A proposed indicator framework for sustainability assessment of energy generation technologies

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Abstract: Renewable-based and distributed energy generation technologies seem to be the solution in the battle against CO_2-emission and energy-dependency in the energy policy of the EU. In spite of the intensive research and regulatory efforts, sustainability advantages of renewable energy sources and distributed technologies over traditional, centralized plants are not justified. This paper attempts to propose an indicator system based on the relevant international literature and by using a Weighted Sum Method methodology for the comparison of the main power generation technology groups and an expert-based weighting of indicators, the sustainability ranking of main power generation technology groups is also elaborated.

Key-Words: sustainable development, electricity generations technologies indicator system, decision model, Guilford pairwise comparison

1 Introduction

Nowadays it has become something of a commonplace that the operation, structure, and impacts of the power system are inconsistent with the goals of sustainable development. Major problems associated with the operation and structural issues of the current power system encompass the extensive use of non-renewable energy and material resources, the high environmental impact pollution of large-scale, fossil fuel-based conventional technologies, inter- and intragenerational inequalities regarding the access to electricity supply, or the ideological basis concealed behind decision-making and system operation processes. In the relevant empirical and theoretical research studies, and policy agendas, two potential solutions – the enhancement of energy-efficiency measures, and the support of the diffusion of distributed electricity generation technologies - are identified by which these aforementioned obstacles and weaknesses can be moderated, minimized or even terminated.

However, in order to define renewable-based power plants and distributed energy generation technologies as the most favorable power generation technologies in terms of sustainability, it should be confirmed that compared to conventional, large-scale electricity generation technologies these types of power generation technologies can have positive social, environmental and economic impacts.

The goal of this paper is to present the sustainability ranking of power generation technology groups based on a multi-criteria decision-making analysis approach and the sustainability indicator framework of electricity generation technologies elaborated by the author.

2. Sustainability indicator system for energy generation technologies

2.1 Comparison of sustainability indicators based on literature survey on past experience

Taking into account the main elements, dimensions and goals of sustainable development sustainable electricity system can be defined as a power system which can guarantee clean, safe, reliable and sufficient electricity supply without the exclusion of anyone, in a socially acceptable manner, at a reasonable price. The power system is a complex system that interacts directly or indirectly with its environment and all systems and subsystems, through its economic, social and environmental impacts due to its operational processes. Identifying the most appropriate electricity generation technologies that best fit to the needs, principles, and goals of sustainable development requires the simultaneous assessment of social, environmental and economic aspects, consequently, sustainability evaluation of power generation technologies depends on a number of economic, environmental, social and technological parameters (Deutsch, 2009: 368). Furthermore, considered impacts may reflect to the knowledge, opinions and preference orders perceived by the members of the society (Berényi, 2015).

Although several types of indicator systems had been elaborated, there is no widely accepted framework for the assessment of the relative sustainability of power generation technologies. Most of the frameworks (e.g. Yang & Chen 2016; Evans et al. 2016; Chong et al. 2016) deal with the relative sustainability ranking of a given generation technology group and/or the related supply chain (see Voß et al. 2005; Volkart et al. 2016), while some frameworks attempt to conceptualize the complexity of sustainability and to serve as a general sustainability indicator system for the assessment of relative sustainability of power generation technologies. In this Chapter, nine of these latter type of indicator systems will be presented in details.

