Electricity generation technologies and sustainability: The case of decentralized generation

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Abstract: In the relevant literature, distributed energy generation (DG) technologies are usually seen as sustainable system innovations which can contribute to the achievement of the key goals of sustainable development in the technology system of power generation and consumption. Despite the intensive research and regulatory efforts, nor the sustainability advantages of distributed technologies over traditional, centralized plants, nor their ability to induce systemic changes in the existing technological regime leading to the appearance of a new power regime consistent with the key requirements of sustainable development have been justified. The aim of this paper is to analyze whether it is possible to define renewable-based power plants and distributed energy generation technologies as the most favorable, disruptive power generation technologies in terms of sustainability by examining twenty electricity and cogeneration technology groups in a proposed multi-criteria sustainability assessment framework and decision model elaborated by the author.

Key-words: sustainable development, electricity generations technologies, indicator system, sustainability ranking, cluster analysis

1 Introduction

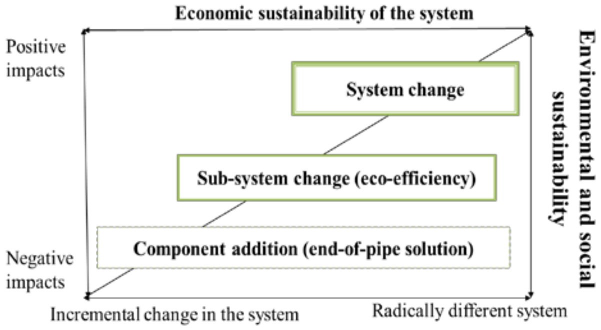
Taking into account the main elements, dimensions, and goals of sustainable development, sustainable electricity system can be defined as a power system which can guarantee clean, safe, reliable and sufficient electricity supply without the exclusion of anyone, in a socially acceptable manner, at a reasonable price. In line with this fundamental goals, the possible characteristics of sustainable electricity systems can be summarized as follows:

- Have low environmental impacts (e.g. air, water, soil pollution) and rely on minimal use of natural resources (e.g. primary energy, land usage, resource needs)
- Support the use of environmentally friendly solutions,
- Support the development and the competitiveness of the markets, and market entry,
- Support the reduction of energy price fluctuations and its spillovers,
- Support the reduction and minimization of supply chain costs,
- Support the security and reliability of supply and the minimization of import-dependency,
- Contribute to the development of energy efficiency,
- Contribute to the development of the standards of living,
- Support inter- and intragenerational equality,
- Support the minimization of the negative impacts on human health,
- Support participative decision making processes and the assertion of local interests.

Moreover, the power system is a complex system that interacts directly and 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 the knowledge, opinions and preference orders perceived by the members of the society (Berényi, 2015).

From systemic approach, Carrillo-Hermosila et al. (2010), and Tukker & Tischner (2006) differentiate three innovation levels regarding the effects having on a given production and consumption system. From this innovation point of view, three potential pathways can be identified which can contribute to the achievement of the sustainability goals of electricity generation and supply (see Fig.1).

Fig.1: Design framework for eco-innovation in view of radical and incremental change and negative and positive impacts on the environment



Source: Carrillo-Hermosilla et al. (2010: 1076)

In system optimization level, the structure of the existing production and consumption system remains unchanged, only small modifications in the systemic elements occur, therefore in this level, innovations are focused only on component additions. These end-of-pipe solutions representing the first option towards the goals of sustainable development are able to treat symptoms rather than the cause. In the technical system of centralized power generation and consumption, air capture of carbon dioxide and carbon capture and sequestration (CCS) are the main examples for end-of-pipe solutions (Unruh & Carrillo-Hermosilla, 2004). For both technological solutions, it can be stated that once the investment and O&M costs of these technology solutions reduce, it is unlikely that serious market, financial, social and institutional obstacles encumber their market penetration and diffusion, since incumbent actors with dominant market share are interested in the development of these technologies (due their potentials to reduce GHG-emissions) that fit well to the existing infrastructure and corporate competencies (Turkenburgh & Hendriks, 1999; Unruh, 2002).

In the level of system redesign institutional frameworks are stable and modifications take place in processes and sub-systems of a given technical system due to the use of incremental and sustaining innovations. Under the term of technical system, we understand the combinations of technological elements, organizations, actors, their networks and interactions, and guiding principles and rules organized around a certain technological base (Carrillo-Hermosila et al, 2010). In the case of the electricity system, these innovations include the use of demand-side energy efficiency measures, power plants with carbon capture-ready designs (CCR), and large-scale renewable-based power plants. From these technological options, the use of energy-efficiency measures and large-scale renewable-based power plants deserve more attention, because both solutions play a critical role in the energy policies and objects of countries worldwide.

While in the early years of electrification, improvement of energy efficiency was one of the most important driving forces of utilities possessing the whole decentralized electricity system, while due to the centralization of the power system, the use of metering systems, the appearance of different consumption modes, the growing number and availability of electrical devices and appliances electricity supply had become an independent service, demand-side energy-efficiency improvement had lost its significance, indeed, in some ways it had become antagonistic to the financial goals of the incumbent firms being active in the power sector.

Large-scale penetration of renewable-based electricity generation technologies represents a significant challenge for the existing centralized power systems. Renewable-based electricity generation technologies - with the exception of large-scale hydropower plants and wind farms - can be considered as small-scale power generation technologies since their electric capacity ranges from watts up to tens of kilowatts. In addition to this, due to their intermittent nature, these technologies seem to be incompatible with the principles and theorems of the traditional centralized power system.

