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Assessment of Energy and Exergy Efficiencies of Power Generation Sub-Sector in Jordan

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Abstract

The present article is dedicated for evaluating the power generation sub-sector in terms of energetic and exergetic aspects. In this regard, energy and exergy utilization efficiencies during the period 1989-2006 are assessed based on real data obtained from main generators in Jordan. Sectoral energy and exergy analyses are conducted to study the variations of energy and exergy efficiencies for each of the studied power plant, and overall energy and exergy efficiencies for the entire sub-sector are found to be in the range of 31.95 to 35.99%. When compared with other neighbouring countries, such as Turkey and Saudi Arabia, the Jordanian power sub-sector is more efficient, but the opposite was noticed as compared with some developed countries, e.g. Norway and Malaysia, for year 2000. Such difference is inevitable due to dissimilar structure of the utility sector in these countries. It is expected that that the results of this study will be helpful in developing highly applicable and productive planning for future energy policies, especially for the power sub-sector.

Keywords: Energy; Exergy; Efficiency; Utility Sector; Jordan

1. Introduction

The need to control atmospheric emissions of greenhouse and other pollutant gases and substances will increasingly shed its light on the efficiency of all energy conversion processes and applications especially power generation, transmission, distribution, and final demand represented by existing consumption patterns and technologies. On the other hand, some of known energy sources have been nearly exhausted nowadays. Hence, issues related to economic costing and efficient utilization of all natural resources, including energy, gained vital importance. For these reasons, deep analysis and evaluation of periodical data for power generation and other final energy-consuming sectors are essential, and are considered as primary conditions to accomplish some of the national goals, which are designed to achieve sustainable development in all sectors of the economy.

The present paper is among a series of practical articles, by authors, aimed to model various sectors and applications by employing insightful energy and exergy analysis [1-3], considered first of its kind in Jordan since there is no such study on energy and exergy utilizations for the power sub-sector. Thus, the prime objective of the present study is oriented towards determining energy and exergy losses and related efficiencies as first step to understand influence and weight of different factors. Furthermore, comparison of obtained results of energy and exergy efficiencies with other countries around the world will be carried out depending on published data in the open literature. As Jordan is considering and implementing the updated national energy strategy with more emphasis on energy efficiency policies in different sectors, it is believed that this investigation will provide a scientific judgment and insight to general performance of main generators and possible future improvements for energy policy implementation within the power sub-sector, and may be useful to engineers and scientists working in the field of energy in Jordan and some neighbouring countries.

2. Electricity Generation in Jordan

At present, after the privatization of the power sub-sector last year, there are three electricity generation companies in Jordan, not counting large industries such as Phosphate Mines, Arab Potash, Cement, Fertilizer Complex, Petroleum Refinery, and other plants owning and operating small and medium size power generation units [4]. Main generators in Jordan are:

2.1. Central Electricity Generation Company (CEGCO)

which was privatised at the beginning of 1999, and the state-shares were sold to Dubai Capital in 2007. It is solely an electric-power generator and main producer with total installed capacity exceeding 1700 MW.

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2.2. Samrah Power Generation Company (SPGCO)

which is a state-owned company that will be privatized in the near future, and it is a single power station utility located north-east of Amman. It is a combined cycle plant, which consists of 2x100 MW gas turbines and 100 MW steam turbine. The power station is supplied with Egyptian imported natural gas.

2.3. Manakher Power Generation Company

which is the 1st independent power producer (IPP) in Jordan located east of Amman; and is based on combined cycle technology firing imported natural gas from Egypt. The installed capacity is about 380 MW and expected to become fully on line next year, i.e. 2009.

It is worth mentioning that the government of Jordan represented by the Ministry of Energy and Mineral Resources and Electricity Regulatory Commission is in the process of licensing the 2^{nd} IPP in Jordan; and will build and operate a combined cycle power plant in Qatranh town, about 90 km south of Amman. It is expected that this plant will become on line by 2010.

