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Sustainability Assessment of Electricity Generation Technologies in Egypt Using Multi-Criteria Decision Analysis

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Abstract: Future electricity planning necessitates a thorough multi-faceted analysis of the available technologies in order to secure the energy supply for coming generations. To cope with worldwide concerns over sustainable development and meet the growing demands of electricity we assess the future potential technologies in Egypt through covering their technical, economic, environmental and social aspects. In this study we fill the gap of a lacking sustainability assessment of energy systems in Egypt where most of the studies focus mainly on the economic and technical aspects of planning future installation of power plants in Egypt. Furthermore, we include the stakeholder preferences of the indicators in the energy sector into our assessment. Moreover, we perform a sensitivity analysis through single dimension assessment scenarios of the technologies as well as a sustainable scenario with equal preferences of all dimensions of the sustainability. We employ two multi-criteria decision analysis (MCDA) methodologies: the analytical hierarchy process for weighing the assessment criteria, and the weighted sum method for generating a general integrated sustainability index for each technology. The study investigates seven technologies: coal, natural gas, wind, concentrated solar power, photovoltaics, biomass and nuclear. The results reveal a perfect matching between the ranking of the technologies by the stakeholders and the sustainable scenario showing the highest ranking for natural gas and the lowest for nuclear and coal. There is a strong potential for renewable energy technologies to invade the electricity market in Egypt where they achieve the second ranking after natural gas. The Monte-Carlo approach gives photovoltaics a higher ranking over concentrated solar power as compared to the sample data ranking. The study concludes the importance of a multi-dimensional evaluation of the technologies while considering the preferences of the stakeholders in order to achieve a reliable and sustainable future energy supply.

Keywords: sustainability; electricity; technology assessment; MCDA; Egypt

1. Introduction

Many national and international organizations have been concerned about sustainable development (SD) and indicators for sustainable energy assessment during the last three decades. In 1987, the World Commission on Environment and Development identified sustainable development as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" [1,2]. In September 2015, world leaders, at an historic United Nations Summit, have adopted 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for SD. The seventh goal of these SDGs is to ensure access to affordable, reliable, sustainable and modern energy fostering the objectives of the Sustainable Energy for All initiative [1].

Renewable energy sources have a large potential to contribute to sustainable development by providing a wide variety of socio-economic benefits, including diversification of energy supply, enhanced regional and rural development opportunities, creation of a domestic industry and employment opportunities [3]. Governments and policy-makers throughout the world introduce legislation and support mechanisms to renewable energy markets and policy frameworks in response to a number of global challenges and concerns, including climate change, increasing energy demand and energy security. Many countries now have ambitious targets for renewable energy generation and addressing carbon emissions [4]. According to the New and Renewable Energy Authority (NREA) in Egypt, the Egyptian government has set a target to boost its renewable energy usage and proposed that renewable energy accounts for 20% of its power generation capacity by 2022, of which 12% would be wind, 6% hydro, and 2% solar [5].

In order to secure electricity supply, there is a need for more diversification of resources and a transition towards sustainable resources. Although fossil fuels are still cheaper as compared to other primary energy sources, they have other features that should be considered as they take part in their long term cost. For instance, they constitute a major source for the emission of Greenhouse Gases (GHGs) and thus a driver of climate change. Moreover, they are expected to be depleted in the near future and in turn their prices will be elevated. However, there are other energy resources that could be exploited and seem to be promising but are still expensive. Several previous studies gave more attention to the sustainability assessment of implemented electricity supply projects on local community development. Terrapon-Pfaff et al. [6] investigated the impacts and the conditions that influence sustainability of 23 small-scale and community-based renewable energy projects post implementation in terms of sources (solar, wind, biomass, hydro), user needs (electricity, food preparation, lighting, productive uses), community management models, finance mechanisms and geographical locations since they are recognized as important forms of development assistance for reaching the energy poor.

Stambouli et al. [7] analyzed the existing renewable energy sector in Algeria and forecasted demand growth, additional capacity, investment requirements and Algeria's ambitious objectives of environmental protection and using renewable energy and. The paper also discusses the current energy scenario and explores alternative energy sources like solar and wind to ensure energy security supply, reliability, and greater efficiency in energy conversion, transmission and utilization. Del Rio and Burguillo [3] studied the impact of renewable energy deployment on local sustainability in Spain by investigating the socio-economic benefits of three renewable energy technologies in three different locations. Tsai [8] analyzed energy sustainability from Taiwan's renewable energy production using the weighted sum method (WSM), showing a significant local progress toward energy sustainability. Different approaches for sustainability assessment of energy systems have been implemented in previous studies. Ness et al. [2], Liu [9] and Singh et al. [10] explained the different methodologies for sustainability assessment by providing an overview of various sustainability indicators, a composite index, development of a general sustainability indicator for renewable energy systems, applying a formulation strategy, scaling, normalization, weighing and aggregation methodology.

Pohekar and Ramachandran [11], Wang et al. [12] and Abu Taha and Daim [13] evaluated different Multi-Criteria Decision Making (MCDM) models for sustainable energy planning and analysis. Doukas et al. [14] assessed rural communities' energy sustainability using the Principal Component Analysis (PCA) which is one of the MCDM models. Troldborg et al. [4] developed and applied a Multi-Criteria Analysis (MCA) for a national-scale sustainability assessment and ranking of eleven renewable energy technologies in Scotland and to critically investigate how the uncertainties in the applied input information influence the result. Evans et al. [15] assessed the renewable electricity generation technologies against sustainability indicators. Islam et al. [16] examined the current energy mix, present energy crisis and its way to overcome such scenario by utilizing alternative energy sources such as biomass, solar, wind and small scale hydropower energy, in the context of Bangladesh. Góralczyk [17], Pehnt [18] and Varun et al. [19] investigated a dynamic approach towards the Life Cycle Assessment (LCA) of renewable energy technologies. Scheffran [20] discussed principles and criteria for establishing and evaluating a sustainable bioenergy lifecycle covering all dimensions of sustainability. Demirtas [21] studied the selection of best renewable energy technology for sustainable energy planning using the Analytical Hierarchy Process (AHP) methodology, which is one of the MCDM methods. Some recent studies [22–25] have applied different MCDA approaches to compare between existing or potential renewable energy technologies in Iran, Kazakhstan, Algeria and Jordan, respectively, whereas others [26–30] have applied the MCDA assessment methodology to compare between energy mix scenarios in Turkey, a Greek Island, Switzerland, Tunisia and European Union, respectively. However, few studies were concerned with a comprehensive sustainability assessment of power production technologies covering all possible energy resources.

During the last seven years Egypt experiences frequent electricity blackouts because of rising demand, natural gas supply shortages, aging infrastructure, and inadequate generation and transmission capacity. According to the US Energy Information Administration, Egypt’s generating capacity was 31.45 gigawatts (GW) in May 2015 which is slightly higher than the expected peak demand in 2015 of 30 GW. About 70% of Egypt’s electricity is fueled by natural gas, 19% by petroleum and 11% by renewable energy which is mostly hydroelectricity (9%). Recently, Egypt has suffered from natural gas shortages, particularly during the summer months. As a result, it imports fuel oil and diesel fuel to cover the shortfall [31,32].

No study for sustainability assessment of electricity technologies in Egypt was previously investigated. Based on interviews with energy experts in Egypt, most of the electricity planning is pursued by assessing the technical and economic aspects only. Policy makers are concerned only with the technical and economic aspects of electricity supply technologies in electricity planning, as evidenced by the study project “Technical Assistance to support the Reform of the Energy Sector” (TARES). This study aims to anticipate the most economic energy mix for Egypt till the year 2035 using the TIMES energy model generator [33], developed as part of the Energy Technology Systems Analysis Program (ETSAP) implemented by the International Energy Agency (IEA). However, it does not take into consideration the environmental and social aspects of energy. With growing concern about the consequences of climate change and their close relationship to energy development, in addition to the need to involve key stakeholders, including end users, in the decision-making process, the concept of sustainable development (SD) has been introduced.

The study aims at answering the research question: How sustainable are the potential electricity generation technologies that could be installed in Egypt? In order to answer this question, different electricity supply technologies will be investigated and compared regarding multiple assessment criteria and the perspectives of the stakeholders to achieve a comprehensive sustainability assessment covering technical, social, economic and environmental aspects of these technologies. The principle of this study is based on and expands the multi-criteria decision analysis (MCDA) approach that incorporates important criteria by their value and weight in the assessment process for the ranking of these alternatives.

