A QUALITATIVE MULTI-CRITERIA MODEL FOR THE EVALUATION OF ELECTRIC ENERGY PRODUCTION TECHNOLOGIES IN SLOVENIA

Marko Bohanec¹, Nejc Trdin¹,², Branko Kontić¹
¹ Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
² Jožef Stefan International Postgraduate School, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
E-mail: {marko.bohanec, nejc.trdin, branko.kontic}@ijs.si

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, decision analysis, multi-criteria decision modelling, decision rules, qualitative model, method DEX

1 INTRODUCTION

Electric energy is a strategic resource that plays a vital role in the operation and development 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 are often 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 [4, 6] that assess decision alternatives using multiple criteria. Each alternative is first assessed according to each criterion. These individual assessments are then 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 [8], either in a general setting [10], or considering the specifics of countries, such as Germany [5] or Portugal [9].

In Slovenia, almost 13 TWh of electricity is consumed annually (net figure for the year 2014). 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 at 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 production.
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 [7] 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 sustainability appraisal and summarize the main results.

2 METHODS

The methodological approach is based on a qualitative MCDM method DEX, which is used in three stages, and involves two MCDM models and one simulation model:

1. Model T: Evaluation of eight individual electric energy production technologies.
2. Model M: Evaluation of mixtures of technologies, considering the shares of individual technologies in the total installed capacity.
3. 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) [1] 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 $A = \{a_1, a_2, \ldots, a_m\}$. These alternatives are described with a set of variables $X = \{x_1, x_2, \ldots, x_n\}$, 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. 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 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 ones. In DEX, each attribute $x_i \in X$ has a value scale $D_i = \{v_{i1}, v_{i2}, \ldots, v_{ik}\}$, where each $v_{ij}$ represents some ordinary word, such as “low”, “high”, “acceptable”, “excellent”. Scales are usually small, containing 2 to 5 values. Also, scales are usually preferentially ordered so that $v_{i1} \preceq v_{i2} \preceq \cdots \preceq v_{ik}$ (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 [4].

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. Suppose that $x(0) \in X$ is some aggregated attribute and that $x(1), x(2), \ldots, x(r) \in X$ are its immediate descendants in the hierarchy. Then, the aggregation function $x(0) = f(0)(x(1), x(2), \ldots, x(r))$ is defined with a set of decision rules of the form
if $x_1 = v_1$ and $x_2 = v_2$ and ... and $x_r = v_r$ then $x_0 = v_0$

Here, $v_i \in D_i$, $i = 0, 1, ..., r$.

The method DEX is implemented as DEXi [2], freely available software that supports both the development of DEX models and their application for the evaluation and analysis of decision alternatives. DEXi checks the quality of decision rules so that its models, when properly developed, 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).

For further information of DEX and DEXi, please refer to [1] and [2], respectively.

### Figure 1: Hierarchical structure and value scales of (a) Model T and (b) Model M, and (c) example of decision rules that aggregate Rationality, Feasibility and Uncertainties into Technology
2.2 Model T: Evaluation of Technologies

The DEX model, used in the first stage of appraisal, 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 organised in a hierarchy shown in Figure 1(a). The hierarchy contains 36 basic and 28 aggregated attributes. There are two aggregated attributes that appear twice in Figure 1(a), because they affect more than one higher-level attribute: Licenses and Contribution to development. Figure 1(a) also shows attributes’ value scales; all scales are preferentially ordered increasingly in the direction from left to right.

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. Uncertainty evaluation 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.

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. Here, we present only the one that corresponds to the root attribute Technology: Figure 1(c) 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, 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 Figure 1(c) represent the importance of each attribute (determined by linear approximation of decision rules, see [2]). As indicated, Rationality is more important (43%) than Feasibility and Uncertainties, which are of similar importance (29% and 28%, respectively).

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\}.

Model M is structured as shown in Figure 1(b). The two top-level attributes, Reasonability and Long-term appropriateness, measure the certainty of supply by some mixture, and fulfilment of goals and interests: environmental, social, and national. In total, Model M has 15 basic and 12 aggregated attributes.

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 gases), Rational land use (from Spatial availability), Nature protection (from Resource protection), and Independence. The input values of the remaining basic attributes are determined from
scenarios (see section 2.4) for each mixture as a whole. The evaluation of mixtures with Model M takes into account the relative shares of individual technologies and employs an evaluation method based on probabilistic value distributions; see [11] for a detailed description of the method.

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’ stands for “Scenarios”) is a simulation model. It uses Models T and M, and “runs” them through the years 2014 to 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:

2. Construction of Unit2 at the NPP Krško by 2025.
3. Finalisation of the two hydro power plants on the lower Sava river by 2025.
5. Closing-down of Unit5 of the coal fired power plant at Šoštanj in 2027.
6. Construction of the chain of hydro power plants on the mid Sava river by 2035.

Since each of these decisions can be either yes or no, they collectively make \(2^6 = 64\) possible scenarios. The simulation of these scenarios is implemented in an on-line decision support system [3].

3 RESULTS

In the first stage, individual electric energy production technologies were evaluated by Model T as shown in Figure 2. In addition to the overall evaluation (second row), Figure 2 displays intermediate evaluation results obtained on two lower levels of the Model T hierarchy. Some evaluation values are presented as intervals, which are 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.

![Figure 2: Evaluation results of individual electric energy production technologies with Model T](image-url)

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 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 [7] for a more detailed justification of this assessment and its consequences.

Results of simulating the 64 scenarios [7, 3] indicate that only the mixtures that include extension of operation of Unit1 of NPP Krško, construction and operation of Unit2 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 Natura2000 protection regime), and are consequently not capable of meeting a substantial share of energy demands; they may only constitute an option for covering 8% to 15% of energy needs.

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 [3].

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 from 8% to 15% of energy in Slovenia.

References