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# Multi-Criteria Assessment of Electricity Generation Technologies Seeking to Implement EU Energy Policy Targets

Rimantas Dapkus [1+], Dalia Streimikiene [2]

[1] Regional Development Department at Kaunas University of Technology, K.Donelaicio str. 20, Kaunas LT- 44239, Lithuania

[2] Lithuanian Energy Institute, Vilnius University, Kaunas Faculty of Humanities, Muitines str. 8, Kaunas LT-44403, Lithuania

**Abstract.** EU energy policy targets sustainable energy development goals. Therefore it is important to provide a rationale for sustainable decision making in energy policy. The aim of this paper is to develop the multi–criteria decision support framework for choosing the most sustainable electricity generation technologies. Given selection of sustainable energy sources involves many conflicting criteria, multi-criteria decision method MULTIMOORA was applied for the analysis. The multi-criteria analysis provided that the future energy policy should be oriented towards the sustainable energy technologies are water and solar thermal ones. It is the proposed multi–criteria assessment framework that can constitute a basis for further sub-regional optimization of sustainable energy policy.

**Keywords:** Multi-Criteria Analysis, Electricity Generation Technologies, Sustainability.

## 1. Introduction

The main EU policy documents and directives which have impact on sustainable energy development are directives promoting energy efficiency and use of renewable energy sources, directives implementing greenhouse gas mitigation and atmospheric pollution reduction policies and other policy documents and strategies targeting energy sector. Promotion of use of renewable energy sources especially biomass and energy efficiency improvements are among priorities of EU energy policy because use of renewables and energy efficiency improvements has positive impact on energy security and climate change mitigation. The directives targeting energy efficiency, renewables and climate change mitigation indicates the EU energy policy priorities: reduction of energy impact on environment, improvements in energy generation and energy use efficiencies, increase in reliability and security of energy supply, promotion of renewables use and climate change mitigation. All these directives have specific targets which can be addressed by quantitative indicators. As targets set by specific directives are related the use of interlinked indicators framework to address these targets can be useful tool for energy policy analysis and monitoring. Such tool applied by EU member states can help to harmonize EU energy policies and enhance its implementation on country level [1]. New energy technologies can be considered to be an important bridge between the Europe 2020 objectives and the EU Sustainable development strategy adopted at the Goteborg European Council.

Indeed, the very selection of sustainable energy sources involves multiple conflicting objectives. It is therefore important to develop multi–criteria decision support frameworks for sustainable energy policy. Multi–criteria decision making (MCDM) methods are suitable to tackle energy source selection problem [1, 4, 5]. A number of the recent studies, therefore, dealt with application of MCDM in energy policy [9, 10, 11, 12, 13, 14, 15, 16].

The aim of the performed research was to develop the multi–criteria decision support framework for choosing the most sustainable electricity production technologies based on EU energy policy priorities. The aim of the paper: to present MULTIMORA method applied for the complex assessment of electricity generation technologies; to discuss the alternative electricity generation technologies as well as criteria for their ranking; to make comparison of these technologies; to provide ranking of electricity generation technologies based on priorities of EU energy policy and ensuring sustainable regional development.

[+] *E-mail:* Rimantas.Dapkus@gmail.com

## 2. Assessment of Electricity Generation Technologies

### 2.1. MULTIMOORA Method

In this paper for electricity generation technologies ranking the MULTIMOORA method was applied. The MULTIMOORA method was developed by Brauers and Zavadskas [1, 17, 18, 19],

MULTIMORA method was employed for prioritization of the electricity generation technologies. MULTIMORA originated from Multi-Objective Optimization by Ratio Analysis (MOORA) method introduced by Brauers and Zavadskas [17] on the basis of previous research. The same authors [18, 19] extended the method and in this way it became more robust as MULTIMOORA (MOORA plus the full multiplicative form).