The structure, composition, and granularity of sustainability indicator systems vary significantly among the studies being analyzed. While Evans 2009), Burton & Hubacek (2007), Afgan et al (2000; 2007), Begic & Afgan (2007) and Gwo-Hshiung et al (1992) use relative few indicators in order to guarantee transparency and to facilitate the collection of data, sustainable indicator systems for the relative assessment of electricity generation technologies developed by PSI (2006), NEEDS (2008) Madlener & Stagl (2005), and Deutsch (2009) are made up of a number of indicators guided by the intention to ensure a more careful and prudent examination. Significant differences are found between the structure and composition of indicator systems. Unlike PSI (2006) and NEEDS (2008), Evans et al (2009), Burton & Hubacek (2007), and Madlener & Stagl (2005) do not classify their indicators explicitly according to the main dimensions (economic, social and environmental) of sustainable development. In the work of Afgan et al (2000; 2007) and Begic & Afgan (2007) LCA-based resource requirements of generation technologies creates an separate dimension while in the frameworks developed by Gwo-Hshiung et al. (1992) and Deutsch (2009) engineering or technological attributes of power generation are classified to a sperate criterion. The composition of sustainable dimensions are far from uniform, indeed, indicators elaborated and used by the authors are not able to cover all the related issues of sustainability. While Afgan et al. (2000, 2007) and Begic & Afgan (2007) stress the importance of the social impacts of power generation technologies, these studies focus exclusively on the job creation potentials of these technologies. Gwo-Hshiung et al (1992) stress the importance of security of supply, possibility of replacing oil energy, popularity of use and the impacts of related industries, others (see PSI 2006, Deutsch, 2009; NEEDS 2008) agree that the indicators reflecting the potential impacts of generation technologies on human health, local infrastructure, and economic development, noise exposure, visual destruction, operational risks, conflicts associated with technologies, educational requirements and the necessity of participatory decision-making processes have a significant but varying degree of weight. The composition of the indicators of economic sustainability of electricity generation technologies differs by research studies. While some authors (see Gwo-Hshiung et al 1992) stress the importance of production costs, development costs, duration of construction, and annual volume of production, others (see PSI 2006; NEEDS 2008) supplement the list of investment costs, operation and maintenance costs, construction time with the specific engineering or technical indicators (e.g. security of supply, availability, load factor, fuel price increase sensitivity, peak load response, etc.). In the study of Gwo-Hshiung et al (1992) and Deutsch (2009), these latter indicators are classified as engineering or technical indicators emphasizing that security and quality of supply is one of the most important strategic aspects of power systems. In the sustainability indicator framework elaborated by NEEDS (2008) indicators of the impact on the overall economy, i.e. the job creation potentials of generation technologies, the independence from foreign energy sources and the risks exposure of fuel price fluctuations were also allocated to this category.

One of the most frequently utilized sub-criterion of environmental sustainability for the sustainability assessment of electricity generation technologies is the global warming potentials of electricity generation technologies. In addition to air pollution, Gwo-Hshiung et al. (1992) emphasize the importance of the indicators of soil pollution, water pollution, and scenic impacts, while in the study of PSI (2006) indicators of regional environmental impact such as the change on unprotected eco-system area, mortality, land requirements of generation technologies, and solid waste generation are classified into this group of indicators. These indicators are also presented in the environmental sustainability criterion defined by Deutsch (2009). Indicators of environmental sustainability developed by the NEEDS project (2008) include the indicators of energy- and material requirements, acidification potentials, eutrophication potentials, ecotoxicity of specific electricity generation technologies and stress the importance of indicators associated with the environmental impacts of radioactivity. It is worth to mention that with the exception of the model developed by Madlener & Stagl (2005) – indicators of environmental sustainability of the indicator systems being analyzed are defined for the total lifecycle of technologies.

2.2. Establishment of the proposed criterions and indicators

In order to eliminate the shortcomings of prior sustainable indicator frameworks presented in Chapter 2.2 and to synthesize the different views and indicators of special issues, based on the requirements of sustainable development, a new sustainability assessment framework was elaborated. Selection of sustainability criterions and indicators were made with the aim of ensuring the comprehensiveness, coherence, and manageability of the analysis and the availability of data i.e. the set of indicators reflects that only current technologies have been considered. Accordingly, the resulted indicatory system contains the four criterions of economic, social, environmental and technical sustainability and 34 indicators.

Engineering or technical dimension of sustainability encompasses the operational efficiency (electric and cogeneration efficiency) of generation technologies, their net energy production potentials (energy payback ratio), the maturity of technologies, and the different aspects associated with the security and the quality of supply (availability, flexibility of dispatch, system balancing, reserve capacity, additional balancing needs, load management capabilities).

Indicators of economic sustainability contains the main indicators reflecting the economic impacts associated with the investments and operation of technologies. Impacts of electricity generation technologies on customers are evaluated by the average flat cost of electricity generation instead of the use of electricity prices since this approach allows ignoring the service- and regulatory-related elements of electricity prices. Risks of operators of technologies are measured by the variables of specific investment costs, construction time and the independence of technologies from fuel prices. Impacts on the overall economy are expressed through the direct job creation potentials of power generation plant, the specific external costs of generation technologies, and the independence of technologies from foreign fuels.

