensors capable of generating such data but the processing of these data is currently becoming an arduous task. This chapter is focused on the analysis of the Big Data associated with the maintenance of wind farms. An analysis of the data coming from Condition Monitoring and Supervisory Control and Data Acquisition Systems will be carried out. This analysis will be done using two methods whose objectives are to reduce the amount of data and, therefore, to facilitate the data processing. Two case studies will be presented in order to clarify how these methods should be applied.

1 Introduction

Nowadays, the amount of data generated by all sectors of the economy and the society is growing exponentially. The information and the communication technologies and the automation of the industrial processes are currently some of the most important generators of data. For instance, the internet has become the biggest producer of data in the entire history of humanity.

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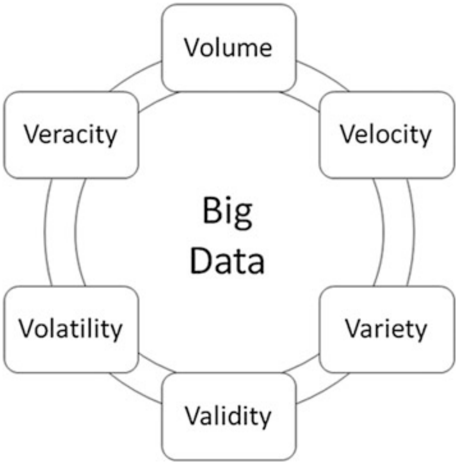

Fig. 1 Dimensions of Big Data

The comprehension of data is an activity that has always accompanied to the human beings. However, in this "Information Age", the capacity and the necessity of acquiring, producing and generating data have reached unimaginable dimensions. As a result, the conventional data processing methodologies have become obsoletes. This is the reason why the new concept of "Big Data" is emerging. Big Data can be considered as a modern socio-technical phenomenon [1] that appears as a consequence of the current massive data generation. Some well-known companies that employ Big Data to obtain useful information are Google, eBay, Amazon, Facebook, Twitter, IBM, LinkedIn, AOL, etc. [2]. For example, it is estimated that Google processes more than 25 petabytes (25×10^{15} bytes) every day.

The Big Data has been defined in the industrial field by six dimensions that can be called "The 6 Vs" (see Fig. 1). This term concerns the following dimensions [3, 4]: Volume (the amount of data), Velocity (the speed at which data is created), Variety (the different natures of the data), Veracity (the certainty of data meaning), Validity (accuracy of data) and Volatility (how long the data need to be stored).

These dimensions will determine the type of Big Data that is being considered. The complexity of the Big Data analysis is further defined by the volume, the velocity, the variety and the volatility. The usefulness of the analysis is usually dependent on the validity and the veracity of the data.

Besides the communication systems, social networks and companies that operate online, there is a significant source of Big Data related to the digital sensors worldwide in industrial equipment, automobiles, electrical meters and shipping crates. These sensors are capable of evaluating locations, movements, voltages, vibrations, magnetic fields and countless variables of a certain system. This concerns not only the volume of data that is generated but also the variety of such data.

This chapter is focused on the particular case of the Big Data generated by the equipment of the wind farms.

2 Big Data and Wind Turbines

The large number of data generated by the monitoring systems results in complex scenarios when they need to be treated. Data can come from different sources and their content can be completely random. Even so, the information can be correlated and their sorting can be useful for decision making. This situation is a common link in almost all industrial sectors where the incorporation of new technologies and the emergence of Condition Monitoring Systems (CMS) supported by Supervisory Control and Data Acquisition (SCADA) systems make the data processing a critical factor [5].

The field of the renewable energies is one of those sectors where the previous issue arises. The high volumes of data used in the operations and maintenance (O&M) tasks makes the introduction of Big Data a key factor. Wind farms usually divide the data analysis in three categories for decision making: descriptive analysis, post-event diagnostics and prognostics. The first category identifies the features with statistical calculations and graphics. The second category analyses the cause-effect of any change from a threshold. Finally, the prognostics predict the system changes [6].

Descriptive analysis is the basis of the following steps. Data collection must be as wide as possible to obtain a first approach. One of the first relationships that wind farms consider is the wind speed and power output connection. This is due to the fact that different wind farms can have wind turbines with similar specifications and their comparison can reveal the most efficient conditions.

The prognostic analysis is based on predictive modelling where several techniques such as regression trees or neural networks can be introduced to have an accurate model. Diverse inputs can be considered, e.g. speeds, electromagnetic data or vibration, to develop the model. The application of the techniques will entail the detection of degraded performances at earlier stages [7].

2.1 Condition Monitoring Approaches for Wind Turbines

Most of the wind turbines (WTs) are three-blade units [8, 9]. The energy generated by the blades is redirected from the main shaft to the generator through the gearbox. At the top of the tower, assembled on the foundation, the nacelle is found. A yaw system controls its alignment from the direction of the wind. The pitch system is mounted in each blade to position them depending on the wind. It also acts as an aerodynamic brake when needed. Finally, a meteorological unit provides information about the wind (speed and direction) to the control system.

Condition monitoring (CM) is implemented from basic operations of the equipment to study [10]. The system provides the "condition", the state of a characteristic parameter that represents the health of the component(s) being monitored. CM operates from different sensors and signal processing equipment in

WTs. The main purpose is to monitor components ranging from blades, gearboxes, generators to bearings or towers.

CM reduces interferences during the features transport. Data processing, sorting and manipulation according to the objectives pursued, are usually performed by a digital signal processor. Then it can be shown, stored or transmitted to another system. One of the advantages for these systems is, therefore, that monitoring can be processed online or in certain time intervals. Thus, it is possible to maximise the productivity, to minimise downtimes, and to increase the Reliability, Availability, Maintainability and Safety (RAMS) levels [11].

Different techniques are available for CM:

- Vibration analysis [12].
- Acoustic emission [13].
- Ultrasonic testing techniques [14].
- Oil analysis [15].
- Thermography [16].
- Other methods.

The accurate data acquisition is critical to determine the occurrence of a failure and the subsequent solution. This can be achieved with the optimal type, number and placement of sensors. Data acquisition is always the first step of the CM process and includes the measurement of the required conditions (e.g. sound, vibration, voltage, temperature or speed), turning them into electronic signals. Then, signal processing introduces the handling (e.g. fast Fourier transform, wavelet transforms, hidden Markov models, statistical methods and trend analysis) and storage of data.

2.2 Supervisory Control and Data Acquisition Systems for Wind Turbines

SCADA systems are currently being introduced in WTs due to their effectiveness has been proved in other industries for detection and diagnostics of failures [17]. They are presented as an inexpensive and optimal solution to [18] control feedback for the health monitoring while reducing the O&M costs [19]. Nevertheless, they also present some minor disadvantages due to the operational or reliability conditions [20].

The SCADA system considers a large amount of measurements such as temperatures or wind and energy conversion parameters [21]. These data have raised considerable interest in different areas, e.g. wind power forecasting [22], production assessment [23] and of course, for fault detection [24].

In the case of the WTs, the introduction of SCADA systems verifies the efficiency when their components deteriorate. This degradation can indicate problems of different nature such as misalignments in the drive-train, friction caused by bearing or gear faults. The basic elements of the performance monitoring consist of a first collection of raw values by the sensors. After the application of the appropriate filters, anomalies are detected. Finally, a diagnosis will be provided. The anomaly detection includes a series of techniques that range from simple threshold checks to statistical analyses [25].

3 Data Reduction Techniques

As aforementioned, the wind farms are becoming a source of massive data. The purpose of these data is to describe the condition of the systems. However, the data are useless by themselves, they are only valuable when information can be gathered from them. It is necessary to process the data in order to extract useful information, but this is an arduous task when there is a very large amount of data. For this reason, it is essential to employ some techniques that allow for reducing the amount of data without losing the main information that they can provide. With this purpose, two procedures are proposed in the following sections. The first one is to analyse a continuous signal coming from a CMS by extracting feature parameters and, the second one provides a reduction for SCADA systems by filtering the unnecessary data.

3.1 Feature Parameters for CMSs Signals

The CMSs installed in WTs are employed to evaluate variables such as vibration, lubrication oil or generator current signal. These systems usually provide a continuous monitoring of the variables. For this reason, it is important to develop algorithms capable of detecting possible abnormal behaviours of the variables over the time [26].

The main goal of this section is to perform a statistical study of the historical data of a CMS in order to achieve some feature parameters. These parameters facilitate to focus the analysis on the information that is really significant. Consequently, an important reduction of the amount of data is obtained. The feature parameters that will be used in this chapter are explained below [27–32]:

- *Average*: the average can be useful for those signals without abrupt changes, i.e. signals that are almost constant. For example, it could be useful for humidity or temperature signals.
- *Peaks*: The more representative peaks are usually those that correspond to a maximum value of the signal within a certain time interval. These peaks can be referred to the time domain or to the different harmonics in the frequency domain. Other feature parameter related to the peaks is the *peak to peak* value

that is defined as the distance between the maximum and the minimum amplitude of the signal.

- *Correlation coefficient (r)*: This coefficient is a statistical procedure used to determine the relationship between several signals. This parameter can be used to identify important changes between a received signal and the historical data. It can run from −1 (perfect negative correlation) to 1 (perfect positive correlation). It is 0 when the signals are totally independent. The correlation coefficient between two signals **x** and **y** can be obtained as follows:

$$r = \frac{N\left(\sum_{n=1}^{N} xy\right) - \left(\sum_{n=1}^{N} x\right)\left(\sum_{n=1}^{N} y\right)}{\sqrt{\left(N\sum_{n=1}^{N} x^2 - \left(\sum_{n=1}^{N} x\right)^2\right)\left(N\sum_{n=1}^{N} y^2 - \left(\sum_{n=1}^{N} y\right)^2\right)}}$$

- *Root Mean Square (RMS)*: This is a time analysis feature that corresponds to the measure of the signal power. It can be useful for detecting some out-of-balance in rotating systems. It can be calculated by:

$$RMS = \sqrt{\frac{\sum_{n=1}^{N} (y(n))^2}{N}}$$

being N the total number of discrete values of the signal **y**. Other common parameter is the *Delta RMS* that is the difference between the current RMS and the previous value.

- *Standard Deviation*: This parameter is used to obtain the dispersion of a data set. It can be calculated by:

$$SD = \sqrt{\frac{\sum_{n=1}^{N} (y(n) - Mean)^2}{N - 1}}$$

- *Skewness*: This parameter is an indicator of the signal symmetry. It is defined by:

$$Skewness = \sqrt{\frac{\sum_{n=1}^{N} (y(n) - Mean)^3}{(N - 1)S^3}}$$

- *Kurtosis*: This parameter corresponds to the scaled fourth moment of the signal. It is a measure of how concentrated the data are around a central zone of the distribution. It is calculated by:

$$Kurtosis = \frac{\sum_{n=1}^{N} (y(n) - Mean)^4}{(N - 1)S^4}$$

- *Crest Factor*: This parameter is capable of detecting abnormal behaviours in an early stage. It is defined by:

$$Crest\,Factor = \frac{Peak}{RMS}$$

- *Shape Indicator*: This factor is affected by the shape of the signal but it is independent of its dimensions. It is obtained as follows:

$$Shape\,Indicator = \frac{RMS}{\frac{1}{N}\sum_{n=1}^{N}|y(n)|}$$

- *Other parameters*: Other parameters are widely used such as enveloping, demodulation, FM0, NA4, FM4, M6A, M8A, NB4, sideband level factor, sideband index, zero-order figure of merit, impulse indicator, clearance factor etc.

These parameters can be only evaluated on finite signals. For this reason, it is necessary to choose some pieces of the continuous signal. The goal is to obtain the main features of the entire signal analysing only some pieces. Therefore, there are two factors why the data are reduced: firstly, a continuous signal is converted into several finite signals and, secondly some parameters of these finite signals are saved.

Table 1 shows a general structure of the data using the method proposed.

The element e_{ij}^{k} corresponds to the j parameter of the k piece collected at the time (date) i.