The MULTIMOORA method begins with a response matrix $X$ where its elements $x_{ij}$ denote $i^{th}$ alternative of $j^{th}$ objective ($i = 1, 2, ..., m$ and $j = 1, 2, ..., n$). The method consists of three parts, viz. the Ratio System, the Reference Point approach, and the Full Multiplicative Form.

*The Ratio System of MOORA.*Ratio system employs the vector data normalization by comparing alternative of an objective to all values of the objective:

$$x_{ij}^{*} = w_j \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \tag{1}$$

where $x_{ij}^{*}$ denotes $i^{th}$ alternative of $j^{th}$ objective and $w_j$ is weight of the $j^{th}$ criterion, $\sum_j w_j = 1$. In the absence of negative values, these numbers belong to the interval [0; 1]. These indicators are added (if desirable value of indicator is maximum) or subtracted (if desirable value is minimum). Thus, the summarizing index of each alternative is derived in this way:

$$y_i^{*} = \sum_{j=1}^{g} x_{ij}^{*} - \sum_{j=g+1}^{n} x_{ij}^{*}, \tag{2}$$

where $g = 1, 2, ..., n$ denotes number of objectives to be maximized. Then every ratio is given the rank: the higher the index, the higher the rank.

Thus MULTIMOORA summarizes MOORA (i.e. Ratio System and Reference point) and the Full Multiplicative Form. Brauers and Zavadskas [19] proposed the dominance theory to summarize the three ranks provided by different parts of MULTIMOORA.

### 2.2. Indicator framework for sustainability assessment of energy technologies

The aims of EU directives targeting sustainable energy development were summarized in Table 1. The security of supply, energy efficiency improvements, promotion of renewable, reduction of greenhouse gas and other atmospheric pollutants emissions are the major targets of EU energy policies. Based on EU energy policy analysis the selected indicators were grouped by 4 priority areas established by EU energy policy: increase of energy efficiency, use of renewables, increase of energy security and greenhouse gas and other atmospheric emission reduction (Table 1).

Table 1. Indicators selected for EU energy policy analysis

| **Indicators** | **Subtheme** | **Directive or policy document** | **Target** | **Date for achievement** |
|---|---|---|---|---|
| **Energy efficiency** | | | | |
| End-use energy intensity of GDP | Energy efficiency | Directive 2006/32/EC on end-use efficiency and energy services | To reduce by 9% the current level (2006) | 2016 |
| Energy saved in buildings | Energy efficiency | 2002/91/EC Directive on the energy performance of buildings | 22% of energy used in buildings | 2010 |
| Savings of primary energy supply | Energy efficiency | The Commission's new Green Paper on energy efficiency COM (2005) 265 | 20% from year 2005 level | 2020 |

| | | | | |
|---|---|---|---|---|
| The share of CHP in electricity production | Energy efficiency | 2004/8/EC Directive on the promotion of cogeneration national energy strategy | Double the current share | 2010 |
| **Promotion of renewables** | | | | |
| The share of renewables in primary energy supply | Renewables | The White Paper on renewable sources | 12% | 2010 |
| The share of renewables in electricity generation | Renewables | Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market | 22,1% (7% for Lithuania) | 2010 |
| The share of renewables in heat production | Renewables | Proposal for Directive promoting the renewable heating and cooling | 25% | 2020 |
| The share of renewables in fuel used in transport | Renewables | 2003/30/EC Directive on the promotion of the use of biofuels or other renewable fuels in transport | 2%<br>5.75%<br>20% | 2005<br>2010<br>2020 |
| The share of renewables in final energy | Renewables | EU energy and climate package: (COM(2008) 30) | 20% | 2020 |
| **Security of supply** | | | | |
| Energy independency | Security of supply | The EU Green paper on European Strategy for Sustainable, Competitive and Secure Energy | 50% | 2030 |
| **Emission reduction** | | | | |
| Greenhouse gas emissions (CO2 emissions from energy sector) | Climate change | Kyoto protocol | Reduction by 8% of year 1990 level<br>Reduction by 20% of year 1990 level | 2008-2012<br><br>2020 |
| SO2 emissions,<br>NOx emissions,<br>VOC emissions,<br>NH3 emissions<br><br>SO2 emissions,<br>NOx emissions,<br>VOC emissions,<br>NH3 emissions | Acidification and eutrophication | Gothenburg protocol<br>NEC directive 2001/81EC | Reduction by<br>35%,<br>30 %,<br>11%<br>0% comparing to 1990 level,<br>Reduction by<br>87%,<br>by 50%,<br>by 46%<br>by 41% compared to 2000 level | 2010<br><br><br><br><br><br>2020 |