Indicators of environmental sustainability are defined in terms of total life-cycle of the technologies. Environmental impacts of technologies on a global scale are characterized and measured by the global warming potentials of technologies, while on regional and local scale acidification and eutrophication potentials, waste management requirements, photochemical smog potentials, and NMVOCs potentials. Indicators of expected health effects of the normal operation and functional damage to the landscape as indirect effects are also incorporated.

Social acceptance of electricity generation technologies and the social impacts of electricity generation technologies on local communities encompass the potential impacts of generation technologies on the quality of life (e.g. specific land requirements, noise exposure and visual destruction), the social and individual risk-taking and management requirements associated with the different generation technologies (risk aversion, personal control of risks, catastrophic potential, educational requirements), and the indicators of social acceptance and legitimation of electricity generation technologies (local resistance, necessity of participative decision-making, familiarity). Due to the fact that indicators of local impacts, such as local income generation potentials, impacts on the local infrastructural development, migration, and local industry development potentials of electricity generation technologies are highly project dependent and difficult to generalized, these impacts are not incorporated into the model.

It is also worth to mention that theoretical and empirical studies (e.g. Zhou et al. 2006; Szántó 2012; Azzopardi et al. 2013; Al Garni et al. 2016; Singh & Nachtnebel 2016; Volkart et al. 2016) dealing with the sustainability assessment of electricity generation technologies stress that while in the case of single objective decision making (SODM) only economic efficiency and monetary-based preference can be (Covello 1987) obtained, multi-criteria decision analysis (MCDA) supports the evaluation of technologies according to different variables and criteria. The most commonly used approaches are the Analytical Hierarchy Process (AHP), the so-called outranking (e.g. ELECTRE and PROMETHEE) methods, and finally the multi-attribute decision-making methods (MAUT). Fig 1 summarizes the main aspects of MAU, AHP and Outranking methods. Despite the fact that these approaches support the use of quantitative and qualitative indicators and incorporate the individual preferences of the decision makers, i.e. value systems of decision makers can be explored through the weighting and scoring mechanisms, repeatability and reproducibility of the results are questionable.

Fig 1: Decision methodologies and models used for sustainability assessments

	MAU	AHP	Outranking
Numer of alternatives	No upper limit		
Number of criteria	No upper limit, however the increasing number of criteria can cause problem in weightining	No upper limit, however pairwise comparison of weights and alternatives increases complexity	ELEKTRE: No upper limit, but additional criteria can reverse the ranking PROMETHE :Supported
Use of qualitative and quantitatve data	Possible, but qualitative measures must be assigned a value	Possible, but qualitative measures must be assigned a value	ELEKTRE: Partly possible PROMETHE: Open for qualitative scales, distances can only be defined between values
Defining weights	Number of methods	Possible - pairwise comparision	ELEKTRE: Weights can be treated as the relative importance of criteria PROMETHE: Possible, increasing number of criteria can cause problem
Use of hierarchies	Possible	Possible	ELEKTRE, PROMETHE: not possible
Critical tresholds	Not possible	Not possible	ELEKTRE: Aveto tresholds obstructs compensation PROMETHE: Partial compensation
Kompenzációs képesség	Full compensation	Full compensation	ELEKTRE: three thresholds PROMETHE: advanced treshold-analysis
Support of group decision making	Yes, Aggregation is easy	Yes,both in the definition of weights and in the assessment of alternatives	ELEKTRE, PROMETHE: External aggregation is needed

Source: own edition, based on Szántó (2012)

Based on these findings in relation to the sustainability assessment framework applicable for power generation technologies (see Appendix 1), and the type of decision models in the following Chapter the relative sustainability ranking of main power generation technology groups will be presented.