In this paper, we implement two MCDA methodologies which are the AHP and WSM in order to perform a sustainability assessment of the technologies. The ranking of the technologies is validated according to the different individual preferences of assessment by the stakeholders through applying the Monte-Carlo validation methodology, and the ranking is compared to other five scenarios. One scenario assumes equal weights of the assessment criteria which is called the sustainable scenario. The other four scenarios are based on each of the four sustainability dimensions used for the assessment of the technologies.

The article is organized as follows: Section 2 identifies the selected technologies to be assessed and shows the selected assessment criteria; Section 3 evaluates the assessment criteria; Section 4 explains the principle of the MCDA and the applied two approaches: the AHP together with the data collection procedure from the stakeholders in the energy sector to get the weights of the assessment criteria; the WSM to generate a general integrated sustainability index per each technology. Section 5 shows the ranking of the technologies from the perspectives of the stakeholders and compares their ranking with the ranking in the other five scenarios. Section 6 summarizes the research outcomes and the recommendations implied by these results, followed by the conclusions.

2. Selection of the Technologies and the Assessment Criteria

Egypt is covered with high intensity direct solar radiation ranging between 2000 and 3200 kWh/m^2/year from North to South. The sunshine duration ranges between 9 and 11 hours/day from North to South, with very few cloudy days. Egypt's first solar-thermal power plant (Integrated Solar Combined Cycle), located in Kuraymat, has the capacity to generate 140 MW with 20 MW solar share [34]. Interestingly, the average wind speed in the Suez Gulf in Egypt reaches 10.5 m/s at 50 m height above ground showing a high wind resource potential. Moreover, other regions especially on the Nile banks in the Eastern and Western Deserts also offer a great wind resource potential. The currently installed wind power plants are 545 MW in Zafarana, 5 MW in Hurghada and 240 MW in Gabal el Zeit. The plan is to expand the total wind capacity to 7200 MW by 2020 [31]. Hydropower, as a major renewable energy resource based on the Aswan High Dam and the Aswan Reservoir Dams across the Nile River, is totally exploited in Egypt constituting 9% of the energy mix. This technology could be hardly extended. Recently some agreements concerning the installation of coal and nuclear power plants have been announced. These announcements include a feasibility study for building a coal-fired power plant in the West Mattrouh region with a capacity of 4 GW, which might cost about 3.50 billion USD [35], the Ayoun Moussa coal-fired power station of 2640 MW capacity in the Suez region [36] and a coal-fired power plant project in the Hamarawein Port power station. Nuclear power in Egypt is greatly under developed where Egypt owns a small reactor which focuses only on some research activities and does not represent a commercial power resource. However, it has been previously proposed to build a nuclear power plant at El Dabaa on the Mediterranean Coast in Matrouh, but the project has been cancelled repeatedly. Again, in November 2015, the idea has been ignited when the news declared that Egypt and Russia sign a deal to build a nuclear power plant that was expected to be completed by 2022 with four reactors producing 1200 MW each [31,37].

In this paper, we select seven technologies based on their potential resources in Egypt and the intention of the government to involve them in their future plan. These technologies are coal-fired power plants, natural gas (NG)-fired power plants, wind, concentrated solar power (CSP), photovoltaics (PV), biomass and nuclear power plants. We do not include oil-fired power plants because oil is almost used in Egypt in co-firing steam power plants that are mainly fueled by NG. Moreover, we exclude Hydropower from the assessment because it can be hardly extended since the resource potential is totally exploited.

Exploring previous studies, we found numerous energy indicators that have been used for the SD assessment. The International Atomic Energy Agency (IAEA), the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA), the European Environment Agency (EEA), and the Statistical Office of the European Communities (EUROSTAT) have developed together 30 indicators covering social, economic and environmental dimensions for the purpose of evaluating energy sustainability [8]. The United Nations Commission on Sustainable Development (UNCSD) derived 58 indicators from a working list of 134 indicators for applications worldwide [10]. Neves and Leal [38] proposed a framework of 18 local energy sustainability indicators to be used both as an assessment and as an action-planning tool.

Too many indicators are not helpful for the sustainable energy decision-making. The indicators should cover all aspects of sustainability but at the same time do not show repeatability and overlap [9] such as the inclusion of fuel cost in operation and maintenance cost, and job creations and social benefits of the energy project [12]. Selection requires a compromise between simplification and complication [10].

Some selection methodologies have been proposed by Singh et al. [10] and Wang et al. [12] as for instance: factor analysis and correlation based methods which elaborate criteria of strong correlation; least mean square and minimax deviation methods which are based on discarding criteria that show very close values among alternatives; the Delphi method which relies on the answers of the experts to a questionnaire for criteria selection with providing the reasons for their selection in two or more rounds. After each round the answers are disseminated among them and the process is repeated to get more interactive understanding of the selected criteria. The detailed procedure and the results of the selection of the sustainability criteria have been investigated in another study (see [39]). Table 1 shows a list of 13 selected criteria that we employ in this paper for the assessment of the technologies together with their units and their targets relevant to sustainability.

Table 1. The selected assessment criteria.

Category	Criteria	Measuring Unit	Sustainability Target
Technical	Efficiency of energy generation	%	Maximize
	Reliability of energy supply	%	Maximize
	Resource Potential	TWh/year	Maximize
	Water consumption	kg/kWh	Minimize
Economic	Investment cost	USD/kW	Minimize
	Job creation	Jobs/MW	Maximize
	Cost of electricity	USD/kWh	Minimize
	Operation and maintenance cost	USD/kW	Minimize
Environmental	CO_2 emission	g/KWh	Minimize
	NO_x emission	g/KWh	Minimize
	SO_2 emission	g/KWh	Minimize
Social	Safety risks	Fatalities/GW_eyr	Minimize
	Social acceptability	Ordinal scale	Maximize

3. Evaluation of the Criteria

Since most of the power plants that are currently installed are not fully based on one primary resource as in the case of steam type and biomass-fired power plants in addition to the different techniques deployed for each type, the values of the indicators vary under each technology type to some extent. For that reason, we use an average value of those we collected from previous studies which have applied a detailed analysis of the technologies.

3.1. Technical Indicators

3.1.1. Efficiency of Energy Generation

Efficiency is the most used technical indicator to evaluate energy systems [12]. According to several previous studies (see [15,40–46]), Figure 1 shows the value range and average value of the efficiencies of electricity generation of the technologies under assessment. It can be observed that natural gas-fired power plants occupy the top efficient technology with an average value of 47%, whereas PV has the lowest efficiency of around 13% with a possible maximum of 22%. However, the German Frauenhofer Institute of Solar Energy Systems and the French Soitec Institute have developed certain types of PV panels that are very expensive to use commercially but can reach an efficiency of 46% [47].

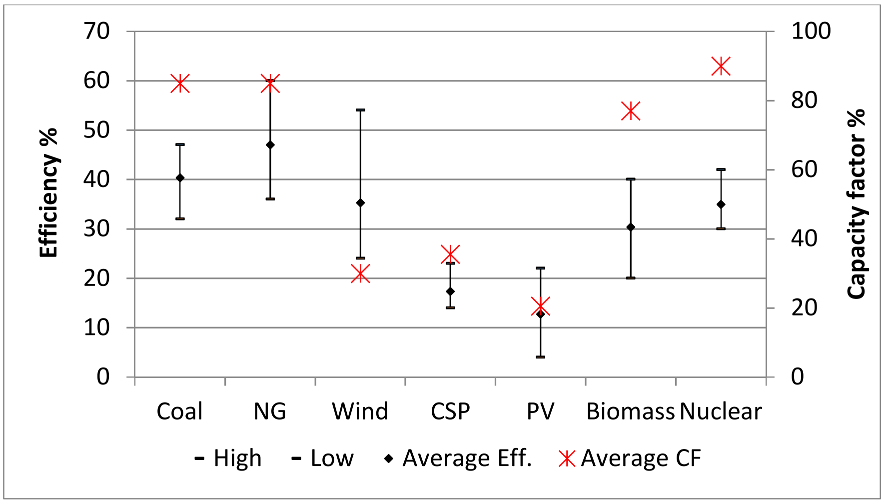


Figure 1. Efficiency of electricity generation and capacity factor of technologies under assessment [15,40–46].

