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Exergy analysis for a proposed binary geothermal power plant in Nisyros Island, Greece

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ABSTRACT

The exergy analysis method constitutes an alternative but very important technique for the evaluation of the utilization level of thermal plants as well for the comparison of different conversion processes. The loss of exergy provides a figure of merit for the inefficiencies of a process and a measure of the quality of the different forms of energy in relation to given environmental conditions. In this paper, data from an experimental geothermal drill in the Greek Island of Nisyros, located in the south of the Aegean Sea, have been used in order to estimate the maximum available work and the efficiency of a potential power plant. Different methods for estimating the exergy term are used and several types of conversion efficiencies have been calculated in order to obtain a more complemented view of the analysis. Overall, a system exergetic efficiency of 41% and a thermal one of 12.8% have been resulted supporting technical feasibility of the proposed geothermal plant.

Nomenclature

Subscripts

0	Atmospheric (ambient) conditions
fg	Geothermal fluid
i	Initial conditions
l	Liquid
out	Intermediate state
s_t	Turbine
s_v	Pump
u	Utilization
v	Vapor (steam)

Greek Symbols

η	Thermal efficiency
ζ	Exergy efficiency

c_p Specific heat capacity (constant pressure) (kJ/kgK)

Mean molar isobaric specific heat for evaluating enthalpy changes (kJ/kgK)

Mean molar isobaric specific heat for evaluating entropy changes (kJ/kgK)

Mean molar isobaric specific heat for evaluating exergy changes (kJ/kgK)

Exergy flow (kJ/s or kW)

E Total exergy (kJ)

e Specific exergy (kJ/kg)

h Enthalpy (kJ/kg)

m Mass (kg)

Mass flow rate (kg/s)

p Pressure (bar)

s Entropy (kJ/kgK)

T Temperature (°C or K)

W Power, work (kJ)

P, W Power, work rate (kJ/hr)

x Mass fraction

0 Atmospheric (ambient) conditions

fg Geothermal fluid

i Initial conditions

l Liquid

out Intermediate state

st Turbine

sv Pump

u Utilization

v Vapor (steam)

η Thermal efficiency

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ζ Exergy efficiency

1. Introduction

The increased concern about the world's limited energy resources has alerted many authorities involved to reconsider their energy policies and take drastic measures in minimizing energy consumption and wasted energy and in utilizing alternative energy sources, such as renewable energy sources (RES) (Lior, 2008; Bataineh and Dalalah, 2013; Izutsu et al., 2012). The goal that has been set focuses on the optimization of energy conversion devices/processes and on the development of new techniques to better utilize the existing limited energy resources (Ali et al., 2012; Raslavičius and Bazaras, 2010; Li et al., 2013). RES offer a great potential when partial or complete (if and where this is possible) replacement of conventional fossil fuel is concerned; however, most forms of RES present problems with high investment costs and low energy density (Hadjipaschalis et al., 2009). Geothermal energy, is not at all dependent on weather conditions, therefore it allows a constant energy flux (Köse, 2005). The use of geothermal energy as a possible source for electricity generation, however, is limited to countries with high enthalpy geothermal sources (Goldstein et al., 2017). The exploitation of geothermal sources may also cause a range of environmental problems depending on the location, on the technology used and on the legal framework for the proper exploitation (Kömürçü and Akpınar, 2009; Al-Dabbas, 2009).

Geothermics, or energetic exploitation of hydrothermal resources, utilizes hot water or steam which can be found in porous or fissured rocks in the Earth's crust. Commercial geothermal electricity generation started in Lardarello, Tuscany, Italy in 1913 with an installed electric capacity of 250 kW (Barbier, 1997). This is one of the rare locations where superheated steam is available from geothermal wells. The first power plant based on geothermal hot water has been in operation in Wairakei, New Zealand since 1958 (Barbier, 1997). Today, the installed electric capacity amounts to some 11 GW worldwide (Holm et al., 2010). The leading producers are the USA, Philippines, Indonesia, Italy and Mexico (Holm et al., 2010). Due to proper geological conditions, Greece has many important geothermal resources (of all three categories – low, medium and high temperature) in relatively economic depths (100–1500 m). The research for geothermal exploration in Greece started in 1971 by the Institute of Geology and Mineral Exploration (I.G.M.E.) and up to 1979 the research program covered only areas considered to contain high enthalpy resources. The most important geothermal fields have been discovered in Milos and Nisyros islands (Institute of Geology and Mineral Exploration (I.G.M.E.), 1981; Public Power Corporation of Greece, Merz – Dal Geothermal Consultants, 1993; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1999; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1985; Mendrinis et al., 2010).