Table 2 presents the full set of indicators covering economic, environmental, and social aspects for long-term sustainability assessment of energy technologies. The proposed indicator framework addresses the EU energy and environmental policy priorities and the three dimensions of sustainable development. Seeking to assess electricity generation technologies based on EU energy policy targets presented in Table 1 the indicators for long–term sustainability of the energy technologies are presented in Table 2.

Table 2. Indicator set for long-term sustainability assessment of electricity generation technologies

| Acronym | Indicator | Units of measurement | Information sources |
|---|---|---|---|
| **Economic dimension** | | | |
| PR COST | Private costs | EURcnt/kWh | [22, 23] |
| AVAILAB | Average availability (load) factor | % | [24] |
| SECURE | Security of supply | Point | [27] |
| GRID COST | Costs of grid connection | Point | [22, 23] |
| PEAK LOAD | Peak load response | Point | [27, 28] |

| | | | |
|---|---|---|---|
| **Environmental dimension** | | | |
| CO2eq | GHG emissions | kg/kWh | [22, 23] |
| ENV | Environmental external costs | EURcnt/kWh | [22, 23] |
| RADIO | Radionuclide external costs | EURcnt/kWh | [22, 23] |
| HEALTH | Human health impact | EURcnt/kWh | [22, 23] |
| **Social dimension** | | | |
| EMPL | Technology-specific job opportunities | Person-year/kWh | [28] |
| FOOD | Food safety risk | Point | [22, 23] |
| ACC PAST | Fatal accidents from the past experience | Fatalities/kWh | [28] |
| ACC FUT | Severe accidents perceived in future | Point | [22, 23] |

The Economic dimension in sustainability assessment of energy technologies is very important as energy supply cost is the main driver for energy technologies penetration in the markets. There are 6 indicators selected to address economic dimension of sustainability assessment in electricity and heat sector: private costs, fuel price increase sensitivity, average availability factor, costs of grid connection, peak load response, security of supply. The most important indicators are: private costs, availability factor and costs of grid connection. The main environmental dimension indicators for energy technologies assessment are: GHG emissions, environmental external costs, radionuclides external costs, severe accidents perceived in future and fatal accidents from the past experience. Additional environmental indicators are land use and solid waste. The main social indicators selected for electricity technologies assessment in this report are technology-specific job opportunities, human health impact, food safety risk and work related fatalities per accident. The most important indicators applied in almost all studies for technologies assessment are: external health costs and technology specific job opportunities.

Table 3 summarizes electricity and heat generation technologies which will be assessed in terms of the previously described sustainability assessment indicators framework.

Table 3. Electricity and heat generation technologies selected for multi–criteria sustainability assessment

| **Technologies and types of power plants** | | | **Acronyms** |
|---|---|---|---|
| ***Electricity production*** | | | |
| Nuclear | | EPR | NUC |
| Fossil fired power plants | oil | heavy oil condensing PP | OIL CL |
| | | light oil gas turbine | OIL GT |
| | coal | condensing PP | COA CL |
| | | IGCC | COA IGCC |
| | | IGCC PP with CO2 sequestration | COA IGCC CCS |
| | lignite | condensing pp | LIG CL |
| | | IGCC | LIG IGCC |
| | | IGCC pp with CO2 sequestration | LIG IGCC CCS |
| | gas | combined cycle | GAS STAG |
| | | combined cycle PP with CO2 sequestration | GAS STAG CCS |
| | | gas turbine | GAS GT |
| Hydropower | run of river | <10 MW | HYD S |
| | | 10 ÷ 100 MW | HYD M |
| | | >100 MW | HYD L |
| | dam | | HYD DAM |
| | pump storage | | HYD PMP |
| Wind | on shore | | WIND ON |
| | off shore | | WIND OFF |
| Solar PV | roof | | PV ROOF |
| | open space | | PV OPEN |
| Solar thermal | | | SOL TH |