In Jordan, there are 20 power stations with a total installed capacity of 2222 MW, 99.50% is thermal, and the remaining small percentage represents hydropower and wind turbines. Most of these are owned and operated by CEGCO with an installed capacity of 1700 MW, i.e. representing 77% of the total installed capacity and generating about 80%, i.e. 8966 GWh of the produced electricity in the kingdom during 2006 [4]. The remaining percentage was provided by SPGCO, the interconnected industrial companies and electricity imports from Egypt. Recently Jordan has not faced electricity shortages, and occasionally small amount of the generated electrical power has been exported to Syria. The supply of electricity is the largest single consumer of primary energy: it accounted for around 40% of primary energy consumption during last two years, compared with only 16% in 1980 [5]. But because of conversion i.e. generation, transmission, and distribution losses the relative importance of electricity in terms of primary energy, and carbon emissions is more than twice as compared to that indicated previously. The national electrical grid is connected to Egypt through a sub-marine cable across the Gulf of Aqaba in the south, and Syria in the north, via an overhead transmission line as part of the regional interconnection plan between seven countries including Egypt, Jordan, Syria, Lebanon, Jordan, Iraq, and Turkey. At present, all of the consumed electricity is produced locally employing conventional thermal power plants. However, small quantities of about 4% and 0.5% of that consumed during 2006 were imported from Egypt and Syria, respectively [5].

Figure 1 shows the percentage of electrical energy by type of generation in 2006 (CEGCO, 2007). It is obvious that almost all generated power came out from thermal power plants, and steam power plants ranked first with sharing ratio exceeding 53% of total generated power. This was followed by combined cycle power plants and gas turbines. Others, which represent only 0.5%, include wind, biogas, and hydro power units. About 99.4% of total electricity generated in 2006 by CEGCO came out from four power plants: Aqaba thermal, Hussein thermal, Risha, and Rehab with total productions of 3740, 1602, 657, and 2435 GWh, respectively. Before 2003, heavy fuel oil (HFO) was the dominant fuel used in the power sub-sector because the two main power stations, Aqaba and Hussein, are conventional thermal plants employing Rankine steam cycle; and are fired by such an inexpensive fuel. However, since 2003, imported natural gas from Egypt replaced HFO in Aqaba power station. In early 2006 diesel fuel at Rehab and Samrah power plants were replaced. In 2006, about 80.1% and 19.3% of the total electricity generated was produced using NG and HFO, respectively. While diesel fuel share dropped to less than 1% due to its substitution by natural gas in Rehab and Samrah power stations. Electricity harnessed via renewable sources like hydropower and wind accounted for only a negligible percentage of the total electricity generated (CEGCO, 2007). The dominant role of steam turbines, diesel-fuel fired gas-turbines, and combined cycle power plants is leading to increased dependence on imported natural gas and oil. Less than 8% of the electrical-power generation, at present in Jordan, arises from the exploitation of the indigenous domestic natural gas from the Risha field.

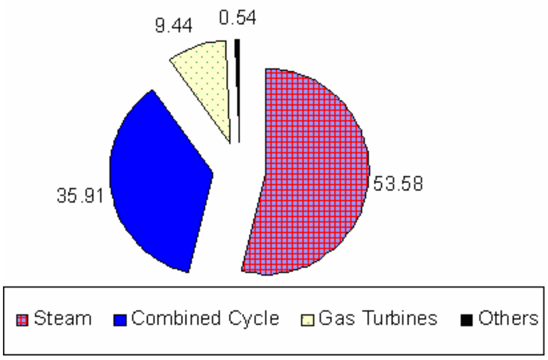

Figure 1 : Generated electrical energy in Jordan by type of generation in 2006.

The system's peak load in 2006 was 1901 MW, compared with 1751 MW in the previous year (2005) with a growth rate of 8.6%. The peak load used to occur during last three decades, late in the summer, i.e. during the July-September period. This is due to the excessive use of air-conditioning and ventilation systems as a result of the dry climate and high temperatures, as well as being the holiday season for tourists and many returning Jordanians, who normally work abroad. However, during the last few years, 2005-2007, the peak occurs during winter time because the government raised unit prices of petroleum products in an attempt to remove state-subsidy from various energy forms and ensure the full coverage of the economic costs involved. But the government postponed increasing the prices of electricity in order to enable consumers in the local market to absorb this price shock, and sooner or later prices of electricity and other strategic commodities will be increased. This is considered as a misleading message to the public, who will use high grade energy, i.e. electricity, for space heating purposes in different sectors instead of traditional petroleum products, i.e. kerosene, diesel, or LPG [6].