Exergy analysis is a valuable tool for this performance evaluation (Madhawa Hettiarachchi et al., 2007; Heberle and Brüggemann, 2010; Guzović et al., 2010; Akpınar and Hepbasli, 2007; Dağdaş et al., 2005; Keçebaş, 2011). Due to the relatively low temperatures of geothermal fluids and thus, the low energy efficiencies and the small difference between energy efficiencies of a well and a poorly performing geothermal power plant, it is necessary that the comparisons made to be based on the quality of the geothermal resources (Kanoglu, 2002; Yuan and Michaelides, 1993). Exergy analysis is a useful methodological tool that accounts for the system's inefficiency in terms of exergy destruction, i.e., the degradation of the system's ability to perform work with respect to its surroundings (Dincer and Rosen, 2006). The concept of exergy was first used to analyze a geothermal power plant by Badvarsson and Eggers (Badvarsson and Eggers, 1972), who compared the performances of single and double flash cycles based on a reservoir water temperature of 250 °C and a sink condition of 40 °C; gave exergetic efficiencies of 38.7% and 49%, respectively, assuming 65% mechanical efficiency (Lee, 2001). DiDippo (DiDippo, 1994) investigated the sec-

ond law assessment of binary plants generating power from low-temperature geothermal fluids. The results show that binary plants can operate with very high second law or exergetic efficiencies even when the motive fluids are low-temperature and low-exergy. Exergetic efficiencies of 40% or greater have been achieved in certain plants with geofluids having specific exergies of 200 kJ/kg or lower. During the past decades numerous studies (Kanoglu and Cengel, 1999a; Kanoglu and Cengel, 1999b; Barbier, 2002; Golove and Schipper, 1997; Gunerhan et al., 2001; Hepbasli, 2003; Esen et al., 2007; Koroneos and Nanaki, 2017; Ozgener et al., 2005a; Ozgener et al., 2005b; Ozgener and Ozgener, 2009; Yari, 2010) have been undertaken for geothermal systems to perform a large range of investigations from system basics to system energy and exergy analyses. Nonetheless it is noted, that there are few studies regarding performance evaluations and optimization techniques for geothermal power plants and reservoirs on a worldwide scale (Yuan and Michaelides, 1993; Kanoglu and Cengel, 1999b; Kanoglu et al., 1998; Cerci, 2003; Paloso and Mohanty, 1993; Subbiah and Natarejen, 1988). Notwithstanding there are many studies concerning geothermal fields located in southern Aegean Sea (Mendrinis et al., 2010; Marini et al., 1993; Lagios and Apostolopoulos, 1995; Brombach et al., 2003), published research dealing with geothermal power plants in that area is scarce.

The objective of this work is to investigate the technical feasibility of constructing a 2 MW commercial geothermal power plant in Nisyros island, thus exploiting one of the most powerful geothermal fields of the Mediterranean sea. Given that the island of Nisyros has significant geothermal energy fields the operation of a geothermal plant is of great significance. Due to legal inefficiencies, the exploitation of this renewable energy source remains at very low levels. Thus the research on the development of a low enthalpy geothermal field is investigated as a very essential investment. The building of small geothermal power plants to supply mini-grid power in remote locations with geothermal resources, has proved to be very important. Data from an experimental geothermal drill in Nisyros (Institute of Geology and Mineral Exploration (I.G.M.E.), 1981; Public Power Corporation of Greece, Merz – Dal Geothermal Consultants, 1993; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1999; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1985) are used in this work in order to estimate the maximum available work and the efficiency of a potential power plant. In order to obtain a more complemented view of the analysis, different methods for estimating the exergy term are used and several types of conversion efficiencies are calculated.

