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Evaluation of Geothermal Energy Resources in Terms of Exergy Analysis

Exergy Analizi Açısından Jeotermal Enerji Kaynaklarının Değerlendirilmesi

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Abstract

Energy is recognized as a crucial element in a country development process. Geothermal resources are a green energy source that can make a considerable contribution in some countries. Also efficient use of resources is important due to availability, economic and environmental issues and comprises the essence of this work. The exergy analysis is a powerful tool for the design, analysis and classification of thermal systems. Using exergy for resource classification benefits their comparison, according to their ability to do work. Specific exergy index (SExI) was calculated to show for classification and capability of some geothermal area. Actual system data are used to assess the district heating system and power plant performance, energy and exergy efficiencies. In this study, specific exergy index for examined field was calculated between 0.026 and 0.947 and sustainability index (SI) was found between 1.250 and 2.782.

Keywords: Exergy, Geothermal, Specific exergy index, Sustainability index

Öz

Enerji ülkelerin gelişiminde çok önemli bir unsur olarak tanınmaktadır. Jeotermal kaynaklar, bazı ülkeler için kayda değer katkı yapan yeşil enerji kaynağı olarak nitelendirilir. Aynı zamanda, kaynakların etkin kullanımı, bulunabilirliği, ekonomikliği ve çevresel konulara bağlı olarak önemlidir ve işin aslını kapsamaktadır. Ekserji analizi, tasarım, analiz ve termal sistemlerin sınıflandırılması için güçlü bir araçtır. Kaynak sınıflandırması için kullanılan ekserji, yapılacak işin niteliğine göre kaynakların verimli kullanılmasının karşılaştırılmasında da kullanılmaktadır. Spesifik ekserji indeksi (SExI), kaynakların sınıflandırılması ve bazı jeotermal alanların kapasitesinin belirlenmesi için hesaplanmaktadır. Bölgesel ısıtma sistemleri ve jeotermal santrallerin performanslarını, enerji ve ekserji verimliliklerini değerlendirmek için gerçek sistem verileri kullanılmıştır. Bu çalışmada, incelenen alanlar için spesifik ekserji indeksi 0.026 ve 0.947 arasında hesaplanmış ve sürdürülebilirlik indeksi (SI) ise 1.250 ve 2.782 arasında bulunmuştur.

Anahtar Kelimeler: Ekserji, Jeotermal, Spesifik ekserji indeksi, Sürdürülebilirlik indeksi

1. Introduction

Energy constitutes one of the main inputs for economic and social development. In line with the increasing population, urbanization, industrialization, spreading of technology and rising of wealth, energy consumption is increasing (Nalan 2009). The rising level of global warming, which has increasing effects and is sourced by climate change, indicates danger alert for the common future of mankind. Hence, increasing the electricity generation from renewable energy sources, named green energy, becomes more and more important, globally (Ozgur 2008). The Renewable Energy Directive sets rules for the European Union (EU) to achieve its 20% renewables target by 2020. Renewables will continue to play a key role in helping the EU meet its energy needs beyond 2020. EU countries have already agreed on a new renewable energy target of at least 27% of final energy consumption in the EU as a whole by 2030 (EC. 2018a). In addition, in line with the Energy Efficiency Directive, the Communication also reports on the outlook for attainment of the 20% target for energy efficiency in 2020 (EC. 2018b). The need to control atmospheric emissions of greenhouse and other gases and substances will increasingly have to focus on efficiency in energy production, transmission, distribution and consumption.

Geothermal energy can be utilized in various forms such as electricity generation, space heating, heat pumps, greenhouse heating, swimming and balneology (therapeutic baths), and industrial processes (Demirbas 2005). The total installed capacity, reported through the end of 2014 for geothermal

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direct utilization worldwide is 70,329 MWt, 45.0% increase over World Geothermal Congress 2010. Energy savings amounted to 350 million barrels (52.5 million tonnes) of equivalent oil annually, preventing 46 million tonnes of carbon and 148 million tonnes of CO_2 being released to the atmosphere, this includes savings for geothermal heat pumps in the cooling mode (compared to using fuel oil to generate electricity) (Lund and Boyd 2015). Also, there is same increase for electricity production from the geothermal energy. An increase of about 1,7 GW in the five year term 2010-2015 has been achieved (about 16%), following the rough standard linear trend of approximately 350 MW/year, with an evident increment of the average value of about 200 MW/year in the precedent 2000-2005 period. Installed capacity in 2015 worldwide of geothermal power plant is 12.6 GWe (Bertani 2015).