The main objective of this method is to determine the condition of the WT by making a comparison between the historic data and the data that is being receiving. With this purpose, the historical data will be subjected to a pattern recognition analysis to determine what features are significant. There are a lot of models for pattern recognition analysis, i.e. statistical model, structural model, template matching model, neural network based model, fuzzy based model, hybrid models, etc. [33, 34].

A neural network (NN) based model will be implemented to analyse the data in this chapter. The NN are complex structures based on the biological neurons. These structures provide a good solution for those problems that cannot be analytically defined. Basically, the NN receives a dataset that is used into a training process to

Table 1 Association of data of the CMS and the condition of the WT

	Signal 1			Signal *k*			Signal M			WT condition
	P1	Pj	PJ	P1	Pj	PJ	P1	Pj	PJ	
Date1	e_{11}^{1}	e_{1j}^{1}	e_{1j}^{1}	e_{11}^{k}	e_{1j}^{k}	e_{1j}^{k}	e_{11}^{M}	e_{1j}^{M}	e_{1j}^{M}	C_1
Date2	e_{21}^{1}	e_{2j}^{1}	e_{2j}^{1}	e_{21}^{k}	e_{2j}^{k}	e_{2j}^{k}	e_{21}^{M}	e_{2j}^{M}	e_{2j}^{M}	C_2
Date*i*	e_{i1}^{1}	e_{ij}^{1}	e_{ij}^{1}	e_{i1}^{k}	e_{ij}^{k}	e_{ij}^{k}	e_{i1}^{M}	e_{ij}^{M}	e_{ij}^{M}	C_i

recognise the parameters. In this process, some weights are adapted to provide an adequate output. The different parameters of the signals will be considered as inputs, whereas the condition of the WT will correspond to the desired output of the NN. Further information about NN can be found in Refs. [35, 36]. A case study is developed in Sect. 4.1 in order to clarify the procedure hereby explained.

3.2 Data Analysis for the SCADA System

Besides the evaluation of the variables cited in the previous section, other signals can be collected to complete the data acquisition of a CMS, such as power, pressures, speeds and temperatures among others. With all these data, it is possible to track and analyse the set from the emergence of incipient failures. A SCADA system consisting of different processing tools that transform the data received into real-time analysable information is involved. The displays that comprise the system are configurable to obtain the information when and where it is needed (see Fig. 2).

One of the main advantages of the SCADA system that will be presented for the cases studies is that allows almost infinite storage data in the original resolution. The software included can create and analyse process flow diagrams and graphics. The settings can be adapted to any operating system through menus and toolbars. In addition, the information can be exported to other formats, such as spreadsheets.

The second purpose in this research is to identify alarms from their location in a power curve. Likewise, it is interesting to know how many of those alarms go unnoticed by the system for being within the prediction bounds. The main problem associated to this task will be the definition of the curve. Due to the high number of data, a previous pre-processing will be done to remove non-significant data. This case could also be extended to other stored signals besides the wind speed and the power.

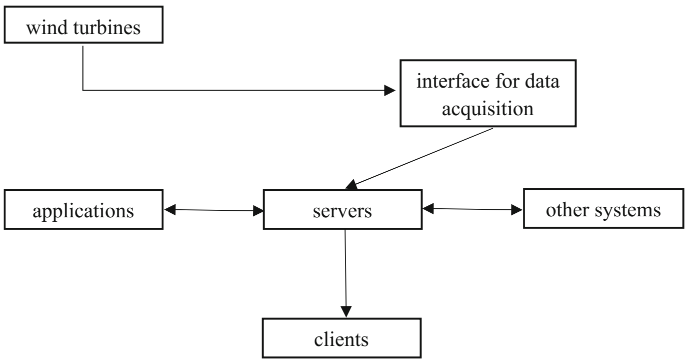

Fig. 2 SCADA system

4 Case Studies

In the former section, two methodologies for processing the Big Data coming from WTs have been proposed and explained. Both methodologies are aimed to reduce the amount of data without losing the main information. In order to clarify how these procedures have to be applied, this section presents two case studies.

4.1 Case Study for CMSs Signals

A drive-train CMS is considered for this case study. This system provides a continuous vibration signal of 8 different points of the drive-train, attending to the point of the drive train that is being monitoring. The sampling rate of the CMS is 1000 samples/s. Therefore, a total of 8000 samples are received per second. The data have been collected during two years, therefore, more than 5×10^{11} samples have been generated by this CMS along that period of time.

In order to apply the methodology explained in Sect. 3.1, pieces of one second each three hours have been considered. Considering the sampling rate of the CMS, a total of 4.6×10^7. As can be observed, this is the first reduction of the amount of data and it corresponds to a reduction of 99.99%. Therefore, the computational costs will be drastically reduced.

Once the set of pieces has been chosen, the following parameters are calculated attending to the definitions in Sect. 3.1: RMS, average, standard deviation, maximum peak, kurtosis, crest factor, shape factor and impulse indicator. The evaluation of these parameters allows for a further reduction of the amount of data to analyse. Concretely, a total of 46,720 data will be used to determine the patterns in the CMS data.

The different conditions of the WT are defined in an alarm report where the state of the WT is collected along the last two years. In this case study, the NN designed is able to differentiate between 4 possible states: "Alarm 1", "Alarm 2", "Alarm 3" or "No Alarms". Each set of inputs is associated with a specific condition of the WT and the relationships are established by the NN. Therefore, the purpose of the NN is to determine the state of the WT when a new set of data is available, i.e. to predict the condition of the WT attending to a new set of inputs. The following Fig. 3 shows the NN designed for this case study.

The NN is formed by three layers. The input layer has 64 neurons that corresponds to the amount of inputs (8 signals by 8 parameters). The output layer is composed by 4 neurons according to the possible outputs considered for this case study. Finally, the hidden layer is composed by 16 neurons because the pyramid rule has been applied [37]. The pyramid rule suggests that the number of neuron of the hidden layer must be equal to the square root of the product between the number of input neurons and the number of output neurons.

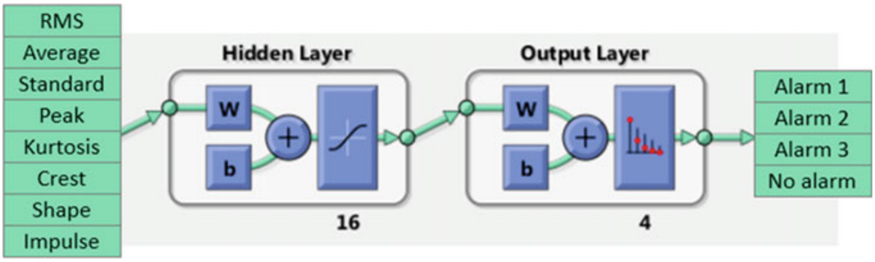

Fig. 3 Neural network designed for the case study

Fig. 4 Confusion matrix. Results of the neural network

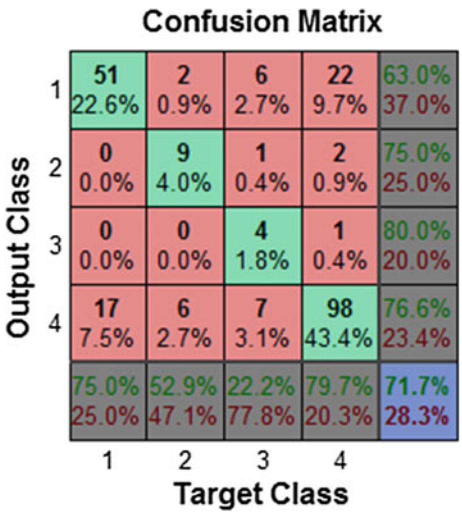

Figure 4 shows the outcomes of the NN through a confusion matrix. The confusion matrix indicates the output provided by the NN (output class) compared with the real condition of the system (target class). The diagonal of the points those cases in which the outcomes of the NN are right (green cells). The values placed in the grey cells provide the percentages of successes and error for each type of output. The percentages in the fifth row provide information about how many conditions of each type the NN is detecting. However, the percentages in the fifth column express the degree of success when a certain condition has been detected. Finally the blue cell shows a summary of the results that determine the goodness of the NN.

Figure 4 shows that the real condition of the WT can be successfully determined by using this method in 71.7% of cases. This is a very good result considering that only the 0.00001% of the total available data have been employed.

Once the patterns have been recognised by the NN, the new data from CMS can be pre-processed in order to achieve the mentioned parameters. These new data should be introduced in the NN and the output can provide information of the state of the WT. In this process the amount of data will be reduced from 8000 samples/s to only 64 samples/s. This technique can reduce the 99.2% of the data. Therefore, this method can result very useful to treat Big Data.

4.2 *Case Study for the SCADA Systems Using Wind Speed-Power Curves*

This second case study will focused on the information related to the wind speed and the power. Both features will be connected from the power curve. The power curve of a wind turbine indicates the electrical power that is available for these devices depending on the wind speed. It is usually close to zero for low speeds. Then, it quickly increases until reaching 10–15 m/s. From those speeds, the curve keeps constant as the result of the limitation devices attached to the turbine. This maximum power is often referred as the nominal power. Once speeds of 20–25 m/s are reached, the wind turbine operation is cancelled due to the activation of protection mechanisms. Therefore, power curves are often not represented at speeds exceeding these limits. In short, it can be said that the power curve is a useful indicator to evaluate the efficiency of a wind turbine.

Power curves are obtained from actual measurements on a wind turbine where an anemometer is strategically positioned. It must be located at certain distance from the rotor to avoid turbulences and therefore, to lose reliability for the stored speed. One of the main constraints of any wind-power curve is that, in practice, the speed fluctuates; so it is important to work with mean values to represent the curve effectively. A non-proper designed curve may show errors of up to 10% between the wind-power ratios.

Regarding the study, the SCADA system stores signals of wind speed and power every ten minutes, i.e. 52,560 samples per year; and subdivides them into sampled, maximum, minimum and average collections, as well as the standard deviation. Once the data are extracted and converted into a readable format by software, it is reordered, from lowest to highest, to get the curve (see Fig. 5). The first representation should fit to the theoretical model expected with minor exceptions (high wind speeds and power outputs).

Figure 6 (left) is the result of introducing Big Data in the case study. This task has been carried out with a curve fitting tool, doing a previous data selection where the appropriate samples are identified from statistical calculations. An exploratory data analysis is used to remove outliers (alarms in some cases) as well as redundant information. This way, it can be seen a reduction of the initial 52,560 to an 841 samples, representing a decrease of the processed data up to 80% of the total amount (Table 2). Figure 6 also represents the data resulting from the descriptive analysis (left) versus the 904 samples indicating the occurrence of an alarm (right). It can be noted that the sum of both graphics still gives an accurate insight to the data registered by the sensors.

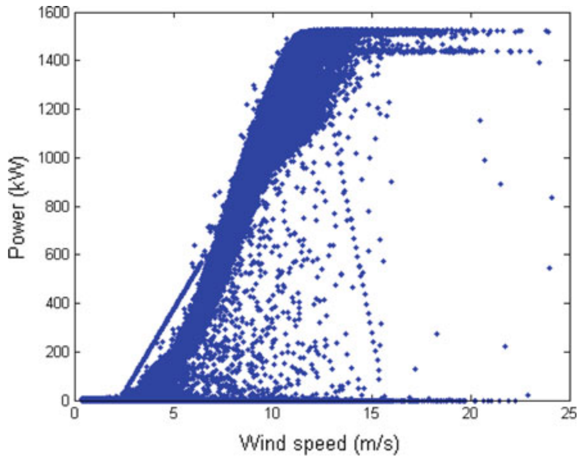

Fig. 5 Initial scenario

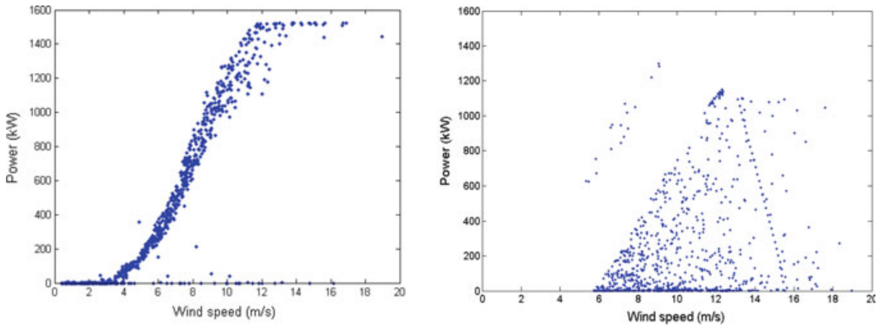

Fig. 6 Post-processed curve (*left*) versus alarms (*right*)

A second regression analysis is conducted to finally obtain Fig. 7. Once the curve that best describes data series is selected, a post processing analysis can be performed. This enables the creation of a graphic with prediction bounds and the calculation of the 95% confidence intervals for the coefficient estimates.