3.1.2. Reliability of Energy Supply

This indicator can be defined as the security of continuous power supply of the system in terms of performance, resistance to failure, and the ability to function as designed without interruption [12]. It could be evaluated in a broad sense qualitatively with an ordinal scale or quantitatively through the technology capacity factor which is the ratio of the actual power output to the theoretical maximum power output from the technology over a period of time and/or the availability factor which is the fraction of time that the technology is able to generate energy over a certain period, divided by the total amount of the time in that period [4]. In practice, these two factors are easily estimated and reflect any kind of interruptions of the system that could arise by evaluating the historical data. Based on data obtained from a platform website linked to the National Renewable Energy Laboratory (NREL) that gathers published data from 2007 till 2015 concerning energy technologies, Figure 1 shows the differences in the capacity factors of energy systems that reflects the reliability indicator [48]. It is quite plausible that fuel-based power plants are more reliable than weather-dependent technologies like solar and particularly wind power plants, varying strongly with weather and climate. However, technology developments are able to overcome this issue by offering energy storage mechanisms (i.e., thermal storage systems, batteries) that could compensate the fluctuation of the supply.

3.1.3. Resource Potential

63% of the world's petroleum reserves and 41% of the world's natural gas reserves are in the Middle East [41]. According to the U.S. Energy Information Administration (EIA) as of 1 January 2015, Egypt held 4.4 billion barrels of proven oil reserves, and 77 trillion cubic feet of proven natural gas reserves [31], but it has no significant reserves for coal. Egypt has significant solar and wind potential. According to a study conducted by Deutschen Zentrums für Luft- und Raumfahrt German Aerospace Center (DLR), Egypt has a potential of 7650 TWh/year, 73,656 TWh/year, 36 TWh/year, 15.3 TWh/year for wind, CSP, PV, and biomass, respectively [49]. In order to estimate the resource potential for coal, natural gas and nuclear in terms of TWh/year, we utilize the reserve capacity of each. Based on an assumption that no more reserves will be discovered, the current reserves will be used till 2100 and they are allocated only for electricity production, we calculate the potential annual electricity production from these reserves. According to US EIA, Egypt has a reserve capacity of 18 million short tons of coal [50] and 77 trillion cubic feet of NG [51]. The average heat rate of coal and natural gas steam power plants is 10,080 Btu/kWh and 10,408 Btu/kWh, respectively. The heat content of coal and natural gas is 19,420,000 Btu/Short ton and 1,029,000 Btu/Mcf (Mcf = 1000 cubic feet, MMcf = 10^6 cubic feet), respectively. The amount of fuel required to produce 1 kWh equals to the heat rate divided by the heat content of the fuel [52]. Therefore, the estimated annual electricity production from the reserve capacity is 0.41 TWh/year and 90,588.24 TWh/year for coal and natural gas, respectively. The reserve capacity of Uranium in Egypt has been recently announced to be 1900 tonnes of type (<260 USD/kgU) [53]. 1 kg of Uranium could generate 24 GWh [54]. Thus, the potential of nuclear power in Egypt is about 536.47 TWh/year. The previous data are summarized in Tables 2 and 3.

Table 2. Energy conversion data for coal, natural gas and nuclear [50–54].

Technology	Reserves	Heat Rate (Btu/kWh)	Heat Content	Amount to Produce 1 kWh	Reserves in TWh
Coal	18 (million short tons)	10,080	19,420,000 (Btu/Short ton)	0.00052 (short tons)	34.6
NG	77 (trillion cubic feet)	10,408	1,029,000 (Btu/Mcf)	0.01 (Mcf)	7,700,000
Nuclear	1900 (tonnes)	-	-	0.042 mg	45,600

Table 3. Resource potential of technology under assessment.

Resource Potential	Coal	NG	Wind	CSP	PV	Biomass	Nuclear
TWh/year	0.41	90,588.24	7650	73,656	36	15.3	536.47

3.1.4. Water Consumption

Water losses can occur during various stages of the life cycle of the power plant, in particular during manufacturing and installation as well as during operation of the system which in the following will be our main focus. Generally, thermal power plants which are fired by fossil fuels or biomass or those heated through solar radiation or nuclear reaction have more water losses especially those using water cooling condensation systems. Alternative solutions are the use of air cooling, pressure management and the use of desalinated sea water or treated sewage water. Solar concentrators and PV panels consume water in the cleaning process but it is negligible. Wind systems have the lowest water consumption followed by photovoltaics as compared to other systems [15]. Biomass has the highest water consumption if we considered the water used in the irrigation of the trees and bio-crops. This indicator shows a great importance to our case study since Egypt is expected to face a shortage of water as a consequence of climate change impacts and because of the Great Renaissance Dam that is nowadays under construction in Ethiopia and could affect water supply to Egypt from the Nile River with potential multiplier effects on agriculture and drinking water. Figure 2 displays the consumed water across different power supply technologies. Coal, NG and nuclear power plants consume water in the range of 15 to 78 kg/kWh, whereas PV consumes water at a rate of 1–10 kg/kWh and wind power plants do not exceed 1 kg/kWh [15,41]. Biomass power plants have a significant variance in water consumption due to the different types of biomass technologies used where it ranges from 18.5 to 250 kg/kWh [44]. It has been estimated that solar thermal power plants consumes water at a rate of 900 gallons/MWh which is equivalent to 3.4 kg/kWh (1 gal = 3.79 kg water) [55] which is quite smaller than that consumed by other thermal power plants.

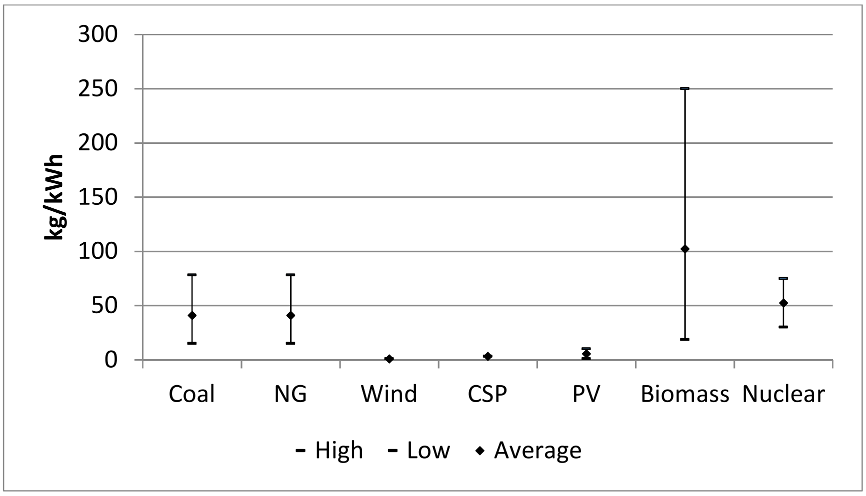


Figure 2. Water consumption by different energy systems [15,41,44,55].

3.2. Economic Indicators

3.2.1. Investment Cost

Investment cost includes all costs related to the construction and installation of power plants, purchased equipment, engineering and consultation services and any costs that may arise before the operation of the power plants. It includes neither fuel costs, nor maintenance costs. Nuclear and coal-fired units are characterized by high investment costs and low operating costs while gas-fired generation is characterized by lower capital costs and higher operating costs [12]. Photovoltaics and solar thermal power still suffer very high investment costs that restrain their propagation although they consume free energy resources. Figure 3 shows a comparative analysis of the investment costs of different power technologies. The investment costs range between 1300 and 2400 USD/kW for coal power plants, 450–1060 USD/kW for NG power plants, 1460–1730 USD/kW for wind power plants, 4260–5850 USD/kW for CSP plants, 2080–5000 USD/kW for PV, 2240–3330 USD/kW for biomass power plants and 2950–7980 USD/kW for nuclear power plants [46,48,56,57]. Still CSP represents the most expensive technology however it shows a comparable average value as that of nuclear. NG shows the cheapest power plants which justifies their preferences by most of the investors. Interestingly the average investment costs of wind power plants are cheaper than that of coal by about 300 USD/kW which is a significant value.

3.2.2. Operation and Maintenance (O&M) Cost

Related cost factors include employees' salaries, fuel costs, engineering and consultation services, and the funds spent on the maintenance of the system including purchasing spare parts in order to prolong energy system life and avoid failures that may lead to interruption of the system. Basically, it is much cheaper to regularly maintain the system than to repair any damage after occurrence and it ensures more security of the system supply [12]. In our case study, these costs are very important since it is often mentioned in the media and during my interviews that one of the major causes of the frequent blackouts is that some parts of the plants became out of service due to the age of these parts as well as improper regular maintenance [31]. Figure 3 shows that the annual average O&M costs [46,48,56,57]. CSP, biomass and nuclear power plants show comparable high values in contrast to coal, wind and PV, whereas NG shows the lowest average O&M costs.