| ***Electricity and heating production (CHP)*** | | | |
|---|---|---|---|
| CHP with an extraction condensing turbine | gas | CC | CHP GAS |
| | | CC PP with CO2 sequestration | CHP GAS CCS |
| | coal | PP | CHP COAL |
| | | IGCC PP with CO2 sequestration | CHP COAL CCS |
| CHP back pressure | gas | | CHP GAS STAG |
| | coal | | CHP COAL BP |
| Biomass CHP with an extraction condensing turbine | straw | | CHP STRAW |
| | wood chips | | CHP WOOD |
| Fuel cells | natural gas | MCFC | MCFC |
| | | SOFC | SOFC |
| | bio gas | MCFC | MCFC BG |

There are 13 the long-term sustainability indicators consisting of 5 economic indicators (private costs, grid costs, availability factor, peak load response and security of supply), 4 environmental (environmental external costs, radionuclides external costs, human health related external costs, GHG emissions), and 4 social indicators (technology-specific job opportunities, food safety risks, fatal accidents from the past and severe accidents perceived in the future). Respective rows describe each of 33 electricity production technologies under consideration.

## 2.3. Results of the Multi – Criteria Assessment

In order to compare the 33 electricity production technologies listed in Table 3 against targets of EU sustainable energy policy development and sustainability criteria provided in Table 2 the four different scenarios were defined (Table 4).

Table 4. Criteria weights under different scenarios

| Criteria | Holistic approach | Economic approach | Environmental approach | Social approach |
|---|---|---|---|---|
| Economic indicators | 0.33 | 0.5 | 0.25 | 0.25 |
| Environmental indicators | 0.33 | 0.25 | 0.5 | 0.25 |
| Social indicators | 0.33 | 0.25 | 0.25 | 0.5 |

As one can note the first scenario is a holistic one, where every of the sustainability dimensions is treated as equally important. The following three scenarios put the most of significance on economic, environmental, or social factors, respectively. More specifically, weights for certain criteria were obtained by dividing indicator group's weight by the number of indicators in that group (i. e. cardinality). For instance, the five economic indicators were attributed with uniform weights equal to according to the economic approach. The decision matrix was normalized by employing Eq. 1. Thereafter Eq. 2 was applied for the Ratio System, which enabled to rank the alternatives. The procedure was repeated for each of scenario defined in Table 5.

Table 5. The ranks of different electricity generation technologies for 4 scenarios

| | Holistic approach | Economic approach | Environmental approach | Social approach |
|---|---|---|---|---|
| 1 | HYD M | HYD M | SOL TH | HYD M |
| 2 | HYD L | HYD L | HYD M | SOL TH |
| 3 | SOL TH | HYD S | HYD L | HYD DAM |
| 4 | HYD S | HYD DAM | HYD S | WIND ON |
| 5 | HYD DAM | CHP WOOD | HYD DAM | PV ROOF |
| 6 | HYD PMP | HYD PMP | HYD PMP | PV OPEN |
| 7 | WIND ON | CHP COAL CCS | WIND ON | HYD L |
| 8 | CHP WOOD | SOL TH | WIND OFF | HYD S |
| 9 | CHP COAL CCS | CHP STRAW | CHP COAL CCS | HYD PMP |
| 10 | WIND OFF | CHP COAL BP | CHP WOOD | CHP WOOD |
| 11 | SOFC | COA IGCC CCS | PV OPEN | WIND OFF |
| 12 | CHP GAS CCS | SOFC | SOFC | CHP GAS CCS |
| 13 | COA IGCC CCS | WIND ON | PV ROOF | SOFC |
| 14 | PV ROOF | WIND OFF | GAS STAG | CHP COAL CCS |
| 15 | CHP STRAW | COA CL | COA IGCC CCS | CHP STRAW |