Furthermore, renewable-based energy generation technologies were developed by organizations operating outside from the existing electricity system, their adaption by incumbent utilities has not grown to such an extent as it was targeted for example in the energy policies of the European Member States. The pace of development of global energy system and the trends and tendencies in association with the use and diffusion of renewable-based electricity generation technologies and efficiency improvement measures indicate that both processes are not fast enough to stimulate the shift towards the goals of sustainable development.

While end-of-pipe solutions - such as the use of air capture of carbon dioxide (Unruh & Carrillo-Hermosilla, 2004), - and CCS, CCR power plants and energy-efficiency improvements can be interpreted as incremental innovations reinforcing existing technology trajectories and supporting the elimination of the environmental problems associated with the dominant electricity system, the use of renewable-based energy generation technologies leads to the third technological option, namely to the use of discontinuity approaches.

System change needs system innovations, which means that not only products, services, and production systems are optimized and new ways of satisfying consumer's needs are found within the existing institutional frameworks and infrastructures, but the whole system – elements, their interactions, and relations, institutional backgrounds, social practices, norms - will change. Unlike end-of-pipe and sustaining innovations, sustainable system innovations are the sum of innovations appearing in the different dimensions of a technical system, which enables the supply of new products and services by generating new logics, practices, and principles and ensuring economic, social and environmental gains. Consequently, system innovations can induce changes in the material, industrial, financial, political and institutional dimensions of a given technical system. In a number of relevant literature sources (e.g. Meyers & Hu, 2001; Unruh, 2002; Mulder, 2007; Kemp, 2008, Somogyvári, 2015) distributed energy generation is interpreted as an example of disruptive innovation, since in theory against the use of large-scale renewable technologies which cause only partial changes in the whole system, small-scale distributed energy generation technologies dramatically influence the material, fiscal, political, sectoral and legal dimensions of the centralized electricity system.

However, the categorization of distributed electricity generation technologies as radical and disruptive technological innovation needs further explanation.

2 Distributed generation technologies as a disruptive sustainable innovation

In the last decades, several definitions of distributed generation (DG), decentralized generation, dispersed generation have been appeared to describe small-scale power generation technologies, however, there is a lack of clear consensus on the special characteristics, size and nominal capacities of these generation technologies. In the relevant literature, the most widely accepted definitions are the followings:

- Willis & Scott (2000:1) states that distributed generation includes all use of small generators, typically ranging in capacity from 15 to 10 000 kW, to provide the electric power needed by electrical customers whether located on the utility system, at the site of a utility customer, or at an isolated site not connected to the power grid. The authors also mention that dispersed generation is one of the subsets of distributed generation, refers to generation located at customer facilities or off the utility system, and have a small capacity range of 10 to 250 kW.
- Borbely & Kreider (2001:2) states that distributed generation can be defined as power generation technologies below 10MW electrical output that can be sited at or near the load they serve".
- Bhatia and Angelou (2014) stress that the term of distributed generation refers to electricity generation systems with capacities of about 200 watts through to a few megawatts (~10MW) which includes isolated, grid-connected home systems as well as micro- and mini-grids.
- According to the definition of the EC (2001: 4) "Distributed generation covers all technical and non-technical aspects of an increased use of RES and other decentralized generation units in distribution networks. Distributed generation can be defined as the integrated or stand-alone use of small, modular electricity generation resources by utilities, utility customers and private individuals or other third parties in applications that benefit the electric system, specific end-use customers, or both".

Ackermann et al. (2001) suggests that in order to define distributed generation more precisely, the purpose of the system, the location of distributed generation, the rating of distributed generation, the power delivery area of distributed generation; the technology of power generation; the environmental impacts associated with distributed generation; the ownership of these generators; the mode of their operation and the nature of their market penetration should be discussed. However, as the authors conclude, on the one hand a general and narrow definition of distributed generation cannot cover all these aspects, and on the other hand differences in the technical specifications of the regional and national energy systems, and in the national and regional specifications and regulations of distribution and transmission networks, maximum penetration and capacity levels, ownership types, operational modes and market penetration make the generalization of the term even harder, while in order to get reliable data on the environmental and network aspects of DG utilization, complex and dynamic models of power network flows and environmental impact assessment need to be prepared.

Despite all these difficulties, Ackermann et al (1999: 237) highlight that “Distributed generation is an electric power source connected directly to the distribution network or on the customer side of the meter.” The authors also suggest the following categories of distributed generation:

- Micro: 1W<5kW
- Small: 5kW<5MW
- Moderate: 5MW<50MW
- Large: 50MW<100MW

Relying on the aforementioned definitions, in this paper, distributed energy generation technologies are defined as modular power generation technologies located near to the consumption nodes with a maximum rated capacity of 100MW, connected directly to the distribution network, or can be operated in off-grid and/or isolated modes by utilities, network companies, utility customers private companies or other market actors. Distributed energy generation technologies encompasses small-scale, renewable-based (solar, wind geothermal, hydropower, and or biomass-based power plants) electricity generation technologies, and small-scale, fossil and/or renewable-based cogeneration plants (such as microturbine, fuel-cell, internal and external combustion engines, condensing and back-pressure turbine based CHPs) by which power and heat can be produced simultaneously.

According to Markard & Truffer (2006: 612), the radicality of innovations can be measured by the degree of change induced by them along the value chain and the degree of change in a single element of the value chain induced by these innovations. Since electricity generation and supply is a large technical system in which innovation processes are more of the incremental than of the radical nature, a number of radical innovations have appeared in the sector associated with power generation technologies. Based on the modification and supplement of the findings of Markard & Truffer (2006), Table 1 summarizes realized and potential changes in the traditional value chain of electricity generation and supply due to the introduction and diffusion of natural gas based conventional power generation plants, nuclear power plants, and distributed power generation technologies.