Exergy analysis is a very useful method, which can be successfully used in the design of an energy system and provides the useful information to choose the appropriate component design and operation procedure. This information is much more effective in determining the plant and operation cost, energy conservation, fuel versatility and pollution (Kuzgunkaya and Hepbasli 2007a). Bejan (1982) pointed out that the minimization of lost work in the system would provide the most efficient system. By using exergy analysis method, magnitudes and locations of exergy destructions (irreversibilities) in the whole system are identified, while potential for energy efficiency improvements is introduced (Kuzgunkaya and Hepbasli 2007b). With the same way, exergy efficiency, specific exergy index and sustainability index will be much more appreciate to determine geothermal sources efficiency (Kuzgunkaya 2015). Sustainable development calls for the use of sustainable energy systems. The sustainable utilization of geothermal energy means that it is produced and used in a way that is compatible with the well-being of future generations and the environment (Shortall et al. 2015).

In this study, firstly, brief information has been given about geothermal plants which used in the paper. Collected some geothermal plant exergy efficiency from the literature was used to calculate sustainability ındex. Using specific exergy index analysis methods, some geothermal energy sources were researched from the point of exergy and also, geothermal resource utilization was tried to evaluate in the way of efficiency. So, capability of geothermal energy sources has been revealed. This paper's main objective is to contribute to towards the aim of ensuring efficient use of resources to achieve sustainable energy.

2. Material and Methods

2.1. Information of the Geothermal Plants

The data about well temperature and pressure and exergy analysis value of geothermal plants collected from the literature are used and brief information has been given. Benefited from geothermal plant's properties are listed as location, type, temperature, power and reference in Table 1 and these areas is shown in the Figure 1.

Exergy analysis of the Dora II geothermal power plant (DGPP) with 9.5 MW net power output has been studied (Ganjehsarabi et al. 2012). The overall energetic and exergetic efficiencies of the plant are calculated to be 10.7% and 29.6%, respectively.

Tuzla geothermal power plant system has a total installed capacity of 7.5 MW. Electricity is generated using a binary cycle. Exergy efficiency values vary between 35% and 49% with an average exergy efficiency of 45.2 % (Coskun et al. 2011).

An average reservoir temperature of the Afyon geothermal district heating system (AGDHS) in this field is 105 °C. Potential of the AGDHS is 48.333 MWt. The energy and exergy efficiencies of the AGDHS are found to be 37.59% and 47.54%, respectively. According to the four production wells, the specific exergy index (SExI) is found to be 0.049 (Keçebas 2011).

The Salihli geothermal field has a minimum capacity of 838 MW at an average reservoir temperature of 95 °C. The energy and exergy efficiencies of the Salihli geothermal district heating system (SGDHS) are determined to be 55.5% and 59.4%, respectively (Ozgener et al. 2007).

In the Balcova geothermal district heating system (BGDHS), the exergy losses has observed occurred mainly due to the losses in pumps, heat exchangers, reinjection sections of the geothermal water back into reservoir and pipeline. Energy and exergy efficiencies of the system are found to be 42.36% and 46.55%, respectively (Ozgener et al. 2006).

The overall energy and exergy efficiencies of the Bigadic Geothermal District Heating System in Balikesir, Turkey for two reference temperatures taken as 15.68 °C for November (e.g., case 1) and 11.8 °C for December (e.g., case 2). The average energy and exergy efficiencies are found to be 30% and 36% for case 1, and 40% and 49% for case 2, respectively (Oktay et al. 2008).

