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Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis

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HIGHLIGHTS

- We rank 13 electricity generation technologies based on sustainability.
- We use 10 indicators in a weighted sum multi-attribute utility approach.
- Weights are calculated based on a survey of 62 academics from the field.
- Large hydroelectric projects are ranked as the most sustainable.
- Decision makers can use the results to promote a more sustainable energy industry.

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ABSTRACT

Solving the issue of environmental degradation due to the expansion of the World's energy demand requires a balanced approach. The aim of this paper is to comprehensively rank a large number of electricity generation technologies based on their compatibility with the sustainable development of the industry. The study is based on a set of 10 sustainability indicators which provide a life cycle analysis of the plants. The technologies are ranked using a weighted sum multi-attribute utility method. The indicator weights were established through a survey of 62 academics from the fields of energy and environmental science. Our results show that large hydroelectric projects are the most sustainable technology type, followed by small hydro, onshore wind and solar photovoltaic. We argue that political leaders should have a more structured and strategic approach in implementing sustainable energy policies and this type of research can provide arguments to support such decisions.

1. Introduction

Over the last decades, the world has become increasingly aware of the environment's limited ability to support the unrestrained development of humanity. Air, water and soil pollution as well as climate change are having a significant effect on human health and quality of life in some of the world's largest developing economies (Kan et al., 2012; Pandey et al., 2005). The fossil fuel intensive energy sector is a substantial contributor to worldwide environmental degradation, with energy related CO_2 emissions expected to produce a 3.6 °C increase in average temperature over the long term (IEA, 2012b).

Simply restricting the expansion of the energy sector would not be a viable approach to managing environmental conservation, considering that economic development – the main goal of governing authorities worldwide – is tightly connected to energy demand (Breeze, 2005). Thus, establishing a balance between economic growth, quality of life and the exploitation of natural resources was deemed necessary as far back as the 1980s.

In response to this need, the specially appointed World Commission on Environment and Development published a report where the concept of sustainable development is defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Measuring the sustainability of the energy sector has evolved around three main dimensions: environmental, economic and social. In their paper, Carrera and Mack (2010) refer to previous research in the fields of sustainability and risk management and state that sustainability concepts that focused primarily on ecology, with social and economic factors seen as secondary, are historically the oldest. These are called “single pillar” models (Voß et al., 2005). More recent research has utilized “multi-pillar” models, which assess the environmental, economic and social dimensions and sometimes bring up the necessity of using other components such as culture or institutions (Carrera and Mack, 2010; Genoud and Lesourd, 2009; Rogner, 2010).

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The aim of this paper is to comprehensively rank a large number of electricity generation technologies based on their compatibility with the sustainable development of the industry. Quantifying the level of sustainability is done through sets of evaluation variables which are generally called "sustainability indicators". Some of the first attempts at creating such sets were made by the International Atomic Energy Agency and the United Nations Department of Economic and Social Affairs in 1995 and then later in 2001. The findings of this early research were refined through an ample project which involved several international organizations and the final results were published in 2005 under the name "Energy Indicators for Sustainable Development" (IAEA, UNDESA, IEA, Eurostat, EEA, 2005). This three-pillar framework now constitutes a significant reference point for research regarding the sustainability of the energy sector.

There is currently no standardized methodology that can be used to evaluate energy sector sustainability. Angelis-Dimakis et al. (2012) conclude that researchers generally have to customize their approach depending on their specific objectives. Several researchers have used the Energy Indicators for Sustainable Development to establish their own set of indicators (Angelis-Dimakis et al., 2012; Streimikiene and Šivickas, 2008), while others have used a new framework altogether (Carrera and Mack, 2010; DECC, 2012; Tsai, 2010). It should be noted that two types of sustainability assessments exist: those referring to a system (e.g. national energy sector of a certain country) (Sheinbaum-Pardo et al., 2012; Streimikiene and Šivickas, 2008; Tsai, 2010) and those referring to electricity generation technologies (e.g. wind, photovoltaic, nuclear) (Evans et al., 2009; Genoud and Lesourd, 2009; Wei et al., 2010). The current paper aims to provide an analysis of the second type.

Several evaluation approaches can be used for sustainability assessment (e.g. input–output analysis, emergy accounting), however life cycle analysis is considered to be the most comprehensive, as it generates an understanding of the effect that power plants of a certain type can have over their entire existence (Evans et al., 2009). The current paper will use the life cycle analysis approach to define the value of the various indicators where applicable (e.g. the technological factors and social acceptance are technology or fuel source specific regardless of the life cycle period).

Researchers can choose from several methodologies to quantitatively measure energy sustainability: system dynamics, energy return on investment, figure of merit etc. (Liu et al., 2013). Due to its effectiveness in supporting decisions which involve trade-offs between conflicting objectives, the most widely used approach is the multi-criteria decision analysis (MCDA) (Wang et al., 2009), which we have also used in the current study.

An assessment of past research on the topic of power technology sustainability, including the extensive literature review provided by Wang et al. (2009), has revealed some improvement opportunities.

First, much of the research observed assesses only a limited number of technologies (Doukas et al., 2007; Evans et al., 2009; Máca et al., 2012) or assesses several technologies, but uses a single sustainability dimension (European Commission, 2003; Wei et al., 2010). We aim to analyse 14 different technologies, thus assessing a virtually complete set of electricity generation alternatives (Breeze, 2005).

Second, the same indicators (e.g. efficiency, pollution) are classified in different dimensions across various studies (Evans et al., 2009; Genoud and Lesourd, 2009; Wang et al., 2009). This can be due to the strict adherence to the traditional three-pillar construct (economic, environmental, social). We propose a four dimensional approach that includes the "technological" component and use the assessment of Wang et al. (2009) to classify "ambiguous" indicators in a manner consistent with relevant past research.

Finally, most research on this topic that utilizes MCDA uses equal weights for the indicators in the ranking calculation (Wang et al., 2009). We use an adapted SWING weighting method based on the results obtained from interviewing 62 academics from the fields of energy and environmental science.

2. Methods

The research methodology employed in this study, summarized in Fig. 1, can be split into four main stages: selection of the electricity generation technologies to be assessed, selection and valuation of the sustainability indicators, weighting of the sustainability indicators and sustainability ranking of the electricity generation technologies. The following subsections address these four stages individually.

2.1. Set of electricity generation technologies to be assessed

The aim of this paper is to provide a sustainability ranking for a large number of power generation technologies. The encyclopaedic work of Breeze (2005) presents an exhaustive set of electricity

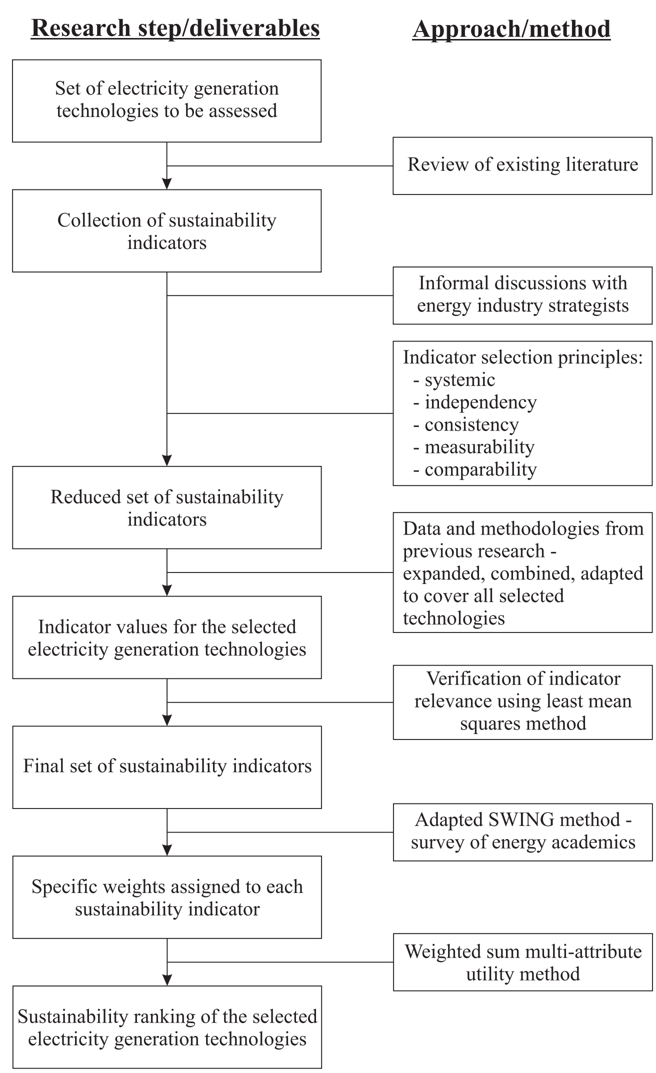

Fig. 1. Summary of research steps and methodology.

generation technologies. By consulting several studies on the topic of energy sector sustainability and various electricity generation technology assessments, we reduced the set presented by Breeze to 14 unit types. Their main characteristics are illustrated in Table 1.