3. Relative sustainability ranking of electricity generation technologies

3.1. Data and method

In order to define the relative sustainability rank of different electricity generation technologies, an MS Excel-based model is created by using the Weighted Sum Method and the Sustainable Indicator System presented in Chapter 2.2. According to Pohekar et al. (2004:369), this is the most commonly used, easiest approach that defines the best alternative which satisfies the following expression:

$$A^{*}_{WSM} = MAX \sum_{i}^{j} a_{ij} w_{ij} \text{ for i=1,2,3,…M, where} \quad (1)$$

A^{*}_{WSN} = WSM score of the best alternative
M=number of alternatives
N= number of criteria
a_{ij}= actual value of the th alternative in terms of the j th criterion
w_j = weight of importance of the jth criterion

In the next step, based on the relevant and available international literature sources, average values for all indicators of economic, social, environmental and engineering sustainability are calculated by power generation technology groups. In order to guarantee the comparability of technologies and indicators, these average values are normalized to 0-1 interval by linear interpolation, where 0 represented the worst, 1 represented the best value.

In the third step, the weights of sub-indicators of economic, social, environmental and engineering sustainability are determined by the Guilford pairwise comparison methodology and expert interviews.

The last step of the process implies the calculation of individual sustainability scores of the given technology groups by summing up the multiplications of normalized values of each indicators and their overall weight coefficient.

3.2. Guilford methodology of pairwise comparison

Weights of indicators of economic, social, environmental and engineering sustainability were determined by the use of Guilford-method. Priorities or weights of the indicators presented in Chapter 2.2 were evaluated in a pairwise manner by 13 energy experts - from education, research and practice.

The main steps of the process of Guilford-pairwise comparison are the followings (Kindler & Papp, 1978:186-188):

1) Completing the hierarchy and structure of the decision model.
2) Creating the random list of indicators' pairs in order to avoid systemic errors and learning distortions.
3) Conducting expert interviews and pairwise comparison of indicators.
4) Compilation of individual preference matrices in order to calculate the consistency level of individual assessments.

Fig 2 illustrates the structure of the individual preference matrices elaborated by the 13 experts.

Fig. 2: Example of an individual preference matrix

Technical	1	2	3	4	5	6	7	8	9	10	a	a2		
1		0	1	0	0	1	0	0	0	0	2	4	Dmax=	40
2	1		1	1	0	1	1	0	0	0	5	25	D=	3
3	0	0		1	0	1	0	0	0	0	2	4	K=	92.5
4	1	0	0		0	1	0	0	0	0	2	4		
5	1	1	1	1		1	1	0	0	0	6	36		
6	0	0	0	0	0		0	0	0	0	0	0		
7	1	0	1	1	0	1		0	0	1	5	25		
8	1	1	1	1	1	1	1		1	1	9	81		
9	1	1	1	1	1	1	1	0		1	8	64		
10	1	1	1	1	1	1	0	0	0		6	36		
Sum	7	4	7	7	3	9	4	0	1	3	45	279		

Source: own calculation

5) Assessment of the consistency level of each individual preferences in order to eliminate inconsistent expert preferences. The number of inconsistent decisions can be determined by the following equation

$$d=\frac{n(n-1)(2n-1)}{12}-\frac{\sum a^2}{2}\text{, where} \quad (2)$$

a=frequency of preferences
n = number of functions.

The maximum value of coefficient of concordance is 1, while the minimum is not fixed, it depends on the number of cases and determined according to the next equation

$$K=\left(1-\frac{d}{d_{\max}}\right)\cdot 100\text{, where} \quad (3)$$

d_{max}= maximum value of triads.

Determination of d_{max} depends on the number of cases, i.e. if "n" is an even number expression (4), if "n" is an odd number, expression (5) should be used.

$$d_{\max}=\frac{n^3-4n}{24}; \quad (4)$$

$$d_{\max}=\frac{n^3-n}{24}; \quad (5)$$

Calculation of frequency of preference is based on the following formula

$$P_a=\frac{a+\frac{m}{2}}{n\cdot m}\text{, where} \quad (6)$$

P_a = frequency of preference
m = number of decision-makers

Due to the fact that the average values of consistency levels of individual assessments in all criterions (economic: 95% social: 95.1%, environmental: 95.0%, technical: 87.5%) exceeded 70%, aggregated preference matrices can be created.