3. Energy and Exergy Modelling

In order to compare the quality levels of various energy carriers, e.g. fuels, it is necessary to determine the equivalents of each energy quantity at a particular grade level. This can be done by using exergy concept, which overcomes the limitations of the first law of thermodynamics; and is based on both the first and the second law of thermodynamics [7-8]. An exergy analysis can identify locations of energy degradation and rank them in terms of their significance [9]. This knowledge is useful in directing the attention of process design, researchers, and practicing engineers to those components of the system being analyzed that offer the greatest opportunities for improvement. Furthermore, exergy analysis has been used to analyze energy utilization on the national level and for various sectors of the economy in order to better understand energy utilization efficiency. This approach was first used by [10] who applied it to the overall U.S. economy in 1970. Since then, it has been adopted by several researchers for other countries such as Japan [11], Canada [12], and Brazil [13]. A summary of exergy analyses for different countries can be found in [14]. The concept has been also applied to cross-country analysis of some industrial segments [15-19], residential sector [20, 1], transportation sector [21-24, 2], agricultural sector [25-26, 3], and utility sector [27-29]. The purpose of this section is to discuss the main mathematical relations necessary to conduct energy and exergy analyses in the utility sector.

3.1. Exergy Calculation

By describing the use of energy resources in society in terms of exergy, important knowledge and understanding can be gained, and areas can be identified where large improvements could be obtained by applying efficient technology in the sense of more efficient energy-resource conversions. In principle, the exergy matter can be determined by bringing it to the dead state by means of reversible processes. The basic formulas used in exergy analysis modelling for this study are given below.

3.1.1. Exergy of Fuel

The specific exergy of the fuel at environmental conditions reduces to chemical exergy, which can be written as:

$$\varepsilon_f = \gamma_f H_f , \qquad (1)$$

where ε_f is the fuel specific exergy, γ_f the exergy grade function, and H_f the higher heating value of the fuel. Table 1 shows higher heating value, chemical exergy, and fuel exergy grade function of different fuels considered in this study [8, 10, 19, and 30]. As shown, in Table 1, all values of the exergy grade function are very close to unity. Consequently, the common practice in such cases is to assume that the exergy of the fuel is approximately equal to the higher heating value [31-32].

3.1.2. Exergy of Electricity

From the definition of exergy, electricity, W_e, is identical to the physical work exergy, E^{We}:

$$E^{We} = W_e , \qquad (2)$$

Table 1 : Higher heating value, chemical exergy, and exergy grade function for different fuels (at 25°C and 1 atm) [8, 10, 19, 30].

Fuel	H_f (kJ/kg)	ε_f (kJ/kg)	γ_f (ε_f /H_f)
Diesel	39,500	42,265	1.070
HFO	40,600	40,194	0.990
Natural Gas	55,448	51,702	0.930

3.2. Energy and Exergy Efficiencies

Energy efficiency (first law efficiency) is the ratio of energy contained in useful products of a process to energy contained in all input streams, while exergy efficiency (second law efficiency) is the ratio of exergy contained in the useful product to the exergy contained in all input streams. Energy efficiency (η) and exergy efficiency (ψ) are defined as:

$$\eta = \left(\frac{\text{energy in products}}{\text{total energy input}} \right) \times 100\% \qquad (3)$$

$$\psi = \left(\frac{\text{exergy in products}}{\text{total exergy input}} \right) \times 100\% \qquad (4)$$

Energy, η_e, and exergy, ψ_e, efficiencies for electricity generation through fossil fuels, m_f, can be expressed as follows:

$$\eta_e = (W_e / (m_f H_f)) \times 100\ \% \qquad (5)$$

$$\psi_e = (E^{We} / (m_f \varepsilon_f)) \times 100\% = (W_e / (m_f \gamma_f H_f)) \times 100\% = \eta_e \qquad (6)$$

Therefore, exergy efficiency for electricity generation process can be taken as equivalent to the corresponding energy efficiency [32].