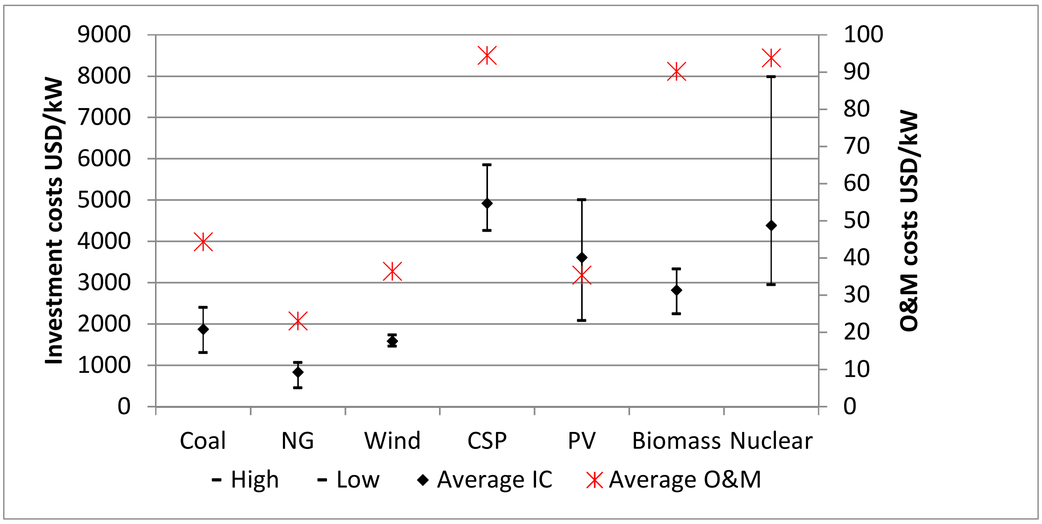


Figure 3. The investment costs and the operation and maintenance (O&M) costs of the assessed technologies [46,48,56,57].

3.2.3. Cost of Electricity

The price of electricity offered by the power generation system includes all the costs over the lifetime of the systems: initial investment, operation and maintenance, fuel cost, and cost of capital [58]. It is also influenced by the typical characteristics of the technology, such as efficiency, annual production, service life, and the nature of the energy source utilized. In Figure 4, the average cost of electricity generation for coal, NG and nuclear are comparable at a value of around 0.05 USD/kWh, for wind and biomass it is almost doubled, whereas for CSP and PV, it is particularly very high of 4 and 6 times the average values of coal, respectively [15,41–43,45,46,48,59]. Surprisingly, we found in the literature [41] a wide value range for PV which again reflects the different designs and technological features.

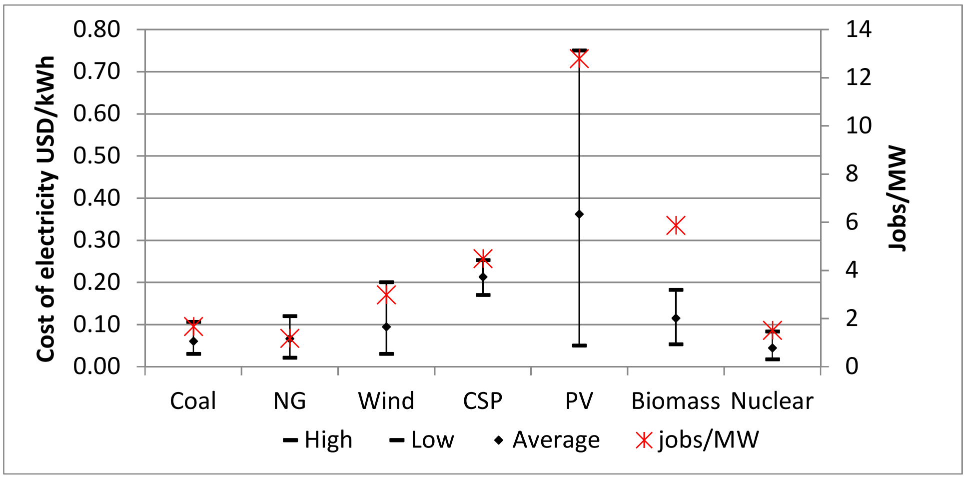


Figure 4. Electricity generation costs and job creation of the assessed technologies [15,41–43,45,46,48,59].

3.2.4. Job Creation

Job creation represents economic and social dimensions of sustainable development. As jobs are created by the energy system, they improve the quality of life of local society [9] and reduce unemployment. Throughout the life cycle of the power plants, many people are employed either in direct jobs like in manufacturing, installation, operation and maintenance or in indirect jobs like the suppliers of equipment, construction and installation materials [12]. A study was done by the World Bank assessing the potential of local manufacturing of concentrated solar power plants in Egypt. The study revealed that Egypt's key strengths on production factors are: low cost of labor and of energy for industrial consumers; availability of glass, steel, and stainless steel; and a strong manufacturing capability [60]. Figure 4 shows the potential jobs that could be created for each type of power systems in the construction, installation, manufacturing, O&M and fuel processing sectors [61,62]. Interestingly, PV shows the highest job creation potential with an average value of 13 jobs/MW whereas coal, NG and nuclear are below 2 jobs/MW.

3.3. Environmental Indicators

3.3.1. CO_2 Emission

CO_2 emissions are mainly released from the combustion of fossil fuels that are chemically composed of hydrocarbons. As the percentage of carbon in the fossil fuels increases, the emission of CO_2 increases (see Figure 5). Coal is the highest emitting source followed by natural gas (methane). Renewable and nuclear systems have the potential for nearly zero CO_2 emissions, as well as hydrogen if provided by non-fossil energy sources. However, the emissions from these energy systems mostly come during the construction phase, in transportation or from the backup fuel combustion. It represents a major greenhouse gas contributing to 9–26% in global warming and climate change [9]. Recently, many international organizations are concerned about climate change and develop mechanisms to reduce CO_2 emissions, giving this indicator a high importance in assessing sustainability. Different methods have been proposed to capture CO_2 emissions either through climate engineering, adaptation or mitigation measures with different degree of success [12].

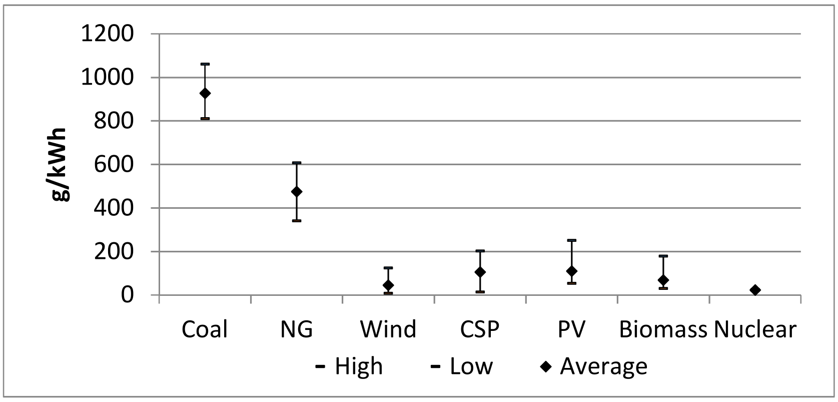


Figure 5. CO_2 emissions from the technologies under assessment [19,40–45,63].

3.3.2. NO_x Emission

Nitrogen monoxide and nitrogen dioxide (NO and NO_2) are emitted from the combustion of biomass and fossil fuels at high temperature. The greenhouse gases contribute to global warming and climate change, and moreover cause local air pollution and acid deposition, may do harm to the health of people, affect agricultural products and cause biological mutation as they form toxic products in reaction with ammonia, moisture, volatile organic compounds, common organic chemicals, and even ozone [9,12]. According to a literature review, Figure 6 gives evidence of the contribution of biomass and fossil combustion to a great extent in the emission of NO_x gases, where it could reach almost 4 g/kWh for coal and NG and more than 1.5 g/kWh for biomass. However, the other technologies show an emission of lower than 0.5 g/kWh.