The prior step is critical for the development of further analysis where alarms and operating states are linked to the power curve. The importance of this research is that some of the considered alarms have been found when the drive-train was monitored. The idea, still in development, is to create a pattern recognition where alarms can be identified from their location. Something similar could happen with the information that is not detectable for being within the prediction bounds.

Through a first approach, some unusual performances have been found such as data being positioned above the power curve. This behaviour corresponds to alarms where currents and temperatures are involved and it results in an uncommon

Fig. 7 Wind-power curve

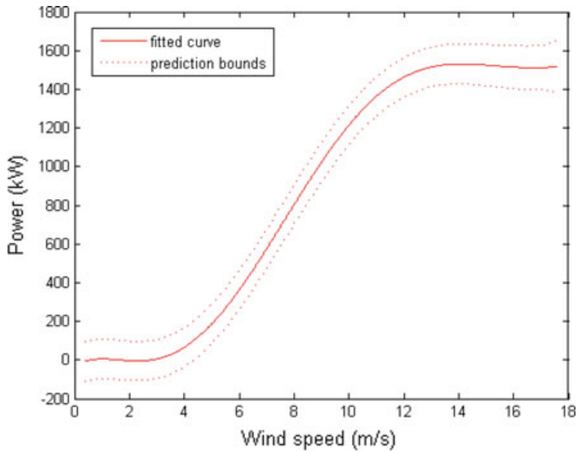

Table 2 Descriptive analysis

	Initial data	Data after the exploratory data analysis	Alarms
Samples	52,560	841	904
Percentage (%)	100	1.6	1.72

speed-power ratio. However, this situation occurs in the 2% of the cases studied. The general trend is to locate the failures up to 500 kW and from 8 to 15 m/s, but usually below the curve. In quantitative terms, this can be translated into up to the 58% of the failures detected in terms of wind speed, and up to the 35% in terms of power. Moreover, it should be mentioned that approximately the 53% of the failures are within the prediction bounds and may go unnoticed if they are based on this technique.

5 Conclusions

This chapter has deepened the analysis of the Big Data generated by the systems associated with the maintenance of wind farms. An introduction about the current importance of Big has been included and Data An analysis of the data coming from Condition Monitoring and Supervisory Control and Data Acquisition Systems has been carried out. Two methods has been proposed in order to facilitate the analysis.

The first one is based on the extraction of feature parameter from the signals provided by the Condition Monitoring System. Once the feature parameters have been obtained, a neural network is designed for pattern recognition. It has been demonstrated that only using less than 1% of the data, it is possible to determine the condition of the WT with a 70% of accuracy.

The second methodology is to analyse the data coming from a SCADA system by prior filtering and selection of the adequate data. An analysis of the wind-power curve has been performed by using data of a real SCADA. The data has been filtered and divided into two groups. The first group correspond to points fitting into the normal levels of wind-power. These points can be used to obtain statistical information about the adequate performance of the Wind Turbine. The second group can be used for detecting failures of certain components. This methodology allows a reduction of data up to the 98% of the total for further analysis without losing precision.

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Societal and Environmental Impact of High Energy Return on Investment (EROI) Energy Access

Reynir Smari Atlason and Runar Unnthorsson

Abstract The Icelandic society is conveniently located where the Eurasian and North-American tectonic plates meet. This allows for relatively easy and cheap access to geothermal energy. Icelanders have benefited from this since settlement, first through direct use of the warm water but later on by co-producing electricity. The nation also benefits from large glacial rivers, offering potential for energy harvesting. This chapter explores the various benefits from utilising renewable energy, using Iceland as a case study. This is demonstrated by exploring the energy return on investment (EROI) for the Nesjavellir geothermal and Fljotsdalsstod hydro power plant and the CO_2 mitigation provided by the resources as the Icelandic society no longer needs to rely on fossil fuels for electricity and heating. This chapter demonstrates systematically how societies may benefit ecologically but also energetically from access to renewable energy sources.

1 Introduction

It is widely known that humans need to convert from reliance on fossil fuel energy sources, to renewable and environmentally friendly sources. The diverse negative environmental effects from human reliance on fossil fuels are appearing in multiple forms, such as in rising global temperatures, sea levels and negative human effects. It has also been shown that easy and cheap access to energy has positive effects on global economies, leading to increased living standards, extended average lifetimes among other positive factors. It is therefore sought after by nations to seek energy solutions reducing negative environmental effects but maximising economic benefits. Some countries have managed to divert the energy product from being fossil fuel

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based to renewable energy based. The Norwegian nation for instance produces most of its electric energy using hydro power. However, if a nation decides to embark on a quest towards renewable energy, it needs to take into consideration the amount of energy needed for infrastructure around the renewable energy source. If calculations demonstrate that more energy is used in the construction, operation and maintenance of the infrastructure needed, then the project is likely to be an energy sink, rather than net energy provider. The ratio between output and input energy in this context is known as energy return on investment (EROI). The concept was put forward in the 1970's by Charles A.S. Hall, who initially used it in his studies on fish species. The concept is however rather universal in application, which has lead to its primary usage, on energy efficiency within industrial ecology. EROI studies provide an insight into the viability of energy sources for societies. For example, in the 1930's fossil fuels such as oil had a rather high EROI (around 100:1), today the ratio is lower (around 10–20). The EROI decline experienced by the oil sector can be explained by the fact that fossil fuels, by nature, become harder to get as easily reachable oil depletes. In turn, more energy is used in the process to retrieve such fuels. Having a good overview of the EROI of various energy sources, policy makers can have a stronger insight into which sources to develop further. However, the knowledge of EROI as a single entity may not provide good enough insights as EROI in itself does not provide information about the potential future developments of a given source. This chapter therefore demonstrates a recent method to calculate the EROI, the so-called $EROI_{ide}$, this EROI factor demonstrates the upper boundary of a resource if all losses are omitted in the production process. Of course, doing so is not possible according to contemporary physics, but the knowledge does however demonstrate how much the potential is.

Of course, when nations do successfully manage to divert from reliance on fossil fuels the energy consumption pattern also changes. In Iceland for example, more than 100 swimming pools are located across the country and some streets are heated during winter. Heavy industries make use of the resources because of how cheap it is and the general public as well. Because of this, the carbon emissions do not change as dramatically as could be expected. If the nation would continue to consume energy as previously, or before energy prices drop, the savings would of course be massive. But because the consumption pattern does change, the savings are less. This is referred to as the rebound effect. When calculating CO_2 emission savings from converting to renewable energy, the change in consumption pattern must be taken into consideration.

In this chapter, two key topics will be discussed regarding the utilization of renewable energy, using Iceland as a case study. Firstly, the energy return on investment will be calculated for geothermal and hydro energy in Iceland, namely the Nesjavellir geothermal and Fljotsdalsstod hydro power plants. Secondly, the CO_2 emission savings will be calculated taking the rebound effect into consideration. The rebound effect takes into account the increased usage because of the inexpensive energy availability, so even if a cleaner energy production method is used, the general public will simply use more of it.

2 Energy Return on Investment

When power plants are built, they are expected to provide more energy to society than the original construction, maintenance and daily operations consume over the power plants life. The power plants pure output can not be the only consideration when deciding if a project should be executed or not. A holistic view is needed to study the viability of power plants construction projects as multiple effects can be experienced. Ecological effects for example are often discussed in detail when energy production projects are initiated. Efficiency of energy producing systems therefore becomes important in the context of sustainability. It has even been stated explicitly that efficiency improvements contribute greatly to the global sustainable development [1]. The method for calculating EROI demonstrated in this chapter is intended to provide deeper insights into energy sources when comparing the viability of energy conversion systems and subsequently provide a guiding light towards sustainability in the energy sector. While energy conversion systems may provide high output, they may initially seem appealing. However, the construction, access to and refinement of the source, maintenance of infrastructure, daily energy use and even the transport of the product (such as oil from the wells) may also be energy intensive processes. Energy Return on Investment is in its simplest form the ratio between energy outputs, that is the used (or total, depending on calculation methods) energy output from the energy source, and inputs from the system under study [2, 3]. In EROI calculations, Inputs are referred to as the energy used to produce, maintain and operate the power plant or systems studied. This is contrary to conventional efficiency analysis, where inputs are rather regarded such as falling water, hot steam etc. The EROI ratio is then computed as a function of time as the system under study is continuously providing output, increasing its EROI. The output is computed as delivered electricity or other types of energy containing products. This can be gas, oil, hot water or even agricultural products. It can safely be assumed that inputs increase gradually throughout the operational lifetime of energy producing systems. It can also be assumed that a large part of the input energy is consumed during the construction process. There are, however, know exceptions; for example, some geothermal power plants consume relatively large portion of their output energy for cooling water pumps over the lifetime.

To date has EROI mostly been used to gain insights into the viability of fossil fuels. The method is however applicable to other industries or energy producing systems. EROI calculations have for example been used to calculate efficiency in agriculture [4], aquaculture [5] and in the fishing industry [6]. Results are generally used to assess the viability of the energy source under study. It has been demonstrated that for electricity producing systems, EROI must be above 3 to serve as a sustainable alternative for modern society [7]. This is of course often not the case for systems not strictly aiming for electricity production. Farms and fisheries have, for example, usually EROI well below 1. In general, EROI calculations do not include economic values, which is evident in farming. For example, a farm might produce a high quality product, but the output is of little quantity. The EROI would therefore be relatively low even though good financial income might be maintained. Economic values may however be used in EROI calculations to retrieve the physical amount of a given product, relating to the energy content of the product. Other systems, such as for various biofuels, might have an EROI around 3 [7]. Under current environment, this might not be considered high next to oil and coal who have an EROI of approximately 20 and 80 respectively [8]. The question for systems under development may therefore rather be in regards to theoretical maximum EROI they can provide and if they will ever be viable. EROI calculations and simulations lacked consistency and a standard methodology for numerous years [9]. No standard was evident for researchers to follow. A proposed standard was however put forward in 2011. The suggested standard included definitions of boundaries, where different factors were included. Such standard allows researchers to be explicit about which EROI they are calculating [9].

EROI results may provide a good platform for comparison of different energy systems with regards to how much energy they return to society against the energy they consume. With rising demand for high efficiency in power production, EROI can demonstrate how efficient the systems are from societies point of view. By calculating the theoretical maximum output from a system, results can be seen that may be a useful tool for policy makers, private and public, but furthermore funds and corporations wanting to promote research on energy efficiency. Supporting further research in a field where room for improvement is high may be more likely to return results of significance than research where small or no possibility is for efficiency improvements. EROI_{ide} estimates the EROI of an energy conversion system if all losses are omitted, access to energy is unlimited, operation is uninterrupted and no power for operations is consumed. EROI_{ide} therefore demonstrates policy makers potential improvements within the energy producing system under study.