The first geothermal district heating system was installed in the Gonen field (in Balikesir) in 1987 in Turkey. Both energy

Table 1. Properties of Used Geothermal Field

Location	Country	Type	Year	Power (Mwe, MWt)	Temperature (°C)	Reference
Afyon	Turkey	GDHS	1994	48.33	105.0	(Keçebas 2011)
Manisa/Salihli	Turkey	GDHS	2004	838.00	98.0	(Ozgener et al. 2007)
İzmir/Balçova	Turkey	GDHS	2001	82.67-104.75	95 - 140	(Ozgener et al. 2006)
Balıkesir /Bigadiç	Turkey	GDHS	2006	15.25	110.0	(Oktay et al. 2008)
Balıkesir/Gönen	Turkey	GDHS	1987	-	70.0	(Ozgener 2005)
Kutahya/Simav	Turkey	GDHS	1991	-	98.0	(Arslan et al. 2009)
Aydın/Salavatlı-Dora II	Turkey	GPP	2010	9.5	171.0	(Durmuş 2006)
Çanakkale/Tuzla	Turkey	GPP	2011	7.5	142.8	(Coskun et al. 2011)
Kutahya/Simav	Turkey	GPP	-	41.20	148.0	(Kose 2007, Arslan 2010)
Dieng	Indonesia	GPP	-	60	178.6	(Pambudi 2014)
Larderello	Italy	GPP	-	51.83	195.0	(Bettagli and Bidini 1996)
Sabalan	Iran	GPP	-	111	155.5	(Jalilinasrabadya et al. 2012)
Takigami	Japan	GPP	1996	25	205.0	(Jalilinasrabady et al. 2010)
Olkaria I	Kenia	GPP	-	45	230-260	(Kwambai 2005)
Kamojang	Indonesia	GPP	1982-2004	180 to 250	235 - 245	(Suryadarma et al. 2005, Adiprana et al. 2015).
Kızıldere	Turkey	GPP	1974	10	242.0	(Dagdas et al. 2005)

***GDHS:** Geothermal direct heating system, **GPP:** Geothermal power plant.*

and exergy efficiencies of the overall Gonen geothermal district heating system (GGDHS) were determined to be 45.91% and 64.06%, respectively (Ozgener 2005).

Simav is one of the most important 15 geothermal areas in Turkey. Simav geothermal district heating system (SiGDHS) has an energetic efficiency of 26.30% and an exergetic efficiency of 37.41% which are relatively lower in comparison with the other geothermal district heating systems in Turkey (Arslan et al. 2009).

Electricity generation from Simav geothermal field operative with Kalina Cycle System (KCS-34) is investigated (Arslan 2010). With the best design, power generation of 41.2 MW and electricity production of 346.1 GWh/a can be obtained with an energetic efficiency of 14.9% and exergetic efficiency of 36.2%.

Exergy analysis and optimization of the Dieng geothermal power plant in Indonesia has been studied and the exergy flow and efficiency has been computed at several plant components, including the separator, turbine, condenser, and for the whole power plant (Pambudi 2014).

Electric power plant in the Larderello area is 51.83 MW and has been founded exergy efficiency equal to 61.85% (Bettagli and Bidini 1996).

The Sabalan geothermal field is in northwest Iran. Downhole temperatures of approximately 240 °C were recorded at the bottom of two wells. In a single flash power plant, the overall exergy efficiency is 32.7% and the overall energy efficiency is 7.3% (Jalilinasrabadya et al. 2012).

The single flash Takigami Geothermal Power Plant is located in Kyushu Island, Japan, with installed capacity of 25 MW. The overall first and second law efficiencies of the power plant had been founded 6.73% and 28.77% respectively (Jalilinasrabady et al. 2010).

According to exergy analysis results of Olkaria I power plant in Kenya, an overall first and second law of efficiency was found 15% and 34.6%, respectively (Kwambai 2005).