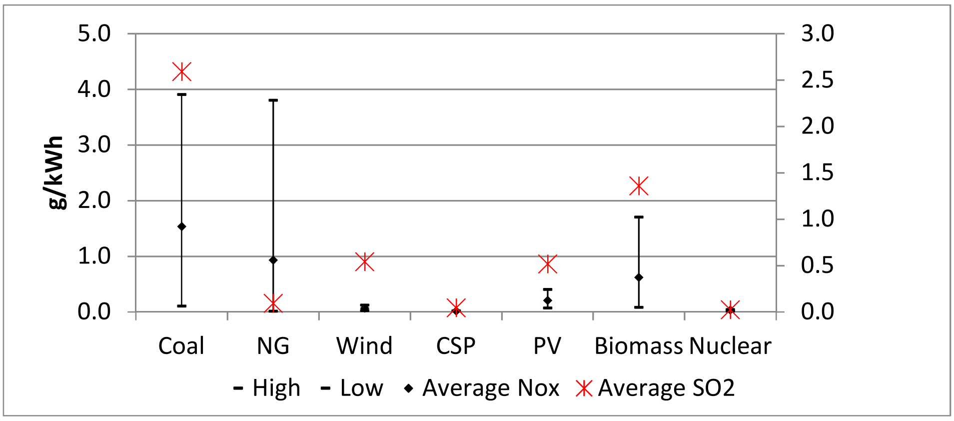


Figure 6. NO_x and SO_2 emissions from the technologies under assessment [40,43,45,63–66].

3.3.3. SO_2 Emission

Sulphur dioxide is a third important harmful gas emitted as a result of fossil fuels combustion and during the smelt of aluminum, copper, zinc, lead and iron that are used for the construction of renewable energy components. It is a physically colorless gas or liquid with a strong offensive choking odor. Additionally, it forms sulphuric acid rain (H_2SO_4) which has very harmful effects especially on the respiratory system of humans and on damaging agricultural products. Again, it contributes to a great extent to climate change and environmental damage. Some efforts have been done to reduce this kind of emissions through chemical processes of desulfurization [9,12]. Figure 6 shows a high potential of SO_2 emissions from coal and biomass due to the high Sulphur content. However, NG emits low SO_2 as compared to wind and PV, although it is a fossil fuel that is combusted to generate electricity. This justifies the contribution of the manufacturing components to the emission of SO_2 but on the other hand it is more controllable than the emission in the operation process.

3.4. Social Indicators

3.4.1. Safety Risks

Safety risks can be assessed in terms of accident fatalities per energy unit produced in different fuel chains [67–69]. It represents a vital issue to society, and people's life including safety measures for employees on site that must be guaranteed. Safety combines both the social and technical dimensions of sustainability [12]. In some cases, power plant accidents are catastrophic affecting residents near the power plants. This perspective on severe accidents may lead to different system rankings, depending on the individual risk aversion [70]. Apparently, safety measures add more costs to the system for preventive measures but at the same time they save much of the costs resulting from accidents due to corrective measures. The assessment of this indicator is presented in Table 4 with an emphasis on the greatest risk potential of nuclear power plants with an average value of 13.6 fatalities/GWeyr while considering immediate and latent fatalities [71]. This explains the tendency of many developed countries to decommission their own nuclear power plants and the transition into safe and clean technologies.

3.4.2. Social Acceptability

Social acceptability ensures the contribution of all stakeholder opinions and interests in the decision-making process and gives the feeling of respect and consideration to the public sector which is affected by the project. It represents a feedback on the perceived impact of the energy system on the landscape from an aesthetical point of view in terms of noise, visual and odor aspects. It is a very important social indicator since the rejection and opposition of the project by a group of people may lead to conflicts, delay the implementation, and in worst cases entirely damage the project. This indicator could be assessed qualitatively through surveys and public hearings with the local community [12]. In order to asses this indicator, we conducted a bi-lingual online anonymous survey. After introducing the main idea and the objective of the survey, it proceeds to five questions that have been designed in a way that insures the validity of the responses.

Table 4. Risk assessment data of energy systems in non-Organisation for Economic Co-operation and Development (non-OECD) countries [71].

Technology	Accidents	Fatalities	Fatalities/GWeyr	Ranking
Coal: w/o China	1600	31,580	1.08	6
China	——————-No Data———————		9.06	
Natural Gas	77	1549	0.202	5
Wind (in OECD)	6	6	0.00829	3
CSP	——————————No Data——————————			1
PV	——————-No Data——————-		0.000245	2
Biomass	3	21	0.0149	4
Nuclear: immediatelatent	1	31 4000–33,000	0.0302 8.76–32.1	7

The first question asks about the awareness and knowledge extent of the technologies under assessment which reflects the weights of their responses on the subsequent questions. The other four questions end up with the same target, the extent of acceptance of the technology, but have been formulated in four different dimensions. Thus, the second question deals with a general support of the installation of the technology in Egypt; the third question is concerned with how fast the technology should be installed; the fourth question focuses on individual concern about the installation of the power plant near to the residence location; the last question asks for ranking the technologies according to preferences. From the survey, we get an average weighted value for each technology and each question as shown in Table 5. Finally we integrate the five questions by multiplying Q1 by the summation of Q2–Q5. Wind comes in the first top accepted technology; however, biomass is the least accepted because of lack of awareness.

$$\text{Social acceptability ranking} = \text{Q1} \times (\text{Q2} + \text{Q3} + \text{Q4} + \text{Q5}) \tag{1}$$

Table 5. Collective responses on social acceptability from the online survey.

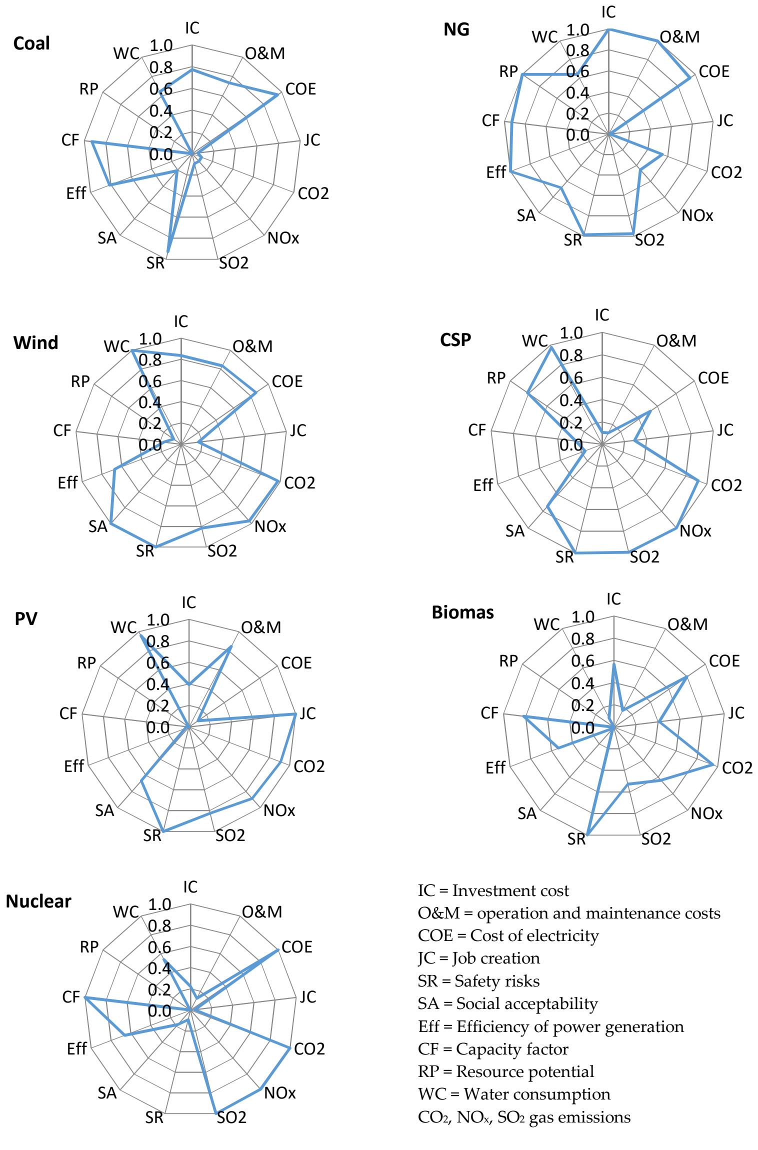
Aim of the Question	Coal	NG	Wind	CSP	PV	Biomass	Nuclear
Q1. Knowledge	1.67	1.93	2	1.53	1.33	0.3	1.23
Q2. Technology Support	1.27	2.83	3.47	3.57	3.6	2.57	1.73
Q3. Years of installation	2.11	3.32	3.82	3.75	3.79	3.357	2.46
Q4. Near to living area	0.5	1.18	2.82	2.82	3.04	2.21	0.32
Q5. Technology Ranking	1.76	4.68	6.08	6.08	6.68	4.44	2.48
Social acceptability ranking	9.42	23.18	32.38	24.82	22.76	3.77	8.60

Some of the selected criteria represent on the one hand costs that investors always seek to avoid or to minimize as in the case of investment cost. On the other hand, the other indicators represent values that are in favor by investors, for example plant efficiency. In other words, some indicators are directly proportional to sustainability while others are inversely proportional to sustainability. Moreover, the integration of values of multi-criteria requires a standardization of the measurement scale. Some studies prefer to use the monetary sensible evaluation of the criteria which influence greatly the decision making process as most of the decisions are built on the economic evaluation. Here we apply the feature scaling standardization method. The formulas are shown below:

$$\frac{(v - v_{min})}{(v_{max} - v_{min})} \tag{2}$$

$$\frac{(v_{max} - v)}{(v_{max} - v_{min})} \tag{3}$$

The first formula is used when the indicator represents a value, whereas the second formula is used when the indicator represents a cost, so that ultimately, we get a value between 0 and 1 for each criterion across the assessed technologies with an equal interpretation (i.e., 1 means the best). A comparison of the normalized multi-criteria evaluation of the technologies under assessment is shown in Figure 7.