The specific technologies utilized by the 14 unit types have been established based on the data sources used for indicator valuation. For example, some sources only assess traditional coal plants (excluding integrated gasification combined cycle, or IGCC, designs) without carbon capture and storage (CCS). Thus, our assessment has eliminated IGCC and CCS from the analysis in order to insure consistency across all valuations.

For a more comprehensive understanding of the history, functioning principles, advantages and disadvantages of these technologies, we recommend that readers consult Breeze (2005) or other similar works.

2.2. Selection and valuation of the sustainability indicators

Establishing the set of sustainability indicators to be used in the assessment is a crucial step in the research process. The constantly evolving literature on the topic provides hundreds of indicators which can be adapted and combined to suit a researcher's specific objectives (IAEA, UNDESA, IEA, Eurostat, EEA, 2005; Neves and Leal, 2010). In the initial stages of this study we reviewed several independent or primary sets of indicators (DECC, 2012; IAEA, UNDESA, IEA, Eurostat, EEA, 2005; Sheinbaum-Pardo et al., 2012; Tsai, 2010), as well as other constructs which were derived from these original sets (Angelis-Dimakis et al., 2012; Streimikiene and Šivickas, 2008).

In order to reduce the resulting collection of indicators to a manageable and functional set, we employed several tactics. First, the current study aims to assess electricity generation technologies

Table 1
Main characteristics of assessed power generation technologies.
Sources: Breeze (2005), IEA et al. (2010), Navigant Research (2012).

Label	Resource/fuel	Characteristics
Coal	Coal	• Assessment focuses on traditional steam turbine based coal plants (non-IGCC), without CCS • Average capacity (plant): ~700 MW
Natural gas	Natural gas	• Study considers both simple-cycle and combined-cycle gas turbines (gas turbine and steam turbine), both without CCS. Due to its wider use (IEA et al., 2010; IEA, 2011b), the combined-cycle technology has a predominant impact on the rating of the "natural gas" technology type • Average capacity (plant): ~600 MW
CHP	Gas/coal/other	• Most combined heat and power (CHP) plants are based on gas or coal units, but other technologies are also used (see Section 2.5) • Average capacity (plant): ~200 MW
Piston engine	Diesel/gas/other	• Also referred to as "reciprocating engine" • Assessment focuses on diesel fuelled engines as these are generally considered to be highly efficient and scalable • Average capacity (unit): ~35 MW
Fuel cell	Hydrogen (pure or extracted from gas)	• Data sources generally provide aggregate information referring to various fuel cell technologies (phosphoric acid, solid oxide etc.) • Average capacity (unit): ~300 kW
Hydro (large)	Water flow	• Includes large reservoir hydroelectric plants (> 10 MW). Does not include pumped storage plants • Average capacity (plant): ~100 MW
Hydro (small)	Water flow	• Includes run-of-river/micro hydroelectric plants with a capacity of 10 MW or less • Average capacity (plant): ~2.5 MW
Wind (onshore)	Wind	• Assessment includes onshore wind farms with turbines of varied capacities • Average capacity (project): ~60 MW
Wind (offshore)	Wind	• Assessment includes offshore wind farms with turbines of varied capacities • Average capacity (project): ~160 MW
Geo-thermal	Geothermal heat	• Bertani's (2005) geothermal fields list suggests that ~90% of worldwide geothermal fields are adequate for flash-steam plants, while the other ~10% use direct-steam plants. Most other sources do not distinguish between the two • Average capacity (plant): ~60 MW
Solar PV	Solar radiation	• Residential, commercial or industrial installations of photovoltaic solar panels. Generally, our data sources do not specifically distinguish among the different panel manufacturing technologies • Average capacity (project): ~5 MW
Solar thermal	Solar radiation	• Solar concentrators using parabolic through/dish or solar towers with heliostats • Average capacity (unit/project): ~60 MW
Biomass	Biomass	• Assessment looks at biomass fired plants using steam turbines, excluding fossil fuel co-firing • Average capacity (plant): ~25 MW
Nuclear	Nuclear fuel	• Pressurised water reactors and boiling water reactors represent ~88% of the global installed base and constitute ~100% of all planned installs (IEA et al. 2010) • Average capacity (plant): ~1300 MW

and not specific (e.g. national) energy systems. Thus, indicators such as "share of renewable energy sources in electricity consumption/generation" are not relevant for our research objective and were removed from the set. Second, as a result of informal interactions with energy industry professionals, we were able to identify certain strategically significant indicators (such as "levelized cost of electricity" and "ability to respond to demand") which we decided to include in the analysis. Finally, we used the five guiding principles for indicator selection proposed by Wang et al. (2009) to complete the functional set. The *systemic* and *independency* principles resemble the "mutually exclusive, collectively exhaustive" concept used in management consulting (Rasiel and Friga, 2001); *consistency* refers to the alignment of the indicators with the research objectives, while the *measurability* and *comparability* are self-explanatory.

The reduced set included 10 indicators, which are categorized, listed and defined in Table 2. Indicators such as "levelized cost of electricity" and "external costs" were preferred because they offer aggregated valuations of several other metrics which previous researchers used as separate indicators (Evans et al., 2009; Genoud and Lesourd, 2009).

The next step was to rate the 14 technologies on each of the 10 indicators based on secondary research. This proved to be a challenging process, as most literature either characterized only 4–6 more common technologies or used methodologies that did not fully meet the requirements of our research. Under these circumstances, it was necessary to combine the results of several studies, to expand the results of others using the original methodology or even to adapt some research methodologies to fit the aims of the current paper. A more detailed description of this process is included in Section 3.1.

After the valuation stage was complete, we sought to conduct an analysis of the results in order to establish whether all the chosen indicators were indeed relevant for our assessment. Based on the approaches used in past research (Wang et al., 2009), we opted for the least mean squares method. This can be used to establish whether certain indicators have a lower contribution to the ranking calculation (due to limited variance of the characteristic among the different technologies) and should thus be eliminated from the analysis altogether. The least mean squares method uses the following equation:

$$S_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(x_{ij}-\overline{x}_j)^2}\ (j=1,2,\ldots,n) \tag{1}$$

where x_{ij} is the ith sample of the jth indicator ($i=1, 2, \ldots, m$) and $\overline{x}_j=(1/m)\sum_{i=1}^{m}x_{ij}$.

If there exists k so that $S_k=\min_{1\le j\le n}\{S_j\}$ and $S_k\approx 0$, then indicator k can be removed from the analysis. After calculating these values for our results ($\overline{S}_j=0.033$, $S_{jmax}=0.041$, $S_{jmin}=0.023$), we concluded that none of our initial 10 indicators should be disregarded from the analysis. Thus, the final set of sustainability indicators remains the one presented in Table 2.

As can be seen from Table 2, we use a four dimension classification of sustainability indicators. We have included the "technological" dimension, which is generally omitted even if technical indicators are utilized in the assessment (Genoud and Lesourd, 2009). The use of this four dimensional approach is also supported by other researchers of energy sustainability (Orecchini, 2011; Sternberg, 2008; Wang et al., 2009).

It should be noted that the ten indicators cover most of the sub-indicators and criteria mentioned by Wang et al. (2009) in their extensive review of past research on the topic.