2.1 Methods for Calculating the Energy Return on Investment

The standard proposed by Murphy et al. should be used for EROI calculations. It is therefor ensured that EROI results can be compared. The EROI equation can be described as [10]:

$$EROI = \frac{\sum ED_{out} + \sum v_j O_j}{\sum ED_{in} + \sum \gamma_\kappa I_\kappa} \tag{1}$$

where ED_{out} is the energy content of all primary products produced and leave the power plants, v_j are co-products, such as brine potentially used by other industries, O_j represents energy content of such co-products produced at the power plant. ED_{in} represents energy content of products entering the system, γ_κ is the amount of

Table 1 System boundaries provided by Murphy et al. [9]

Boundary for energy inputs	1. Extraction	2. Processing	3. End Use
1.Direct energy and material inputs	$EROI_{1,d}$	$EROI_{2,d}$	$EROI_{3,d}$
2.Indirect energy and material inputs	$EROIs_{stnd}$	$EROI_{2,i}$	$EROI_{3,i}$
3.Indirect labor consumption	$EROI_{1,lab}$	$EROI_{2,lab}$	$EROI_{3,lab}$
4.Auxiliary services consumption	$EROI_{1,aux}$	$EROI_{2,aux}$	$EROI_{3,aux}$
5.Evironmental	$EROI_{1,env}$	$EROI_{2,env}$	$EROI_{3,env}$

co-efficient (input) products, such as the energy used for producing the material used for maintenance, I_κ is subsequently the energy content of those products.

Equation 1 does only provide a preliminary concept for EROI calculations, as there are indirect inputs and outputs along the direct inputs and outputs. Murphy et al. demonstrate this in more detail. A further separation of EROI boundaries can be seen in Table 1. The further right in the table, or down, expands the boundaries of a system under study. For instance, if the output energy after extraction is considered, one would refer to the first column. If data about the energy usage in the energy processing is available (such as refinery of oil) one would use the EROI factors in the second column. If data of how much energy is then delivered to the end user is available, the EROI factors in the last column are used. When looking at inputs, the rows in Table 1 should be looked at. For example, if data for all indirect energy and material inputs is available, it would be correct to refer to row number 2. Therefore, if one has knowledge on all indirect energy and material inputs, including all direct energy and material inputs, as well as the data about the quantity of energy delivered to the end user, the $EROI_{3,i}$ is to be calculated.

The $EROI_{stnd}$ results provide a baseline for $EROI_{ide}$ calculations. There, the output (numerator) has to be modified. That is, removing losses in the system in order to provide a theoretical maximum output. This is essentially a limit never to be reached with regards to EROI. Therefore, to calculate the theoretical maximum EROI, Eq. 1 is modified to be as follows:

$$EROI_{ide} = \frac{\sum \beta}{ED_{in} + \sum \gamma_\kappa I_\kappa} \tag{2}$$

where $\sum \beta$ is the theoretical maximum output from a system under study, omitting all losses. As raw inputs to systems vary tremendously (such as wind, solar, hydro etc.), the $\sum \beta$ has to be adjusted for different systems. For example, if a hydro power plant is being examined, the $\sum \beta$ would be replaced with the output from the designed capacity from the plant.

For geothermal power plants, exergy from all wells is used as the ideal output. For wind turbines, the theoretical maximum output is shown as [11]:

$$P = d(KE)/dt = (1/2mU^2)/dt = 1/2U^2dm/dt = 1/2ApU^3 \quad (3)$$

where area A with a flow of airmass dm. In the time dt the air will travel the distance U dt, where the cylinder of volume A U dt containing mass dm = A p U dt, where p is the air density [12], which under normal pressure is roughly 1.2 kg/m^3. There are certain physical laws that can not be left without inclusion. While calculating the total wind energy does prove a theoretical maximum, Betz has previously showed that by doing so would create a problem. If wind would be harvested fully, it would subsequently come to a halt directly behind the turbine. This effect would then in essence stop incoming airflow through the area. Accounting for Betz law, only 59.3% (16/27) of the air can theoretically be harvested from any wind turbine design. Betz law should therefore be taken into consideration when EROI_{ide} calculations are made for wind turbines.

As has previously been suggested by Murphy et al., EROI_{stnd} should be calculated when EROI is studied for energy systems. It is therefore recommended that the inputs from the EROI_{stnd} are used in EROI_{ide} calculations.

2.2 *EROI Results*

In this section we demonstrate how EROI_{ide} may provide a deeper understanding of energy systems in conjunction with EROI_{stnd} calculations. The first case is from a study by the authors [13] where the EROI for Fljotsdalsstod hydroelectric power plant was estimated, the second is a the Nesjavellir geothermal power plant which was also studied by the authors [14], and the third is a hypothetical wind turbine farm, where data was gathered from an LCA study [15, 16].

2.2.1 Fljotsdalsstod Hydroelectric Power Plant

Fljotsdalsstod, Icelands largest hydroelectric power plant, is located on the eastern part of Iceland. The plant produces roughly 4,600 GWh annually. The maximum flow to the plant is 144 m/s with a total fall from the reservoir mouth to turbines of 599 m [17]. Table 2 demonstrates the total energy input required in the EROI calculations for 7 different components. Table 2 also shows demonstrates total energy input over the plants lifetime, including maintenance. The table also demonstrates the maximum theoretical output per year, as well as over the plants 100 year lifetime. Inputs have been summarised into seven categories:

1. Embodied energy in materials used in the construction of the plant
2. Energy used for groundwork
3. Energy used in maintenance of equipment per year
4. Energy consumed in maintenance of dams per year

Table 2 Summarised inputs to the EROI calculations for Fljotsdalsstod hydroelectric power plant. The outputs are based on Eq. 3

Input phase	GJ
Emb. plant energy	4,607,600
Groundwork	166,300
General maintenance p. year	3,300
Concrete maintenance p. year	7,500
Preparation work	32,000
Emb. energy of engines	209,400
Roadwork	20,900
Total input over lifetime	6,107,900
Output (ide)	
Per year	21,760,000
Over lifetime	2,176,000,000

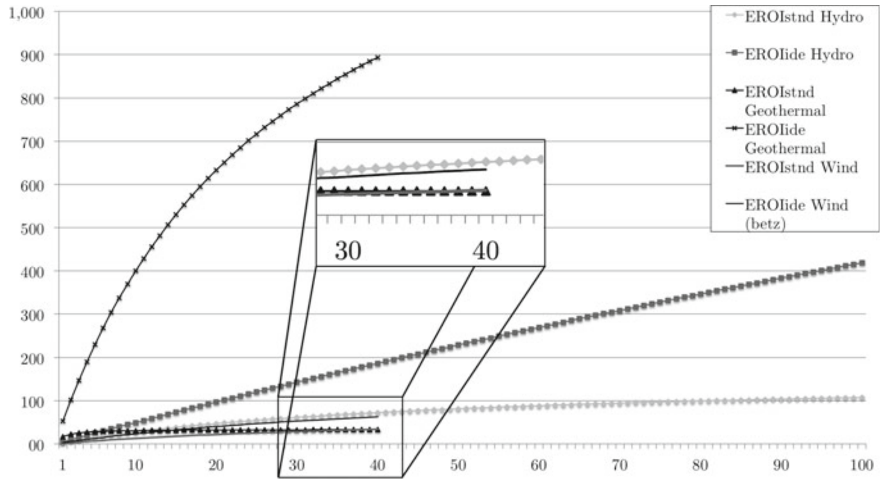

Fig. 1 Improvement for various energy *Source* X-axis shows years, y-axis shows EROI values [15]

5. Energy used for preparation, this mainly entails transportation of materials,
6. Embodied energy of engines and electrical equipment
7. Energy used for road construction conducted during construction.

Table 2 demonstrates the annual and accumulated output of the plant using Eq. 3. The important factor is however the $EROI_{ide}$ compared to $EROI_{stnd}$ results demonstrated in Fig. 1. The difference between the two curves deriving from the same source, gives an indication of the room for improvement if no losses occur and all energy is utilised. But as has been stated, this can according to modern physics never be achieved. Efficiency of energy systems may potentially be improved, so $EROI_{stnd}$ comes closer to EROI ideal, however the two indicators will never become equal as losses can not be avoided when energy is converted.

As Fig. 1 demonstrates, $EROI_{ide}$ is more than 3 fold greater than the $EROI_{stnd}$ after the first 100 years of operation. Results indicate potential efficiency improvements at the plant studied. The usage of power by the plant itself, structural maintenance, along with initial construction of the plant contribute to the lower $EROI_{stnd}$ results. Francis turbines, as are installed at Fljotsdalsstod have gained maturity from many years and much experience through operation world wide and are therefore very efficient (up to 95%) [18]. Results indicate that improvements should be focused on maintenance, construction and consumption of the plant itself, whereas opportunities for efficiency improvements of the turbines may prove to be more difficult.

2.2.2 Nesjavellir Geothermal Power Plant

Nesjavellir geothermal power plant, Icelands second largest geothermal power plant, produces 300 MW of hot water, used for residential heating, and for 120 MW of electricity [19]. We have previously shown that the largest single consumer of energy from the plant is the plant itself for its daily operations [14]. This is mostly due to pumping of cooling water towards the plant. We have shown the plant to have an $EROI_{stnd}$ of approximately 33 but when looking at $EROI_{ide}$, that number jumps to 894, using total exergy as the estimated output [14, 15].

Exergy at Nesjavellir was estimated using the following equation:

$$e = h - h! - T!(s - s!) \tag{4}$$

where h is observed enthalpy (kJ/kg), s is enthropy (kJ/kg), T is the ambient temperature measured in Kelvin and 0 is sink conditions. The exergy estimation here is based on the assumptions that ambient temperature is 283.2 K (10 degrees celcius), exergy is reached in electricity production and hot water production is done in the same quantity as is currently observed (300 MW). Real data was used provided by Reykjavik Energy about the wellhead conditions. Seventeen wells are included in this study with the total flow of 590 kg/s. Steam is approximately 290 kg/s and brine 300 kg/s. The average enthalpy from the wells is approximately 1800 kJ/Kg. Table 3 summarises inputs for the $EROI_{ide}$ calculations into 5 categories. These are:

Table 3 Inputs and outputs for the Nesjavellir geothermal power plant $EROI_{ide}$ calculations

Input phase	GJ
Embodied plant energy	307,865
Embodied energy of pump station	62,697
Groundwork	21,725
Transport to Iceland	9,211
Maintenance per year	13,849
Total input over lifetime	941,622
Output (ide)	
Per year	21,041,000
Over lifetime	841,640,000

1. Embodied energy in the construction materials of the power plant
2. Embodied energy in the pump station
3. All groundwork which took place in the construction phase
4. Transportation of all materials to Iceland via freight ship
5. Assumed amount of energy used for maintenance annually.

In Fig. 1 we demonstrate two curves for the Nesjavellir plant, one indicating the EROI_{stnd} while the other indicates the EROI_{ide}. The surface between the curves therefore indicates the potential for efficiency improvements. Calculations demonstrate the room for improvement at Nesjvellir geothermal power plant to be approximately 27 fold as Fig. 1 shows. That means, that if all losses are omitted while the power plant would have unlimited access to energy and work at full capacity throughout its lifetime while not consuming energy for daily operation, its EROI would improve by a factor of staggering 27. By estimating the exergy from the wells at geothermal power plants may potentially demonstrate a more realistic EROI_{ide} than total enthalpy. This is because not all power coming from the wells can be harvested, the total enthalpy is therefore not a suitable indicator for the theoretical maximum, but rather the exergy as the exergy is the full and total amount of power available for harvest from geothermal resources. As mentioned, EROI_{ide} calculations exclude the plants own usage of power while including construction of the plant, drilling of wells and maintenance within EROI_{stnd} boundaries.