6) Creation of aggregated preference matrix based on the consistent individual preference tables (i.e. K≥0.70).
7) Calculation of group level consensus by Kendall's coefficient of concordance for pairwise comparison (ν) by using the following equation (Kendall, 1970):

$$\nu=\frac{2G}{-\binom{m}{2}\binom{n}{2}}-1\text{, where} \quad (7)$$

$$V_{max}=-\frac{1}{m-1}.$$

V_{min}= 1

The significance test of group level consensus is as follows (Kindler & Papp 1978:187):

$$\mu=\sqrt{2\omega^2}-\sqrt{2df-1}\text{, where} \quad (8)$$

where γ represents the sum of values below the main diagonal in the aggregated preference matrix, i.e. the number of non-preferred incidences; n is the number of factors and χ^2, d_f are determined as follows:

$$\omega^2=\frac{4}{m-2}\cdot\left\{G-\frac{1}{2}\binom{n}{2}\binom{m}{2}\cdot\frac{m-3}{m-2}\right\} \quad (9)$$

$$df=\binom{n}{2}\cdot\frac{m(m-1)}{(m-2)^2} \quad (10)$$

8) Transformation of preference rates (Pa) to U values according to the standard normalized distribution.
9) Transformation of U scores to interval scale by using the following formula:

$$Z=\frac{U_i-(U_{\min})}{U_{\max}-U_{\min}}\cdot 100\text{, where} \quad (11)$$

Z = scale value
$U_{min} \rightarrow Z_{min} = 0$
$U_{max} \rightarrow Z_{max} = 100$

10) Linear transformation of Z scores by the next equation in order to weights sum to 1.
f(x)=ax+b, where (12)
a≠0; a, b= constant

In order to validate the analysis Fig. 3 illustrates the aggregated preference matrix and the final weights of technical indicators.

Fig. 3: Example of Aggregated matrix and the weights of technical/engineering indicators

Technical	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	a	a2	p	u	z	w
E1		8	7	9	8	12	10	9	8	7	78	6084	0.65	0.39	0.95	16.87
E2	5		6	9	8	9	6	10	7	6	66	4356	0.56	0.15	0.68	12.59
E3	6	7		9	10	9	10	10	10	9	80	6400	0.67	0.43	1.00	17.62
E4	4	4	4		5	5	4	7	6	4	43	1849	0.38	-0.30	0.17	4.59
E5	5	5	3	8		6	6	8	2	3	46	2116	0.40	-0.24	0.23	5.66
E6	1	4	4	8	7		5	8	5	6	48	2304	0.42	-0.20	0.28	6.36
E7	3	7	3	9	7	8		10	7	8	62	3844	0.53	0.07	0.59	11.21
E8	4	3	3	6	5	5	3		2	5	36	1296	0.33	-0.45	0.00	2.00
E9	5	6	3	7	11	8	6	11		7	64	4096	0.54	0.11	0.63	11.90
E10	6	7	4	9	10	7	5	8	6		62	3844	0.53	0.07	0.59	11.21
Sum	39	51	37	74	71	69	55	81	53	55	585	36189	5.00	0.00	5.12	100.00
n:	10		b:	2		Kat	87.5	y	260		G	2644			u	16.889478
m:	13		a:	15.6				y2	1734		v	0.5065527			df	58.016529
															w2	381.28926

Source: own calculation

3.3. Results

By using the results of expert interviews, Weighted Sum Method was applied to determine the relative sustainability rank of each electricity generation technology. Fig. 5 illustrates the results of the baseline analysis representing the approach of sustainable development, where the weights of the four main criterions of sustainability - i.e. economic, social, environmental and engineering sustainability – are equal ($w_1=w_2=w_3=w_4=25\%$).

Fig. 5: Sustainability rank of electricity generation technology groups – baseline concept

Electricity generation technology	I. (w1=w2=w3=w4)	
Group names	**Value**	**Rank**
Run-of-the-river hydropower	**15,86**	**1**
Nuclear power plant	58,36	19
Biomass based power plant	44,13	14
External combustion engine (CHP)	33,23	6
Back-pressure turbine (CHP)	34,20	8
CCGT (CHP)	34,93	10
Geothermal power plant	44,22	15
Small-scale hydropower	**18,00**	**2**
Condensating turbine (CHP)	32,23	4
Conventional gas	52,00	16
Conventional coal	62,87	20
Microturbine (CHP)	32,75	5
Photovoltaic systems	37,76	12
Conventonal oil	55,77	18
Internal combustion engine CHP	34,90	9
Wind turbines	43,02	13
IGCC coal-based	54,31	17
Solar-thermic systems	33,57	7
Pumped-and-storage hydropower	**21,73**	**3**
Fuel-cell (CHP)	35,17	11