2.3. *Weighting of the sustainability indicators*

In the next phase of the MCDA process, the researcher needs to establish whether there are differences among the various indicators with regard to their overall importance in the analysis. If such variations do exist, these can be quantified through the use of different weights when calculating the ranking scores.

It has been argued that using equal weights often produces results nearly as good as optimal weighting methods (Dawes and Corrigan, 1974). This is the most popular approach used in sustainable energy assessments due to the minimal additional input required to conduct the analysis (Wang et al., 2009).

In order to compensate for the potential shortcomings of the equal weights approach, the rank-order weighting method has been utilized. This implies that different weights should be attributed to the various indicators, so that $w_1 \ge w_2 \ge \ldots \ge w_n \ge 0$, and $\sum_{i=1}^{n} w_i = 1$. Wang et al. (2009) classify the rank-order weighting methods into three categories: subjective, objective and combination. While the subjective methods provide a clearer explanation of the evaluation, the judgments offered by the respondents depend on their level of knowledge or information.

In our study, we opted for a subjective rank-order weighting of the sustainability indicators. The specific approach was an adaptation of the SWING method as it is described by Wang et al. (2009). We created an online questionnaire asking respondents to rate the 10 indicators on a scale of 1–10 based on their importance for the long-term development of mankind (1—not important at all, 10—very important). In order to compensate for the "lack of knowledge" issue

Table 2
Sustainability indicators and definitions.

Dimension	Indicator name	Definition
Economic	Levelized cost of electricity (LCOE)	The average cost of producing electricity over the entire lifetime of the unit; it takes into account all investment, operation and maintenance, fuel, decommissioning and even CO_2 emissions costs
Technological	Ability to respond to demand	The ability to respond to peak demand and to insure overall grid stability in the long term in the context of a growing share of intermittent generation from some renewable energy sources
	Efficiency	The efficiency with which input energy (e.g. chemical energy extracted from fuels) is transformed into useful output energy (i.e. electricity and useful heat)
	Capacity factor	A measure of the actual electricity produced over a period of time divided by the maximum theoretical electricity that could have been produced if the plant had been running at nameplate capacity
Environmental	Land use	Land used over the entire lifecycle of the unit (e.g. fuel extraction, processing and delivery, construction, operation and decommissioning)
	External costs (environmental)	Cost generated over the entire lifecycle of an electricity generation unit that are supported by entities other than the parties directly involved with the unit; this component refers to environmental costs (soil maintenance, clean-up of dust etc.)
Socio-political	External costs (human health)	Cost that are generated over the entire lifecycle of an electricity generation unit which are supported by entities other than the parties directly involved with the unit; this component refers to human health costs (hospital and medication, loss of productivity etc.)
	Job creation	"job-years" of full time employment created over the entire lifecycle of the unit
	Social acceptability	Public preference for the deployment or utilization of a certain electricity generation technology
	External supply risk	The risk of supply shock incidence due to fuel imports

specific to subjective weighting, we first asked respondents to assess their own level of familiarity with the issues concerning the electricity sector. We then calculated the weighted arithmetic average of the importance ratings for each indicator, using the respondents' familiarity scores (i.e. 1–10, as seen in Q1 of the questionnaire) as weights. A translated version of the questionnaire is available in Appendix A.

A message was sent to 292 email addresses of academics from the energy and the environmental science departments of six Romanian universities, ensuring a wide geographical distribution and a respondent sample with a high understanding of the research problem. Academics were chosen due to their relative neutrality regarding the various dimensions of sustainable development and due to their potential influence over any significant energy policies adopted by the Government.

The survey yielded 62 responses. Twelve of the email addresses proved to be invalid. This translates to a response rate of 22%. Two of the responses were filtered out of the analysis due to ambiguity regarding the respondent's academic status.

There was a wide distribution of respondents among the four largest cities in Romania (Bucharest—32%, Iaşi—20%, Timişoara—18% and Cluj—17%, other—13%), which also have the largest student populations in the country. A relatively even distribution was also observed among the four main academic ranks (Assistant—28%, Lecturer—25%, Associate professor—13%, Professor—27%, with the rest being unspecified).

The weights assigned to the ten sustainability indicators were calculated by normalizing and averaging the importance scores given to each of them by the respondents. The average values were then converted into weights so that $\sum_{i=1}^{10} w_i = 1$.

2.4. Sustainability ranking of the electricity generation technologies

Ranking the various technologies is done using the multi-attribute utility method for value normalization (Dyer, 2005) coupled with a weighted sum approach to calculate the aggregate scores. The weighted sum is one of the most commonly used methods in the field due to its straightforward nature (Tsai, 2010; Wang et al., 2009).

Value normalization is used in the MCDA method to calculate a utility value on a scale of 0 to 1 for each of the ten indicators. Given that some of them are directly correlated with utility (e.g. efficiency, job creation) and others are inversely correlated with utility (e.g. land use, LCOE), two different equations are used for converting the values to the 0–1 scale:

$$\text{direct correlation with utility}: \ u(x_k) = (x_k - x_{\min})/(x_{\max} - x_{\min})$$

$$\text{inverse correlation with utility}: \ u(x_k) = (x_{\max} - x_k)/(x_{\max} - x_{\min})$$

where x_k is the indicator value for technology k; x_{min} the minimum value of the indicator; x_{max} the maximum value of the indicator.

The total utility score was calculated by multiplying each of these partial utilities with their corresponding indicator weight and then summing them up for each technology. This aggregated score provides the ranking of the various electricity generation technologies based on their compatibility with sustainable development.

2.5. Main assumptions used in the technology assessment

Due to limited data availability, several assumptions had to be made regarding technology types such as "CHP", "piston engine" and "geothermal". Some of these assumptions are used across several indicators and are presented in more detail within the current subsection. Other assumptions are indicator specific and are discussed in the respective indicator subsections.

Our first assumption refers to the "piston engine". As mentioned in Table 1, the assessment focuses on diesel engines. Several data sources do not specifically rate piston engines or "diesel" as a fuel source in comparison to the other technology types, but they do use "oil" as a separate category. Given the fact that diesel is a substance derived from petroleum and it carries more similarity to "oil" than to other fuels such as "natural gas" or "coal", the piston engine is rated using the "oil" category for the indicators "levelized cost of electricity", "external costs" and "external supply risk".

Our second assumption refers to the rating of CHP plants in situations where data is not available. This type of plant is generally based on a gas or steam turbine, especially if they are used for base-load electricity generation (Breeze, 2005). Piston engines and fuel cells can also be used in CHP plants. A report published by SETIS states that, with regard to fuels, natural gas constitutes 40% of the European CHP market, with "solid fossil fuels" (i.e. coal) in second place with 35% and renewable fuels and combustible waste covering nearly 12% (SETIS, 2013). In order to obtain a reasonable estimation of CHP ratings while avoiding ambiguity, we have used a simple average of the values obtained by "natural gas" and "coal", the two most commonly used fuels for CHP plants for indicators such as "land use", "external costs", "job creation", "social acceptability" and "external supply risk".

Alternatively, given sufficiently precise data, the proportion of "natural gas" and "biomass" could be increased when calculating the ratings for CHP, as these are considered to be more desirable CHP fuels going forward (SETIS, 2013; IEA, NEA, OECD 2010). Data regarding piston engines could also be added to this weighted average (Breeze, 2005; IEA, 2011b). After running several simulations using various weighting assumptions by combining information from SETIS (2013), IEA (2011b), IEA, NEA, OECD (2010) and Breeze (2005), the only observed change was an increase of CHP utility from 0.538 to ~0.55, placing CHP above Biomass, which has a utility of 0.539.

3. Results

The results will be presented in three subsections. The first and most extensive will illustrate the indicator valuation process. The second will present the findings of the weighting survey. The third will focus on the aggregated utility calculation and the sustainability ranking of the assessed technologies.

3.1. The valuation of the sustainability indicators

As seen in Table 2, the research has used four dimensions to categorize the 10 sustainability indicators: economic, technological, environmental and socio-political. This classification does not impact the results of the study, because the chosen weighting approach independently labels each indicator with its own importance score. This section will present the data sources and methodologies used in the assessment of the selected technologies for each indicator. These will be addressed in the same order as presented in Table 2.