2.2.3 Theoretical Calculations for Wind Power

To demonstrate EROI_{ide} further, we provide calculations of a hypothetical wind turbine farm. The farm scenario consists of 18 turbines with a theoretical 500 kW output each. The output of 19,800 MWh annually or 71,280 GJ is assumed. It is further assumed that production took 46,761 GJ for all the turbines [16]. Data was gathered from a published LCA study on wind turbines [16]. We further estimate that 2.5% of initial material cost is used maintenance on an annual basis, or 34.9 GJ per year. We exclude the demolition scenario of the turbine. Within the EROI_{stnd} boundaries, the wind farm is estimated to have an EROI of 28.5 over a lifetime of 30 years. The equipment is however only estimated to withstand 20 years [16]. The farm with a lifetime of 20 years would have an EROI of 21.7. Such results are similar to other EROI studies for wind farms [20]. It must however be kept in mind that wind farms are location, size and weather dependent. To continue and estimate the EROI_{ide}, one must continue on the EROI journey and calculate other factors. The blades of a turbine in this theoretical farm have a diameter of 39 m. The turbine is furthermore placed where annual average wind speed is 15 m/s. Using Eq. 4, it is possible to calculate the average wind power flowing through the turbine area to be 389.8 watts per turbine, or 12,299 GJ per annum. Figure 1 demonstrates room for improvement at the wind farm. As previously stated, some restraints can not be overlooked when calculating the maximum energy output, namely restraints in harnessing wind energy previously put forward by Betz. According to Betz, 59.3% of the wind power could be transformed to mechanical energy [21]. Calculations for EROI Ideal for wind energy should therefore include betz law in the calculations for a more plausible view on the ROI_{ide}.

2.3 EROI in Perspective

When simulating the $EROI_{ide}$, the $EROI_{s\ tnd}$ needs to be calculated in advance for a given system. Using the extra effort to calculate $EROI_{ide}$ may provide stronger insights on possible improvements within a given system. The $EROI_{ide}$ does not allow for visualisation for single parts such as turbines, but rather on the lifecycle of energy producing systems. For instance, by simulating the EROI results from the hydro plant, one might choose to support incentives for developments of less energy consuming concrete production methods. Doing so would likely lead to increased EROI as minimum energy would be spent in production of concrete for the dam construction. $EROI_{ide}$ is hopefully of value to policymakers as it provides a sharp image of potential improvements for a given system and where such potentials hide. Incentives are already being provided for renewable energy programs and using the method demonstrated above should strengthen the process leading to such decisions [22, 23].

The concepts of the Carnot heat engine as well as the Betz' law have existed for number of years [24]. The application of these concepts has however not been integrated into the EROI literature. Also, it should be considered that other input boundaries in the $EROI_{ide}$ calculations are possible. For instance, it would be possible to use limits put forward by physics rather than of the turbines themselves as we demonstrated in the hydro case. By doing so, the input to the $EROI_{ide}$ equation would be the outcome from $e = mgh$, where m is mass, g is gravity and h is height, provided the knowledge of the total fall and mass of water flowing towards the turbines. Doing so would of course increase the gap between $EROI_{stnd}$ and $EROI_{ide}$. In Table 4 the reason for difference in time scenarios is based on infrastructure lifetime (for the hydro and wind) or estimated lifetime of the resource (geothermal). We assume a 100 year lifetime of the hydro plant, it is further estimated that the wind farm lasts 20 years. We have however projected the lifetime of the wind farm to 40 years to give a sharper understanding of the EROI development. We further estimate the energy production from Nesjavellir to last 30 years [14].

When studying the cases demonstrated above, it is clear that the potential for improvement is largest for the geothermal power plant. This might be because the technology is in its infancy and under rapid development. It may be in societies interest if such energy sectors increase efficiency as it will relieve some pressure from fossil fuel consumption. By using results as provided above, a policy maker might be inclined to incentivise geothermal power developments more than hydroelectric power. Such decisions could be based on the fact that calculations showed the room for improvement to be much greater for the geothermal plants. By paying attention to

Table 4 EROI results from various energy sources

Source	Hydro	Hydro	Geothermal	Geothermal	Wind	Wind
Year	$EROI_{stnd}$	$EROI_{ide}$	$EROI_{stnd}$	$EROI_{ide}$	$EROI_{stnd}$	$EROI_{ide}$ Betz
1	3.3	4.1	17.0	52	1.4	2.8
5	15.1	20.3	28.2	230	6.9	12.8
10	27.6	40.2	30.7	400	12.7	23.4
15	38.1	59.7	31.7	530	17.5	32.4
20	47.0	78.8	32.2	633	21.77	40.1
25	54.7	97.5	32.5	717	25.4	46.8
30	61.4	116	32.7	786	28.5	52.6
35	67.3	134	32.8	844	31.3	57.8
40	72.5	151.7	33.0	894	33.8	62.3
45	77.1	169				
50	81.3	186.1				
55	85.0	202.8				
60	88.4	219.3				
65	91.5	235.4				
70	94.4	251.3				
75	97.0	266.8				
80	99.4	282.1				
85	101.6	297.1				
90	103.7	311.9				
95	105.6	326.5				
100	107.4	340.7				

detail, one can see that the room for improvement over the plant lifetime is almost 4 fold at the hydro power plant, 5 fold at the wind turbine and 27 fold at the geothermal power plant. Keep however in mind that the wind calculations are based on a theoretical case and may perhaps not provide reliable $EROI_{ide}$ results. Regardless, it can be seen that $EROI_{stnd}$ rises from 21.77 after two decades to 33.8 after four decades. EROI results can demonstrate the benefits of prolonging wind turbine lifespan. Even though the EROI results shown in this chapter are based on a hypothetical case, we have seen that the EROI of wind turbines is somewhere in the proximity demonstrated in this chapter [25]. When $EROI_{ide}$ calculations are conducted, one has to have a sharp image of the possible maximum energy availability. For instance, in the case of geothermal power plants, the full enthalpy is not available for harvest, therefore the exergy has to be estimated to visualise available energy. When looking at results in Fig. 1, it can be seen that the Nesjavellir geothermal power plant can potentially be as efficient as the Fljotsdalsstod hydroelectric plant. This can be seen as its $EROI_{ide}$ is high and the potential for improvement great. For pure speculation, this may be because geothermal energy conversion is in its infancy compared to hydro. We can also see that the hydroelectric plant does not offer as much potential for improvement as the other systems as the technology has matured greatly and Francis turbines have become very efficient. Previous literature has however shown that the EROI of hydroelectric power plant seems to be dependent on plant size [25]. We can see that sub-MW hydroelectric power plants can be estimated to have a relatively low EROI. Large hydroelectric plants can however result in EROI in the >100 range [25]. Previous published results correlate nicely with the $EROI_{stnd}$ results for Fljotsdalsstod. The wind farm example provided in this chapter is hard to compare to the other two examples as it is not based on real observations. It should also be noted that calculations are based on single cases, which may be sensitive to location. Other geothermal power plants might therefore return different $EROI_{ide}$ results.

In this section we have described the $EROI_{ide}$. The indicator demonstrates an upper EROI limit for a energy producing system under study. We further demonstrated how to calculate the $EROI_{ide}$. We hope that the method, and future results from researchers will provide value to policymakers and parties with interests in energy production efficiency. When calculating $EROI_{ide}$ in combination with $EROI_{stnd}$ demonstrates the potential for improvement within a given system. A deeper look at such results can further demonstrate where improvements can be made within the systems, allowing policymakers to focus on such areas.

Even though EROI provides a relatively good insight into a viability of a resource, it does not consider factors such as potential environmental impact of the resource being examined. In the next section, we attempt to demonstrate how environmental mitigation from a resource can be estimated.

3 CO_2 Savings by Converting to Renewable Energy in Iceland

As demonstrated previously in this chapter, the Icelandic nation relies almost solely on hydro and geothermal. However, by converting to renewable energy sources, nations may be prone to change their consumption patterns. This is because of the newly gained knowledge that the energy consumed has less effects on the environment and less expensive than energy previously consumed. This is known as the rebound effect [26]. It has previously been estimated that the rebound effect is not so significant but is sensitive to the sector affected [26].

The effect has been estimated to be between 0 and 30% depending on sector [26]. This means that up to 30% of the energy savings gained because of increased efficiency can be offset because of increased energy consumption. Therefore, the rebound effects needs to be considered when attempting to visualize the perceived environmental and economic benefits of moving from finite to renewable energy sources. In a recent publication from the Icelandic National Energy Authority (NEA) [29], an attempt was made to demonstrate the benefits in environmental and economic terms from converting from fossil fuel energy in the late 1960's to geothermal and hydro power. The publication by the NEA is acknowledged by the authors to be a good starting point for visualizing the benefits of converting to renewable energy, but eventually lacks taking into consideration the rebound effect. The NEA assumes that the same consumption pattern would prevail even if geothermal energy would not be utilized in Iceland. This means that Iceland would have consumed little less than 7 million tonnes of coal in 2014 (if coal would be the primary source of energy). Such consumption of coal would be approximately the same as in Columbia [27] and the Icelandic nation would have spent approximately a staggering 500 million US dollars (1,515 USD per capita) in 2014 alone to purchase the European coal [28]. It can be seen that such assumptions can be improved, which will be done in this chapter.

The hypothesis of this chapter is that the rebound effect for the Icelandic society is relatively large. This is because the nation has built infrastructure heavily reliant on geothermal energy. For example, more than 120 thermal swimming pools have been built around the country since the geothermal exploitation began. Waste heat from district heating allows for the streets in the capital center are heated during the coldest months. Because of the cheap, abundant energy, heavy industries have settled within the country, benefiting from the renewable energy sources. It can be argued that providing access to energy sources in Iceland for heavy industries, eventually producing products for export the energy in itself is being exported. It is therefore of little debate, that if the Icelandic society would not have easy access to geothermal or hydro power, the consumption pattern of the society would be different to a large extent.

- In this chapter, we estimate the greenhouse gas emission savings of the Icelandic nation from converting to renewable energy, considering the rebound effect.

3.1 Calculating Emission Savings

To estimate the energy consumption patterns and subsequent greenhouse gas emissions of the Icelandic nation had it not converted to renewable energy, consumption patterns of nations living in similar climate were examined. In this case, the United Kingdom (UK) and Czech Republic were chosen as reference nations. These two nations are subject to similar climate as in Iceland, where temperatures fluctuate in a similar manner, hence their choice. Figure 2 demonstrates the similarity in temperature fluctuations between all three nations. We then analyze the consumption patterns of chosen nations and the methods of energy production. We assume that nations in a similar climate can to some extent represent the consumption pattern of the Icelandic nation if it had not began exploration and utilization of renewable energy. The aggregated emission savings (ES) can be demonstrated as:

Fig. 2 Average monthly temperatures (measured in degrees Celsius) in the countries examined in this chapter [31]

$$ES = \sum_{i=q}^{d} a_i \sum_{j=p}^{n} b_{ij} k_j - \sum_{i=q}^{d} c_i \frac{I_p}{I_{ref}} \sum_{j=p}^{n} d_{ij} k_j \tag{5}$$

where a_i is the energy consumption for given year i for the country studied, in this case Iceland. Let b_{ij} denote the portion of the energy mix from a given resource j for a year i, for example hydro or coal and k_j the CO_2 equivalent per energy unit from that given resource j. On the right side of the equation, the reference consumption pattern is included. c_i is the energy consumption from a reference nation for a given year i. I_p is the size of the Icelandic population for the year i and I_{ref} is the size of the reference nation for the same year. d_{ij} is the portion consumed of given resource j for year i and kj is the emission factor for resource j.

In this study we estimate the CO_2 savings between 1969 and 2014. Nineteen sixty nine marks the year when the first geothermal power plant in Iceland, the 3 MW Bjarnaflag station, began operation. The development of the energy grid mix is then adopted from the above countries when calculating the potential consumption and emissions in Iceland if geothermal or renewable in energy in general would not be used. This means that several scenarios are to be developed, based on consumption patterns and emissions from the energy grid mix of the countries used in this study.

For comparison, emission factors from different energy producing systems are gathered from the Intergovernmental Panel on Climate Change (IPCC). In this study, the following emissions factors are used, note that numbers in brackets are grams of CO_2 equivalents per kilowatt hour (gCO_2 eq/kWh): Coal (820), Gas—combined cycle (490), Geothermal (38), hydro power (24), nuclear (12) [30]. The numbers detailed above are used except when more detailed numbers are provided from official sources. For example, the NEA provides detailed information about total emissions from Icelandic geothermal power plants, which are then used as a basis for that particular emission source. In this study, only the CO_2 equivalents are examined.