Table 1: Degree of radicality of different power generation technologies based on their vertical and horizontal impacts in the traditional value chain of power supply

0	Conventional natural gas combustion technologies	Nuclear power plants	Distributed energy generation technologies	
			Renewable-baseed energy generation technologies	CHP technologies
Electricity consumption	No change	No change	Customers as producers, possibility to use heat and power	
Electricity trade	No change	No change	Green marketing	Waste-heat utilisation,, biomass/hydrogen-based CHPs with green marketing options
Electricity transmission and distribution	No change	No change	Decentralised distribution, New structures (Virtual grids, microgrids, etc.)	
Electricity generation	New generation technologies	New generation technologies, new safety and waste management issues	New generation technologies, ittermittent generation	
Transport of primary energy carriers	New infrastructures and networks	New infrastructures, networks, transportation technologies, new safety issues	No use of transportation infrastructure, new networks and supply chains in the case of biomass-utilisation	Enlargement of gas supply networks, hydrogen industry and new supply chains, new networks and supply chains in the case of biomass-utilisation
Explotation of primary energy carriers	New resources, substitution of wood and coal	New resources, new explotation technologies	New resources, possibility to substitute fossil fuels and uranium	New resources, possibility to substitute fossil fuels and uranium

Source: adapted and modified model of Markard & Truffer (2006: 613.)

It is important to note that the darker the cell is, the higher the degree of horizontal novelty is associated with the given function of the system. As Table 1 illustrates, market penetration and diffusion of natural gas based conventional combustion power plants had a radical impacts only in the exploitation and transport functions or phases of the traditional value chain of power generation and supply, while it left untouched those network and retail functions and activities which had been induced by the coal-based power generation and had incrementally become the main feature of centralized power systems. As a result, the introduction and diffusion of conventional gas combustion power plants can be seen only as a moderately radical or sustaining innovation in the centralized power system.

The use of nuclear power plants was supported by national governments all over the world. Although, these technologies were at the beginning of their life-cycle, and due to their special safety requirements, high overnight and investment costs, and the need for new capabilities and skills in association with new operational methods utilities resisted to use nuclear energy to generate power, the availability of support mechanisms guaranteed by the government and the high compatibility with the dominant centralized power system led to the a more or less slow release of the initial internal resistance of incumbent actors. Indeed, although over the past decades, nuclear accidents and social resistance against nuclear energy resulted in a slight decline in nuclear power utilization, compared to fossil-fuel based energy generation technologies, nuclear power at the point of electricity generation does not produce any GHG emissions that damage local air quality which seems to justifies that nuclear power can play a dominant role in the struggle against environmental degradation. In sum, it can be stated that nuclear energy based electricity generation technologies can be considered as radical innovations with a moderate degree of vertical and high degree of horizontal novelty (Markard & Truffer, 2006:515)

On the contrary, as it is indicated in Table 1, the introduction of small-scale cogeneration and renewable-based distributed power generation technologies affect the entire value chain. While the high penetration of renewable-based electricity generation technologies can contribute to the substitution of fossil and nuclear fuels and the related processing and transportation activities, fossil (mainly natural gas) based cogeneration power plants can support the extension of the existing exploitation and transportation infrastructure of natural gas value chains, renewable-based combined heat and power plants can lead to the appearance and expansion of hydrogen-based economy and to the strengthening of biomass-based electricity generation infrastructure. Additionally, most types of distributed generation technologies are in the initial phase of their life-cycle and due to their technological features, - e.g. intermittent power generation capability - connection to the distribution and transmission lines, as well as the fit to the traditional power system represent key challenges for them (Levin & Thomas, 2016). Due to their small-scale nature and physical proximity to consumption nodes, distributed generation technologies encourage customers to become the producers of power (and heat), i.e. to generate power (and heat) for own consumption or for commercial purposes. Furthermore, renewable-based electricity and cogeneration technologies give a new feature to power and heat, which led to the appearance of green marketing and trading strategies and tools. Therefore, in theory, the degree of horizontal and vertical novelty of distributed generation technologies along the electricity value chain is so high as to argue the disruptive nature of these technologies.

However, in order to confirm that distributed generation technologies represent sustainable system innovations in the current power system, and to define appropriate policy measures by which the diffusion and adaption of these technologies can be encouraged and guided, three basic questions should be answered, which together has not been studied or taken into account sufficiently in the relevant literature dealing with the system innovation potentials of distributed generation technologies.

- Evolutionary theories of innovation dealing with disruptive and system innovations (see e.g. Christensen, 1997; Kemp et al. 1998; Elzen et al. 2004; Yu & Hang, 2010) argue that technological change is an interplay between variations of technologies and selection processes, which has a path-dependent nature due to the increasing returns of adaption, with possibilities of “locked-in”. While incremental innovations favor the existing trajectory of the technology system, internal and external shocks or the appearance of new requirements can erode the problem-solving capacity of existing technologies leading to the development of new solutions with promising new functions. Therefore, according to the representatives of dominant design and path dependency theories (Anderson & Tusman, Liebowitz & Margolis, 1995; Arthur, 1994; Berkhout, 2002; David, 1985) and quasi evolutionary theory (Nill & Kemp, 2009; Kemp & Zundel, 2007; Sartorius & Zundel, 2005) in order to identify the potential competition between old and new technologies, differentiation of new, disruptive technologies from the existing, dominant ones is required based on their key attributes.
- In spite of the fact that distributed generation technologies can be treated as eco-innovations since they can support the minimization or elimination of the environmental problems associated with power generation and supply, their contribution to sustainability has not been proved.
- Even though distributed generation technologies can be considered as sustainable system innovations, in order to confirm that these types of technologies have the ability to support or induce the whole transformation of the existing technical system of power generation and consumption, it is important to analyze and confirm that beyond technological substitution, distributed generation technologies have the ability to induce or coevolve with such kind of changes in the institutional, material, political,

organizational, structural dimensions of the existing technological regime of power generation and consumption enabling the supply of new products and services by generating new logics, practices and principles and ensuring economic, social and environmental gains. Furthermore, it is important to note, that sustainable system innovation potential of distributed generation technologies does not mean or cause the automatic exclusion of end-of-pipe solutions or sustaining innovations.