Kamojang is the first Geothermal Field in Indonesia, and it is known as one of vapor dominated systems in the world. The Kamojang geothermal reservoir is dominated by vapor with temperature of 235 - 245 °C and pressure of 34 - 35 bar abs. Based on an exergy analysis, Kamojang Unit 1-2-3 has an exergy efficiency of 57.62% (Suryadarma et al. 2005, Adiprana et al. 2015).

Kızıldere geothermal area is the first geothermal power plant in Turkey. The first and second law efficiencies of the plant are 4.556% and 19.97%, respectively (Dagdas et al. 2005).

Figure 1. Geothermal plants' area. **A)** World; **B)** Turkey.

2.2. Analysis Method

Exergy is a measure of the maximum capacity of a body or an energy system to perform the useful work, as it proceeds to a specified final equilibrium state with its surroundings. The amount of the available work will be higher when there is a large difference between the energy source and its surroundings. The convertible energy of a system is proportional to the difference between an energy source and its surroundings. Therefore, energy and exergy do not stand for the same meaning (Saidur et al. 2007a). Exergy can also identify better than energy the environmental benefits and economics of energy technologies. The results suggest that exergy should be utilized by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies in tandem with other objectives and constraints (Rosen et al. 2008).

Dincer (2002) reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail. Considering the discussions and literatures above, it is obvious that analysis of exergy is crucial for energy planning, resource optimization and global environmental, regional, and national pollution reduction (Saidur et al. 2007).

2.2.1 General Relations

The mass balance equation can be expressed in the rate form as

$$\sum m_{in} = \sum m_{out} \tag{1}$$

Where m is the mass flow rate, and the subscript in stands for inlet and out for outlet.

The general energy balance can be expressed below as the total energy inputs equal to total energy outputs.

$$\sum E_{in} = \sum E_{out} \tag{2}$$

The general exergy balance can be written as follows:

$$\sum Ex_{in} - \sum Ex_{out} = \sum Ex_{dest} \tag{3a}$$

or

$$Ex_{heat} - Ex_{work} + Ex_{mass,in} - Ex_{mass,out} = Ex_{dest} \tag{3b}$$

with

$$Ex_{heat} = \sum \left(1 - \frac{T_0}{T_k}\right) Qk \tag{4a}$$

$$Ex_{work} = W \tag{4b}$$

$$Ex_{mass,in} = \sum m_{in} \psi_{in} \tag{4c}$$

$$Ex_{mass,out} = \sum m_{out} \psi_{out} \tag{4d}$$

where Q_k is the heat transfer rate through the boundary at temperature T_k at location k and W is the work rate.

The flow (specific) exergy is calculated as follows:

$$\psi = (h - h_0) - T_0 (s - s_0) \tag{5}$$

where h is enthalpy, s is entropy, and the subscript zero indicates properties at the restricted dead state of P_0 and T_0.

The rate form of the entropy balance can be expressed as

$$s_{in} - s_{out} + s_{gen} = 0 \tag{6}$$

2.2.1.1 Exergy efficiencies

Numerous ways of formulating exergetic (or exergy or second-law) efficiency (effectiveness, or rational efficiency) for various energy systems are given in detail elsewhere (Cornelissen 1997). It is very useful to define efficiencies based on exergy (sometimes called Second Law efficiencies). Whereas there is no standard set of definitions in the literature, two different approaches are generally used-one is called "brute-force", while the other is called "functional" (DiPippo 2004).

- A "brute-force" exergy efficiency for any system is defined as the ratio of the sum of all output exergy terms to the sum of all input exergy terms.
- A "functional" exergy efficiency for any system is defined as the ratio of the exergy associated with the desired energy output to the exergy associated with the energy expended to achieve the desired output.

Here, in a similar way, exergy efficiency is defined as the ratio of total exergy output to total exergy input, i.e.

$$\varepsilon = \frac{Ex_{out}}{Ex_{in}} = 1 - \frac{Ex_{dest}}{Ex_{in}} \tag{7}$$

where "out" stands for "net out" or "product" or "desired value" or "benefit", and "in" stands for "given" or "used" or "fuel".

