A QUALITATIVE MULTI-CRITERIA MODEL FOR THE EVALUATION 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, 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 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* $A = \{a_1, a_2, \dots, a_m\}$. 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*. 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* $D_i = \{v_{i1}, v_{i2}, \dots, v_{ik_i}\}$, 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 $v_{i1} \preccurlyeq v_{i2} \preccurlyeq \dots \preccurlyeq v_{ik_i}$ (here, $a \preccurlyeq b$ 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 $x_{(1)}, x_{(2)}, \dots, x_{(r)} \in X$ are its immediate descendants in the hierarchy. Then, the aggregation function $x_{(0)} = f_{(0)}(x_{(1)}, x_{(2)}, \dots, x_{(r)})$ is defined with a set of decision rules of the form

if $x_{(1)} = v_{(1)}$ **and** $x_{(2)} = v_{(2)}$ **and** ... **and** $x_{(r)} = v_{(r)}$ **then** $x_{(0)} = v_{(0)}$

Here, $v_{(i)} \in D_{(i)}, i = 0,1, \ldots, r$.

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.

(a) Model T

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

(b) 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
Fulfilment 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

DEXi

(c) Decision rules

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

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: $A =${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 gasses*), *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:

1. Closing-down of the nuclear power plant (NPP) Krško Unit1 in 2023.
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.
4. Construction of a gas fired power plant 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.

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

Figure 2: Evaluation results of individual electric energy production technologies with Model T

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.

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