The aim of this paper is to analyze whether it is possible to define renewable-based power plants and distributed energy generation technologies as the most favorable, disruptive power generation technologies in terms of sustainability, i.e. that distributed generation technologies and conventional power generation technologies belong to different technological clusters, and compared to large-scale electricity generation technologies distributed generation technologies can have positive social, environmental and economic impacts.

Based on the sustainability indicator framework of electricity generation technologies and a multi-criteria decision-making analysis approach elaborated by the author, cluster analysis and sustainability ranking of power generation technologies are conducted.

3 A proposed model of sustainability indicator system for electricity generation technologies

3.1 Sustainability indicators for electricity generation technologies – literature review

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.

3.2. Proposed criterions and indicators for sustainability assessment of electricity generation technologies

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 contain 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 generalize, these impacts are not incorporated into the model.

Fig.2: 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)

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, Dombi et al. 2014) 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 2 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.

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 Chapters, results of cluster analysis and the relative sustainability ranking of main power generation technology groups will be presented.

3 Sustainability ranking of electricity generation technologies

3.1. Data and method of analysis

Technology groups in this paper are consistent with those in previous studies described in Chapter 2.2, and contain conventional coal power plants, conventional gas power plants, conventional oil power plants, nuclear power plants, biomass-based combustion power plants, wind turbines, solar thermal power plants, photovoltaics systems, geothermal power plants, run-of-river hydropower plants, pumped-and-storage hydropower plants, small scale hydropower plants, internal combustion engine based CHPs (Otto and diesel type), back-pressure turbine based CHPs, microturbine based CHPs, condensing turbine based CHPs, integrated gasification combined cycle based coal power plants (IGCC), combined-cycle power plants, and fuel cell based CHPs.

Economic, social, environmental and technical/engineering features of these technology groups were systematized according to the Sustainable Indicator System presented in Chapter 2.2. According to the relevant and available international literature sources, average values for all indicators of economic, social, environmental and technical/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. It is important to note, that in cluster analysis levelised costs of power generation technologies were also taken into account.

Finding the answers to the first research question requires the creation of homogeneous groups of electricity generation by using cluster analysis methodologies. In this paper, hierarchical and k-means cluster analysis was also conducted. Hierarchical cluster analysis is a procedure that attempts to identify relatively homogeneous subgroups of cases or variables based on selected characteristics, using an algorithm that starts with each case or variable in a separate cluster and combines clusters until only one is left (IBM, 2006:412). At each step, the two clusters that are most similar are joined into a single new cluster and these initial groups are merged according to their similarities. In hierarchical cluster analysis, distances and the calculation method of distances play the key role.

In the Furthest Neighbour approach defines the dissimilarity between clusters to be the maximum distance between any two points from the two clusters (Székelyi & Barna, 2004: 121). Although this method usually yields clusters that are well separated and compact, in order to handle its sensitivity to outliers (Yim & Ramdeen, 2015), the hierarchical clustering was also conducted with the Within-Groups linkage method in which the dissimilarity between cluster A and cluster B is represented by the average of all the possible distances between the cases within a single new cluster determined by combining cluster A and cluster B (Yim & Ramdeen, 2015).

Against the hierarchical cluster analysis, K-means cluster analysis does not require computation of all possible distances, since this procedure attempts to identify relatively homogeneous groups of cases based on selected characteristics, using an algorithm that can handle large numbers of cases (IBM, 2006:417). In this method number of clusters (i.e. Value of k) is determined by the user.

Relative sustainability ranking of different electricity generation technologies was defined by the use of an MS Excel-based Weighted Sum Method. 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:

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

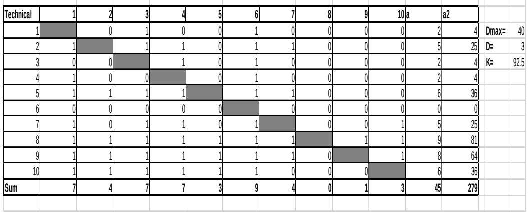
A^{*}_{WSN} = WSM score of the best alternative
M=number of alternatives
N= number of criteria
a_{ij}= actual value of the th alternative in terms of the j^{th} criterion
w_j = weight of importance of the jth criterion

The weights of sub-indicators of economic, social, environmental and technical/engineering sustainability are determined by the Guilford pairwise comparison methodology and expert interviews. Priorities or weights of the indicators were evaluated in a pairwise manner by 13 energy experts - from education, research and practice.

The main phases 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 (Fig. 3 illustrates the structure of the individual preference matrices elaborated by the 13 experts) in order to calculate the consistency level of individual assessments.

Fig. 3: 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		

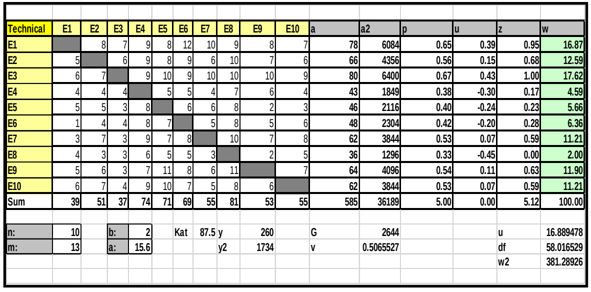
Source: own calculation

5) Assessment of the consistency level of each individual preferences in order to eliminate inconsistent expert preferences. 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). In order to validate the analysis Fig. 4 illustrates the aggregated preference matrix and the final weights of technical indicators.

