

# A qualitative multi-criteria modelling approach to the assessment of electric energy production technologies in Slovenia

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**Abstract** A methodological approach to the strategic evaluation of electric energy production technologies in Slovenia is presented. The aim of this work is to make a transparent and reproducible identification of reliable, rational, and environmentally sound production of electric energy in Slovenia by 2050. The approach is based on a qualitative multi-criteria modelling method DEX and consists of three stages: (1) assessment of individual technologies for electricity production, (2) assessment of mixtures of technologies and (3) evaluation of scenarios of shutting-down existing old power plants and constructing the new ones until 2050. Technology alternatives include both conventional and renewable energy sources: coal fired, gas fired, biomass fired, oil fired, nuclear, hydro, wind, and photovoltaic. The results indicate that only mixtures of nuclear, hydro, and gas fired technologies can meet expected energy needs in a sufficiently reliable and rational way.

**Keywords** Electric energy production technology · Power plants · Multi-criteria decision modelling · Qualitative model · Decision rules · Method DEX

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## 1 Introduction

Electric energy is a strategic resource that plays a vital role in the performance of every country. Electric energy production is a complex process, which requires strategic management and careful planning years ahead. The selection of appropriate technologies for electric energy production depends on a number of factors: energy needs of a country, availability of fuel and other natural resources, feasibility, efficiency, effectiveness and rationality of production, environmental impacts, and many more. Not only that these factors are multiple, they often appear conflicting and influence the decisions in a variety of ways; thus they have to be carefully assessed individually and against each other.

For this kind of problems, Operations Research provides Multi-Criteria Decision Modelling (MCDM) methods (Figueira et al. 2005; Ishizaka and Nemery 2013) that assess decision alternatives using multiple criteria. Each alternative is first assessed according to each criterion. These individual assessments are aggregated into an overall evaluation of the alternative, which provides a basis for comparison, ranking and analysis of alternatives, and eventual selection of the best one. MCDM methods are commonly employed in the assessment of electric energy production (Pohekar and Ramachandran 2004), either in a general setting (Stein 2013), in specific environments such as islands (Wimmler et al. 2015), or in individual countries, such as Germany (Hirschberg et al. 2004), Bosnia (Begić and Afgan 2007), Turkey (Kahraman and Kaya 2010) and Portugal (Ribeiro et al. 2013).

In Slovenia, almost 13 TWh of electricity is consumed annually (this is net figure for the year 2014, estimations for the period January–December 2015 show the increase of 2.4%). The electricity is produced by thermal, hydro, and nuclear power plants in approximately equal shares. After a recent introduction of a controversial and expensive Unit 6 of the coal-fired power plant in Šoštanj (TEŠ6), which is expected to produce up to 3.5 TWh of electricity annually, there are important decisions to be taken for the next decades. Slovenia has one nuclear power plant in Krško, which produces around 5 TWh of electricity annually, and which will be according to plans closed down in 2023. However, there is an option to extend its operation until 2043. Another large power plant, coal-fired unit TEŠ5, will be closed down in 2027. There are plans to finalize, by 2025, two hydro power plants on the lower Sava river, which is the last Slovenian water resource available for hydro power plants. There are also plans to introduce gas fired plants, and energy production from renewable sources: wind, biomass and sun.

In order to contribute to strategic planning of electrical energy production in Slovenia, a project called OVJE (Kontić 2014; Kontić et al. 2016) was conducted with the aim to make a transparent and reproducible identification of reliable, rational, and environmentally sound production of electric energy in Slovenia by 2050. Eight electric energy production technologies were considered: hydro, coal, oil, gas, nuclear, biomass, photovoltaic (PV), and wind. Hereafter we present the methodological approach to this identification and summarize the main results. In contrast with the publication (Kontić et al. 2016), which presents the project OVJE and its results in the context of formulating energy policies and, particularly, seeking for sustainable energy man-

agement, this paper focuses on the MCDM methodology employed in the project and presents it as a use case of qualitative multi-criteria modelling using the method DEX.

## 2 Methods

The methodological approach is based on a qualitative MCDM method DEX, enhanced with the use of uncertainty intervals and value distributions (Sect. 2.1). The method takes place in three stages, involving two MCDM models and one simulation model (Sects. 2.2–2.4):

- *Model T*: Evaluation of eight individual electric energy production technologies.
- *Model M*: Evaluation of mixtures of technologies, considering the shares of individual technologies in the total installed capacity.
- *Model S*: Simulation of possible implementations of technology mixtures in the period 2014–2050, taking into account various scenarios of shutting down the existing power plants and constructing new ones.

### 2.1 Qualitative multi-attribute modelling method DEX

DEX (Decision EXpert) (Bohanec et al. 2013) is a *multi-criteria decision modelling method*. As all other MCDM methods, it is aimed at the evaluation and analysis of a set of decision *alternatives*  $A = \{a_1, a_2, \dots, a_m\}$ . These alternatives are described with a set of variables  $X = \{x_1, x_2, \dots, x_n\}$ , called *attributes*. Each attribute represents some observed or evaluated property of alternatives, such as “price”, “quality”, and “efficiency”.