| | | | | |
|---|---|---|---|---|
| 16 | PV OPEN | LIG IGCC | CHP GAS CCS | GAS STAG |
| 17 | LIG IGCC | CHP GAS CCS | CHP STRAW | MCFC |
| 18 | CHP COAL BP | GAS STAG | CHP GAS | COA IGCC CCS |
| 19 | GAS STAG | PV ROOF | LIG IGCC | CHP COAL BP |
| 20 | MCFC | GAS GT | CHP COAL BP | COA CL |
| 21 | CHP COAL | MCFC | GAS GT | GAS GT |
| 22 | COA CL | CHP COAL | MCFC | MCFC |
| 23 | GAS GT | OIL CL | CHP GAS STAG | CHP COAL |
| 24 | OIL CL | CHP GAS | CHP COAL | CHP GAS |
| 25 | CHP GAS | CHP GAS STAG | GAS STAG CCS | CHP GAS STAG |
| 26 | CHP GAS STAG | PV OPEN | LIG IGCC CCS | GAS STAG CCS |
| 27 | COA IGCC | COA IGCC | COA IGCC | COA IGCC |
| 28 | OIL GT | LIG CL | COA CL | OIL GT |
| 29 | MCFC | OIL GT | OIL CL | NUC |
| 30 | GAS STAG CCS | MCFC | LIG CL | LIG IGCC |
| 31 | LIG IGCC CCS | GAS STAG CCS | OIL GT | OIL CL |
| 32 | LIG CL | LIG IGCC CCS | MCFC | LIG IGCC CCS |
| 33 | NUC | NUC | NUC | LIG CL |

The Table 5 presents the results. As one can note, renewable energy sources-based technologies were the most preferable ones according to every approach. Ranking with equal significance of every sustainability dimension (i. e. holistic approach) suggests hydro power (HYD M, HYD L, HYD S) and solar thermal (SOL TH) technologies being the most sustainable. Meanwhile, the economic approach is also related with similar technologies with exception of solar thermal energy (SOL TH) which is no longer among the most sustainable technologies. At the other end of spectrum, wood and coal CHP (CHP WOOD, CHP COAL) graduated in the technology list. The environmental approach supports solar energy, hydro energy and wood CHP. Finally, the social approach suggests hydro (HYD L, HYD M, HYD DAM), solar thermal (SOL TH), and on-shore wind (WIND ON) electricity production. The results of multi-criteria assessment indicated that conventional energy technologies (oil, gas, coal, nuclear) as the most unsustainable.

## 2.4. Conclusions

EU policy analysis performed and the main quantitative targets are presented in the framework of indicators. Analysis of methods and tools for sustainability assessment and studies dealing with assessment of technologies was performed. Based on these analyses indicators for technologies assessment were selected and integrated sustainability indicators integrating these indicators were developed. Electricity generation technologies were assessed in terms of sustainability.

The selected energy technologies were assessed on a basis of information gathered during the projects dedicated to the long-term assessment of these technologies. The MULTIMOORA method was employed in order to rank electricity generation technologies based on priorities of EU energy policy.

The multi–criteria analysis showed that renewable energy sources-based electricity production technologies are to be preferred. To be specific, hydro and solar power systems were identified as the most sustainable, whereas wood CHP and wind power remained some positions behind. At the other end of spectrum, conventional energy technologies, namely oil, gas, coal, and nuclear power, were the most unsustainable according targets of EU sustainable energy policy development and sustainability criteria provided.

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