Fig. 4: Example of Aggregated matrix and 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

7) Calculation of group level consensus by Kendall's coefficient of concordance for pairwise comparison (ν) defined by Kendall (1970).

8) Transformation of preference rates (Pa) to U values according to the standard normalized distribution.

9) Transformation of U scores to interval scale

10) Linear transformation of Z scores by the next equation in order to weights sum to 1.

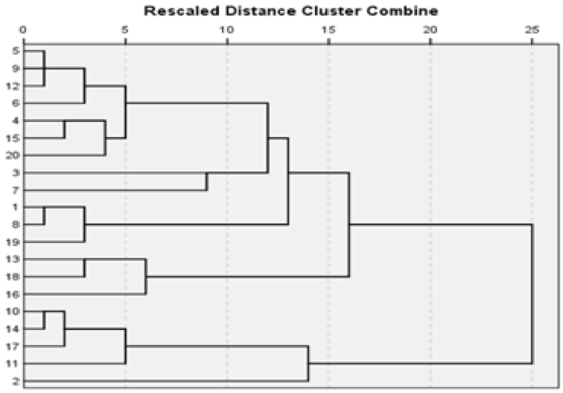
The last step of the ranking process implies the calculation of individual sustainability scores of the given technology groups by summing up the multiplications of normalized values of each indicator and their overall weight coefficient.

3.3 Results regarding the clustering electricity generation technologies

3.3.1. Results of hierarchical cluster analysis

Results of hierarchical clustering with the complete linkage method which considers the furthest distance between pairs of cases are shown in Fig. 5 and Table 2.

Fig. 5: Dendrogram of hierarchical cluster analysis by using "Furthest Neighbour" method



Source: own edition based on SPSS 18.0.

Examining the dendrogram (see Fig. 5). from left to right, clusters that are more similar to each other are grouped together earlier The largest gap can be identified between the stages of 16 and 25 suggesting a 2-cluster solution. For a more accurate evaluation of data, Agglomeration Schedule should be analyzed (see Table 2).

Table 2: Agglomeration Schedule of hierarchical cluster analysis by using „Furthest Neighbor" method

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	5	9	5.293	0	0	3
2	1	8	6.551	0	0	8
3	5	12	8.068	1	0	9
4	10	14	9.571	0	0	6
5	4	15	12.488	0	0	10
6	10	17	16.833	4	0	12
7	13	18	22.705	0	0	13
8	1	19	23.513	2	0	16
9	5	6	24.948	3	0	11
10	4	20	32.835	5	0	11
11	4	5	39.112	10	9	15
12	10	11	39.48	6	0	17
13	13	16	45.154	7	0	18
14	3	7	61.153	0	0	15
15	3	4	82.501	14	11	16
16	1	3	95.427	8	15	18
17	2	10	96.826	0	12	19
18	**1**	**13**	**113.805**	**16**	**13**	**19**
19	**1**	**2**	**178.979**	**18**	**17**	**0**

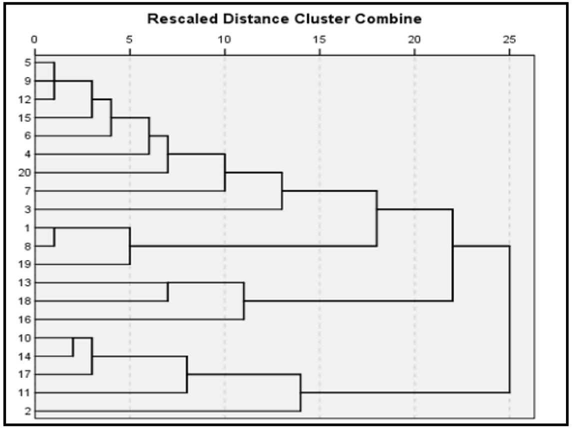
Source: own edition based on SPSS 18.0.

The agglomeration schedule is a numerical summary of the cluster solution that displays how the hierarchical cluster analysis progressively clusters the cases or observations (columns of Cluster Combine) and helps to determine the appropriate number of clusters (column of Coefficients). Due to the fact that agglomeration coefficients measure the increase in heterogeneity that occurs when two clusters are combined, in order to find the largest gap between the stages, differences between the agglomeration coefficients should be determined and the number of clusters prior to the largest difference (or gap) is the most probable solution. As Table 2 indicates, the largest gap in the coefficients column occurs between stages 18 and 19 indicating a 2-cluster solution which is the same as the finding from the dendrogram.

These results suggest, that by using the Furthest Neighbour method, electricity generation technologies can be grouped into two clusters. The first cluster includes distributed power generation technologies and large-scale hydro-power plants. The second cluster contains conventional large-scale centralized electricity generation technologies, such as large-scale fossil-fuel (based on oil, coal or natural gas) and nuclear power plants.

Results of hierarchical cluster analysis using “Within Groups” algorithm are interpreted by Fig. 6 and Table 3. From these illustrations, it can be concluded, that although the 2-cluster solution with same cluster memberships also exists, the hierarchical cluster analysis with “Within-Groups” approach supports a 4-cluster solution.

Fig.6: Dendrogram of hierarchical cluster analysis by using “Within-groups” method



Source: own edition based on SPSS 18.0.