DEX is a *hierarchical method*. This means that the attributes  $X$  are organized in a *hierarchy*, in the same way as in, for instance, the well-known MCDM method AHP (Saaty 2008). Observed in the top-down direction, the hierarchy represents a decomposition of the decision problem into sub-problems. The bottom-up direction denotes dependence, so that higher-level attributes depend on the lower-level, more elementary ones. The most elementary attributes, called *basic attributes*, appear as terminal nodes of the hierarchy and represent the basic observable characteristics of alternatives. Higher-level attributes, which depend on one or more lower-level ones, are called *aggregated attributes*; they represent evaluations of alternatives. The topmost nodes (usually, there is only one such node) are called *roots* and represent the final (also called overall or comprehensive) evaluation(s) of alternatives.

Furthermore, DEX is a *qualitative method*. While most of MCDM methods are quantitative and thus use numeric variables, qualitative methods use symbolic, verbal ones. In DEX, each attribute  $x_i \in X$  has an associated *value scale*  $D(x_i) = D_i = \{v_{i1}, v_{i2}, \dots, v_{ik_i}\}$ , where each  $v_{ij}$  represents some ordinary word, such as “low”, “high”, “acceptable”, “excellent”. Scales are usually small, containing 2–5 values. Typically, they are designed so that they contain the least number of values that still discriminate between importantly different characteristics of alternatives, which are relevant for the decision (Bohanec 2015). Also, scales are usually preferentially ordered so that  $v_{i1} \preceq v_{i2} \preceq \dots \preceq v_{ik_i}$  (here,  $a \preceq b$  denotes weak preference:

the value  $b$  is preferred equally or more than  $a$ ). Attributes that have preferentially ordered scales are called *criteria* (Figueira et al. 2005).

Finally, DEX is a *rule-based method*. The bottom-up aggregation of alternatives' values is defined in terms of *decision rules*, which are specified by the decision maker and usually represented in the form of decision tables. Each aggregate attribute in the model has an associated decision table that defines how the value of that attribute is determined (aggregated) from the values of its immediate descendants in the hierarchy.

*Decision tables and rules* In the following, let us focus on a single aggregated attribute and denote it  $y \in X$ . The value scale of  $y$  is denoted  $D_y$ . To simplify the notation, let us without the loss of generality assume that  $x_1, x_2, \dots, x_r \in X$  are immediate descendants of  $y$  in the hierarchy. For the purpose of aggregation, the decision maker has to define an *aggregation function*

$$f_y : D_1 \times D_2 \times \dots \times D_r \rightarrow D_y$$

In DEX, the aggregation function  $y = f_y(x_1, x_2, \dots, x_r)$  is defined with a set of decision rules of the form

**if**  $x_1 = v_1$  **and**  $x_2 = v_2$  **and**  $\dots$  **and**  $x_r = v_r$  **then**  $y = v_y$ .

Here,  $v_i \in D_i$  and  $v_y \in D_y$ .

In principle, any number of decision rules can be defined by the decision maker for each aggregate attribute. However, the decision maker is encouraged [and actively supported by the modelling software (Bohanec 2015)] to define as many rules so that the decision space  $D_1 \times D_2 \times \dots \times D_r$  is covered as completely as possible. For parts that still remain uncovered, DEX employs the principle of dominance (Greco et al. 2010). This means that for each undefined part of the decision space a lower and upper bound are determined from other already defined rules.

*Evaluation of alternatives* Having defined the attributes, their structure, scales and decision rules, the model is ready for the evaluation of alternatives. In the case when all decision tables and alternatives are completely defined, this is as a straightforward bottom-up aggregation procedure. Each alternative is described by the values of basic attributes, using a single qualitative value for each attribute. These values are gradually aggregated towards the roots of the hierarchy. The value of each aggregate attribute along the way is determined by a simple lookup into the corresponding decision table.

For cases when decision tables or decision alternatives are incompletely defined (due to uncertainty, missing information or decision-maker's hesitation), DEX provides evaluation procedure based on sets. Instead of a single value  $v_i \in D_i$ , each attribute  $x_i \in X$  can now be assigned a *set of values*  $V_i \subseteq D_i$ . When evaluating the function  $y = f_y(x_1, x_2, \dots, x_r)$ , the values of function arguments are now sets  $V_1, V_2, \dots, V_r$ . In this setting, the function  $f$  is evaluated for all possible combinations of single argument values, in general yielding a set of values  $V_y \subseteq D_y$ :

$$V_y = \bigcup_{(v_1, v_2, \dots, v_r) \in V_1 \times V_2 \times \dots \times V_r} f(v_1, v_2, \dots, v_r)$$

Furthermore, in order to better quantify uncertainty or represent objects composed of other objects with given shares, the value sets can be extended to value distributions (Žnidaršič and Bohanec 2010; Trdin and Bohanec 2014). A value distribution  $Q_i$ , which corresponds to attribute  $x_i$ , is defined as a tuple  $(V_i, P_i)$ , where  $V_i \subseteq D_i$  and  $P_i : V_i \rightarrow [0, 1]$ . For some specific  $Q_i$ , we use the notation  $Q_i = \{v_1/p_1, v_2/p_2, \dots, v_{k_i}/p_{k_i}\}$ , where  $v_j \in D_j$  and  $p_j = r(v_j)$  for each  $j = 1, 2, \dots, k_i$ . Usually,  $p_j$ 's are interpreted as probabilities or relative shares, therefore they are normalized so that  $\sum_{j=1}^{k_i} p_j = 1$ .