2. Characteristics of geothermal well Nis-2 on Nisyros Island

Flow tests were carried out in 1981, 1983 and 1985 at a geothermal field in Nisyros (Institute of Geology and Mineral Exploration (I.G.M.E.), 1981; Public Power Corporation of Greece, Merz – Dal Geothermal Consultants, 1993; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1999; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1985). Carriers of these tests were Public Power Corporation of Greece and I.G.M.E. The tests were an attempt to evaluate the production characteristics and the composition of fluids from the Nis-2 well. The well was drilled slightly in 1985 and was subjected to flow tests for three months. From the collected data (Institute of Geology and Mineral Exploration (I.G.M.E.), 1981; Public Power Corporation of Greece, Merz – Dal Geothermal Consultants, 1993; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1999; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1985), presented below, Public Power Corporation and I.G.M.E. estimated that the field under study could supply a 2 MWe geothermal power plant.

- Steam flow: The calculated flow of steam (average value) at a separation pressure of 15 bar-g is about 5.2 kg/s.
- Brine flow: The calculated flow of brine (average value) at atmospheric conditions was 12.5 kg/s.

- Aquifer temperature: It was not possible to make downhole logs of temperature and pressure due to bent airlift tubing in the well. From chemical analysis of the discharged fluids, the aquifer temperature was estimated at 290 °C.

3. Methodology: exergy analysis and the second law of thermodynamics

The first law of thermodynamics deals with the quantity of energy and states that energy cannot be created or destroyed (Clausius, 1865). This law merely serves as a necessary tool for quantifying energy conversion during a process. The second law, however, is related to the quality of energy. More specifically, it is concerned with the degradation of energy during an energy conversion process, the entropy generation and the irreversibilities (Cengel and Boles, 2017). The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems and through exergy analysis, assists in finding ways and solutions to problems such as high energy use, high wasted energy, environmental pollution and resource depletion.

The exergy value of energy represents its quality value. An exergy balance can be performed for a whole plant or for different unit operations. Exergy (also called available energy) (Rosen, 1995) is defined as “the maximum useful work that could be obtained from the system at a given state in a specified environment (Cengel and Boles, 2017)”, or as “the maximum amount of work that can be obtained from a stream of matter, heat or work as it comes to equilibrium with a reference environment; it is a measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment (Baehr, 1973)”. The work potential of the energy contained in a system at a specified state is simply the maximum useful work that can be obtained from the system. The work output is maximized when the process between two specified states is executed in a reversible manner and all the irreversibilities are disregarded in determining the work potential. A system at the dead state has zero availability (exergy), and thus no work can be produced from a system that is initially at the dead state (Cengel and Boles, 2017). It is important to realize that exergy represents the upper limit on the amount of work a device can deliver without violating any thermodynamic laws (Cengel and Boles, 2017).

The conversion of all energy forms, allowed by the second law of thermodynamics, is included under the general term of exergy. While, according to the first law of thermodynamics, only an amount (a portion) of the total energy can be converted into another form and, the remaining amount (portion) of that total energy, which cannot be converted to work, is called unavailable energy. Exergy analysis when compared to an energy analysis (Rosen, 1995):

- provides a better view on the efficiency of a process;
- it is very useful in finding the unit operation where efficiency improvements are the most useful or suitable.

In order to make all exergy losses visible in a process under study an exergy analysis is required. The method is very powerful when comparing two or more solutions in an objective and quantitative manner. The exergy analysis does not give direct answers on how to improve the process but it shows the path, where to start, i.e. at the point where the largest exergy losses occur (Rosen, 1995). Exergy analysis is especially useful in the design phase and during optimization of new processes.