According to this method, the composition of the four clusters is the follows:

- Cluster 1: Cogeneration plants, biomass combustion plants, geothermal power plants.
- Cluster 2: Small and large-scale hydro-power plants,
- Cluster 3: Wind power plants, PVs, and solar thermic power plants,
- Cluster 4: Conventional oil, conventional coal, conventional natural gas, nuclear power plants

In sum, the aforementioned findings of the two types of hierarchical cluster analysis suggest, that based on the economic, social, environmental and technical attributes of power generation technologies, two heterogeneous groups of electricity generation technologies can be distinguished: the cluster of conventional large-scale, centralised (fossil and nuclear) power plants and the group of distributed electricity generation technologies together with the large-scale hydropower plants. Bearing in mind, this 2-cluster solution of hierarchical cluster analysis, in the case of K-means cluster analysis, the specified number of clusters was two. Based on the results of hierarchical cluster analysis, K-means cluster analysis was also completed.

Table 3: Agglomeration Schedule of hierarchical cluster analysis by using „Within-groups” method

Stage	**Cluster Combined**		**Coefficients**	**Stage Cluster First Appears**		**Next Stage**
	Cluster 1	**Cluster 2**		**Cluster 1**	**Cluster 2**	
1	5	9	5.293	0	0	2
2	5	12	6.503	1	0	5
3	1	8	6.551	0	0	8
4	10	14	9.571	0	0	6
5	5	15	11.935	2	0	7
6	10	17	12.143	4	0	12
7	5	6	15.621	5	0	9
8	1	19	16.342	3	0	17
9	4	5	18.775	0	7	10
10	4	20	21.792	9	0	13
11	13	18	22.705	0	0	14
12	10	11	23.69	6	0	16
13	4	7	30.068	10	0	15
14	13	16	31.859	11	0	18
15	3	4	37.056	0	13	17
16	**2**	**10**	**39.697**	**0**	**12**	**19**
17	**1**	**3**	**50.416**	**8**	**15**	**18**
18	1	13	59.838	17	14	19
19	1	2	70	18	16	0

Source: own edition based on SPSS 18.0.

3.3.2. Results of k-means cluster analysis

Table 4 summarises the clustering results of K-means cluster analysis. According to this, the first cluster of electricity generation technologies encompasses large-scale run-of-river hydropower plants, wind turbines, photovoltaic systems and solar-thermal power plants, geothermal power plants, black-pressure cogeneration power plants, compensating turbine and microturbine CHPs, internal and external engine based cogeneration power plants, and fuel-cell based CHPs. The second cluster of electricity generation technologies contains biomass-based combustion power plants, large-scale pumped-up-storage hydropower plants, nuclear power plants, large-scale conventional fossil-fuel based electricity generation technologies, coal-based IGCC and CCGT-based cogeneration plants.

Table 4: Cluster membership by using K-means cluster analysis

Technology	Cluster	Distance
Run-of-river hydropower plants	1	6.164
Nuclear power plants	2	6.405
Biomass based power plants	2	6.463
Diesel motor (CHP)	1	5.174
Back-pressure turbine (CHP)	1	3.818
CCGT (CHP)	2	4.097
Geothermal power plants	1	5.229
Small-scale hydropower	1	5.642
Condensating turbine (CHP)	1	3.897
Conventional gas	2	2.082
Conventional coal	2	5.771
Microturbine (CHP)	1	3.343
Photovoltaic systems	1	6.521
Conventional oil	2	3.175
Otto motor (CHP)	1	4.605
Wind turbines	1	6.113
IGCC coal-based	2	3.128
Solar therial power plants	1	5.221
Pumped-and-storage hydropower	2	5.816
Fuel-cell (CHP)	1	4.456

Source: own edition based on SPSS 18.0.

Table 5: ANOVA table of K-means cluster analysis

	Cluster		Error		F	Sig.
	Mean Square	df	Mean Square	df		
Zscore(Investment_costs)	0.762	1	1.013	18	0.752	0.397
Zscore(O&M_costs)	1.872	1	0.952	18	1.967	0.178
Zscore(LCOE_costs)	3.837	1	0.842	18	4.555	0.047
Zscore(External_costs)	4.15	1	0.825	18	5.031	0.038
Zscore(Fuel_price_risk)	1.42	1	0.977	18	1.454	0.244
Zscore(Construction_time)	9.024	1	0.554	18	16.283	0.001
Zscore(Electric_efficiency)	1.001	1	1	18	1.002	0.33
Zscore(Cogeneration_efficiency)	1.132	1	0.993	18	1.141	0.3
Zscore(Energy_payback)	0.035	1	1.054	18	0.033	0.858
Zscore(Import_dependency)	7.729	1	0.626	18	12.343	0.002
Zscore(Maturity)	8.172	1	0.602	18	13.585	0.002
Zscore(Participation_system)	3.753	1	0.847	18	4.431	0.05
Zscore(Availability)	1.254	1	0.986	18	1.272	0.274
Zscore(Dispatch)	11.026	1	0.443	18	24.889	0
Zscore(Balancing_needs)	5.406	1	0.755	18	7.158	0.015
Zscore(Reserve_capacity)	2.235	1	0.931	18	2.4	0.139
Zscore(Load_following)	3.167	1	0.88	18	3.6	0.074
Zscore(GWP_emission)	3.226	1	0.876	18	3.682	0.071
Zscore(PM10_emission)	1.108	1	0.994	18	1.115	0.305
Zscore(NMVOC-emission)	0.311	1	1.038	18	0.3	0.591
Zscore(Acidification)	1.876	1	0.951	18	1.972	0.177
Zscore(Eutrphication)	4.437	1	0.809	18	5.484	0.031
Zscore(Job_creation)	0.203	1	1.044	18	0.195	0.664
Zscore(Land_requirements)	2.224	1	0.932	18	2.386	0.14
Zscore(Visual_impacts)	6.314	1	0.705	18	8.958	0.008
Zscore(Noise_exposure)	2.42	1	0.921	18	2.627	0.122
Zscore(Waste_management)	5.146	1	0.77	18	6.686	0.019
Zscore(Conflicts)	11.639	1	0.409	18	28.458	0
Zscore(Participative_decisions)	11.029	1	0.443	18	24.908	0
Zscore(Heath_impacts)	8.444	1	0.586	18	14.4	0.001
Zscore(Risk-taking)	10.61	1	0.466	18	22.764	0
Zscore(Risk_control)	6.016	1	0.721	18	8.34	0.01
Zscore(Catastrophic_potential)	8.439	1	0.587	18	14.383	0.001
Zscore(Functional_damage)	11.316	1	0.427	18	26.509	0
Zscore(Education)	0.264	1	1.041	18	0.254	0.621