With value distributions, the evaluation of function  $y = f_y(x_1, x_2, \dots, x_r)$  involves function arguments that are, in general, probability distributions  $Q_1, Q_2, \dots, Q_r$ . and the function itself is expected to yield a value distribution  $Q_y$ . The evaluation proceeds by taking into account all distributions

$$E = \{v_1/p_1, v_2/p_2, \dots, v_r/p_r\} \in Q_1 \times Q_2 \times \dots \times Q_r.$$

The probability (or share) of each  $E$  is

$$g(E) = g(\{v_1/p_1, v_2/p_2, \dots, v_r/p_r\}) = \prod_{i=1}^r p_i$$

The evaluation of  $f_y(E) = f_y(v_1, v_2, \dots, v_r)$  in general yields another distribution  $\{y_1/u_1, y_2/u_2, \dots, y_{k_y}/u_{k_y}\} \in Q_y$ , where  $k_y = |D_y|$ . Consequently, the contribution of each  $E$  to the overall probability of each value  $y_i \in D_y$  equals  $u_i g(E)$ . In the evaluation, these contributions are summed up over all  $E$ 's. In summary, this gives the overall distribution

$$Q_y = \{y_1/w_1, y_2/w_2, \dots, y_{k_y}/w_{k_y}\}$$

where for each  $i = 1, 2, \dots, k_y$

$$w_i = \sum_{E \in Q_1 \times Q_2 \times \dots \times Q_r : y_i/u_i \in f_y(E)} u_i g(E)$$

*Implementation* The method DEX is implemented as DEXi (Bohanec 2015), a freely available computer program that supports both the development of DEX models and their application for the evaluation and analysis of decision alternatives. In the development stage, DEXi checks the quality of decision rules; as long as quality checking is enabled, developed models are guaranteed to be *complete* (they provide evaluation results for all possible combinations of basic attributes' values) and *consistent* (defined aggregation functions obey the principle of dominance, i.e., they are monotone with

respect to all preferentially ordered basic criteria). In the evaluation stage, DEXi supports evaluation based on sets, while various DEX extensions (Trdin and Bohanec 2014) are available for the evaluation using value distributions.

For further information of DEX and DEXi, please refer to Bohanec et al. (2013) and Bohanec (2015), respectively.

## 2.2 Model T: evaluation of technologies

The DEX model, used in the first stage of appraisal of electric production technologies, is called *Model T* ('T' stands for "Technologies"). It is aimed at the evaluation and comparison of *individual* energy production technologies:

$$A = \{\text{Hydro, Coal, Oil, Gas, Nuclear, Biomass, PV, Wind}\}$$

Evaluation criteria  $X$  are organized in a hierarchy shown in Fig. 1. The hierarchy contains 36 basic and 28 aggregated attributes. There are two aggregated attributes that appear twice in Fig. 1, because they affect more than one higher-level attribute: *Licenses* and *Contribution to development*. Figure 1 also shows attributes' value scales; all scales are preferentially ordered increasingly in the direction from left to right. Consequently, all attributes in the model represent criteria. Value scales are of moderate size from 2 to 5 values. The number of values gradually increases from basic attributes towards the root of the model, which uses the 5-valued scale {unsuit(able), weak, suit(able), good, exc(ellent)}. The worst (undesired) and best (desired) values of each scale are emphasized by using red/bold and green/italic typeface, respectively.

Model T consists of three main sub-trees of criteria: *Rationality*, *Feasibility*, and *Uncertainty*. *Rationality* assesses how much a particular technology contributes to the overall societal development, the economy, and the prudent use of land with low pollution. Each of these aspects is represented by a corresponding attribute and decomposed further. The sub-tree *Land use and pollution*, for instance, specifically addresses *Spatial availability*, *Pollution*, and *Health impacts*. Similarly, the assessment of *Feasibility* takes into account *Technical*, *Economic* and *Spatial feasibility*. The evaluation of *Uncertainty* comprises *Technological dependence* (in terms of foreign, uncontrollable factors, operation of supplier, and political stability), *Possible changes* in society and in the world, and *Perception of risks* with respect to technical advancement of a technology and trust into safety management system.

For a more detailed description of attributes used in Model T, particularly about their meaning, justification and acquisition in the context of energy policies and management, the reader is referred to Kontić et al. (2016).