4. Results and Discussion

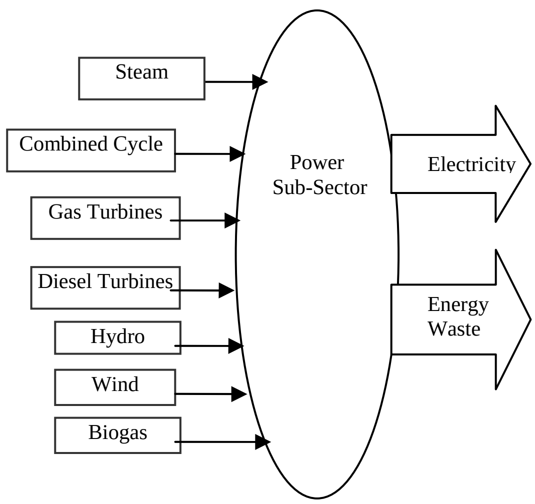

Figure 2 : An illustrative presentation of electricity production in Jordan.

As stated previously, electricity is mainly produced by means of thermal power plants in addition to small portions produced by using available renewable sources. Figure 2 shows an illustrative presentation of electricity production in Jordan. In order to simplify the analysis of energy and exergy efficiencies for this sector, energy consumption and electric production flows are analyzed for four power plants namely steam, combined cycle, gas turbines, and diesel engines that consume most of fuels, i.e. 99.5%, supplied to the power sub-sector.

Real data from the field has been obtained by compiling and analyzing scattered data collected from CEGCO, NEPCO, and SPGCO for a period spanned from 1989 to 2006 [4-5, 33]. This forms a unique point in this study by developing a comprehensive data, which is not published elsewhere. Tables 2 and 3 show energy consumption and electricity generation, respectively for each of studied four power stations.

Table 2: Primary energy consumption according to type of generator during the period 1989-2006 (1000 toe).

Year	Overall	Steam units	Gas turbines	Diesel engines	Combined cycle
1989	752.56	655.28	76.50	20.79	0.00
1990	813.20	681.76	117.09	14.35	0.00
1991	846.58	710.56	119.31	16.71	0.00
1992	1029.76	860.41	141.76	27.64	0.00
1993	1138.67	931.46	177.14	30.08	0.00
1994	1253.87	948.93	281.45	23.49	0.00
1995	1343.24	1016.21	308.01	19.02	0.00
1996	1448.85	1068.94	360.09	19.80	0.00
1997	1527.64	1065.74	443.08	18.83	0.00
1998	1632.09	1206.03	406.56	19.49	0.00
1999	1617.40	1355.63	260.02	1.75	0.00
2000	1686.09	1443.03	242.51	0.56	0.00
2001	1706.44	1471.99	234.05	0.40	0.00
2002	1808.04	1580.80	226.52	0.72	0.00
2003	1850.35	1558.55	291.51	0.28	0.00
2004	2118.57	1763.88	354.23	0.45	0.00
2005	2246.18	1860.12	273.90	0.51	111.65
2006	2183.13	1439.00	296.37	0.82	446.94

Table 3: Electricity generation according to type of generator being employed during 1989-2006 (GWh).

Year	overall	Steam units	Gas turbines	Diesel engines	Combined cycle
1989	3028.08	2657.03	282.14	88.91	0.00
1990	3246.43	2751.23	434.10	61.10	0.00
1991	3334.14	2835.25	428.13	70.75	0.00
1992	4001.92	3400.76	484.77	116.39	0.00
1993	4361.62	3628.91	608.56	124.15	0.00
1994	4658.56	3599.68	959.86	99.02	0.00
1995	5174.91	4057.36	1036.82	80.73	0.00
1996	5621.64	4319.54	1218.13	83.97	0.00
1997	5883.04	4269.40	1534.44	79.20	0.00
1998	6280.59	4847.29	1352.52	80.78	0.00
1999	6632.96	5745.43	880.82	6.72	0.00
2000	6901.13	6078.95	820.32	1.85	0.00
2001	7093.50	6240.92	851.23	1.35	0.00
2002	7568.46	6770.52	795.33	2.60	0.00
2003	7439.03	6430.20	1007.87	0.95	0.00
2004	8409.07	7168.12	1239.52	1.43	0.00
2005	9042.81	7524.22	958.33	1.86	558.40
2006	8924.92	5730.93	1010.24	3.05	2180.70