2.2.2 Specific Exergy Index

Geothermal resources have been classified as low, intermediate or high enthalpy resources according to their reservoir temperatures. The temperature ranges used for these classifications are arbitrary and they are not generally agreed upon. The temperature is used as the classification parameter because it is the earliest to measure and understand. However, the temperature alone is not a good classification parameter. Like temperature, it is alone inappropriate to define or classify the geothermal resources by enthalpy alone. The lower enthalpy fluid is classified as a high enthalpy resource by its temperature and the higher enthalpy one as an intermediate resource according to its temperature. Indeed, it is difficult to tell which is the better 'quality' resources of the given "p", "T" and "h" information alone. However, it can be easily shown that the lower temperature and high enthalpy fluid is nearly three times exergetically better than the other. The normalized exergy values, henceforth known as SExI for 'specific exergy index', vary between 0 and 1 for saturated steam and water and its equation is shown in following Equation (8) (Lee 2001).

$$SExI = \frac{h_{brine} - 373.16 s_{brine}}{1192} \quad (8)$$

The equation for SExI is a straight line on an h-s plot of the Mollier diagram. Straight lines of SExI = 0.5 and SExI = 0.05 can, therefore, be drawn in this diagram and used as a map for classifying geothermal resources (Figure 2).

- SExI < 0.05 for low-quality geothermal resources,
- 0.05 ≤ SExI < 0.5 for medium-quality geothermal resources, and
- SExI ≥ 0.5 for high-quality geothermal resources.

In order to map any geothermal field on the Mollier diagram as well as to determine the energy and exergy values of the geothermal brine, the average values for the enthalpy and entropy are then calculated from the following equations:

$$h_{brine} = \frac{\sum_i^n m_{w,i} h_{w,i}}{\sum_i^n m_{w,i}} \quad (9)$$

$$S_{brine} = \frac{\sum_i^n m_{w,i} s_{w,i}}{\sum_i^n m_{w,i}} \quad (10)$$

Hence, by plotting the enthalpy and entropy of a resource's fluid on the map, the category of the geothermal resource can immediately be identified. The thermodynamic properties of water are taken from Cengel and Boles (1996).

2.2.3 Sustainability Index

The sustainable supply of clean and affordable energy resources as well as efficient usage of them are vital for sustainable development. Exergy analysis has a big potential to improve efficiency by maximizing the benefits and efficient using of resources as well as minimizing