IC = Investment cost
O&M = operation and maintenance costs
COE = Cost of electricity
JC = Job creation
SR = Safety risks
SA = Social acceptability
Eff = Efficiency of power generation
CF = Capacity factor
RP = Resource potential
WC = Water consumption
CO_2, NO_x, SO_2 gas emissions

Figure 7. Normalized multi-criteria evaluation of energy systems.

4. The Multi-Criteria Decision Analysis

The multi-criteria decision analysis MCDA represents a decision-making approach for the evaluation of sustainability of a system in an integrated form. It addresses complex problems while considering the evolving biophysical and socio-economic systems. It has been widely applied in different fields like social, economic, agricultural, industrial, ecological and biological systems. Moreover, it plays an important role in energy systems planning especially after the increased concern on environmental protection. The theory is based on comparing different alternatives by identifying a set of evaluation criteria applicable to all of these alternatives. The values of these criteria are then normalized, and their weights are determined according to the relative importance of the criteria. The main objective of MCDA is to integrate the weights and the normalized values of the criteria so that each alternative acquires an integrated value that reflects its ranking as expressed by the following matrix [12]:

$$\begin{array}{ccc}
 & \textit{Criteria} & \begin{array}{cccc} a_1 & a_2 & \cdots & a_n \end{array} \\
 & \textit{Weights} & \begin{array}{cccc} w_1 & w_2 & \cdots & w_n \end{array} \\
\textit{Alternatives} & & \\
\begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & & \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}_{mxn}
\end{array} \tag{4}$$

where x_{ij} is the performance of the jth criteria of the ith alternative, w_j is the weight of criteria j, n is the number of criteria and m is the number of alternatives.

4.1. The Analytical Hierarchy Process (AHP)

The analytical hierarchy process (AHP) was proposed primarily by Saaty [72] and is based on the decomposition of a complex problem into a hierarchy with an objective at the top of the hierarchy, indicators and sub-indicators at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy as shown in Figure 8. Here, we evaluate the weight of the indicators in a pair-wise comparison using the scoring system presented in Table 6 with an objective of their importance regarding energy technology selection according to the perspectives of participants in the questionnaire we designed.

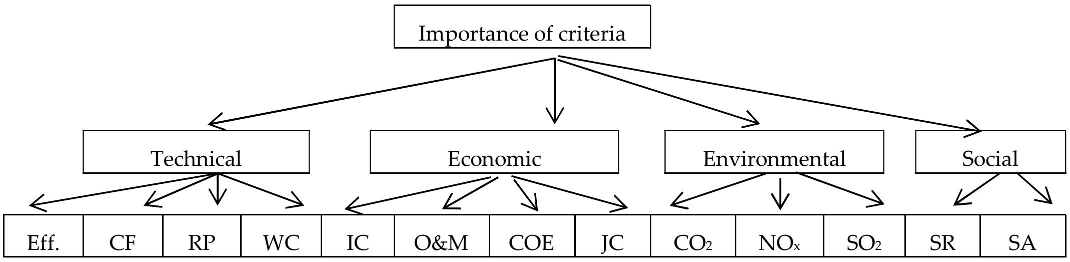


Figure 8. Illustrative scheme of the AHP network (IC: Investment cost; O&M: operation and maintenance costs; COE: Cost of electricity; JC: Job creation; SR: Safety risks; SA: Social acceptability; Eff.: Efficiency of power generation; CF: Capacity factor; RP: Resource potential; WC: Water consumption; CO_2, NO_x, SO_2 gas emissions).

Table 6. Scoring scale of AHP and its interpretation [12].

Scale	Degree of Preference
1	Equal importance
3	Weak
5	Strong
7	Very strong
9	Extreme importance
2, 4, 6, 8	Intermediate values

As can be seen in Table 7, the assessment indicators (C1–C7) are sorted in a matrix to enable the pair-wise comparison between them. Then, we performed the following steps:

Table 7. Illustrative example for the explanation of the AHP methodology.

	A	B	C	D	E	F	G	H			
1		C1	C2	C3	C4	C5	C6	C7			
2	C1	1.00	0.11	0.14	0.20	0.20	0.13	0.11			
3	C2	9.00	1.00	3.00	4.00	4.00	2.00	1.00			
4	C3	7.00	0.33	1.00	2.00	2.00	0.50	0.33			
5	C4	5.00	0.25	0.50	1.00	1.00	0.33	0.20			
6	C5	5.00	0.25	0.50	1.00	1.00	0.33	0.20			
7	C6	8.00	0.50	2.00	3.00	3.00	1.00	0.50			
8	C7	9.00	1.00	3.00	5.00	5.00	2.00	1.00			
9	Total	44.00	3.44	10.14	16.20	16.20	6.29	3.34			
10											
11		C1	C2	C3	C4	C5	C6	C7	Total	Average	Consistency measure
12	C1	0.02	0.03	0.01	0.01	0.01	0.02	0.03	0.15	0.02	7.04
13	C2	0.20	0.29	0.30	0.25	0.25	0.32	0.30	1.90	0.27	7.24
14	C3	0.16	0.10	0.10	0.12	0.12	0.08	0.10	0.78	0.11	7.18
15	C4	0.11	0.07	0.05	0.06	0.06	0.05	0.06	0.47	0.07	7.10
16	C5	0.11	0.07	0.05	0.06	0.06	0.05	0.06	0.47	0.07	7.10
17	C6	0.18	0.15	0.20	0.19	0.19	0.16	0.15	1.20	0.17	7.26
18	C7	0.20	0.29	0.30	0.31	0.31	0.32	0.30	2.02	0.29	7.27
19										CI	0.03
20										RI	1.32
21										CR	0.02

Step 1: we compare each criterion in column A with the criteria row 1 according to their importance in the assessment of the technologies from the perspectives of the stakeholders. Thus, for example when comparing C1 with C2, if C1 is more important than C2, therefore C1 will acquire one of the integer values presented in Table 6 except the value 1 which means an equal importance, whereas C2 when compared with C1 will acquire the reciprocal of the value of C1.The cells in the lower left triangle (the blue cells) are the reciprocal of those in the upper right triangle (the red cells) of the matrix. Actually the data acquired from the questionnaire to apply this methodology are the answers of the pair-wise comparison of the red cells only.

Step 2: we sum up the scores in each column vertically and we add the total values in row 9.

Step 3: we construct a similar matrix below the old one in which the score value in each equivalent cell is divided by the total value in each column. For instance, in column B, 1 is divided by 44; then 9 is divided by 44 and so on.

Step 4: we sum up the normalized values in each row of the new matrix horizontally forming a new column called total.

Step 5: we divide the values in the total column by the number of indicators to get the average values which corresponds to the weights of the indicators in each row [73].

One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision maker's inconsistency and randomly generated index. This index is important for the decision maker to assure that his/her judgments were consistent and that the final decision is made well. The inconsistency index should be lower than 0.10. Although a higher value of inconsistency index requires re-evaluation of pair wise comparisons, decisions obtained in certain cases could also be taken as the best alternative [11]. In order to measure the consistency of our collected data, we calculate the consistency ratio (CR). We first calculate the consistency measure (CM) by multiplying all the values of the corresponding row in the first colored matrix (i.e., the one with the original scores) by all values in the average column then divide it by the corresponding cell in the average column:

$$\text{CM12} = \frac{\text{MMULT (B2:H2, Average12:Average18)}}{\text{Average12}} \tag{5}$$

Then we calculate the consistency index value (CI) is calculated through subtracting the number of indicators (n) from the average value of the consistency measure (λ) and divide it by the ($n - 1$)

$$CI = \frac{(\lambda - n)}{(n-1)} \tag{1}$$

$$CR = \frac{CI}{RR} \tag{2}$$

The random index (RI) is the CI of randomly generated pair-wise comparison matrix (see Table 8) [72].