As can be seen from these tables, both fuel consumption and electricity generation were increased three times during the study period. More importantly, is the introduction of combined cycle fired by imported natural gas two years ago, i.e. 2005. This will have a dramatic effect on the performance of the power sub-sector in Jordan since it has the highest efficiency as compared with other available thermal technologies of power generation.

The analysis has been carried out based on input and output energies and exergies given in Tables 2 and 3. Energy and exergy efficiencies for each year have been determined by using equations 5 and 6, considering energy grade function as unity. The overall efficiency has been estimated by dividing total electrical energy produced by the total input energy. A sample calculation for the year 2006 was developed and provided in Appendix I: Table 4 shows both of energy and exergy efficiencies for the whole sub-sector and studied four power plants.

Table 4: Calculated energy and exergy efficiencies during 1989-2006 (%).

Year	Overall	Steam units	Gas turbines	Diesel engines	Combined cycle
1989	34.60	34.87	31.71	36.77	
1990	34.33	34.70	31.88	36.62	
1991	33.86	34.31	30.86	36.42	
1992	33.42	33.99	29.40	36.21	
1993	32.94	33.50	29.54	35.49	
1994	31.95	32.62	29.32	36.25	
1995	33.13	34.33	28.94	36.49	
1996	33.36	34.75	29.09	36.46	
1997	33.11	34.45	29.78	36.17	
1998	33.09	34.56	28.60	35.63	
1999	35.26	36.44	29.13	33.02	
2000	35.19	36.22	29.09	28.41	
2001	35.74	36.46	31.27	29.14	
2002	35.99	36.83	30.19	31.25	
2003	34.57	35.48	29.73	28.88	
2004	34.13	34.94	30.09	27.09	
2005	34.62	34.78	30.08	31.11	43.00
2006	35.15	34.24	29.31	32.07	41.95

In general, for the utility sector, several investigators have come up with the same results that energy and exergy efficiencies for similar activities are almost identical for the power sub-sector sector. This result indicates that inefficiencies in this sector are not caused by mismatch in the input-output quality levels but rather by the presently available techniques used for conversion processes. Substantial improvements in this sector are expected to be difficult to obtain, and will involve major changes in the conversion methods [32].

Although the sectoral coverage is different for each country, it is useful to illustrate how energy and exergy efficiencies vary. A comparison of the calculated overall energy and exergy efficiencies of the national power sub-sector with other countries was carried out for year 2000 since sectoral published data available for this particular year [27-29, 34]. Figure 3 shows energy and exergy efficiencies for selected countries. It can be seen that the local power sub-sector is found to be less efficient than that of Norway. Such large difference can be attributed to the fact that Norway has no thermal power plants and has relatively large contributions from Hydro-power units. Therefore, irreversibilities or exergy losses of its power sub-sector are minor as compared to the case of Jordan, which enjoys exactly the opposite: where it has a major contribution from thermal power plants while hydro-electricity is negligibly small. Although, the contribution of hydro-electricity is large in the Turkish utility sector of about 25% [29], energy and exergy efficiencies are slightly lower than those occurred locally because of relatively low efficiency of thermal power plants fuelled by hard coal. Again, energy and exergy efficiencies for the Malaysian power sub-sector are slightly higher than that of Jordan due to significant contribution, i.e. about 10%, of hydro-power [28]. When compared to Saudi Arabia for the same year, energy and exergy efficiencies of the Jordanian utility sector were higher. Such slight difference can be attributed to increased role of gas turbines, as simple cycle, in the Saudi electrical system and sea water desalination as part of main thermal power plants.