*w_1: Economic sustainability, w_2: Engineering sustainability, w_3: Social sustainability, w_4: Environmental sustainability

Source: own calculations

It can be concluded that the best alternatives that satisfy the equally defined sustainability criteria are large-scale hydropower plants, large.-scale run-of-river hydropower plants and small-scale hydropower plants. These technology groups are closely followed by small-scale CHP (i.e. combined heat and power) plants, solar thermal and photovoltaic technologies and wind power plants. Geothermal power stations and biomass-based combustion technologies are in the middle of the ranking. In this case, from a sustainability point of view large-scale, fossil-fuel based conventional combustion technologies and nuclear power plants are at the end of the line.

The „baseline" model was supplemented with four extreme approaches representing the dominantly economy-oriented (II. $w_1=70\%$,), the dominantly supply-oriented (III. $W_2=70\%$), the dominantly social-oriented (IV. $W_3=70\%$) and the dominantly environment-oriented (V. $w_4=70\%$) views.

Fig. 6: Sustainability rank of electricity generation technologies in the dominantly economy-oriented view

Electricity generation technology	II. w1=0,7 0,1=w2=w3=w4	
Group names	**Value**	**Rank**
Run-of-the-river hydropower	**11,87**	**1**
Nuclear power plant	53,87	15
Biomass based power plant	60,69	17
External combustion engine (CHP)	34,02	9
Back-pressure turbine (CHP)	36,55	11
CCGT (CHP)	34,81	8
Geothermal power plant	47,51	14
Small-scale hydropower	**15,59**	**3**
Condensating turbine (CHP)	35,76	10
Conventional gas	58,67	16
Conventional coal	68,71	20
Microturbine (CHP)	37,36	12
Photovoltaic systems	31,63	5
Conventonal oil	64,99	19
Internal combustion engine CHP	33,35	6
Wind turbines	35,30	9
IGCC coal-based	62,67	18
Solar-thermic systems	18,41	4
Pumped-and-storage hydropower	**14,94**	**2**
Fuel-cell (CHP)	40,64	13

*w_1: Economic sustainability, w_2: Engineering sustainability, w_3: Social sustainability, w_4: Environmental sustainability

Source: own calculations

Findings suggest that raising the weights of environmental and social dimensions resulted only in the modification of the order inside the clusters of distributed and large-scale electricity generation technologies, while the increase of the importance of economic and technical sustainability aspects brings surprising results.

Renewable-based electricity generation technologies and CHP plants received better ranking in the dominantly economic-oriented view than expected from prior studies (see Fig. 6). With the exception of large-scale hydropower technologies, due to the high uncertainties associated with the operational performance, repair and maintenance requirements and expected lifetime of renewable-based electricity generation technologies and cogeneration plants investments and O&M costs of these technologies are not competitive with the conventional solutions. However, operational costs of power plants and their impacts on the economic actors are affected by the unfavorable changes in fuel prices (e.g. oil and natural gas prices), the availability of fuels and the external costs of the given technologies. These unfavorable impacts can be avoided if the given power generation technology can switch easily to operate on other fuels if it is needed because of fuel shortages or fuel price increases. Operational performance of renewable-based electricity generation technologies depends on the availability of natural resources and weather conditions, operational and maintenance costs of these technology groups are independent of the price of fossil fuels. Although, in the case of biomass-based combustion technologies and CHP plants some fuel-type flexibility exists, it is difficult to convert these plants to operate on other fuels inducing high additional costs (Deutsch 2010).

Fig. 7: Sustainability rank of electricity generation technologies in the dominantly supply-oriented view

Electricity generation technology	III. w2=0,7 0,1=wG=wK=wT	
Group names	**Value**	**Rank**
Run-of-the-river hydropower	**16,04**	**1**
Nuclear power plant	50,1,6	15
Biomass based power plant	41,36	8
External combustion engine (CHP)	40,28	6
Back-pressure turbine (CHP)	47,92	13
CCGT (CHP)	36,08	4
Geothermal power plant	63,99	17
Small-scale hydropower	**22,75**	**3**
Condensating turbine (CHP)	41,38	9
Conventional gas	47,71	12
Conventional coal	51,96	16
Microturbine (CHP)	41,01	7
Photovoltaic systems	73,54	20
Conventonal oil	49,24	14
Internal combustion engine CHP	40,06	5
Wind turbines	71,05	19
IGCC coal-based	47,32	11
Solar-thermic systems	71,00	18
Pumped-and-storage hydropower	17,33	2
Fuel-cell (CHP)	44,26	10