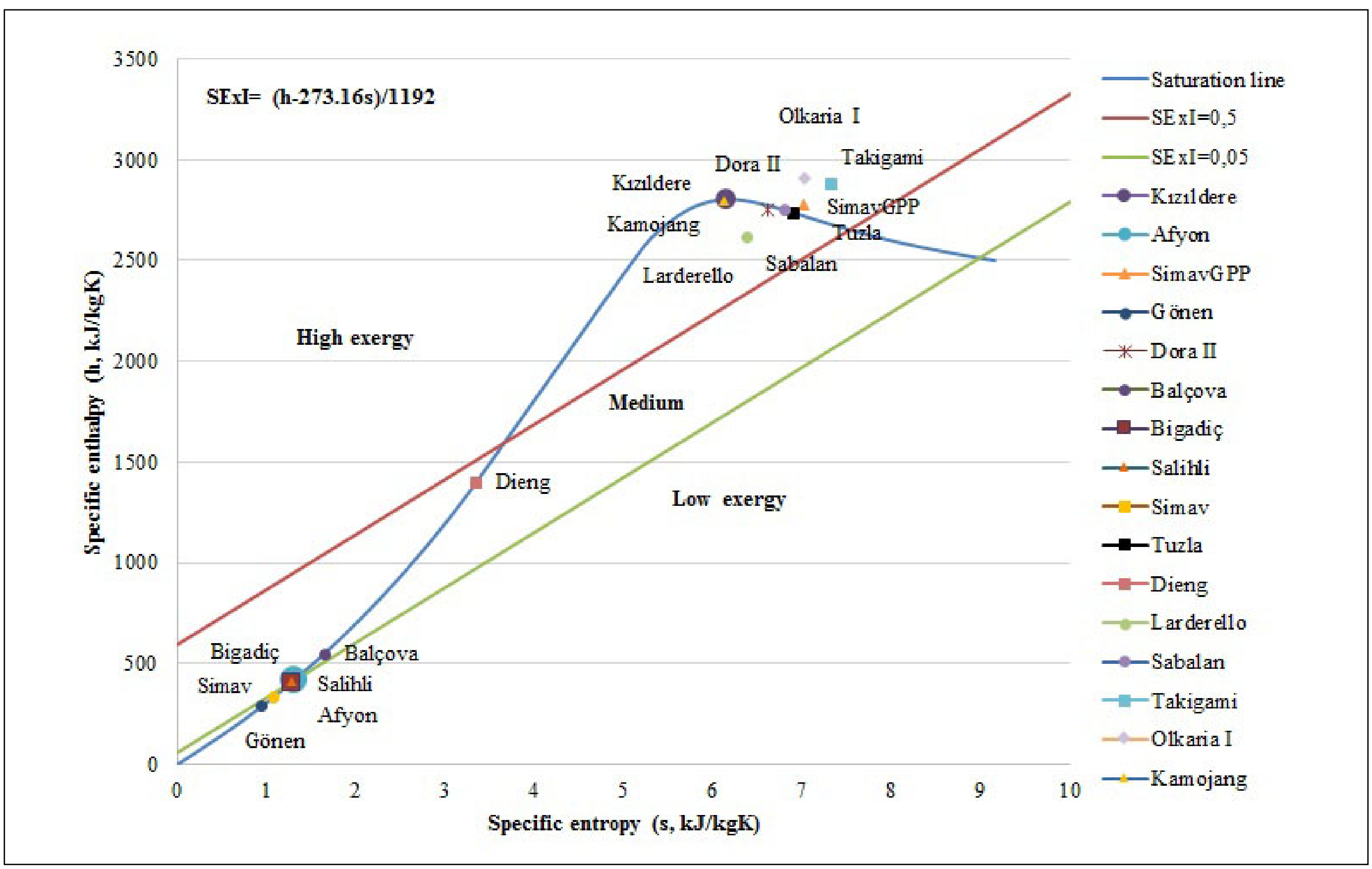

Figure 2. Examples of geothermal fields plotted on the classification map of geothermal resources.

the detrimental effects such as environmental damages. Therefore, the exergy analysis can be applied to amend the efficiency and sustainability of the thermal systems. The relation between exergy efficiency and the sustainability index can be expressed as follows (Gungor et al. 2011):

$$\varepsilon = 1 - \frac{1}{SI} \tag{11}$$

here, SI is the sustainability index.

3. Results and Discussion

Specific Exergy Index of some geothermal resources was studied and specific enthalpy-specific entropy (h–s) diagram was used for classification of some geothermal resources as shown in Figure 2. Using data from Dagdas et al. (2005), SExI values of Kızıldere geothermal fields was calculated and plotted on the classification map in Figure 2 and SExI values of Kızıldere was listed in Table 2. In a similar manner, other areas was plotted in Figure 2. As shown in Figure 2, hot water resources at atmospheric pressure have SExI=0.05 like Afyon, Gönen, Balçova, Salihli, Bigadiç and Simav of which are low exergy resources. These areas are more appropriate for direct heating and currently, these areas are used in thermal tourism, direct heating and green house application (Table 1). SExI values of Kızıldere, Dora II, Olkaria I, Takigami, Simav, Tuzla, Salaban, Larderello and Kamojang was calculated as over 0.5 and they are plotted at the high exergy zone of the diagrams. As is also understood from Figure 2, these areas are used for electricity production and convenient area for electricity production.