Since Model T contains 28 aggregated attributes, there are also 28 corresponding decision tables, which were defined by experts and decision analysts in the OVJE project (Kontić 2014; Kontić et al. 2016). Here, we present only one table that corresponds to the root attribute *Technology*: Table 1 shows a condensed form of decision rules that aggregate intermediate assessments of *Rationality*, *Feasibility* and *Uncertainties* into the overall evaluation of *Technology*. The first rule, for instance, says that whenever *Rationality* is inappropriate, then *Technology* is considered unsuitable,

**Fig. 1** Hierarchical structure and value scales of Model T

Attribute	Scale
<b>Technology</b>	<b>unsuit</b> ; weak; suit; <b>good</b> ; <b>exc</b>
<b>Rationality</b>	<b>inapprop</b> ; low; <b>med</b> ; <b>high</b>
<b>Contribution to development</b>	<b>low</b> ; med; <b>high</b>
Economic	<b>low</b> ; med; <b>high</b>
Societal	<b>low</b> ; med; <b>high</b>
<b>Economic-Technical advancement</b>	<b>low</b> ; med; <b>high</b>
Technical level	<b>low</b> ; med; <b>high</b>
Expected development	<b>low</b> ; med; <b>high</b>
<b>Economy</b>	<b>low</b> ; med; <b>high</b>
<b>Financial aspects</b>	<b>less_suit</b> ; suit; <b>more_suit</b>
Energy price	<b>high</b> ; med; <b>low</b>
<b>Financing</b>	<b>less_suit</b> ; suit; <b>more_suit</b>
Financial sources	<b>uncertain</b> ; less_certain; <b>certain</b>
Financial shares	<b>less_suit</b> ; suit; <b>more_suit</b>
Long-term liabilities	<b>less_suit</b> ; suit; <b>more_suit</b>
<b>Efficiency</b>	<b>low</b> ; med; <b>high</b>
Energy ratio	<b>low</b> ; med; <b>high</b>
Return period	<b>long</b> ; med; <b>short</b>
<b>Independence</b>	<b>low</b> ; med; <b>high</b>
Dependence	<b>v_high</b> ; high; med; low; <b>none</b>
<b>Land use and pollution</b>	<b>unsuit</b> ; <b>less_suit</b> ; suit; <b>more_suit</b>
<b>Spatial availability</b>	<b>less_suit</b> ; suit; <b>more_suit</b>
Land availability	<b>low</b> ; med; <b>high</b>
Energy share provision	<b>low</b> ; med; <b>high</b>
<b>Resource protection</b>	<b>weak</b> ; present; <b>effective</b>
Water protection	<b>weak</b> ; present; <b>effective</b>
Land protection	<b>weak</b> ; present; <b>effective</b>
Landscape protection	<b>weak</b> ; present; <b>effective</b>
Pollution	<b>high</b> ; med; <b>low</b>
<b>Health impact</b>	<b>high</b> ; med; <b>low</b>
<b>Air pollution</b>	<b>high</b> ; med; <b>low</b>
Greenhouse gases	<b>high</b> ; med; <b>low</b>
Other pollutants	<b>high</b> ; med; <b>low</b>
<b>Public health status</b>	<b>low</b> ; med; <b>high</b>
Contribution to development	<b>low</b> ; med; <b>high</b>
<b>Feasibility</b>	<b>low</b> ; med; <b>high</b>
<b>Technical feasibility</b>	<b>low</b> ; med; <b>high</b>
Technological complexity	<b>less_suit</b> ; suit; <b>more_suit</b>
Infrastructure availability	<b>low</b> ; med; <b>high</b>
<b>Accessibility</b>	<b>low</b> ; med; <b>high</b>
Fuel availability	<b>low</b> ; med; <b>high</b>
Fuel accessibility	<b>low</b> ; med; <b>high</b>
<b>Economic feasibility</b>	<b>low</b> ; med; <b>high</b>
Investment feasibility	<b>low</b> ; med; <b>high</b>
Return of investment	<b>less_suit</b> ; suit; <b>more_suit</b>
<b>Spatial feasibility</b>	<b>low</b> ; med; <b>high</b>
<b>Societal feasibility</b>	<b>low</b> ; med; <b>high</b>
Social acceptance	<b>low</b> ; med; <b>high</b>
Permitting	<b>no</b> ; <b>yes</b>
Spatial suitability	<b>low</b> ; med; <b>high</b>
<b>Uncertainties</b>	<b>v_high</b> ; high; med; low; <b>none</b>
<b>Technological dependence</b>	<b>v_high</b> ; high; med; low; <b>none</b>
<b>Foreign dependence</b>	<b>v_high</b> ; high; med; low; <b>none</b>
<b>Construction</b>	<b>high</b> ; med; <b>low</b>
<b>Licences</b>	<b>strong_restr</b> ; moder_restr; <b>no_restr</b>
<b>Operation</b>	<b>high</b> ; med; <b>low</b>
<b>Licences</b>	<b>strong_restr</b> ; moder_restr; <b>no_restr</b>
Contracts	<b>strong_restr</b> ; moder_restr; <b>no_restr</b>
Special materials	<b>strong_restr</b> ; moder_restr; <b>no_restr</b>
Weather dependence	<b>high</b> ; med; <b>low</b>
Fuel supply dependence	<b>high</b> ; med; <b>low</b>
Political stability	<b>no</b> ; low; <b>high</b>
<b>Possible changes</b>	<b>neg</b> ; no; <b>pos</b>
Possible societal changes	<b>neg</b> ; no; <b>pos</b>
Possible world changes	<b>neg</b> ; no; <b>pos</b>
Perception of risks	<b>v_high</b> ; high; med; low; <b>none</b>