Other environmental effects, such as radiation and possible long term effects from nuclear are omitted. For the Icelandic scenario, coal consumption is included. Oil consumption in Iceland is mostly used in transport and is therefore excluded. Oil consumption for the transport sector in other countries is also excluded to maintain comparability. Year by year values for the portion of the energy grid mix for energy sources within UK in the time series under analysis are used. For the Czech republic scenario, data was also available allowing for inclusion of variable grid mix, this was therefore included to increase data and calculation precision. Data about average energy consumption per capita in the UK and Czech Republic was gathered from the World Bank development indicators. The development of energy grid mixes was further more gathered from the World Bank development indicators and simulated on a year by year basis throughout the time series under evaluation. In this study, seven scenarios are calculated, each portraying the potential CO_2 emission savings from the Icelandic nation. The scenarios are:

1. Emission savings if the Icelandic nation would consume as much energy as history has shown but would have relied on fossil fuels in the process. This scenario is based on previous calculations by the Icelandic National Energy authority.
2. Emission savings if the Icelandic nation would consume as much energy as the UK nation per capita. In addition, it is assumed that the energy is produced in the same way as is done in the UK.
3. In this scenario, the Icelandic consumption pattern is based on the Czech Republic. Also, the energy grid mix is based on the Czech mix.
4. In this scenario, it is assumed that the Icelandic nation would have consumed energy like the UK, but not gained access or decided to utilize geothermal energy. The energy grid mix is based on known grid mix developments in Iceland where geothermal energy is excluded. For example, if at one point oil, coal, hydro and geothermal shared the energy grid mix equally (1/4 each), then in this scenario oil, coal and hydro would share the same amount of energy production (1/3 each).
5. In this scenario, same assumptions are given as in the previous scenario, except for the consumption pattern which is assumed to follow the Czech pattern.
6. Here it is assumed that the Icelandic nation would have utilized renewable energy as history has shown. However, it is assumed that the consumption pattern is conservative, following the UK consumption pattern.
7. In this scenario, the same assumptions are given as in the previous scenario. The difference lies in the consumption pattern development where here the Czech consumption pattern is used.

3.2 *Results from Emission Saving Scenarios*

In this section we provide the results in various terms. In Sect. 3.2.1 we provide the estimated emissions from the Icelandic nations under the current, real scenario. In

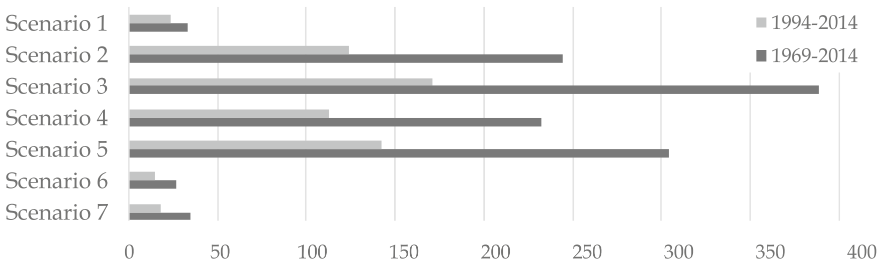

Fig. 3 Total CO_2 emissions measured in million tonnes between the years 1969 and 2014 for all scenarios

Sect. 3.2.2 we provide the emission scenario if the Icelandic nations would consume and produce electricity and thermal energy as is done in the United Kingdom. In Sect. 3.2.3 we estimate emissions as if the Icelandic nation would have consumed and produced energy as the Czech republic. In Sect. 3.2.4 results are provided assuming Icelanders used energy in the same way as in the UK but without adopting or developing the energy grid mix beyond what was being used in 1969, namely coal, oil and hydro. In Sect. 3.2.5 results are shown based on Scenario 5, where Icelanders would not have gained access to geothermal energy. In Sect. 3.2.6, results are portrayed where Icelanders have access to renewable energy but consumed it like the UK nation. In Sect. 3.2.7, we demonstrate the effects where Icelanders gained access to renewable energy sources but consumed them like the Czech. Finally, the results are compared to visualize the real effects on emission from converting to renewable energy in Iceland. An aggregated view of total emissions from all scenarios calculated can be seen in Fig. 3. It can be seen that results vary based on assumptions, results for each scenario will now be explained.

3.2.1 Scenario 1

In this scenario, total emissions are estimated from Icelandic power plants. Domestic combustion from transport is excluded, which is furthermore estimated to be relatively similar regardless of which scenario is calculated. Data regarding energy production from various sources was gathered from the NEA. Total emission values where then calculated using emission factors provided in Sect. 3.1. This holds true for the sources used except for emissions from geothermal resources, where more reliable data is available from the NEA. When looking at the energy consumption by primary energy source in Iceland, it can be seen that a majority of energy is produced using geothermal energy, followed by hydro. However, when looking at the CO_2 emissions, hydro and geothermal dwarf next to the emissions from the use of coal in Iceland. Figure 4 further depicts the distribution of different energy production technologies used in Iceland between 1969 and 2014. Total

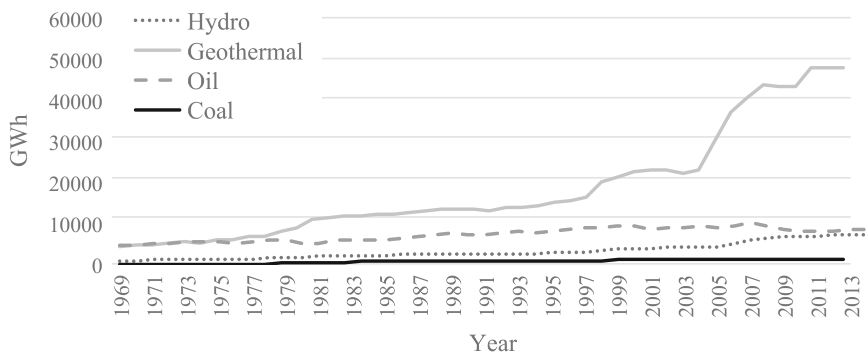

Fig. 4 Energy production by primary source in Iceland between 1969 and 2014 measured in Gigawatt hours

emissions savings estimated by the NEA is 341 Mt/CO_2 equivalents between 1969 and 2014. If only looking at the interval between 1994 and 2014, that number is 239 Mt/CO_2 equivalents. These results are contested in this chapter, as this scenario estimates the exact same consumption pattern before and after Icelanders began using geothermal energy.

3.2.2 Scenario 2

Figure 5 demonstrates the developments of CO_2 savings between the years 1969 and 2014. The calculations show, that if Icelanders would consume energy in the same manner as is done in the United Kingdom, and use the same energy sources, they would have saved 164 Mt/CO_2 equivalents between 1969 and 2011 compared to current consumption. One can see that the largest amount of savings where made between 1969 and 1977, where the consumption of the Icelandic nation was converting from conventional energy sources to renewable and heavy industries had yet to establish themselves in the country. Another explanation for the high savings early on, is that the United Kingdom had already established itself as a highly industrialized country at this time, therefore resulting in higher energy consumption per capita. The total savings calculated for this scenario between 1994 and 2014 are 97 Mt/CO_2 equivalents. The results from this scenario indicate that the NEA over estimates the CO_2 savings roughly twofold between 1969 and 2014, and threefold when looking at the interval between 1994 and 2014.

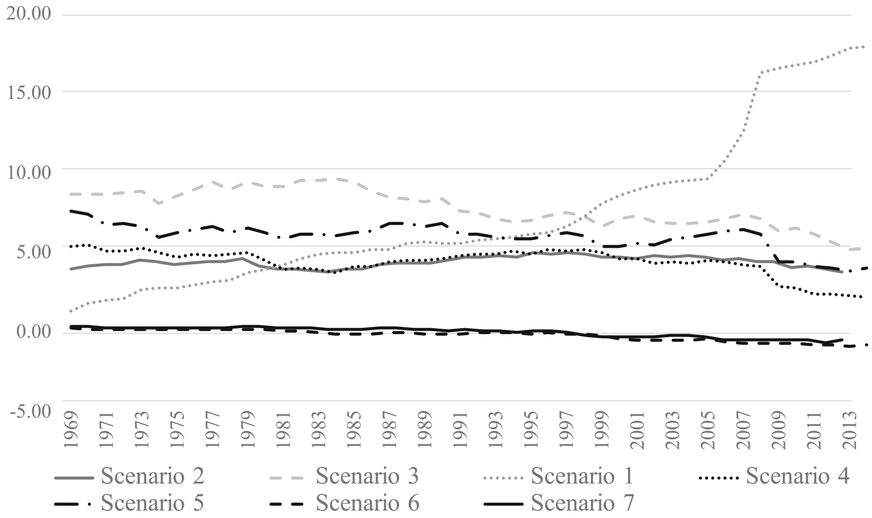

Fig. 5 Total CO_2 emissions savings from the calculated scenarios measured in million tonnes between the years 1969 and 2014

3.2.3 Scenario 3

If Icelanders would use energy in the same way as the Czech, with a similar energy grid mix, the total CO_2 emissions would amount to approximately 380 million tonnes. This amounts to savings of approximately 360 million tonnes between 1969 and 2014, which is in fact not far away from the predictions made by the NEA. This can be explained by the heavy usage of coal by the Czech population throughout the period studied. As is similar, and even more evident are the large savings visualized in the beginning of the period, namely between 1969 and approximately 1985, where the Icelandic nation has not begun the utilization of renewable energy in a large quantity and consumes it moderately. When looking at a later period, namely between 1994 and 2014, one can see that the savings are much less than estimated by the NEA, or 142 Mt/CO_2 equivalents compared to 239 Mt/CO_2 equivalents.

3.2.4 Scenario 4

It can be argued that this method will provide most realistic results, as it portrays a continuum of the energy grid mix in Iceland based on historical facts about the developments.

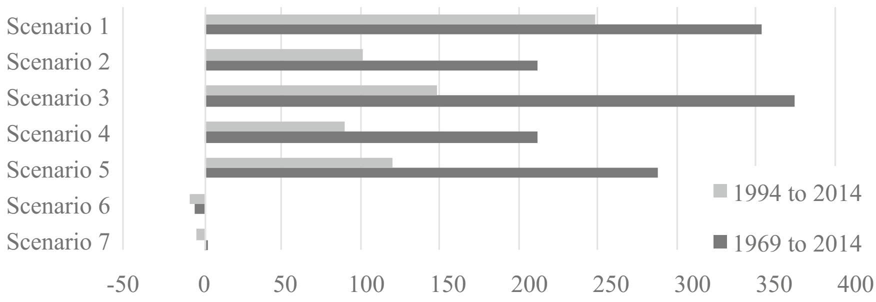

Fig. 6 Total aggregated CO_2 emissions savings from all scenarios measured in million tonnes between the years 1969 and 2014 and 1994 and 2014

Using consumption patterns from the UK but the Icelandic energy grid mix excluding geothermal, one can see that aggregated savings between 1969 and 2014 amount to 204 Mt/CO_2 equivalents. When looking at the time frame between 1994 and 2014, the savings are estimated to be approximately 86 Mt/CO_2 equivalents.

3.2.5 Scenario 5

Using the same method as in the previous scenario, and assuming Czech consumption pattern, savings would amount to 277 Mt/CO_2 equivalents in the time frame between 1969 and 2014. Between 1994 and 2014, savings amount to 114 Mt/CO_2 equivalents. Aggregated results from both scenarios can be seen in Fig. 6.