3.1.1. Levelized cost of electricity

There are several cost related factors that need to be taken into consideration in order to accurately characterize the various technologies from an economic point of view (Wang et al., 2009). We have opted to use an aggregated cost indicator called "Levelized Cost of Electricity" because it allows us to cover all the relevant financial aspects without overcomplicating the overall analysis.

LCOE is generally used to compare the average production cost (or break even sale price) of electricity for various generation technologies over their entire lifecycle. Although it has some limitations with regard to its rigid forecasting approach, it is regarded as a valid comparison tool by several international energy agencies and large companies (IEA, NEA, OECD 2010). LCOE calculations take into consideration investment costs, operation and maintenance costs, fuel costs, decommissioning costs and, where applicable, CO_2 emissions costs. More information regarding this indicator and the methodology behind it is available in IEA, NEA, OECD (2010) as well as other LCOE assessment reports.

The "Projected Costs of Electricity Generation" report published in 2010 by the International Energy Agency and the Nuclear Energy Agency displays the LCOE for approximately 200 power plants located in 21 countries which can be classified into various technology types. Using this data, we estimated a weighted LCOE average using the nameplate capacity of the power plant as a weight. The results (Table 3) can be used to compare the various technologies on the economic dimension.

The main limitation of this approach results from the reduced volume of data, especially in the case of the less common technologies (e.g. fuel cells and piston engines). Weighting the LCOE with the nameplate capacity can also generate errors given that not all power plants operate under the same regime (e.g. base load or peak load), which translates to different maintenance and operating costs among otherwise identical units.

The data in Table 3 shows that large hydroelectric, geothermal, nuclear, biomass and conventional thermal projects generate the lowest costs. There is limited shift in ranking among these technologies when the discount rate changes from 5% to 10%. On the other end of the metric are the more costly small hydroelectric, wind and solar technologies.

3.1.2. Ability to respond to demand

The first indicator from the technological class refers to a unit's ability to respond to varying electricity demand (e.g. for peak load and grid fluctuations). If they possess this capability, they can be used for grid balancing—a function that is becoming more important as the share of intermittent generation capacity from solar PV and wind units increases.

This indicator can be used to rate electricity generation technologies in three ways: "yes, rapid" (response time is measured in minutes), "yes, slow" (response time is measured in hours or even days) or "no" (unable to generate electricity on demand). For the purpose of this analysis, we will exclude special cases such as the presence of limited storage capacity at the generation site to insure short term backup delivery to the grid or the conversion of biomass into biogas to be used in a rapid response gas turbine.

Table 4 shows that large hydroelectric plants as well as natural gas units, piston engines and fuel cells are capable of providing rapid grid balancing services. At the same time, some of the most popular renewable energy technologies can contribute to increased grid instability.

3.1.3. Efficiency

The second technology indicator is calculated as a ratio between the useful energy output and the total energy input and is expressed in percentages. The difference between 100% and the efficiency score represents a loss of energy (Table 5).

For this valuation we used the data included in the 2011 IEA Energy Outlook model (IEA, 2011a). The IEA and Eurostat use the "Physical Energy Content" method to compensate for potential underestimation of renewable energy technologies. Thus, renewable energy sources which are available directly as secondary energy (as opposed to primary energy) have an efficiency rating of 100% (IRENA, 2013). The efficiency rating for the piston engine is from Breeze (2005).

In the case of varying efficiency scores for the same technology type (e.g. natural gas units in simple or combined cycle etc.) we recorded only the highest score, as it illustrates the best potential option for that technology type.

3.1.4. Capacity factor

The capacity factor is calculated as a ratio between the actual electricity production of a unit during a certain time period and the maximum theoretical output of the unit if it had been running at full capacity for the entire time period. This indicator shows, on average, how much of the nameplate capacity of a plant is actually used in practice (Table 6).

The capacity factors for most renewable energy technologies are from the IEA World Energy Outlook 2011 model (IEA, 2011a) and the rest are from IEA, NEA, OECD (2010).

Significant variations in capacity factors were observed based on geographical location (e.g. 26–54% for large hydroelectric plants and 9–20% for Solar PV). Calculating a relevant average value was not possible given the available data. Thus, in all cases, we used the highest available value, which shows the current maximum potential of the technology.

3.1.5. Land use

Land use is the first of the two environmental indicators used in this study. The use of land for power generation creates an opportunity cost both for human habitation and use and for flora and fauna. In order to produce a fair comparison of technologies, we take into consideration the land use over the entire lifecycle of the power plants: the extraction, processing, transportation and waste disposal of fuels and the construction, operation and decommissioning of the plant. Few studies exist which provide such analyses (Eurelectric, 2011), and the results vary from one source to another (EPRI, 2012; Fthenakis and Kim, 2009; Gagnon et al., 2002), though the technology rankings are similar (Table 7).

3.1.6. External costs (environmental)

The "land use" indicator only refers to the area of land used and does not cover land degradation. This aspect is largely covered by the "external costs (environmental)" indicator. This is a complex aggregated indicator which can be used to valuate most of the impact that electricity generation has on the environment and human health. It covers an ample array of pollutants and forms of environmental impact, ranging from noise pollution to hazardous emissions (see Appendix B), and assesses them over the entire unit lifecycle.

Table 3
LCOE ($/MW h) for various technologies at 5% and 10% discount rates.

LCOE—5% discount rate		LCOE—10% discount rate	
Technology	*LCOE* ($/MW h)	*Technology*	*LCOE* ($/MW h)
Hydro (large)	26.35	Hydro (large)	46.66
Geothermal	39.98	Geothermal	68.45
Nuclear	53.79	CHP	74.65
CHP	62.81	Coal	79.36
Coal	64.37	Natural gas	85.30
Biomass	72	Nuclear	87.29
Wind (onshore)	76.28	Biomass	97.10
Natural gas	78.06	Wind (onshore)	109.61
Piston engine	104.63	Piston engine	119.03
Hydro (small)	124.97	Wind (offshore)	178.93
Wind (offshore)	128.68	Fuel cell	213.14
Solar thermal	177.80	Hydro (small)	237.55
Fuel cell	181.17	Solar thermal	269.67
Solar PV	202.94	Solar PV	301.89

We would like to point out that the environmental impact of electricity generation can be more complex than that covered by the “land use” and “external costs” indicators. Wang et al. (2009) list eight environmental indicators used in previous research on the topic, all of which are effectively covered by our “land use” and “external costs”. Examples of factors not taken into consideration by our study include the visual impact of wind farms, as studied by Ladenburg (2009), any unique land habitat reduction and the impact of forced population displacement specific to large hydroelectric projects (Breeze, 2005), as well as biodiversity loss (Máca et al., 2012). Such environmental effects would be difficult to assess in a way that would allow for a correct comparison of the different power generation technologies.

Costs can be classified as external when they result from the activity of one entity, but are incurred by a different entity. One example is the soiling of buildings due to the particulate emissions of a coal plant. The clean-up cost is incurred by the building administrators, not by the plant operator. This is because damages to air quality are not subject to propriety rights, so a commercial relationship on the issue cannot be established between the two entities. This institutional deficiency can be mitigated through the evaluation of external effects in such a way that the governing authority can “internalize” the external costs by, for example, imposing taxes on the use of polluting fuels (European Commission, 2003). Environmental agencies are in favour of placing a monetary value on external effects, because most pollution control measures also use financial mechanisms (EEA, 2005). While the conversion of pollutant effects into costs produces an indirect assessment of the environmental impact, we believe that a rigorous valuation provides solid arguments for the implementation of unambiguous legislation regarding environmental protection.

The European Commission financed a large scale research project on the topic of external costs called ExternE. The study helped develop an extensive methodology for the monetary valuation of the negative impact that electricity generation can have on society and the environment. The research also created instruments to facilitate external cost calculations across various time frames and geographical contexts (European Commission, 2010).

In spite of the fact that this methodology now represents a landmark for governing authorities and researchers from outside the European Union (Owen 2006; Bozicevic Vrhovcak et al., 2005), very few studies exist that aim to refine or develop the methodology or results proposed by the ExternE team.