**Table 1** Example of decision rules that aggregate *Rationality*, *Feasibility* and *Uncertainties* into *Technology*

	<b>Rationality</b>	<b>Feasibility</b>	<b>Uncertainties</b>	<b>Technology</b>
	43%	29%	28%	
1	<b>inapprop</b>	*	*	<b>unsuit</b>
2	<=low	<=med	<b>v_high</b>	<b>unsuit</b>
3	<= <b>med</b>	<b>low</b>	<b>v_high</b>	<b>unsuit</b>
4	>=low	<b>low</b>	high:med	weak
5	>=low	<b>high</b>	<b>v_high</b>	weak
6	>= <b>med</b>	>=med	<b>v_high</b>	weak
7	<b>high</b>	<b>low</b>	<=med	weak
8	<b>high</b>	*	<b>v_high</b>	weak
9	low: <b>med</b>	<b>low</b>	>=low	suit
10	>=low	<b>low</b>	low	suit
11	>=low	>=med	high	suit
12	low	>=med	>=med	<b>good</b>
13	low: <b>med</b>	med	med:low	<b>good</b>
14	>=low	>=med	med	<b>good</b>
15	<b>high</b>	<b>low</b>	<b>none</b>	<b>good</b>
16	>= <b>med</b>	>=med	<b>none</b>	<b>exc</b>
17	>= <b>med</b>	<b>high</b>	>=low	<b>exc</b>
18	<b>high</b>	>=med	>=low	<b>exc</b>

regardless on its *Feasibility* and *Uncertainties* (the symbol ‘\*’ denotes any value). The last rule defines *Technology* as excellent when its *Rationality* is high, *Feasibility* at least medium and *Uncertainties* low or better (the symbols ‘>=’ and ‘<=’ denote weak preference). The percentages shown in Table 1 represent the importance of each attribute [determined by linear approximation of decision rules, see Bohanec (2015)]. As indicated, *Rationality* is more important (43 %) than *Feasibility* and *Uncertainties*, which are of similar importance (29 and 28 %, respectively).

Let us also note that all decision tables in Model T, as well as in the Model M (next section), are complete and consistent.

### 2.3 Model M: evaluation of technology mixtures

While Model T evaluates individual technologies, *Model M* evaluates technology mixtures. A *technology mixture* is defined as a collection of technologies, considering a specific share of each technology in the total installed capacity. For example, some technology mixture may employ three technologies, nuclear, coal and hydro, with respective relative installed capacity shares of 0.3, 0.6 and 0.1; this mixture is denoted {Nuclear/0.3, Coal/0.6, Hydro/0.1}. The model also considers relative shares of produced energy. The need to formulate decision alternatives in terms of their shares naturally leads to the use of value distributions in DEX.

Model M is structured as shown in Fig. 2. The two top-level attributes, *Reasonability* and *Long-term appropriateness*, measure the certainty of supply by some technology mixture, and fulfilment of goals and interests: environmental, social, and national. In total, Model M has 15 basic and 12 aggregated attributes.



**Fig. 2** Hierarchical structure and value scales of Model M

Attribute	Scale
Technology mix	unsuit; weak; suit; good; exc
Reasonability	unreas; less_reas; reas; desired
Energy demand coverage	low; med; good; high
Reliability of supply	low; med; high; v_high
Availability	low; med; high
Installed capacity	unsuit; suit; exceed
Energy produced	unsuit; suit; exceed
Base load	low; med; high
Peaks	no; yes
Uncertainties	v_high; high; med; low
Health impacts	high; med; low
Possible changes	neg; no; pos
Feasibility and rationality	weak; low; med; high
Feasibility	low; med; high
Economy	low; med; high
Long-term appropriateness	low; med; high
Fulfillment of goals and interests	low; med; high
Environmental goals	low; med; high
Low carbon	low; med; high
Rational land use	low; med; high
Nature protection	low; med; high
National interests	low; med; high
Independence	low; med; high
Energy users capabilities	low; med; high
Energy supply to all	low; med; high
Protection of vulnerable groups	low; med; high
Lifetime of supply	short; med; long

An important property of Model M is that it evaluates technology mixtures from two viewpoints. The first viewpoint considers a technology mixture just as a collection of individual technologies: each technology contributes to the overall assessment in proportion with its share. This viewpoint is suitable for aspects that *sum up*, such as produced energy, land use, and emission of greenhouse gases. The second viewpoint recognizes the existence of aspects that can be assessed only looking at a mixture as a *whole*. For instance, the ability of a mixture to provide energy continuously or to serve peak loads requires a proper composition of the mixture, and only some technologies can contribute to these aspects.