Source: own edition based on SPSS 18.0.

However, as the results of ANOVA analysis (see Table 5 illustrates, k-means cluster analysis was completed with a relatively small number of cases (20) with a higher number of variables (35) which resulted in the relatively low performance of certain clustering variables (see the column of F-statistics and significance). As the poor choice of clustering variables leads to inaccurate assignments of observations to clusters (Milligan, 1989), clustering variables with the lowest clustering performance were removed step-by-step by an iterative process until there were no significant differences in cluster centres by clustering variables. Final cluster-membership with reduced clustering variables are illustrated by Table 6.

Table 6: Cluster membership for the two-cluster analysis with reduced clustering variable set

Technology	Cluster	Distance
Run-of-river hydropower plants	1	4,698
Nuclear power plants	2	4,782
Biomass based power plants	1	3,407
Diesel motor (CHP)	1	3,160
Back-pressure turbine (CHP)	1	2,493
CCGT (CHP)	1	2,867
Geothermal power plants	1	2,903
Small-scale hydropower	1	4,044
Condensating turbine (CHP)	1	2,583
Conventional gas	2	1,267
Conventional coal	2	2,691
Microturbine (CHP)	1	2,022
Photovoltaic systems	1	2,904
Conventional oil	2	1,165
Otto motor (CHP)	1	3,339
Wind turbines	1	2,701
IGCC coal-based	2	2,368
Solar therial power plants	1	2,807
Pumped-and-storage hydropower	2	4,183
Fuel-cell (CHP)	1	3,193

Source: own edition based on SPSS 18.0.

Accordingly, due to the reduction of clustering variables electricity generation technology had been reclassified. In this new solution the first cluster is composed of large-scale run-of-river and small-scale hydropower plants, wind turbines, small-scale cogeneration plants (CHP), geothermal power plants, PV-systems, solar-thermic power plants, and biomass-based combustion power plants., while conventional coal combustion plants, conventional gas combustion plants, conventional oil combustion plants, nuclear power plants, coal-based IGCCs and large-scale pumped-and-storage hydropower plants belong to the second cluster.

Table 7: Final Cluster Centres

Clustering variables	Cluster	
	1	2
Zscore(External_costs)	-0.39389	0.91908
Zscore(Construction_time)	-0.35258	0.82269
Zscore(Cogeneration_efficiency)	0.34046	-0.79441
Zscore(Import_dependency)	-0.41693	0.97284
Zscore(Maturity)	0.50328	-1.17432
Zscore(Participation_system)	0.32212	-0.75161
Zscore(Dispatch)	0.45259	-1.05604
Zscore(Balancing_needs)	0.37784	-0.88163
Zscore(GWP_emission)	-0.30939	0.7219
Zscore(Visual_impacts)	-0.41178	0.96082
Zscore(Waste_management)	-0.36865	0.86018
Zscore(Conflicts)	-0.50578	1.18015
Zscore(Participative_decisions)	-0.43039	1.00425
Zscore(Heath_impacts)	-0.46288	1.08004
Zscore(Risk-taking)	-0.53611	1.25093
Zscore(Risk_control)	-0.37784	0.88163
Zscore(Catastrophic_potential)	-0.41895	0.97756
Zscore(Functional_damage)	-0.46794	1.09186

Source: own edition based on SPSS 18.0.

Based on the clustering variables and the standardized values of the two clusters by these variables (see Table 7) it can be stated, that electricity generation technologies belonging to the first cluster can be characterized by relatively lower (negative) environmental and social impacts and the ability to reduce the energy import dependence of a certain region or country, however, from technical point-of-view, in order to maintain the stable operation of the centralised electricity system, these technology groups require significant back-up services (e.g. storage and back-up capacity). Technology groups belonging to the second cluster are large-scale centralized power plants having opposite properties. Their favorable technical characteristics are overwhelmed by the disadvantageous environmental and social impacts, higher specific external costs, long construction time, and low fuel-flexibility of these types of generation technologies.

Results of the K-means cluster analysis confirm that the large-scale electricity generation technologies represent a fundamentally different group of technologies than distributed energy generation technologies while according to the clustering variables being used, large-scale run-of-river hydropower plants are more akin to decentralized generation technologies.

In sum, these results of cluster analysis stress that distributed generation technologies defined by their size and location in the relevant literature belong to a heterogeneous group that is well-separated from the cluster of traditional, large-scale, centralized fossil and nuclear power plants.

3.4 Results of the relative sustainability assessment of power generation technologies

By using the results of expert interviews, Weighted Sum Method was applied to determine the relative sustainability ranking of each electricity generation technology. Table 8 illustrates the results of the baseline analysis, where the weights of the four main criterions of sustainability - i.e. economic, social, environmental and technical/engineering sustainability – were equal ($w_1=w_2=w_3=w_4=25\%$).