Table 8. Random consistency index (RI) at different number of indicators (n) [72].

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

We apply this methodology to collect subjective data via developing a questionnaire that has been distributed to stakeholders through interviews and emails. In the questionnaire we expect the stakeholders to answer the research question: How important are the assessment indicators relative to each other in their evaluation of power plants? The questionnaire includes pair-wise comparison questions of the assessment criteria regarding their importance in the assessment of the technologies. The main objective of this questionnaire is to know the preference order of the sustainability assessment criteria in the evaluation of the technologies by the stakeholders. Then we use these inputs in getting the weights of the criteria and subsequently the weights of the sustainability assessment dimensions using the AHP methodology. Although we faced some difficulties to arrange for meetings with some important actors in the energy sector in Egypt, we were able to collect 40 responses.

4.2. The Weighted Sum Meod (WSM)

The weighted sum method (WSM) is the most commonly used approach in sustainable energy systems [12] and satisfies the following expression:

$$A_i = \sum_{j=1}^{n} \left(a_{ij} w_j\right), \text{ for } i = 1, 2, 3, \ldots, m$$

where A_i is the WSM score of alternative i, n is the number of decision indicators, m is the number of alternatives, a_{ij} is the normalized value of the jth indicator in terms of the ith alternative and w_j is the weight of the jth indicator that has been obtained from the AHP. The total value of each alternative is equal to the sum of products, which is ultimately used to rank, screen or choose an alternative with the maximum score. From this step we get the general integrated sustainability index of the technologies through the multiplication of the normalized values of the assessment indicators by the weights of the indicators that have been obtained from the AHP. From this index we get the ranking of the technologies per each stakeholder and for each scenario.

Iorder to validate the individual responses in getting the weights of the criteria, we applied the Monte-Carlo validation. Monte-Carlo methodology is a widely used class of computational algorithms for simulating the behavior of various physical and mathematical systems, and for other computations. It is used also to find solutions to mathematical problems that cannot easily be solved. Additionally, it is a statistical simulation technique that provides approximate solutions to problems expressed mathematically. It utilizes a sequence of random numbers to perform the simulation. In this approach the probability of technology ranking by the contributors in the questionnaire is compared with simulated probability of technology ranking over a specified number of simulated observations that generate a random value between 0 and 1. The number of the simulated observations could be from hundreds to thousands of values based on the accuracy of the simulation needed. The more simulated observation is, the higher the accuracy will be. Here, we run the simulation over 1000 random values.

Table 9 shows an illustrative example for explaining the Monte-Carlo methodology. We have seven possibilities of the ranking order of one of the assessed technology as can be observed in Column G. Column B shows the real observations of the stakeholders of the ranking order of technology X as we obtained after applying the MCDA. In this example we have only nine observations whereas in our study we have 40 observations.

Table 9. Illustrative example for the explanation of the Monte-Carlo validation technique.

Technology X									
A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
Random	**Value**	**Frequency**	**Probability**	**Low Value Range**	**Cum. Prob.**	**Possible Value**	**Value Lookup 3**	**Frequency Simulated**	**Prob. Sim.**
0.820153	1	1	0.11	0	0.11	1	6	117	0.117
0.629366	2	1	0.11	0.11	0.22	2	5	138	0.138
0.65743	3	2	0.22	0.22	0.44	3	5	239	0.239
0.53468	4	1	0.11	0.44	0.56	4	4	100	0.1
0.668602	5	2	0.22	0.56	0.78	5	5	207	0.207
0.145975	6	1	0.11	0.78	0.89	6	2	98	0.098
0.039551	7	1	0.11	0.89	1	7	1	101	0.101
0.590085	5	9	-	-	-	-	5	1000	-
0.698039	3	-	-	-	-	-	5	-	-
n = 1000	-	-	-	-	-	-	-	-	-

In Column C, we calculate the frequency of each possible value in Column G in the observations column (Column B). Then in Column D, we calculate the probability of each corresponding value in the frequency column by dividing the frequency value by the total number of observations. In Columns E and F, we build up a value range of the probability. In column A, we generate a random value from 0 to 1 in a number of cells based on the desired simulated iteration (e.g., 1000). In Column H, we pick up the corresponding possible value when the random value falls in the corresponding range. For instance, the first random value equals to 0.820153 which falls in the range between 0.78 and 0.89 which in turn corresponds to the possible value 6. Thus, the first cell in Column H will be 6. In column H, we get 1000 values of simulated ranking of the technology. In Columns I and J, we calculate again the frequency and the probability of the possible values but in the simulated observations [73].

The Monte-Carlo methodology could be applied also to assess the uncertainty of ranking of the technologies due to the wide range of values of the criteria. Thus, the ranking could change dramatically if the high or the low values instead of the average values of the indicators are used.

5. Results and Discussion

By applying the AHP approach after including the responses of the stakeholders on the questionnaire, we are able to get the weights of the criteria and subsequently the weights of the sustainable dimensions. We are concerned here more with the weights of the sustainable dimensions than the weights of the criteria since the assessment of the technologies could include other criteria than the ones we used. Moreover, we would like to highlight which dimension the stakeholders prefer and are attracted to in their assessment. The average weights of the sustainability dimensions based on the preferences of the stakeholders show a higher affinity towards the economic and the social dimensions than towards the technical and the environmental dimensions as shown in Figure 9. In the sustainable scenario all dimensions have an equal weight of 0.25, whereas in the other four single dimension scenarios each scenario has a weight of one for a single dimension.

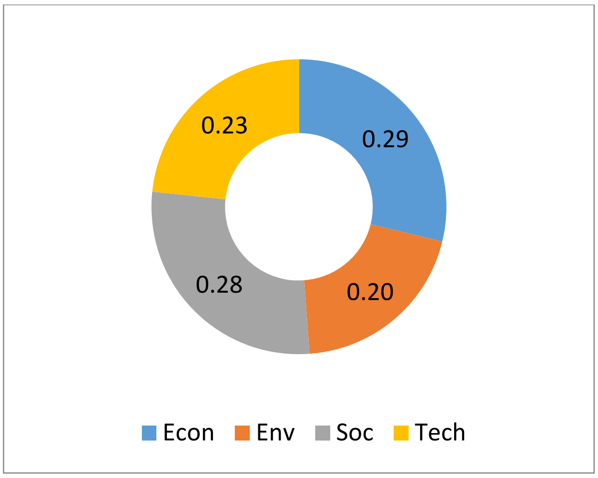


Figure 9. Weights of the sustainability dimensions according to the analysis of the preferences of the stakeholders.

After integrating the weights of the sustainability dimensions and the normalized values of the indicators using the WSM, we are able to get a general sustainability index of each technology per scenario covering the subjective and objective analysis. The values of these indices for each technology per scenario are shown in Figure 10. From these indices, we ranked the technologies in an order from 1 to 7, where 1 is the highest general integrated sustainable index technology as shown in Table 10.

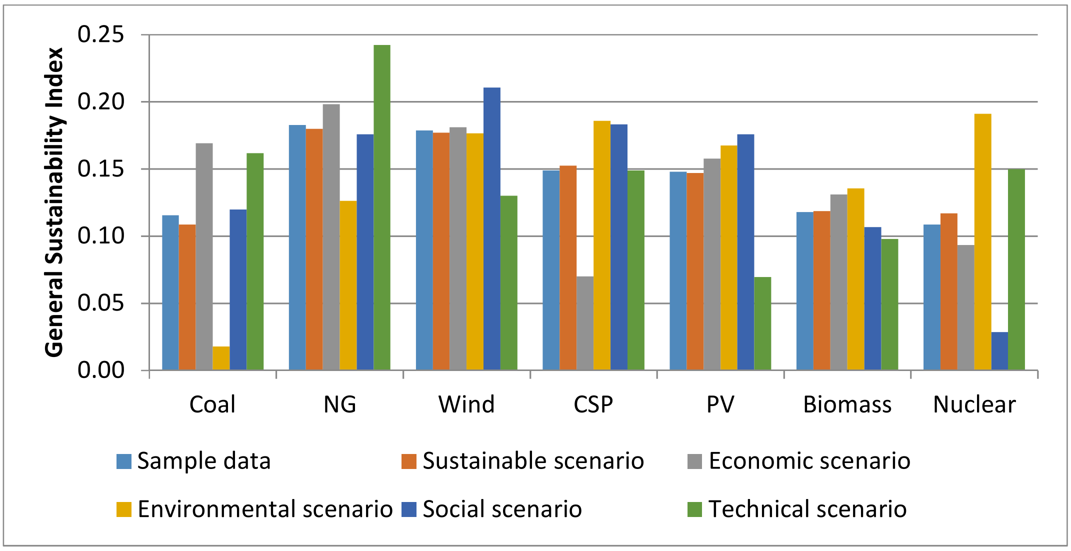


Figure 10. The general sustainability index of the technologies for the six assessed scenarios.