Models T and M are connected and used in succession. When evaluating mixtures with Model M, some of its basic attributes receive values from Model T: *Health impacts*, *Possible changes*, *Feasibility*, *Economy*, *Low carbon* (determined from *Greenhouse gasses*), *Rational land use* (from *Spatial availability*), *Nature protection* (from *Resource protection*), and *Independence*. The input values for these attributes in Model M are formulated as value distributions of the output values coming from Model T, taking into account the relative share of each technology in the mixture. To illustrate the procedure, let us consider the mixture {Nuclear/0.3, Coal/0.6, Hydro/0.1}. Suppose that at some attribute *x* in Model T these technologies are evaluated as follows: Nuclear as medium, Coal as medium, and Hydro as high. The distribution that is assigned as input to Model M is then {medium/(0.3 + 0.6), high/0.1} = {medium/0.9, high/0.1}.

The input values of the remaining basic attributes are determined from scenarios (Sect. 2.4) for each mixture as a whole. This includes attributes *Installed capacity*, *Energy produced*, *Base load*, *Peaks*, *Energy supply to all*, *Protection of vulnerable groups*, and *Lifetime of supply*.

## 2.4 Model S: simulation of implementation scenarios

In contrast with the two Models T and M, which are of multi-attribute type, *Model S* ('S' can stand for both "Scenarios" and "Simulation") is a simulation model. It uses Models T and M, and "runs" them through the years 2014–2050. For each year, Model S evaluates technology mixtures that are expected to be in place in Slovenia in that year according to different management scenarios. The following management decisions have been considered:

1. Closing down the nuclear power plant (NPP) Krško unit 1 (capacity: 700 MW) in 2023, i.e., not extending its operation until 2043;
2. Construction of unit 2 at the NPP Krško (1600 MW) by 2025;
3. Finalization of the two hydro power plants on the lower Sava river (74 MW) by 2025;
4. Construction of a gas fired power plant (600 MW) by 2025;
5. Closing down unit 5 of the coal fired power plant at Šoštanj (345 MW) in 2027;
6. Construction of the chain of hydro power plants on the mid Sava river (330 MW) by 2035.

Each of these decisions can be either yes or no. Consequently, this gives  $2^6 = 64$  possible scenarios. For each scenario and for each year 2014–2050, the input values for Model M are determined depending on the type and role of input attributes. For attributes that refer to *individual technologies* (i.e., *Health impacts*, *Possible changes*, and others listed in Sect. 2.3), input values are determined from the results of evaluating individual technologies by Model T (Fig. 3) and represented as value distributions using the procedure illustrated in Sect. 2.3. The input values for the remaining attributes are determined for each year and each scenario as follows.

*Energy produced* is calculated as the sum of energy produced by individual technologies included in the mixture in the given year. This sum is qualitatively assessed according to the expected energy needs, which are estimated from a starting base-load of 13 TWh and peak-load of 1 TWh in 2013, and considering the expected annual growth of energy needs at 2.2% per year for the whole period (Kontić et al. 2016). Energy produced is assessed as unsuitable if it is below base-load, excess if it is above the sum of base-load and peak-load, and suitable otherwise.

Similarly, *Installed capacity* is assessed from the total expected installed capacity over time. In the years until 2025, the values unsuitable, suitable and excess are assigned when the total installed capacity is below 1700 MW, between 1700 and 1800 MW, or above 1800 MW, respectively. After 2025, these boundaries are changed to 2200 and 2300 MW, in order to take into account higher energy needs in that period, and a planned construction of the second unit of NPP Krško.

*Base load* assesses the capability of key technologies (hydro, coal, oil, gas and nuclear) to provide the needed base load, either when all power plants are working normally, or under failure of one power plant. Until and after 2025, the required base load is estimated at 1000 and 1200 MW, respectively. *Base load* is determined as high when it is exceeded even with one power plant not working, medium if it is achieved only with all power plants working, and low otherwise.

Attribute	Hydro	Coal	Oil	Gas	Nuclear	Bio	PV	Wind
<b>Technology</b>	suit - exc	unsuit	unsuit	weak - good	weak - exc	unsuit	unsuit	unsuit
<b>Rationality</b>	low - high	inapprop	inapprop	high	high	inapprop	inapprop - low	inapprop
Contribution to development	med - high	high	med	high	high	med	low - med	low
Economy	med - high	high	low	med - high	med - high	low	low	low
Land use and pollution	less_suit - more_suit	unsuit	unsuit	more_suit	more_suit	less_suit	unsuit - more_suit	unsuit - less_suit
<b>Feasibility</b>	high	high	high	high	low - high	low - med	low	low
Technical feasibility	high	high	high	high	high	med	med - high	med
Economic feasibility	high	med	med	med	high	low - med	low	low
Spatial feasibility	high	high	high	high	low - high	low - high	low - high	low - high
<b>Uncertainties</b>	high - none	low	v_high - low	v_high - med	v_high - low	low	v_high	v_high
Technological dependence	high - none	low	v_high - med	v_high - med	v_high - low	med	v_high	v_high
Possible changes	pos	pos	no	no	pos	no	no	no
Perception of risks	med - none	med - low	none	high - med	v_high - low	none	low	none

Fig. 3 Evaluation results of individual technologies with Model T

Criterion *Peaks* is assessed according to the number of technologies in the mixture that are capable of covering peak loads. At least two such technologies are required in the mixture to assess *Peaks* as yes.