*w_1: Economic sustainability, w_2: Engineering sustainability, w_3: Social sustainability, w_4: Environmental sustainability
Source: own calculations

Against the initial expectations based on prior research findings, raising the weight of the technical aspects to 70% (see Fig. 7) does not overthrow the order of the alternatives to the benefits of conventional large-scale fossil and nuclear power plants. Even in this case ranking is led by hydropower technologies followed by CHP stations, biomass-based combustion technologies, and large-scale fossil and nuclear power plants. At the end of the ranking geothermal power plants, wind turbines, photovoltaic and solar thermal systems are located. However, these results necessitate further explanation.

Fig. 8: Sustainability rank of electricity generation technologies in the dominantly social-oriented view

Electricity generation technology	IV. w3=0,7 0,1=wG=wE=wK	
Group names	**Value**	**Rank**
Run-of-the-river hydropower	**23,44**	**2**
Nuclear power plant	77,08	20
Biomass based power plant	40,49	14
External combustion engine (CHP)	24,48	4
Back-pressure turbine (CHP)	27,51	9
CCGT (CHP)	35,76	11
Geothermal power plant	38,74	12
Small-scale hydropower	**20,61**	**1**
Condensating turbine (CHP)	26,72	7
Conventional gas	49,35	16
Conventional coal	56,46	19
Microturbine (CHP)	26,93	8
Photovoltaic systems	25,95	6
Conventonal oil	50,86	17
Internal combustion engine CHP	25,60	5
Wind turbines	42,89	15
IGCC coal-based	51,46	18
Solar-thermic systems	**23,43**	**3**
Pumped-and-storage hydropower	39,99	13
Fuel-cell (CHP)	28,74	10

*w_1: Economic sustainability, w_2: Engineering sustainability, w_3: Social sustainability, w_4: Environmental sustainability
Source: own calculations

The majority of technologies falling into the category of distributed energy generation have much lower efficiency ratios than conventional electricity generation technologies. Furthermore, due to the intermittent nature of wind turbines and photovoltaic systems and their limited capabilities of contributing to the general load management, maintaining stability and uninterruptedness of electricity supply require high reserve capacity. Although conventional fossil-based technologies and nuclear power plants have favorable performance values regarding the indicators of security and quality of supply, energy payback ratios of these technology groups are much lower than those of distributed generation which cannot be compensated by their higher electric efficiency. With regard to availability and load management issues, biomass-based combustion technologies and CHP plants are similar to conventional large-scale generation technologies while the utilization of waste-heat is also economically feasible (Deutsch 2010).

Fig. 9: Sustainability rank of electricity generation technologies in the dominantly environmental-oriented view

Electricity generation technology	V. w4=0,7 0,1=wG=wE=wT	
Group names	Value	Rank
Run-of-the-river hydropower	**12,09**	**1**
Nuclear power plant	53,33	17
Biomass based power plant	33,98	13
External combustion engine (CHP)	34,14	14
Back-pressure turbine (CHP)	25,82	9
CCGT (CHP)	33,06	12
Geothermal power plant	26,62	10
Small-scale hydropower	**13,06**	**2**
Condensating turbine (CHP)	25,07	7
Conventional gas	52,29	16
Conventional coal	74,33	20
Microturbine (CHP)	25,60	8
Photovoltaic systems	19,92	4
Conventonal oil	57,96	19
Internal combustion engine CHP	40,59	15
Wind turbines	22,85	6
IGCC coal-based	55,78	18
Solar-thermic systems	21,45	5
Pumped-and-storage hydropower	**14,76**	**3**
Fuel-cell (CHP)	27,03	11

*w_1: Economic sustainability, w_2: Engineering sustainability, w_3: Social sustainability, w_4: Environmental sustainability