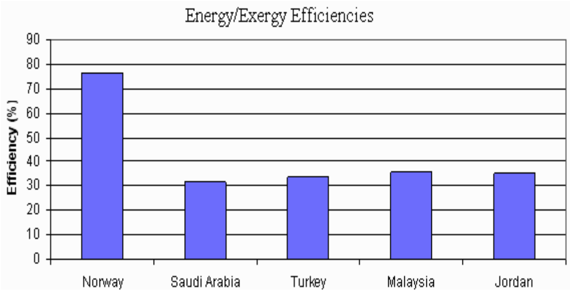

Figure 3 : Comparison of energy and exergy efficiencies of the utility sector of Jordan with other countries for the year 2000.

For comparison purposes, energy and exergy efficiencies for main generating plants for year 2006 are indicated in Figure 4. It is obvious that combined cycle units have the highest values. This should attract the attention of planners and policy makers to upgrade all existing power plants based on gas turbines to operate as combined cycle in the near future. Moreover, future expansion in power generation projects should be limited to combined cycle plants, especially when fired with natural gas. Such trend has the extra advantage of reducing total gaseous emissions, including greenhouse gases from the power sub-sector [35].

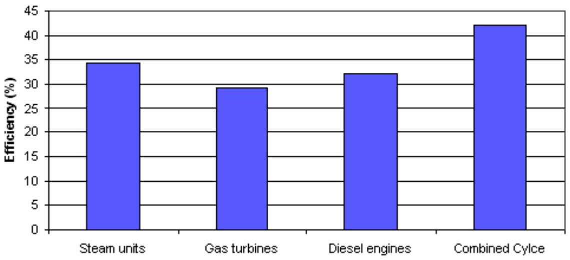

Figure 4 : Energy and exergy efficiencies of power plants of the utility sector in Jordan for the year 2006.

5. Conclusions

In this study, energy and exergy efficiencies of the Jordanian utility sector were determined for period spanning from 1989 to 2006. Calculated exergy efficiency of the power sub-sector sector is the same as its corresponding energy efficiency since for fossil fuels energy, which is the prime energy source for electricity production in Jordan, the exergy grade function is almost unity. The average overall energy and exergy efficiencies are found to be about 34.14%. Comparing obtained results with other countries shows that the local power sub-sector energy and exergy efficiencies are slightly better than those incurred in Saudi Arabia and Turkey. But these efficiencies were far less than those reported for the Norwegian and Malaysian power sub-sectors due to differences in the structure and technologies being employed in these countries.

The calculated efficiencies over the studied period can be considered as an important tool for policy makers, energy planners, and operators to get deeper insight into the performance of the power sub-sector. Furthermore, such results could provide important guidelines for future research work since large energy and exergy losses, which are reported in this study, should be taken as a challenge by the society, and concerned governmental institutions and generators achieve sustainability goals.

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Appendix

A sample calculation of energy and exergy efficiencies of the Jordanian utility sector for the year 2006 was developed and provided as follows:

1- For steam power plant:

$$\eta_e = W_e /(m_f H_f) = \psi_e = (5730.93 GWh /(1439.00 \times 10^3 toe)) \times 100\% = 34.24\%$$

2- For gas turbines plants:

$$\eta_e = W_e /(m_f H_f) = \psi_e = (1010.24 GWh /(296.37 \times 10^3 toe)) \times 100\% = 29.31\%$$

3- For Diesel engines plants:

$$\eta_e = W_e /(m_f H_f) = \psi_e = (3.05 GWh /(0.82 \times 10^3 toe)) \times 100\% = 32.07\%$$

4- For combined cycle plants:

$$\eta_e = W_e /(m_f H_f) = \psi_e = (2180.7 GWh /(440.94 \times 10^3 toe)) \times 100\% = 41.95\%$$

5- Overall plants:

$$\eta_e = W_e /(m_f H_f) = \psi_e = (8924.92 GWh /(2183.13 \times 10^3 toe)) \times 100\% = 35.15\%$$

Similarly, calculations for the remaining years have been made using the same method. Table 4 shows both of energy and exergy efficiencies for the whole sub-sector and studied four power plants.