Appendix B shows that external costs (also known as externalities) cover both the environmental and the human health impact. The latter was included in a different indicator as part of the socio-political dimension of our analysis and had to be separated from the whole. In order to perform this division, we combined the research results of Máca et al. (2012) and an example proposed by Friedrich (2005), a member of the ExternE team.

The example of Friedrich splits externalities into four impact components: human health, crops, materials and climate change. These are used to compare ten electricity generation technologies in the context of 2010 Germany (Friedrich, 2005). The scenario uses a 19 EUR/t of CO_2 parameter, which is also used in the more recent work of Máca et al. (2012). The technology types assessed are nuclear, natural gas, various types of renewable energy and several specific coal plant applications. Máca et al. perform a similar analysis, but only assess conventional thermal technologies set in various Eastern European countries. Our valuation combines the renewable and nuclear data of Friedrich with the coal and petroleum data of Máca et al. Both studies provide an assessment of natural gas, which can be used to test the congruity of the two data sets.

The first step in combining the data was to insure that it was calculated in a consistent way across the two sets. The study of Máca et al. includes an assessment of the external cost associated with the loss of biodiversity, which is not incorporated in the study of Friedrich. The data of Máca et al. also use a cost component which combines human health with crop and material

Table 4
Ability to respond to demand.
Sources: Breeze (2005), Diakoulaki and Karangelis (2007).

Technology	Values	Technology	Values
Hydro (large)	Yes, rapid	Geothermal[a]	Yes, slow
Natural gas	Yes, rapid	Solar thermal	Yes, slow
Piston engine	Yes, rapid	Biomass	Yes, slow
Fuel cell	Yes, rapid	Hydro (small)	No
Coal	Yes, slow	Wind (onshore)	No
CHP[a]	Yes, slow	Wind (offshore)	No
Nuclear	Yes, slow	Solar PV	No

[a] Some geothermal and CHP applications do have the potential for rapid response, but are not used as such because it would not be feasible (Kaplan, 2008).

Table 5
Efficiency ratings.

Technology	Values (%)	Technology	Values (%)
Wind (onshore)	100	Piston engine	50
Wind (offshore)	100	Coal	48
Solar PV	100	Fuel cell	45
Hydro (large)	100	Solar thermal	40
Hydro (small)	100	Biomass	35
CHP	79	Nuclear	33
Natural gas	59	Geothermal	15

Adapted from: IEA (2011a).

Table 6
Capacity factors.

Technology	Values (%)	Technology	Values (%)
Nuclear	85	Biomass	70
Coal	85	Hydro (large)	54
Natural gas	85	Hydro (small)	50
CHP	85	Solar thermal	45
Piston engine	85	Wind (offshore)	40
Fuel cell	85	Wind (onshore)	27
Geothermal	73	Solar PV	20

Adapted from: IEA (2011a); IEA et al. (2010).

Table 7
Land use (m^2/MW h).

Technology	Values	Technology	Values
Biomass	12.65	CHP[c]	0.35
Hydro (large)	4.1	Solar PV	0.33
Wind (offshore)[a]	2.76	Natural gas	0.31
Wind (onshore)	1.57	Nuclear	0.12
Geothermal[b]	0.74	Hydro (small)[a]	0.02
Solar thermal[a]	0.46	Piston engine[d]	–
Coal	0.39	Fuel cell[e]	–

Adapted from: Bertani (2005), Fthenakis and Kim (2009).

[a] Estimated based on the project data presented by Fthenakis and Kim (2009).
[b] Calculated based on the geothermal fields listed by Bertani (2005), assuming a 73% capacity factor and a 40 year unit lifetime.
[c] Average of natural gas and coal values.
[d] No data available, but is expected to be among the lower values (below wind technologies).
[e] No data available.

costs. As mentioned above, Friedrich presents these separately. Insuring a compatible calculation meant that biodiversity costs had to be eliminated from the total externality cost and that the crop and material costs had to be split from the aggregate "human health/environment" dimension of Máca et al. This latter step was performed using Eq. (2).

$$HH_F \approx HH'_M = HH_M \times \left(1 - \frac{Mat_F + Crop_F}{Mat_F + Crop_F + HH_F}\right) \quad (2)$$

where HH_F is the "health impacts" dimension of Friedrich, HH_M the "human health/environment" dimension of Máca et al., HH'_M the "human health" component of HH_M, Mat_F the external cost regarding "materials" of Friedrich, and $Crop_F$ the external cost regarding "crops" of Friedrich.

The proportion of externalities associated with human health (PrH) out of the total external cost is calculated according to Eq. (3).

$$\frac{HH_F}{HH_F + Mat_F + Crop_F + CC_F} = \frac{HH_F}{Ext_F} = \boldsymbol{PrH_F} \approx \boldsymbol{PrH_M} = \frac{HH'_M}{Ext_M - Bio_M} \quad (3)$$

where Ext_F/Ext_M is the total external cost of Friedrich/Máca et al. CC_F the external cost regarding "climate change" of Friedrich, and Bio_M the external cost regarding "biodiversity loss" of Máca et al.

Because Máca et al. present externalities data for each technology type across several countries, the average PrH value has been calculated for each type. Establishing the PrH value also provides the complementary environmental externalities proportion: $PrE = (1 - PrH)$, as seen in Table 8.

Although the PrH values for natural gas are somewhat different for the two data sets ($PrH_F = 28\%$; $PrH_M = 20\%$), the absolute value of the health externalities (expressed in constant 2000 Euros) is almost identical ($HH_F = 0.31$ €c$_{2000}$/kW h $\approx HH'_M = 0.33$ €c$_{2000}$/kW h). A perfect balance between the two would have been highly improbable given both the temporal and geographical differences between the two studies. However, an approximate balance was to be expected, given that both approaches are based on the ExternE methodology and use similar parameters.

In order to calculate the values for the "external costs (environmental)", we multiplied the PrE proportion with the absolute values published in the ExternE report (European Commission, 2003). As these results are presented in the form of intervals, we multiplied PrE with both ends of the interval (Table 9).

The use of externalities remains the only method of providing a nearly exhaustive comparison of electricity generation technologies from an environmental and human health impact perspective. However, considering that the absolute values of external costs have a temporal and geographical variance, the data presented above is only estimative.

3.1.7. External costs (human health)

This is the first factor from our socio-political dimension. The impact of electricity generation on human health was valuated using the same approach as "external costs (environmental)" (Table 10). In this case, the ExternE data was multiplied with the PrH values listed in Table 8.

3.1.8. Job creation

Although job creation is strongly connected with the economic development of a community or country, it is generally classified as a social factor of sustainable development (Wang et al., 2009). "Job creation" provides a lifecycle assessment showing the number of employees involved in the implementation and operation of a power generation project. The measurement unit is called "job-years" (a full time employee hired over 12 months) per unit of electricity produced. A large number of studies are aimed at assessing the job market impact of various generation technologies (California ISO, 2012; Wei et al., 2010). Such information is becoming increasingly relevant for governmental authorities given the prolonged worldwide economic slump which has led to high unemployment.

Because most researchers only assess a very limited set of technologies and use heterogeneous measurement units, Wei et al. (2010) have combined and normalized the data from 15 such studies, covering nearly all main generation technologies. The only one that is not included is large hydroelectric. The reason for this omission may be the lack of data or the low relevance of large hydro for the specific research objective.

The indicator values for this technology were calculated using the data provided in a study performed by Navigant Consulting for the US National Hydropower Association (Navigant Consulting, 2009). We used the same calculation methodology as Wei et al. to insure data compatibility (Wei et al., 2010). The parameters used for the valuation were: average planning and construction period for a large hydroelectric project—10 years (CEA, 2008; IEA, NEA, OECD, 2010), unit lifetime without additional investment – 50 years (Breeze, 2005; European Commission, 2011), capacity factor – 54% (IEA, 2011a).

The indicator values (Table 11) only reflect direct hires over the entire unit lifecycle. Indirect hires (e.g. the production of building materials for the project) and induced hires (resulting from income spent by direct and indirect hires) are not included, as there is limited compatibility regarding this data in the reviewed studies (Wei et al., 2010).