Finally, input values for criteria *Energy supply to all*, *Protection of vulnerable groups*, and *Lifetime of supply* are determined by considering both the scenarios and the expected energy price coming from a particular technology mix. The scenarios influence values in the way that each construction of a new unit/plant contributes positively to all three criteria (i.e., it increases their qualitative value by one level), while omission to do so, together with closing down the old thermal units, results in low values of the three criteria. The initial values for the three criteria in 2014 are high, {low/0.2, medium/0.8}, and short, respectively.

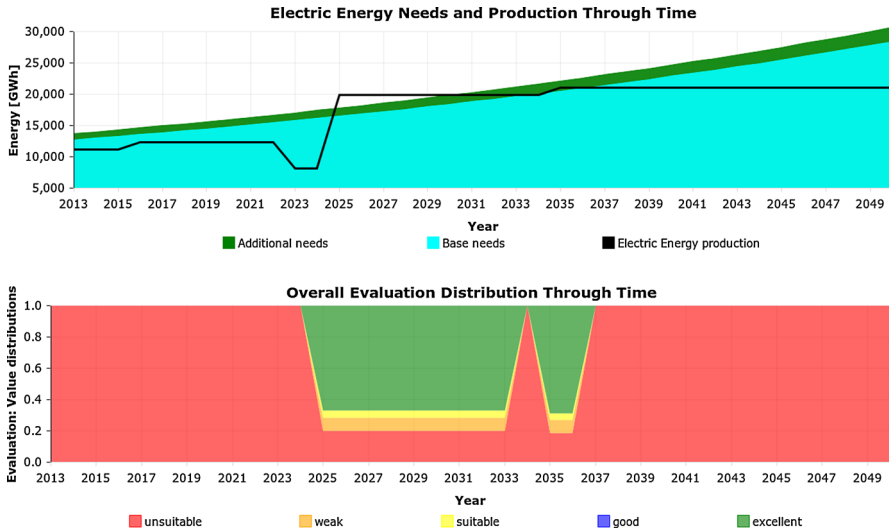
After determining the input values of Model M for each scenario and each year, Model M is evaluated by the DEX evaluation procedure (Sect. 2.1), giving an assessment of the technology mixture in terms of a value distribution.

The simulation algorithm was implemented specifically for this project in java language, using the software library DEXx (<https://bitbucket.org/nejctrdin/dexx>) that implements the extended DEX method (Trdin and Bohanec 2014). The simulation of scenarios and graphic presentation of results are accessible through an on-line decision support system [http://sepo.ijs.si/naloge/OVJE/energetic\\_scenario\\_comparative\\_model/](http://sepo.ijs.si/naloge/OVJE/energetic_scenario_comparative_model/).

### 3 Results and discussion

In the first stage, individual electric energy production technologies were evaluated by Model T as shown in Fig. 3. In addition to the overall evaluation (second row), Fig. 3 displays intermediate evaluation results obtained on two lower levels of the Model T hierarchy. It is worth noting that some evaluation values are presented as intervals, which are used due to uncertainties regarding future values of several evaluation criteria. The lower and upper interval bounds correspond to pessimistic and optimistic assessment of evaluation criteria, respectively.

These results indicate that there are only three technologies of sufficient suitability for Slovenia: Hydro, Gas, and Nuclear. Among these, Hydro is the best. Gas and Nuclear are similar, with Nuclear worse in terms of *Feasibility* and *Perception of risks*, but better in terms of *Economic feasibility* and *Possible changes*. Coal and



**Fig. 4** Results of simulating the scenario consisting of: closing down unit 1 of NPP Krško in 2023, constructing unit 2 of NPP Krško in 2025, and building all hydro power plants on the Sava river

Oil are unsuitable particularly because of inappropriate *Rationality* due to *Land use and pollution*. All the remaining “green” technologies are unsuitable for a number of reasons, including *Economy*, *Land use*, *Economic feasibility* and *Technological dependence*. See [Kontić et al. \(2016\)](#) for a more detailed justification of this assessment and its consequences.

The evaluation of technology mixtures and scenarios with Models M and S gave 64 time series, presented by the decision support system in the form illustrated in Fig. 4. Specifically, Fig. 4 shows one of the more interesting and realistic scenarios, according to understanding in 2014, which presumes four management decisions: closing down unit 1 of NPP Krško in 2023, constructing unit 2 of NPP Krško in 2025, and building hydro power plants on both the lower (in 2025) and mid (2035) Sava river. The chart at the top displays expected energy needs in terms of the base and peak loads (shaded area), and expected annual production of energy (black line). The production until 2025 is clearly below the needs and shows a considerable decline in the period 2023–2025. After 2025, the production, due to the new NPP, rises above the needs, and remains such until 2035. It is interesting to note that the construction of new hydro power plants in 2035 just barely matches the increasing needs and satisfies them for just a few years. The bottom chart presents annual evaluations of the above time series in terms of value distributions. Individual values are represented by colors: unsuitable is red, excellent is green, and the other values are shown in intermediate colors. Apart from a small disorder around 2035, the chart reveals three main areas. Two of them are entirely “red”, indicating unsuitable situations in the periods until 2025 and after 2037. The third area in the period 2025–2037 is represented by the value distribution {unsuitable/0.20, weak/0.08, suitable/0.05, excellent/0.67}, which indicates a much better situation. Even though this evaluation is prevalently excellent, it is not entirely

“green” because it still contains unsuitable technologies, such as Coal and Oil (see Fig. 3).