Sustainability index for each instruction was calculated from the Equation (11) and shown calculated values in Table 2. As shown Table 2, the highest SI value was found in Balıkesir/Gonen with 2.782 and the lowest SI value was found in Kızıldere with 1.250. SI value of other geothermal plant was calculated 1.906 for Afyon, 2.463 for Manisa/Salihli, 1.871 for İzmir/Balçova, 1.739 for Balıkesir /Bigadiç, 1.598 for Kutahya/Simav, 1.420 for Aydın/Salavatlı-Dora II, 1.825 for Çanakkale/Tuzla, 1.567 for Kutahya/Simav (GPP), 1.574 for Dieng, 2.621 for Larderello, 1.486 for Sabalan, 1.404 for Takigami, 1.529 for Olkaria I, and 2.360 for Kamojang, respectively.

The "projection" of the geothermal areas, SExI and exergy efficiency for each plant is plotted in Figure 3. Relation between SExI and exergy efficiency could be easily identify from the Figure. Kamojang, Larderello, Salihli and Gönen are the most efficient use of resources. Although Landerelo's SExI value is lower than Kamojang, it is used more efficiently than Kamajong. There are same situation between Salihli and Gönen for direct use (for SExI=0.05). In the evaluation of resources (SExI) and plant (SI), while Dora II in GPP has a good SExI value (0.790), it has found the lowest exergy efficiency (0.30) and SI value (1.420). It is understood that improvements for Dora II and Takigami are required from

Table 2. Evaluation with Exergy Index of Completed Investment of Some Geothermal Field

Location	Type	Energetic efficiency	Exergetic efficiency	SExI	SI
Afyon	GDHS	0.38	0.48	0.051	1.906
Salihli	GDHS	0.56	0.59	0.050	2.463
Balçova	GDHS	0.42	0.47	0.086	1.871
Bigadiç	GDHS	0.35	0.42	0.049	1.724
Gönen	GDHS	0.46	0.64	0.026	2.782
Simav	GDHS	0.26	0.37	0.035	1.598
Dora II	GPP	0.11	0.30	0.790	1.420
Tuzla	GPP	-	0.45	0.714	1.825
Simav (GPP)	GPP	0.15	0.36	0.725	1.567
Dieng	GPP	-	0.36	0.408	1.574
Larderello	GPP	-	0.62	0.728	2.621
Sabalan	GPP	0.07	0.33	0.753	1.486
Takigami	GPP	0.07	0.29	0.735	1.404
Olkaria I	GPP	0.15	0.35	0.832	1.529
Kamojang	GPP	-	0.58	0.944	2.360
Kızıldere	GPP	0.05	0.20	0.947	1.250

the calculations. SExI value of Kızıldere geothermal power plant is remarkably high, but plant has low exergy efficiency and studies on efficiency are especially required. Gönen with the lowest SExI value (0.026) in resources has taken an attention reason of the highest exergy effiency value (0.64). On the other hand, Balçova's SExI value is higher than the other ground direct heating systems. Its SI value is quite low with compare to other place for example Afyon GDHS. When we compare Gonen and Simav geothermal direct heating system, there are quite high differences between Gonen (0.64) and Simav (0.37) exergy efficiency values despite the fact that the SExI values are very close together. This is also direct related with use and installation of Simav's system.

High SI values mean that the system or process has high efficiency with a low environmental impact. There is a direct relation between exergy efficiency and SI values (Figure 4). We can say Afyon, Salihli, Gönen, Larderello and Kamojang have the highest SI values and the lowest environmental impact. In SI values of Gönen and Simav, it was observed the difference of SI values was very high.

4. Conclusions

The use of sustainable energy not only entails providing sufficient energy for present and future energy needs, but also protecting the environment and the integrity of ecosystems. In addition, it provides measures to avoid security threats