3.2.6 Scenario 6

Using the assumptions that the Icelandic energy consumption would continue to be conservative, regardless of the abundant amount of renewable energy available, one can see that the CO_2 savings are minimal or even negative. If the Icelandic nation would consume energy in the same way as the UK, and using the same energy grid as has been available, the savings actually diminish. It seems that the Icelanders have emitted 6.05 Mt/CO_2 equivalents between 1969 and 2014 than they would had the consumption pattern not changed. When looking at the interval between 1994 and 2014, it is evident that the emission savings are negative again, where Icelanders have emitted 9.0 Mt/CO_2 equivalents more in the real scenario scenario.

3.2.7 Scenario 7

Using the same methodology as in Scenario 6, but assuming Czech consumption pattern, one can see that the savings amount to 34.6 Mt/CO_2 equivalents in the

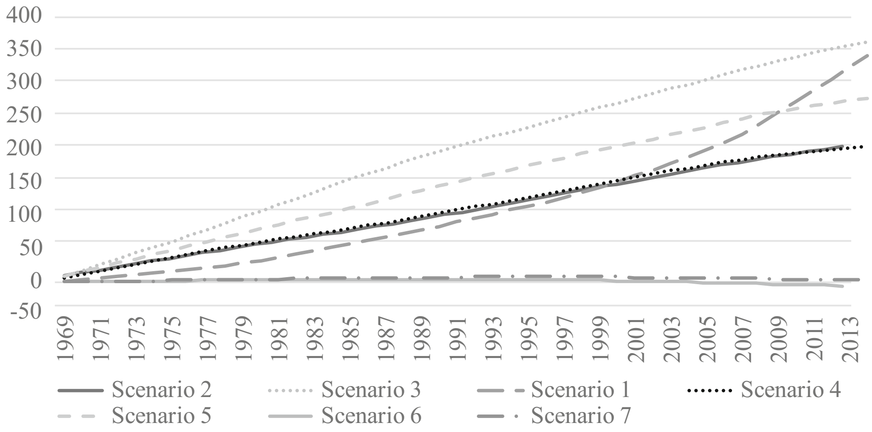

Fig. 7 A comparison of accumulative CO_2 savings from using renewable energy in Iceland as estimated by the Icelandic National Energy Authority, excluding the rebound effect, and scenarios calculated in this study [29]

period between 1969 and 2014. When looking at the time interval between 1994 and 2014 the emission savings amount to 17.6 Mt/CO_2 equivalents. (Fig. 7)

3.3 Emission Savings in Perspective

It is of little surprise that Scenarios 6 and 7 showed small or negative savings. The scenarios basically describe the same consumption of renewable energy grid mix available but a more conservative consumption pattern. When looking at aggregated results from all scenarios, and comparing with official numbers from the NEA excluding any change in consumption pattern one can see that compared to Scenario 2, the NEA doubles the estimated emission savings, and triples the estimation between the years 1994 and 2014. For Scenario 3, the NEA overestimates the emissions by 94% between 1969 and 2014 and overestimates by 168% between 1969 and 2014. Now, interestingly, if Icelanders would consume energy in the same way as the English, but still have access to renewable energy, the emissions are 136 Mt/CO_2 equivalents less than the NEA official numbers. One can argue that using the savings from Scenarios 4 and 5 may provide the most realistic results as Icelanders in these scenarios do no consume or discover geothermal energy, but still avoid the heavy exploitation of the available energy sources. One can therefore say that approximate savings between the years 1969 and 2014 are between 204 and 277 Mt/CO_2 equivalents based on scenarios 4 and 5.

It is not deniable that even though the CO_2 emission savings are much less than previously estimated, simply because of the increase in energy consumption, the lives of the general public has improved generously since the dawn of renewable energy utilisation. Economic benefits are also estimated to be great, but similar analysis has to be done on that issue as has been demonstrated here to get a clearer image about real economic benefits.

4 Conclusion

Advancements in methodologies to calculate the energy return on investment are now providing a platform for studies to be compared. We demonstrated above in some detail how such calculations are carried out. We also demonstrated the so called $EROI_{ide}$, providing policymakers with knowledge about the theoretical upper efficiency boundary of energy sources. Involved players may therefore not only gain insights into the current energy return to society, but also which energy sources have possibilities for improvements and where such improvements are situated.

We have also demonstrated how environmental mitigation can be calculated using alternative scenario analysis and consider the rebound effect. It was demonstrated that emission savings in Iceland are somewhere between 200 and 360 million tonnes of CO_2 equivalents between the years 1969 and 2014. The actual savings are however difficult to estimate as scenarios are simply sets of assumptions used to create alternative realities which never materialised. The calculations demonstrated in this chapter to estimate emission savings do however provide an indication of how much emissions can be saved by converting to renewable energy, in particular geothermal and hydro.

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Future Maintenance Management in Renewable Energies

Carlos Quiterio Gómez Muñoz and Fausto Pedro García Márquez

Abstract This chapter describes the future on maintenance management in renewable energy industry. The main advances and research studies shows that it will be based on non-destructive testing (NDT). NDT are tests performed to detect internal or surface discontinuities in materials or determine certain properties. NDT leads to improvement of product quality, public safety and prevention of catastrophic failures. NDT techniques are used in Structural Health Monitoring (SHM) systems for Fault Detection and Diagnosis (FDD). Some NDT techniques are used to prevent serious failures in critical components such as blades, gearbox, tower or receiver tubes. NDT is increasing in many scientific and industrial fields, from wind energy production to the transportation of gases and liquids. Consequently, it is possible to reduce the corrective/preventive maintenance tasks, and to increase the life cycle of the structure.

1 Introduction

Non-Destructive Testing (NDT) is used in Structural Health Monitoring (SHM) systems for Fault Detection and Diagnosis (FDD) [1]. Within the context of Condition Based Maintenance (CBM), some NDT techniques are used to prevent serious failures in critical components such as blades, gearbox, tower or receiver tubes [2, 3].

NDT has become an essential technique for the development of SHM systems. NDT uses are increasing in many scientific and industrial fields, from wind energy production to transport. The NDT progress depends on the continuous changes of the industry to suit current scenarios. The benefits that these new techniques provide are related to the improvement of the product quality, public safety and

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especially the prevention of faults. The main consequence is the reduction of costs, since they can anticipate potential failures that could involve both material and human losses to reduce the corrective/preventive maintenance tasks, and to increase the life cycle of the structure. Other advantages that they present are related to the forecasting analysis based on the data acquired in a real-time mode, as well as the establishment of FDD techniques [4, 5].

NDT are tests performed to detect materials for internal or surface discontinuities, or to determine properties of the same. It is also applied to view the properties of welds, parts and components or to determine the thickness of a material. The indications must be performed by qualified operators.

Compared with destructive testing, it provides less accurate data about the object under study but are usually less expensive because the part is not destroyed. The damage suffered by the piece is zero or almost zero and does not alter its physical, chemical, or mechanical dimensional properties.

Application Areas:

- *Quality control*: This includes the tests performed to detect discontinuities, impurities and defects, characterization of materials and dimensional metrology.
- *Maintenance of facilities and equipment*: The purpose of these is to evaluate corrosion and deterioration caused by environmental agents, determining stresses, leak detection, etc.
- *Preservation and study of cultural heritage*: These tests look for defects and information about the structural state of historical monuments.

2 Classification

Penetrating Liquids

Liquid Penetrant Inspection (LPI) or Dye Penetrant Inspection (DPI) has wide applicability. It is used to detect flaws or surface discontinuities on nonporous materials such as metals, glasses, ceramics, etc. It was introduced in the industry looking for an alternative method of magnetic particles, which requires materials with ferromagnetic characteristics [6] (Fig. 1).

Magnetic Particle Inspection (MPI) is acting on the principle of the capillary effect (i.e. the ability of certain liquids to penetrate and be retained in the surface discontinuities). It depends on three properties: Wettability, surface tension and viscosity.

Magnetic Particle Inspection

It is used to detect cracks, surface or subsurface discontinuities in ferromagnetic materials. It is based on the physical principle of magnetism (attractiveness between metals).

This method involves to inspect the magnetized piece, then magnetic particles are applied subsequently and the results are studied according to the grouping of particles [7]. Finally, the piece is demagnetized and cleaned.

Fig. 1 Inspection employing penetrating liquid

Eddy Current or Foucault

It is based on the principle of electromagnetic driving. For that purpose, a AC generator is used. The generator is connected to a test coil that produces a magnetic field [8]. If the coil is placed near a material which is electrically conductive, the field of the coil will induce an electric current in the material to be inspected. This current will produce a new magnetic field, which is called secondary field and will be proportional to the first field but opposite sign. As the induced current is alternating, whenever the current becomes zero, the secondary magnetic field will induce a new electric current in the coil. This occurs when the current changes phase.

Industrial Radiography

A body exposed to X- or Gamma rays absorbs energy in proportion to its thickness, density or configuration [9]. This method involves bombarding an object with a beam of X or Gamma rays. Part of the radiation is absorbed by the object itself and the unabsorbed part is recorded by a printing plate. This is revealed displaying an image and it can be observed changes in tonality which are associated with changes in the material, like defects.

Thermography

When a material contains imperfections, they alter the rate of heat flow there around due to high temperature gradients and hot spots are formed. In this technique a coating which acts temperature is applied to the material surface [9]. After the material is heated uniformly and then allowed to cool. The temperature around imperfections is higher than in other areas, so with the help of coating can be detected those points with different colour.

Among other applications with thermography they are: to detect faulty joints or delamination of layers that are part of composite materials.

Acoustic Emission

Acoustic Emission (AE) is a passive but dynamic Non-Destructive Evaluation (NDE) technique which is extensively used for SHM by the industry. The principle of AE is based on the detection of transient elastic waves emitted when the component under evaluation is loaded up to a sufficient level to cause damage growth. AE signals are high frequency events with very small magnitude. In order to detect AE signals very sensitive piezoelectric sensors are employed. The piezoelectric crystals convert the resulting displacement in the surface of the component to electric signals which are then suitably amplified using appropriate amplification.

AE signals can be generated from various sources including dislocation movement, plastic deformation, crack growth, corrosion, erosion, impact, friction and even phase transformation. In composite materials signals can arise from fibre deboning, delamination, matrix cracking and fibre failures. Depending on the type of damage evolution mechanism different wave types may appear [10]. Crack growth in a metal will usually give rise to a burst type waveform. By analysing the different waveforms and other features of the AE signal it is possible to recognise the feature in the material that is giving rise to specific aspects of the recorded AE activity (Fig. 2).

It is a method used to detect elastic waves occurring spontaneously. When a material is subjected to repetitive strain it is produced micro-cracks in the material releasing energy that is directed to the outside of the piece. This energy is released as elastic wave that produces sound. Through sensors disposed on the surface it is possible to capture and record the sound. These sensors convert the mechanical energy of that sound into small electrical pulses that are often accompanied by amplifiers to record and analyse the signal more clearly.

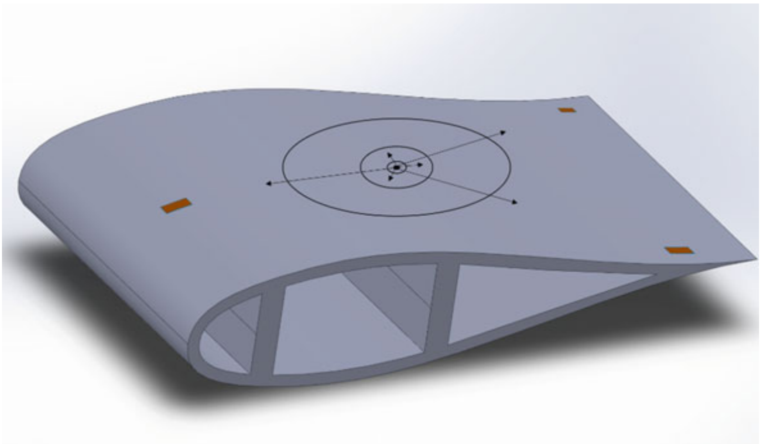

Fig. 2 Mechanical and elastic waves propagation from the acoustic emission source

Ultrasonic Inspection

Ultrasonic inspection is a non-destructive method where a set of mechanical high frequency waves (above 20 kHz) are applied to the material to be examined. These waves travel through the material, being reflected when it reaches the interface or a discontinuity. This beam is then analysed paying attention to three points:

- The Wave reflection on the interfaces
- The Transit time (Time of flight or ToF) of the ultrasound wave.
- The Attenuation of sound waves in the workpiece due to absorption and scattering within the workpiece.