Table 8
Proportions of externalities associated with "health" and "environment".

Technology	*PrH* (%)	*PrE* (%)	Technology	*PrH* (%)	*PrE* (%)
Coal	51	49	Solar PV	73	27
Natural gas[a]	20	80	Solar thermal[c]	73	27
Piston engine[b]	45	55	Hydro (large)	67	33
Nuclear	82	18	Hydro (small)[c]	67	33
Biomass	85	15	Fuel cell	42	58
Wind (onshore)	67	33	CHP[d]	–	–
Wind (offshore)[c]	67	33	Geothermal[d]	–	–

[a] The value provided by Máca et al. (2012) was used, as this is more recent.
[b] The values from the "oil" unit type were used.
[c] Assumed to be identical among similar technologies.
[d] No data available.

3.1.9. Social acceptability

"Social acceptability" and the "potential for conflict generation" are both used as energy sustainability indicators and are connected to the "perceived risk" of the technology (Bronfman et al., 2012; Carrera and Mack, 2010). Better data availability due to its wider use among researchers (Wang et al., 2009) means that social acceptability has a better fit with our research goals.

More than 1000 various studies have been published on this topic over the last decades (Greenberg, 2009). This indicator was valuated using the results from three large scale studies with a very wide geographical coverage. The first is a special edition of the Eurobarometer (2007), which addressed the population of the EU-25 countries and whose results were re-confirmed by recent research (Corner et al., 2011). The second is a study conducted by Greenberg (2009) in the USA. The third is a study published by Ipsos Public Affairs, which covers the USA as well as 22 other countries from various continents (Ipsos Public Affaris, 2010). We chose to use all three of these studies in order to limit any errors which could arise from the geographical coverage or from the methodological approach. All three studies assess the social acceptability of the fuel/resource used, rather than actual technologies (Table 12).

Table 9
External costs associated with the environment (€c/kW h).

Technology	Ext_{min}	Ext_{max}	Technology	Ext_{min}	Ext_{max}
Wind (onshore)	0.017	0.083	Biomass	0.030	0.750
Wind (offshore)[a]	0.017	0.083	Natural gas	0.800	3.200
Nuclear	0.036	0.126	CHP[b]	0.890	5.275
Solar PV	0.162	0.162	Piston engine	1.650	6.050
Solar thermal[a]	0.162	0.162	Coal	0.980	7.350
Hydro (large)	0.010	0.330	Geothermal[c]	–	–
Hydro (small)[a]	0.010	0.330	Fuel cell[d]	–	–

[a] Assumed to be identical to the technology listed above it.
[b] Average of natural gas and coal values.
[c] No data available, however we expect it to be similar to the value recorded for biomass, given the low level of emissions (Kagel and Gawell, 2005) and the use of conventional construction materials, but also the negative impact it can have on the environment (Breeze, 2005).
[d] No data available.

Table 10
External costs associated with health (€c/kW h).

Technology	Ext_{min}	Ext_{max}	Technology	Ext_{min}	Ext_{max}
Wind (onshore)	0.034	0.168	Natural gas	0.200	0.800
Wind (offshore)[a]	0.034	0.168	CHP[b]	0.610	4.225
Solar PV	0.438	0.438	Biomass	0.170	4.250
Solar thermal[a]	0.438	0.438	Piston engine	1.350	4.950
Nuclear	0.164	0.574	Coal	1.020	7.650
Hydro (large)	0.020	0.670	Geothermal[c]	–	–
Hydro (small)[a]	0.020	0.670	Fuel cell[d]	–	–

[a] Assumed to be identical to the technology listed above it.
[b] Average of natural gas and coal values.
[c] No data available, however we expect it to be similar to the value recorded for biomass, given the low level of emissions (Kagel and Gawell, 2005) and the use of conventional construction materials, but also the negative impact it can have on the environment (Breeze, 2005).
[d] No data available.

Table 11
Number of employees per unit of electricity produced (job-years/GW h).

Technology	Values	Technology	Values
Solar PV	0.87	Wind (offshore)	0.17
Hydro (large)	0.55	Nuclear	0.14
Hydro (small)	0.27	Natural gas	0.11
Geothermal	0.25	Coal	0.11
Solar thermal	0.23	CHP[a]	0.11
Biomass	0.21	Piston engine[b]	–
Wind (onshore)	0.17	Fuel cell[b]	–

Adapted from: Wei et al. (2010).

[a] Average of natural gas and coal values.
[b] No data available, however we expect it to be among the medium to low values, given the largely autonomous operation, relative ease of installation, as well as mass production of the units.

The positive replies regarding acceptability are expressed in percentages of the total population. In order to compare the results of the three studies, the values were normalized using the same approach as the multi-attribute utility method (Dyer, 2005) (see Eq. (4)), and were then split into three value intervals of equal size: 0–0.33 ("low"), 0.34–0.67 ("medium"), 0.68–1 ("high").

$$acc(x_k) = x_k - x_{min}/x_{max} - x_{min} \tag{4}$$

where x_k is the public acceptability of resource k, x_{max} is the highest acceptability level out of all resources, and x_{min} the lowest acceptability level out of all resources.

Table 13 shows that all three studies provide the same ranking for the assessed generation technologies, but none of them provides a value for geothermal energy. Very few studies exist regarding public preference for geothermal energy (Upham, 2011). In order to evaluate this technology, we utilized the results of an Australian study (Dowd et al., 2011), which used a similar methodology with the three main studies. We also utilized an analysis performed on the population of Istanbul (Erbil, 2011), which used a different methodology compared to the others. Both studies place geothermal energy in the upper end of the middle interval. Thus, the classification for this technology type is "medium".

3.1.10. External supply risk

A key motivating factor in the development of the EU energy policies is energy security. Energy security requires that, at any given time, there is sufficient energy on the market as to satisfy all existing demand at a reasonable price. Given that much of Europe is importing fuels for its energy needs from several politically unstable regions, a relevant level of supply risk exists. Market shocks, such as those resulting from disputes between Russia and various transit countries for natural gas, have a disruptive effect on the economic development and the quality of life in European countries. This is why external supply risk needs to be taken into consideration when assessing the sustainability of electricity generation technologies.

There are numerous papers on the topic of energy dependence and security of supply (de Jong et al., 2006; Gupta, 2008; Kruyt et al., 2009; Löschel et al., 2010). Out of these, the methodology and research results of Le Coq and Paltseva (2009) were used to valuate this indicator. This study was primarily chosen because it assessed various fuel types separately. The paper also distinguishes itself by using a series of measures for risk assessment (e.g. supplier diversification, transit risk, fungibility of supply etc.), while most others simply focus on import dependence.

Le Coq and Paltseva only provide indicator values for coal, natural gas and oil. In order to have a complete assessment of the chosen technologies, we needed to calculate the indicator value for nuclear energy using the same methodology. In order to insure data compatibility, we used information regarding the import and production of nuclear fuel in 2006. There are slight differences between our approach and that used in the reference paper: due to limited data availability (ESA, 2007) we calculated the indicator for the entire European Union directly (as opposed to doing it at a

Table 12
Studies used to assess social acceptability.

Published by	Year	Population surveyed	Total respondents	Question analyzed[a]
Eurobarometer	2007	EU-25	24,815	Are you in favour or opposed to the use of…? ("in favour")
Michael Greenberg	2009	USA	2,701	Do you favour an increase or decrease in reliance on …? ("increase")
Ipsos Public Affairs	2010	23 countries from: North and South America, Asia, Europe and Australia	23,000	"… is an energy source I trust" ("slightly/well above average")

[a] The analysis will take into consideration the positive answers (written between brackets) regarding acceptability.

Table 13
Social acceptability levels.