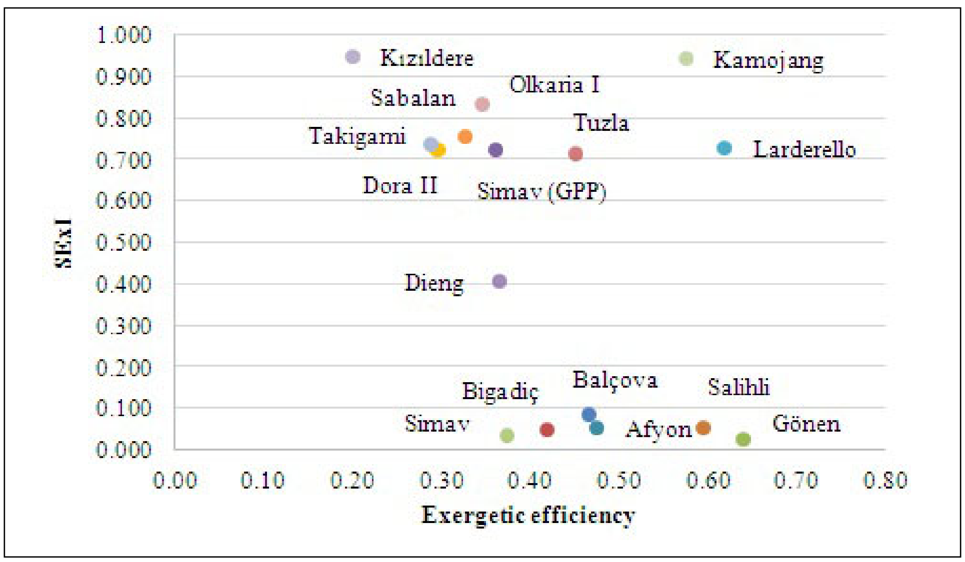

Figure 3. Exergy efficiency and SExI diagram for each plant.

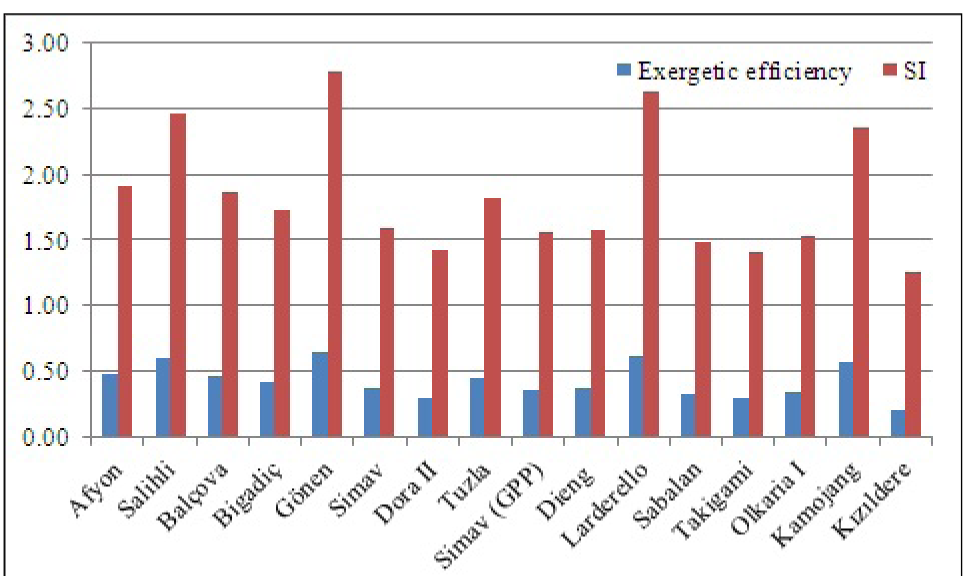

Figure 4. Exergy efficiency and SI diagram for each plant.

and potential geopolitical conflicts that might occur from increasing competition for the improperly scheduled distribution of energy resources (IEA 2016b).

The main conclusions derived from the present study may be summarized as follows:

For the governments or societies to attain sustainable development, much effort should be devoted to utilizing sustainable energy resources in terms of renewable.

The results suggest that exergy should be utilized by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies in tandem with other objectives and constraints. Exergy clearly identifies efficiency improvements and reductions in thermodynamic losses attributable to green technologies. Thus, exergy has an important role to play in increasing utilization of green energy and technologies.

As can be seen from the SExI analysis, only to investigate efficiency of installed plant was inadequate it should also be pay attention the capacity of the geothermal field.

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