Thus the presence, size and location of discontinuities is determined.

Ultrasonic Inspection Phased Arrays

Ultrasonic phased arrays consisting of several elements can increase the speed and accuracy of the inspection as well as remove some of the limitations related with the accessibility to the surface of the component since the interrogating beam can be scanned and steered in the direction of interest without having to move the probe itself. Furthermore, ultrasonic phased arrays can produce detailed C-scan images providing a useful visual record of the inspection. Two-dimensional images can be used to reconstruct three-dimensional images of the inspected component (Fig. 3).

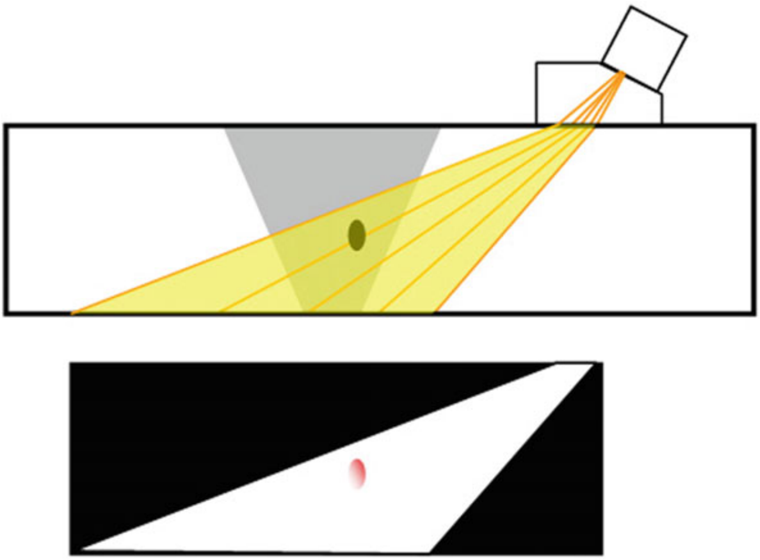

Fig. 3 Checking phased array probe resolution

3 Guided Waves

Inspection techniques using guides waves have gained popularity among structural monitoring techniques. This is due in large part to the drawbacks encountered in other NDT techniques, such as thermography and radiography. An example of one such drawback occurs when examining solar concentrator pipes. Thermography has a limited ability to identify internal defects if they are not outwardly manifested as temperature, and industrial radiography is dangerous for people who are close to the inspection site. Furthermore, the long range of the guided waves can inspect a greater distance than other techniques (Fig. 4).

The inspection by guided waves consists of the excitation of an ultrasonic transducer, which generates ultrasonic waves that are propagated through the pipe [11]. The main advantage offered by this technique, compared with traditional ultrasonic methods, is the ability to inspect structures, such as plates or pipes, along several meters. This technique permits us to know the state of the pipe at a particular location. In some cases, hundreds of meters can be inspected without the relocation of the transducer.

Novel methodologies in signal processing are being published [12], such as predictive analysis online, in order to be employed in structural health monitoring and ultrasonic waves. This waves can be generated in structures like plates or pipes.

3.1 Structures with Two Surfaces Like Plates

In these structures Lamb waves and Shear Horizontal (SH) waves are generated. Lamb waves are guided waves propagating in plate or shell type structures. His interest has been growing for its ability to detect damage to these structures (Fig. 5).

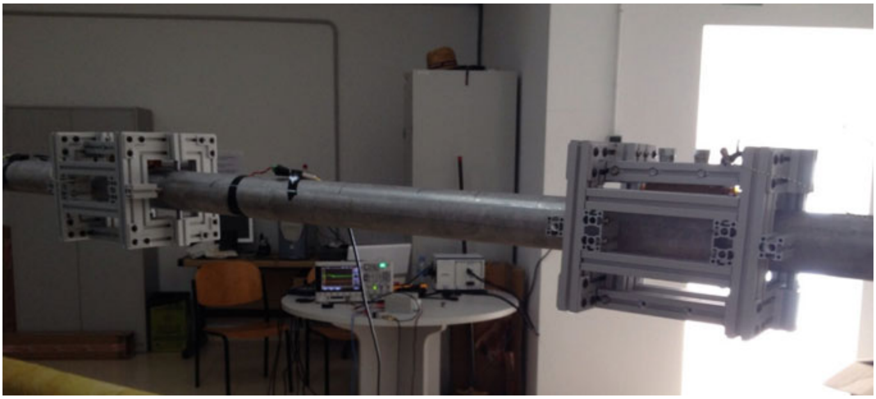

Fig. 4 Inspection of pipes by long rage ultrasonic

Fig. 5 Inspection of delamination in a wind turbine blade employing ultrasonic guided waves

In Lamb waves, energy is confined between the two surfaces and its attenuation is lower [13]. Lamb waves are composed of two different vibration modes, the symmetric and anti-symmetric modes (S0 and A0).

The SH waves have a direction of propagation perpendicular to the particle movement direction. As Lamb waves, SH waves also have the symmetric modes or antisymmetric (SH0, SH1…). These waves are used to inspect plates are embedded, because hardly affected by external forces.

3.2 *Pipe Type Structure*

Cylindrical Lamb Waves

Lamb waves are guided waves that propagate in thin plate structures or shell structures. The interest in using Lamb waves to identify structural damage has increased in recent years. Damage identification using Lamb waves is in an early stage of development compared with other techniques such as ultrasonic scanning [14–16]. Lamb waves can also be generated in tubular structures such as in a pipe where thickness is much smaller compared to diameter. The propagation of Lamb waves in pipes is similar to those in thin plates with the addition of some peculiarities. Cylindrical Lamb wave's modes are longitudinal, torsional and flexural, labelled with L, T and F respectively. The cylindrical Lamb modes have two integers, $L(n, m)$, $T(n, m)$, and $F(n, m)$, $(n, m = 0, 1…)$. Specifically, $n = 0$ indicates that the pipe is axially symmetric which is the case in most applications. The integer m indicates the mode number, in particular, $L(0, 1)$ propagates through the thickness of the pipe similar to the A_0 mode in flat plates, and $L(0, 2)$ mode propagates

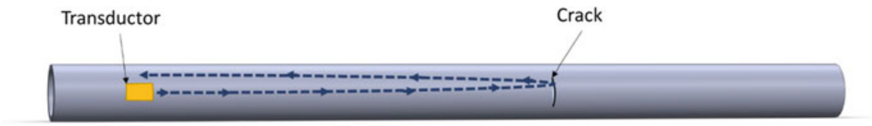

Fig. 6 Inspection of pipes employing guided waves

similar to the S_0 mode in plates. $L(0, 1)$ and $L(0, 2)$ are the most appropriate modes for damage identification because their axisymmetric properties facilitate the inspection along the circumference of the pipe.

- Longitudinal waves: This mode is very similar to the symmetric and antisymmetric modes which appear in plates
- Flexural waves: These modes are not symmetrical about the axis (Fig. 6).
- Torsional waves: They are similar to the Shear Horizontal waves and are primarily used to inspect buried or embedded pipes, due to they suffer less attenuation. This mode has axial symmetry and the particles only have circumferential displacement.

4 Theoretical Principles of the Infrared Thermography

Infrared thermography is the technology that, using the physical principles described above, considers the use of optical-electronic devices to detect and measure the radiance emitted by a specific object or surface.

The beginning of the thermography can be attributed to the German astronomer Sir William Herschel, who conducted experiments with sunlight in 1800 [17]. Herschel discovered infrared radiation by passing sunlight through a prism and measuring the temperature in different colours obtained with sensitive mercury thermometer. Twenty years later, the German physical Thomas Seebeck discovered the thermoelectric effect [18], given the origin of the "thermomultiplier". Macedonio Melloni improved the thermomultiplier, creating the thermopile, a set of thermomultipliers in series, and concentrating the thermal radiation for detecting the body heat from a distance of 9 m [19]. The thermography was used for non-military applications in the sixties in a variety of industrial applications [20, 21], e.g. in the inspection of large electrical transmission and distribution systems, but the equipment employed were big, slow to data acquisition and with low resolution. Continuing advances in military applications in the seventies led to the first portable systems that could be used in industrial applications such as building diagnostics [22] and NDT of materials [23].

Remote sensing techniques are based on the reception and analysis of the electromagnetic energy reflected or emitted by a surface (Fig. 7). Data collected by

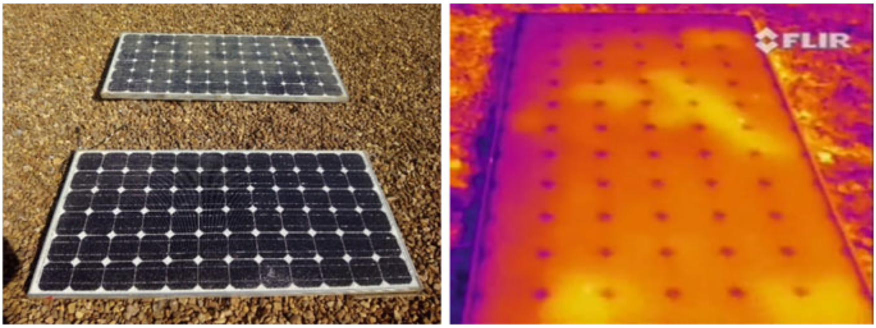

Fig. 7 Infrared thermal inspection of solar panels

remote sensors can be used to retrieve features and parameters of the observed surface, without physical contact [24].

In the thermal infrared, the emitted energy is related to the kinetic temperature of the radiating body though the well-known Planck's law (first assuming a perfect radiator or black body):

$$B_\lambda(T) = \frac{C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)} \tag{1}$$

where B is the spectral radiance (W m^{-2} µm^{-1}), at wavelength λ (µm), C_1 and C_2 are physical constants ($C_1 = 3.74 \times 10^8$, $C_2 = 1.439 \times 10^4$), and T (K) represents the physical temperature of the object. Thermal infrared is the region of the electromagnetic spectrum ranging between 3.0 and 100 µm. However, the spectral window 8-14 µm is traditionally used in remote sensing applications due to the low absorption of the water vapour and the neglected contribution of reflected sunlight in this range.

In practice, real objects are not ideal blackbodies and the radiance of a body at kinetic temperature T is reduced by the emissivity (ε_λ) factor according to:

$$L_\lambda(T) = \varepsilon_\lambda B_\lambda(T) \tag{2}$$

where L is the emitted radiance. Emissivity depends on the substance and varies with wavelength, so that every single surface or body is characterized by its spectral signature.

This emissivity has an effect on the environmental radiance reflected by the surface and also measured by the remote sensor. According to the radiative transfer equation:

$$L_\lambda(T_R) = \varepsilon_\lambda B_\lambda(T) + (1 - \varepsilon_\lambda) L_\lambda^{\downarrow} \tag{3}$$

where T_R is the radiometric temperature corresponding the real temperature T, and $L^{\downarrow}$ is the down welling environmental radiance.

5 Conclusions

Wind and solar energy powers have become the most important renewable energies worldwide in recent years. The reduction in operating and maintenance costs of the turbines has been identified as one of the biggest challenges to establish this energy as an alternative to fossil fuels. Predictive maintenance can detect a potential failure at an early stage reducing operating costs, especially in areas of difficult access.

Non-destructive tests have emerged as an effective method to detect defects and failures in those crucial pieces for the proper functioning of the plant. Guided ultrasonic waves offer possibilities as NDT to inspect structures for large cracks and corrosion.

Infrared thermography presents a simple and effective way to increase productivity in solar plants by detecting the broken cells [25]. This helps to generate a more optimal maintenance strategy, reducing costs and making more efficient the production of renewable energy.

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