Table 8: 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
Diesel 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**
Condensing 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
Otto motor (CHP)	34,90	9
Wind turbines	43,02	13
IGCC coal-based	54,31	17
Solar-thermal 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

In the baseline case, the best technologies that satisfy the equally weighted 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 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. Findings suggest that raising the weights of environmental and social dimensions (see Table 9 and Table 10, respectively) 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.

Table 9: Sustainability rank of electricity generation technologies in the dominantly social-oriented view

Electricity generation technology	IV. w3=0,7	
	0,1=w1=w2=w4	
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
Diesel 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**
Condensing 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
Otto motor (CHP)	25,60	5
Wind turbines	42,89	15
IGCC coal-based	51,46	18
Solar-thermal 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

Table 10: Sustainability rank of electricity generation technologies in the dominantly environmental-oriented view

Electricity generation technology	V. w4=0,7	
	0,1=w1=w2=w3	
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
Diesel 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**
Condensing 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
Otto motor (CHP)	40,59	15
Wind turbines	22,85	6
IGCC coal-based	55,78	18
Solar-thermal 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

Table 11: 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
Diesel 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**
Condensing 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
Otto motor (CHP)	33,35	6
Wind turbines	35,30	9
IGCC coal-based	62,67	18
Solar-thermal 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

Renewable-based electricity generation technologies and CHP plants received better ranking in the dominantly economic-oriented view than expected from prior studies (see Table 11). With the exception of large-scale hydropower technologies, due to the high uncertainties associated with the operational performance, repair and maintenance requirements and the 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, converting these plants to operate on other fuels induce high additional costs (Deutsch, 2010).

Against the initial expectations based on prior research findings, raising the weight of the technical aspects to 70% (see Table 12) does not overthrow the order of the alternatives to the benefits of traditional large-scale power plants. Even in this case, the 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. 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 requires 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).

Table 12: Sustainability rank of electricity generation technologies in the dominantly supply-oriented view

Electricity generation technology	III. w2=0,7 0,1=w1=w3=w4	
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
Diesel 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**
Condensing 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
Otto motor (CHP)	40,06	5
Wind turbines	71,05	19
IGCC coal-based	47,32	11
Solar-thermal 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

4 Conclusions

4.1. Key findings and conclusions

Distributed energy generation technologies are usually interpreted as sustainable system innovations supporting the emergence of the new technical regime of sustainable power generation and supply. In line with the key theorems of path dependency and system innovation theories, this paper aims to highlight that distributed generation technologies represent new technological solutions comparing to conventional power generation technologies, and have relative sustainability advantages of distributed generation technologies over traditional, large-scale power generation technologies.

Key findings of hierarchical and k-means cluster analysis highlight that power generation technologies defined as distributed generation by their size and location are well-separated from the cluster of conventional power generation technologies.

Results of sustainability ranking 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 indicator, 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	Type
Technical dimension	Electric efficiency ($\eta_E=E_{out}/E_{in}=P_{out}/P_{in,}$)	Quantitative (%)
	Cogeneration efficiency ($\eta_{CHP}=(Q_{out}+E_{in})/E_{in}$)	Quantitative (%)
	Energy payback ratio (Energy delivered / Energy required to deliver that energy)	Quantitative (%)
	Maturity	Qualitative (1:known-mature, 2:known-new, 3:new-under development/introduction)
	Participation in system balancing	Qualitative (1:appropriate, 2: not appropriate for secondary balancing, 3: not appropriate for system balancing)
	Availability	Quantitative (%)
	Dispatch	Qualitative (1: dispatchable, quasi dispatchable, 3: not dispatchable)
	Additional balancing requirements	Qualitative (1: equals to average forced outage, 2: equals to nominal capacity)
	Reserve capacity	Qualitative (1: need, 2: no need))
	Load following capability	Qualitative (1: able, 2: not able)
Economic dimension	Investment costs	Quantitative (USD/kWh)
	Operation &Maintenance costs	Quantitative (USD/kWh)
	External cost	Quantitative (USD/kWh)
	Dependency on foreign fuels	Qualitative (1: renewable, 2: local, 3: renewable-fossil, 4: fossil)
	Job creation potential	Quantitative (person/GWh)
	Construction time	Qualitative (1:days, 2: weeks, 3:months, 4:years)
	Dependency on fuel price	Quantitative (fuel price/O&M costs)
Environmental dimension	GHG- potential	Quantitative (g/CO2eq/kWh)
	Acidification potential	Quantitative (mgSO2eq/kWh)
	Eutrophication potential	Quantitative (mgPO3/4/kWh)
	Waste management requirements	Qualitative (scale: 1 (lowest) – 9 (highest)
	PM 10 emission	Quantitative (mg/kWh)
	NMVOC-emission	Quantitative (mg/kWh)
	Functional damage	Qualitative (scale: 1 (lowest) – 9 (highest)
	Health impacts of normal operation	Qualitative (scale: 1 (lowest) – 9 (highest)
Social Dimension	Land requirements	Qualitative (scale: 1 (lowest) – 9 (highest)
	Visual destruction	Qualitative (scale: 1 (lowest) – 9 (highest)
	Noise exposure	Qualitative (scale: 1 (lowest) – 9 (highest)
	Conflicts	Qualitative (scale: 1 (lowest) – 9 (highest)
	Risk-taking	Qualitative (scale: 1 (lowest) – 9 (highest)
	Risk control	Qualitative (scale: 1 (lowest) – 9 (highest)
	Catastrophic potential	Qualitative (scale: 1 (lowest) – 9 (highest)
	Educational requirements	Qualitative (scale: 1 (lowest) – 9 (highest)
	Participative decision-making	Qualitative (scale: 1 (lowest) – 9 (highest)

Source: own edition