Source: own calculations

4. Conclusions

4.1. Key findings and conclusions

Key findings and results of the analysis suggest that distributed energy generation technologies, renewable-based electricity generation technologies, and CHP plants are much closer to enforce the principles and rules of sustainable development than their conventional, large-scale counterparts, which contradicts to the findings of PSI (2006) and Afgan & Carvalho (2002). By assigning equal weights to the economic, social, and environmental dimensions of sustainability, in the ranking of electricity generation technology groups elaborated by PSI (2006) hydropower plants, wind power plants and nuclear power plants are the leader technologies, which are followed by conventional natural gas technologies, photovoltaic systems and conventional coal-based combustion power plants. According to the list of PSI (2006) from a sustainability point of view, large-scale conventional oil-combustion technologies seem to be the worst alternatives. In the sustainability ranking of electricity generation technologies of Afgan & Carvalho (2002) the order of alternatives from the best to the worst technologies is the following: hydropower stations, nuclear power plants, natural gas-based power plants, wind power geothermal power plants, solar thermal systems, coal-based technologies, ocean-based technologies, photovoltaic units, biomass-based electricity generation technologies. In order to validate the reliability of data and the functionality of the model used in this paper, the Weighted Sum Model was also executed with the criterions, indicators, and weights applied by these prior studies. With the incorporation of CHP technologies results were entirely the same. Based on these findings it can be stated that the differences in the rankings of electricity generation technology groups can be explained by the differences in the scope of the analysis, i.e. in the selection of technology groups, in the composition of the indicator systems being used and the in the weights assigned to indicators. However, these conclusions have some limitations.

4.2 Limitations of the study

The most important limitation of the research is the availability of reliable data regarding technology groups and indicators. Due to the fact that in most of the cases only average values or interval scales are available for the performance of technology groups without distribution functions, mode values of performance cannot be determined for each indicators, consequently, the use of average values can distort findings. Furthermore, the use of power plant-related data instead of typical values of power generation technology groups could raise the sophistication of the results. Another bottleneck of the analysis presented in this paper is the actuality of data. Continuous improvement of generation technologies especially in the case of renewable-based and distributed generation technologies leads to the fast obsolesce of data and to the rearrangement of the relative sustainability orders of power generation technology groups. Reliable and thorough comparison of electricity generation technologies from a sustainable point of view and the selection of R&D projects consistent with the main principles and goals of sustainable development requires the elaboration of key stakeholders, the development of a commonly accepted notion of sustainable power system and a widely accepted sustainability assessment framework which relies on continuously updated and available databases and dynamic indicators.

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Appendix 1. : Sustainability Indicator System for electricity generation technologies

Dimension	Indicator
Technical dimension	Electric efficiency (η_E=E_{out}/E_{in}=P_{out}/$P_{in,}$ (%))
	Cogeneration efficiency (η_{CHP}=(Q_{out}+E_{in})/E_{in} (%))
	Energy payback ratio (Energy delivered / Energy required to deliver that energy)
	Maturity (qualitative scale)
	Participation in system balancing (qualitative scale)
	Availability (%)
	Dispatch (qualitative scale)
	Additional balancing requirements (qualitative scale)
	Reserve capacity (qualitative scale)
	Load following capability (qualitative scale)
Economic dimension	Investment costs (USD/kWh)
	Operation &Maintenance costs (USD/kWh)
	External costs (USD/kWh)
	Dependency on foreign fuels (qualitative scale)
	Job creation potential (person/MWh)
	Construction time (years)
	Dependency on fuel price (fuel price/O&M costs)
Environmental dimension	GHG- potential ((g/CO2eq/kWh))
	Acidification potential (mgSO2eq/kWh)
	Eutrophication potential (mgPO3/4/kWh)
	Waste management requirements (qualitative scale)
	PM 10 emission (mg/kWh)
	NMVOC-emission (mg/kWh)
	Functional damage (qualitative scale)
	Health impacts of normal operation (qualitative scale)
Social Dimension	Land requirements (m2/MW)
	Visual destruction (qualitative scale)
	Noise exposure (qualitative scale)
	Conflicts(qualitative scale)
	Risk-taking (qualitative scale)
	Risk contol (qualitative scale)
	Catastrophic potential qualitative scale)
	Educational requirements (qualitative scale)
	Participative decision-making (qualitative scale)

Source: own edition