Technology	Euro-barometer	Greenberg	Ipsos	Values
Solar PV	High	High	High	High
Solar thermal[a]	High	High	High	High
Wind (onshore)	High	High	High	High
Wind (offshore)[a]	High	High	High	High
Hydro (large)	High	High	High	High
Hydro (small)[a]	High	High	High	High
Geothermal	–	–	–	Medium
Biomass	Medium	–	–[b]	Medium
Natural gas	Medium	Medium	Medium	Medium
CHP[c]	Low	Low	Low	Low
Piston engine	Low	Low	Low	Low
Coal	Low	Low	Low	Low
Nuclear	Low	Low	Low	Low
Fuel cell[d]	–	–	–	–

[a] Technologies using the same resource are not assessed separately.
[b] The Ipsos study refers to bio-fuels as an energy source, which are different from biomass as an electricity generation source.
[c] Average of natural gas and coal values.
[d] No data available.

country level first and then using the average value). Consequently, we used the geographical centre of the EU-25 to calculate transit distances (as opposed to using national capitals as a reference point) (IGN, 2007). Finally, we calculated political risk as an average of the "institutions" and "goods market efficiency" assessed by the World Economic Forum, which include similar components to the PRS risk index used by Le Coq and Paltseva (PRS Group, 2013; World Economic Forum, 2012). The resulting value of 1.8 places nuclear energy at a similar level to coal. Its main advantages over other fuels are supplier diversity, fungibility of supply and the political stability of suppliers, but it is negatively affected by the EU's high import dependency of nearly 98%.

External supply risk for biomass is assumed to be null. This is because, in general, the shipment of biomass fuels over large distances is not economically feasible (Breeze, 2005), resulting in a net import dependency ≈ 0. All other technologies do not rely on imported fuels, making the external supply risk also null (Table 14).

3.1.11. Resolving the issues of missing data and alternative valuation approaches

The values obtained for several indicators offer various alternatives for the calculation of the numerical utility score. This subsection will explain which approach was used for each of these indicators (see Table 15) and also clarify any ambiguity regarding the score assigned to technologies with missing data values.

Due to limited data availability, the "geothermal", "piston engine" and "fuel cell" technologies were not scored on all indicators. In each case, a qualitative evaluation was conducted, which is presented in more detail in the table notes for each indicator. In the case of the "geothermal" technology, we have assigned the estimative values 0.75 and 4.25 respectively for the indicators presented in Sections 3.1.6 and 3.1.7 (the two external cost indicators). The "piston engine" was rated with 1 for "land use" and 0.13 for "job creation". The use of such estimations is not uncommon when researching energy sustainability (Genoud and Lesourd, 2009). If these estimative values would not have been assigned, the two technologies could not have been included in the sustainability ranking.

Recent market research reports estimate that the global installed base of hydrogen fuel cells could reach 4.5 GW in 2017 or 5.9 GW in 2030 (Navigant Research, 2012; Lux Research 2013), representing less than 0.1% of global installed capacity for electricity generation (EIA, 2013). Due to the high number of missing values and considering that the technology still has a limited impact on global electricity generation, the hydrogen fuel cell was excluded from the ranking.

3.2. Weighting of the sustainability indicators

After providing scores for the selected technologies across the ten sustainability indicators, the next step in the MCDA was to assign a weight to each indicator based on its perceived importance. After conducting the survey on academics from the fields of energy and environmental studies according to the methodology described in Section 2.3, we calculated the weights (Table 16).

Table 16 shows that the indicators perceived by our respondents to be most important were LCOE and efficiency, followed by the ability to respond to demand. The indicator perceived to be least important was social acceptability, followed by job creation and land use.

3.3. Sustainability ranking of the electricity generation technologies

The final step of our analysis – ranking the selected technologies based on their compatibility with sustainable development – was done using the methodology presented in Section 2.4.

An alternate approach would have been to obtain an intermediate utility score for each of the four dimensions using equal weighting for the indicators. The actual weights would then be

Table 14
External supply risk.

Technology	Values	Technology	Values
Natural gas	9.8	Wind (onshore)	0
CHP[a]	5.7	Wind (offshore)	0
Piston engine	4.4	Solar PV	0
Nuclear	1.8	Solar thermal	0
Coal	1.6	Hydro (large)	0
Biomass	0	Hydro (small)	0
Geothermal	0	Fuel cell[b]	–

Adapted from: Le Coq and Paltseva (2009).
[a] Average of natural gas and coal values.
[b] No data available.

Table 15
Chosen numerical valuation approaches.

Indicator	Valuation approach
LCOE	• We used the 5% discount rate data • This level is better suited for developed countries (which represent the geographical context for several indicator scores)
Ability to respond to demand	• "Yes, rapid" = 1; "yes, slow" = 0.5; "no" = 0 • Values chosen based on the perceived usefulness of the ability to respond • Values fit naturally with the utility method
External costs (environmental) External costs (human health)	• Maximum cost values were used for each technology • These values allow for a clearer comparison • The minimum values or an estimative average level could create ambiguity
Social acceptability	• "High" = 1; "medium" = 0.5; "low" = 0 • Values fit naturally with the utility method: same normalized values would result from any three level score with equal distances

Table 16
Sustainability indicator weights.

Indicator (section)	3.1.1	3.1.2	3.1.3	3.1.4	3.1.5	3.1.6	3.1.7	3.1.8	3.1.9	3.1.10
Weight	0.114	0.112	0.114	0.097	0.088	0.109	0.110	0.082	0.076	0.099

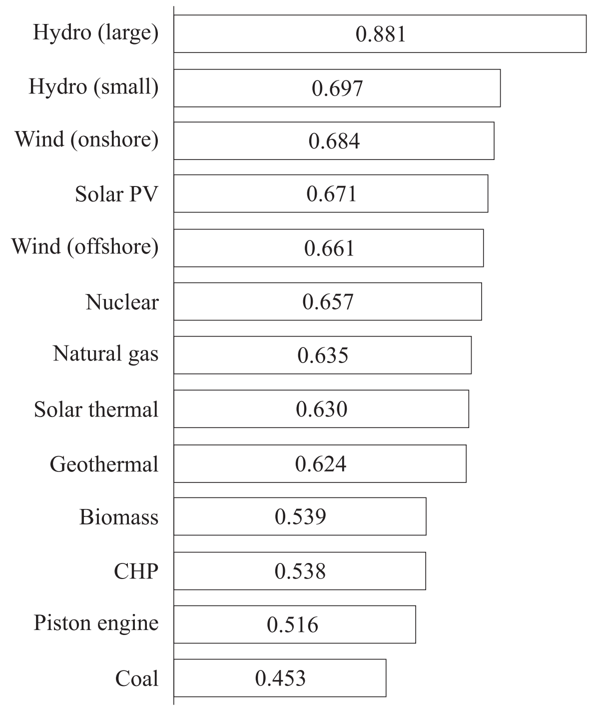

Fig. 2. Sustainability ranking of the electricity generation technologies.

assigned at a dimension level before summing up the intermediate utilities. This approach would have allowed indicators such as LCOE to gain a more significant impact on the total utility score, while the individual effect of indicators such as Sections 3.1.7–3.1.10 would have been reduced. However, this method could have confused respondents as to what each dimension actually refers to. We believe that the adapted SWING weighting method, which allowed respondents to rate each indicator individually, was better suited for our research goal.

The overall sustainability ranking based on the total utility scores is illustrated in Fig. 2.

As seen in Fig. 2, the large hydroelectric technology significantly outranks all other alternatives from an overall sustainability point of view. The next most sustainable technologies are small hydro and onshore wind followed by solar PV and offshore wind. Nuclear and natural gas are ranked above several less widespread renewable energy technologies. Biomass is the lowest ranked among renewables, with a score very close to that of CHP. The coal and piston engine generation technologies are ranked lowest.

4. Discussion

The discussion will first provide more detail regarding the results of the MCDA analysis. We will then compare our own results with those of past research on the subject and explore some of the implications of our sustainability ranking.

Fig. 2 shows that biomass has the lowest score out of all the other renewable energy technologies. This is mainly due to the high externalities and the large land surface used by such projects. In addition, biomass and geothermal are the only renewable energy technologies classified as "medium" with regard to social acceptability.

Natural gas and nuclear plants are ranked highest among all non-renewables, surpassing even technologies such as geothermal and solar thermal. Their sustainability scores are in line with the recent "repositioning" of these sources as low carbon alternatives to other traditional generation technologies (IEA, 2012a).