In summary, results of simulating the 64 scenarios (Kontić et al. 2016) indicate that only the mixtures that include extension of operation of unit 1 of NPP Krško until 2043, construction and operation of unit 2 of NPP Krško, construction of all planned hydro power plants on the Sava river and construction of the gas fired thermal power plant ensure coverage of energy needs by 2050 in Slovenia. Renewable energy sources—wind and PV—do not constitute a sustainable choice since they are not reliable due to land-use context; almost 40 % of the Slovenian territory is under Natura 2000 protection regime, which does not allow economic activities in these areas. Consequently, these technologies are not capable of meeting more than 15 % of energy needs, assuming positive attitudes towards these installations in future permitting processes at local levels.

For the coming years until 2025, all scenarios were assessed as unsuitable. This is mainly because the current technology mixtures do not satisfy the energy needs. Even though this can be partly compensated by importing the energy, it indicates a considerable departure from the ideal of self-sufficient and optimized sustainable energy production. Furthermore, the situation is becoming worse because of increasing needs. Such evaluation results give a clear sign that Slovenia is getting late in defining its energy production strategy, with an alert that without policy decisions the situation is going to get even worse.

In terms of checking the trustworthiness of results of this work, one may consult some of the most recent worldwide publications on the topic; we refer to just few of these indicating a harmony among strategic/sustainability evaluation of long-term energy options (Legget 2016; Mainali and Silveira 2015; National Renewable Energy Laboratory (NREL) 2014; Santoyo-Castelazo and Azapagic 2014; World Nuclear Association (WNA) 2016).

From the methodological viewpoint, the method DEX turned out to be suitable for the purpose. Initially, we chose it for several reasons. Due to the complexity of the problem, we expected a large number of criteria, which we knew were easier to handle in a hierarchical rather than linear setting. Due to considerable uncertainties expected in this long-term assessment, we knew we could not make accurate predictions and that we had to rely on qualitative judgements; thus, a qualitative method seemed more suitable than a quantitative one. We also expected complex relations between attributes, for which decision rules may be a better choice than linear functions, which are prevalently used in some other methods. Last but not least, we knew we were going to assess technology mixtures, for which the representation using value distributions seemed a suitable choice. All these expectations eventually turned out as facts. With DEX, we were able to formulate two relatively large and complex multi-criteria models, which are guaranteed to be complete and consistent. The models are transparent in the sense that they contain decision rules, which are easy to audit. The uncertainties associated with this assessment were of such a nature that even single qualitative values, such as “low”, “weak” or “good”, were insufficient to represent them; we had to use intervals and sets of such values, and this was easily accommodated by DEX’s set-based and distribution-based evaluation procedures.

DEX is not the only method capable of addressing problems of this type. In the literature (Pohekar and Ramachandran 2004; Kahraman and Kaya 2010; Wimmer et al. 2015), a successful use of a number of other MCDM methods is reported, most commonly AHP, PROMETHEE, ELECTRE, TOPSIS and PARIS. In the course of the OVJE project, we did not aim—nor was this possible due to the time constraints and experts' availability—to compare DEX with any other method, so this remains an interesting challenge for the future.

## 4 Conclusion

With the aim to contribute to better strategic planning of electrical energy production in Slovenia, this work proposes a systematic, transparent and reproducible sustainability appraisal of technologies and strategic management scenarios. The approach is based on qualitative multi-attribute modelling and simulation, and proceeds in three stages: assessment of (1) individual technologies, (2) technology mixtures and (3) management scenarios in the period 2014–2050. The method is implemented in an on-line decision support system.

Among the important features of the developed assessment method, we wish to emphasize the completeness, consistency and transparency of the two multi-criteria models. A distinguishing feature of Model M, which evaluates technology mixtures, is combining two viewpoints: “a mixture as a sum of its parts” and “a mixture as a whole”. This has been achieved by combining (1) attributes that are connected with and take inputs from Model T, (2) attributes that are defined for a mixture as a whole, and by (3) representing mixtures by value distributions. Overall, the approach using the qualitative modelling method DEX and software DEXi was found suitable for this long-term strategic assessment problem.

Evaluation results clearly identify three main technologies that are most suitable for Slovenia: Hydro, Gas, and Nuclear. Only a proper mixture of these technologies is reliable and rational in the context of meeting expected energy needs. Biomass, wind and photovoltaic sources of energy are less sustainable than others and may provide only up to 15 % of energy in Slovenia.

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