Table 10. Ranking of the technologies in the six scenarios.

Ranking	Sample Data	Sustainable Scenario	Economic Scenario	Environmental Scenario	Social Scenario	Technical Scenario
1	NG	NG	NG	Nuclear	Wind	NG
2	Wind	Wind	Wind	CSP	CSP	Coal
3	CSP	CSP	Coal	Wind	NG	Nuclear
4	PV	PV	PV	PV	PV	CSP
5	Biomass	Biomass	Biomass	Biomass	Coal	Wind
6	Coal	Nuclear	Nuclear	NG	Biomass	Biomass
7	Nuclear	Coal	CSP	Coal	Nuclear	PV

Comparing the sample data scenario with the sustainable scenario, we find that the values of the general integrated indices of the technologies are very close. We find also a conformity in the ranking of the technologies except in the last two rankings where nuclear shows the lowest ranking in the sample data scenario while coal shows the lowest ranking in the sustainable scenario. Although natural gas is a non-renewable technology, based on the employed assessment criteria it represents the highest-ranking technology in all scenarios except in the environmental and social scenario. This can be justified by its higher technical and economic viability as compared to other technologies. However, all renewable technologies are highly-ranked by the stakeholders and in the sustainable scenario than coal and nuclear in the ranking order: wind, CSP, PV and biomass. Moreover, the values of the general sustainable indices of natural gas and wind are very close showing a strong competition between both technologies. In the economic scenario, coal shows a higher potential than PV and nuclear, whereas CSP comes in the lowest ranking which explains why investors prefer to avoid this type of technology. In the environmental scenario, nuclear has the highest ranking in terms of the gas emissions. However, if we include the radioactive emissions and their ecological impacts, the ranking of nuclear will be most probably changed. It is plausible to have coal and natural gas in the lowest ranking of the environmental scenario due their major contributions to the gaseous emissions. In the social scenario, wind shows the highest acceptance and lowest safety risks as compared to other technologies. On the contrary nuclear brings high social rejection and low safety. Technically, PV still faces some challenges which lead to have the lowest ranking. However, CSP has a higher technical viability in Egypt than wind and comparable to nuclear.

Due to the individual variation in the ranking of the technologies among the stakeholders, we applied the Monte-Carlo validation methodology to measure the uncertainty of the ranking of the technologies which is based on the average values of the weights of the sustainability dimensions. The results of the Monte-Carlo simulation methodology over 1000 random values as shown in Figure 11 show some differences in the ranking of the technologies. PV shows a higher probability to occupy the third ranking position instead of CSP. Likewise, CSP shows a higher probability to occupy the fourth ranking position than the third one. The same applies between coal and biomass where the ranking of coal seems to be higher than biomass in contrast to their ranking based on the average values.

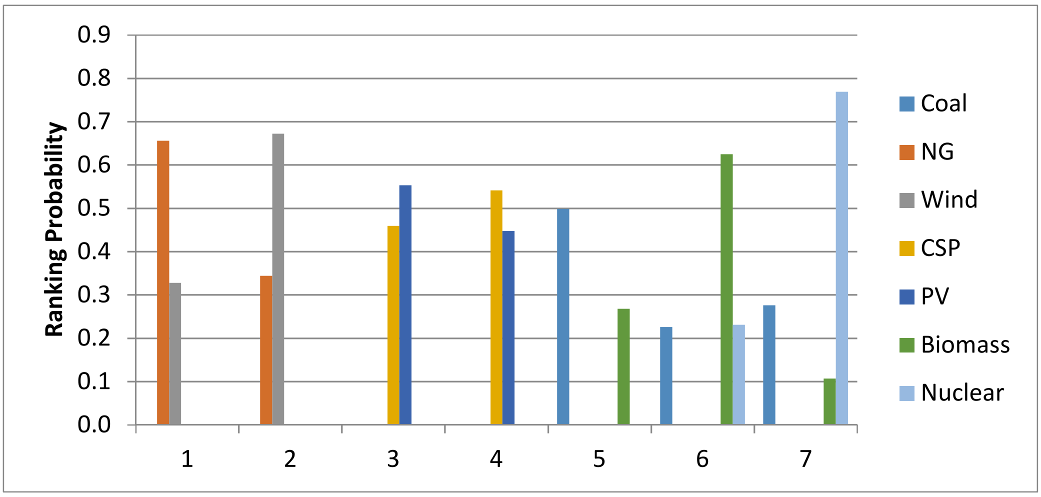


Figure 11. The probability of the simulated ranking of the technologies over 1000 observations by Monte-Carlo validation.

6. Summary and Conclusions

From this study, we conclude the affinity of the stakeholders toward natural gas power plants being ranked as the most sustainable technology in Egypt in comparison to other technologies followed by renewable energy technologies. However, coal and nuclear show a weak sustainability performance that would give them a low chance to invade the energy market in Egypt. Decision makers should spend their efforts on exploiting the potential renewable energy resources in Egypt. The social and environmental aspects of the technologies play an equally important role or may be higher as compared to the economic and technical aspects. There is interdependency between all the dimensions where the deficiency in one aspect would impact on all other aspects. The sensitivity analysis helps to correlate between specific technologies and certain dimensions of the sustainability. This in turn could influence the preferential evaluation of the indicators by the stakeholders in the future. The calculation of uncertainty using the Monte-Carlo approach increases the accuracy and the reliability of the results.

Moreover, we conclude two other important things in order to secure a sustainable development in the energy sector with its multiplier effects in other sectors. First, it is crucial to apply a multi-dimensional analysis while assessing potential electricity production technologies for future energy planning in Egypt as well as in any other countries. Second, it is necessary to include the behaviors of the stakeholders in their assessment of these technologies and to compare the results of their preferences with the results of objective assessment of the technologies. Last but not least, it is recommended to validate the results especially when there is a wide variation in the input data. For a future analysis, it is also recommended to assess the technologies in a dynamic fashion by considering the temporal and spatial variations of the values of the criteria and of the preferences of the sustainability dimensions given by the stakeholders.

Author Contributions: M.S., being the main author, was responsible for the idea and the conception of the study. He conducted different parts of the study that concerns with data collection, applying the methodology, analyzing and validating the results and writing the paper. J.S., J.B. and M.S.E. have assisted M.S., with their extended experience in research and publication, in data collection through the arrangement of the interviews with the stakeholders, in getting access to some literature, in the validation of the methodology and the results and provided valuable comments on the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

List of Abbreviations

AHP	Analytical Hierarchy Process
Btu	British thermal unit
CI	Consistency index
CM	Consistency measure
CR	Consistency ratio
CSP	Concentrated solar power
DLR	Deutschen Zentrums für Luft- und Raumfahrt (German Aerospace Center)
EEA	European Environment Agency
EEHC	Egyptian Electricity Holding Company
EgyptERA	Egyptian Electric Utility and Consumer Protection Regulatory Agency
ETSAP	Energy Technology Systems Analysis Program
EUROSTAT	Statistical Office of the European Communities
GHGs	Greenhouse Gases
GW	Gigawatt
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LCA	Life Cycle Assessment
MCA	Multi-Criteria Analysis
MCDA	Multi-criteria decision analysis
MCDM	Multi-Criteria Decision Making
MW	Megawatt
NG	Natural gas
NREA	New and Renewable Energy Authority
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
PCA	Principal Component Analysis
PV	Photovoltaic
SD	Sustainable development
SDGs	Sustainable Development Goals
TARES	Technical assistance to support the reform of the energy sector
TWh	Terawatt hour
UN	United Nations
UNCSD	The United Nations Commission on Sustainable Development
UNDESA	United Nations Department of Economic and Social Affairs
US EIA	United States Energy Information Administration
USD	United States Dollars
WSM	Weighted sum method

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