The purpose of any such study is to provide guidance to decision makers. In order to support the sustainable development of society, political leaders should promote energy policies that encourage investors to opt for those generation technologies ranked at the top of the utility scale. Global industry outlooks show that this may indeed be the case, with 50% of production capacity additions by 2035 forecasted to be from renewable energy projects. This growth is expected to come primarily from wind, followed closely by hydroelectricity and then by solar PV (IEA, 2012a).

Large hydroelectric is the technology rated highest in our sustainability ranking. The development of projects using this application has several benefits: a free renewable fuel source, production flexibility, low LCOE and synergy opportunities with irrigation and entertainment projects. One of the problems of large hydroelectricity is that most developed economies in Europe and North America have already constructed such projects in those locations deemed most technologically feasible and economically viable (IPCC, 2011). This translates to limited undeveloped potential and increased marginal costs. The highest increase in hydro generating capacity is expected to originate from non-OECD countries, where 42% of renewable energy growth will result from such projects (IEA, 2012a). However, in spite of having greater unexploited hydroelectric potential, developing economies may find the high investment cost to be prohibitive, as is the case with several African nations (IEA, 2012a).

This technology type has also gained a negative reputation over the last decades, so much so that large hydro projects were, in some cases, not even classified as renewable energy (Breeze, 2005). Any mass rejection of this technology by public opinion can put additional pressure on elected governments to avoid the development of such projects. But recent research, has repeatedly argued in favour of the responsible development of hydroelectricity as a clean, sustainable energy source, which also indirectly benefits local economies (Liu et al., 2013; Yüksel, 2008).

Several energy sustainability studies also rate hydroelectricity, large hydroelectric projects in particular, as the most sustainable electricity generation technology (Afgan and Carvalho, 2002; Chatzimouratidis and Pilavachi, 2009; Genoud and Lesourd, 2009). However, the sustainability ranking beyond that is different for every study. These dissimilarities generally arise from the use of different indicators and weighting methods. For example, the study of Genoud and Lesourd (2009) uses close to 20 indicators and assigns equal weights in the calculation, while Chatzimouratidis and Pilavachi (2009) use 9 indicators and assign a 55.5% weight to the less commonly used "reserves-to-production ratio".

We believe that our approach is more robust and better suited for such an assessment. Where available, we opted for widely accepted aggregate indicators which provide a more complete evaluation of issues such as pollution or costs. The values used for all other indicators were verified across multiple studies to insure consistency. In addition, we also opted for a weighting method based on a survey of energy experts. This is likely the first study of its kind to implement such a methodology on a diverse sample of Romanian academics.

The large number of similar studies with diverging results means that we cannot guarantee that this is the ideal approach for the topic. The issue that we mentioned in the introduction, regarding the lack of a stable and widely accepted methodology for this type of research, has a clear impact on the comparability of similar studies.

Finally, such hierarchies are only useful as long as decision makers take them into consideration when designing and implementing various energy policies. Unfortunately, governmental authorities also have to take into consideration other factors, such as the support of domestic industries. A relevant example is that of the US, where the classification of natural gas as a “clean energy” type, along with renewables, has allowed the industry to flourish (IEA, 2012a), especially in the context of a steady increase in shale gas extraction. Another example is that of China, which saw rapid growth in its wind turbine and solar cell manufacturing capacity. Chinese authorities recently made an upward revision of their plans to develop new wind and solar PV generation capacity (IEA, 2012a). It is likely that this change was at least partially motivated by the relatively sudden drop in demand for such equipment in the EU and across the world.

5. Conclusions

Our study aimed to provide a comprehensive sustainability assessment of a diverse set of electricity generating technologies using multi-criteria decision analysis. As opposed to previous work, which generally analysed a more high-level set of applications or focused only on a certain category (e.g. renewables), we provide a raking of thirteen technology types. We aimed to increase the robustness of the study by using widely accepted aggregate indicators for issues such as costs and pollution. We also used an adapted version of the SWING method for the weighting of the sustainability indicators in what may be the first such survey of Romanian academics from the fields of energy and environmental science.

Our findings rank hydroelectric, onshore wind and solar PV as the most sustainable generation technologies. The weighting approach and MCDA analysis can serve as an example for future researchers of this topic, while the results themselves can provide argumentation for future energy policies.

Indicator values tend to vary among different locations (e.g. continents). Similarly, the importance weights may also vary among academics from different countries. Thus, the research can be further improved by providing geographically specific analyses. Another improvement is possible with regard to indicator valuation. Values for certain indicators, external costs in particular, could be updated based on more recent or emerging research. The inclusion of missing or specific data for technology types such as CHP and hydrogen fuel-cells would also enhance the quality of the analysis.

Setting the energy sector on a sustainable development path is imperative in the long term. Although the political environment generally functions in a conjectural and tactical manner, such research can provide guidance for decision makers to act in a more structured and strategic way. It is our hope that world governments will commit themselves to pursuing sustainable development before a proverbial point of no return is reached.

Appendix A

Q1: How familiar are you with the issues concerning the electricity sector? (1—not at all familiar, 10—very familiar)

Q2: In order to rank the different electricity generation technologies from the point of view of their compatibility with humanity's sustainable development (economic, social and environmental), we identified a series of sustainability indicators. Please give a score from 1 to 10 for each indicator (1—not at all important, 10—very important), depending on the importance that you consider it has for humanity's long term development.

Indicator	Score
Cost—investment, operation and maintenance, fuel and decommissioning	
Ability to respond to demand—the ability and the time required to respond to grid demand; a shorter response time means that the technology can be used for grid balancing, while inability (e.g. in the case of wind energy) creates grid instability	
Efficiency—the efficiency with which input energy (e.g. chemical energy extracted from fuels) is transformed into useful output energy (i.e. electricity and useful heat)	
Capacity factor—the efficiency with which a unit's generation capacity is used, calculated as a ratio between actual output and maximum theoretical output	
Land use—the use of land over the entire life cycle (fuel extraction, processing and delivery, construction, operation and decommissioning)	
External costs (environmental)—costs which the production of electricity creates by polluting the environment (e.g. the cost to clean-up dust or to decontaminate crop fields)	
External costs (human health)—costs which the production of electricity creates by affecting health (e.g. the cost of treatment for respiratory illnesses)	
Job creation—the number of people hired during the implementation and operation of an electricity generation project	
Social acceptability—the measure in which the public agrees with the development of electricity production using various technologies	
External supply risk—characteristic for fossil fuel and nuclear energy; it represents the risk that fuel supply will be perturbed due to supplier or transit issues	

Q3: Gender
Q4: Academic rank
Q5: City of residence
Q6: Academic institution

Appendix B

Impact category	Pollutant/ Burden	Effects
Human health—mortality	PM_{10}, SO_2, NO_x, O_3	Reduction in life expectancy
	Volatile organic compounds	Cancers
	Noise	Loss of amenity, impact on health

	Accident risk	Fatality risk from traffic and workplace accidents
Human health—morbidity	PM_{10}, SO_2, O_3	Respiratory hospital admissions
	PM_{10}, O_3	Restricted activity days
	PM_{10}, CO	Congestive heart failure
	Volatile organic compounds	Cancer risk (non-fatal)
	PM_{10}	Cerebro-vascular and respiratory hospital admissions and symptoms
	O_3	Asthma attacks; Symptom days
	Noise	Myocardial infarction; Angina pectoris; Hypertension; Sleep disturbance
	Accident risk	Risk of injuries from traffic and workplace accidents
Building material	SO_2 Acid deposition	Ageing of galvanised steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings
	Combustion particles	Soiling of buildings
Crops	SO_2, NO_x	Yield change for wheat, barley, rye, oats, potato, sugar beet
	O_3	Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed
	Acid deposition	Increased need for liming
Global warming	CO_2, CH_4, N_2O, N, S	World-wide effects on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise
Amenity losses	Noise	Amenity losses due to noise exposure
Ecosystems	Acid deposition, nitrogen deposition	Acidity and eutrophication (avoidance costs for reducing areas where critical loads are exceeded)

Adapted from: European Commission (2003)

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