Specific exergy (available work) of a given stream based on specific enthalpy and specific entropy at any given point of a system disregarding kinetic and potential energy terms is given in Eq. (1).

$$e = h_i - h_0 - T_0(s_i - s_0) \quad (1)$$

For a given process the change in specific exergy from point 1–2 is given by Eq. (2).

$$\delta e = h_2 - h_1 - T_0(s_2 - s_1) \quad (2)$$

In terms of a specific case, Eq. (1) describes a process in which an ideal heat engine extracts an amount of heat ($h_i - h_0$) from a medium. Part of this enthalpy difference is reversibly converted to work and the rest $T_0(s_i - s_0)$ is rejected to the sink as waste heat at ambient temperature. The term $T_0(s_i - s_0)$ is called irreversibility or exergy loss or exergy destruction.

The exergy of the steam and liquid (water) fraction is calculated separately and the total exergy amount of the stream is derived by multiplying the exergy of each component by the corresponding mass fraction.

The exergy terms of a specific media can be calculated in several ways. The methods used for estimation of exergy and of the different types of efficiencies are analysed below.

3.1. Exergy calculation methods

The following exergy calculations methods were used in this paper as a first approach to evaluate the geothermal reservoir.

3.1.1. Exergy calculation using temperature charts and steam tables

Exergy can be calculated using temperatures charts. Exergy values for saturated steam and saturated water can be found in thermodynamic properties tables (Edwards et al., 1982). Giving values on the variables on Eq. (3), we can calculate the specific exergy, and given the mass flow rate, the total exergy can be calculated. Thermodynamic properties of saturated steam and saturated water at the conditions of the separator and at the dead state (ambient) can be found in thermodynamic properties tables (Clausius, 1865; Babcock and Wilcox, 1978; Sotiropoulos, 1982).

3.1.2. Constant $\tilde{c}_p^h, \tilde{c}_p^s$ assumption

Assuming a constant specific isobaric heat capacity for the liquid fraction of the geothermal fluid, the exergy of saturated steam and saturated water can be calculated by Eqs. (3) and (4) respectively.

$$e_v = h_{fg} \left(1 - \frac{T_0}{T_{in}} \right) + \tilde{c}_{pl}^h (T_{in} - T_0) - T_0 \left(\tilde{c}_{pl}^s \ln \left(\frac{T_{in}}{T_0} \right) \right) \quad (3)$$

$$e_l = \tilde{c}_{pl}^h (T_{in} - T_0) - T_0 \left(\tilde{c}_{pl}^s \ln \left(\frac{T_{in}}{T_0} \right) \right) \quad (4)$$

$\tilde{c}_p^h$ and $\tilde{c}_p^s$ are given by Eqs. (5) and (6) respectively.

$$\tilde{c}_p^h = \left[\frac{\tilde{h} - \tilde{h}_0}{T - T_0} \right] = \frac{1}{T - T_0} \int_{T_0}^T \tilde{c}_p dT \quad (5)$$

$$\tilde{c}_p^s = \left[\frac{\tilde{s} - \tilde{s}_0}{\ln \left(\frac{T}{T_0} \right)} \right] = \frac{1}{\ln \left(\frac{T}{T_0} \right)} \int_{T_0}^T \frac{\tilde{c}_p}{T} dT \quad (6)$$

Eq. (3) represents two consecutive reversible processes. The first process accepts an amount of heat h_{fg} equal to the evaporation enthalpy from the condensing vapor at constant temperature T_{in} , produces useful work $h_{fg} \left(1 - \frac{T_0}{T_{in}} \right)$ and rejects an amount of heat to the atmosphere. The second process extracts the remainder of heat from the liquid condensate.

3.1.3. Thermal efficiency

Thermal efficiency represents the fraction of the thermal energy that can be converted to mechanical or electrical energy subjected to the Second Law. The shaded area in Fig. 1 represents the differential of ideal work δW_k . The energy bounded by the same interval of the curve down to 0 K is δE . The Carnot efficiency (Clausius, 1865) is given by Eq. (7).

$$\eta_{carnot} = \frac{\delta W_k}{\delta h} = 1 - \frac{T_0}{T_{in}} \quad (7)$$

where, δh is the difference in the heat content of the media between initial and discharge conditions and δW_k the available work.

Integration of δW_k between the limits T_{in} and T_0 results in Eq. (8) where the thermal efficiency is calculated.

$$\eta_{thermal} = \frac{\delta W_k}{h} = 1 - \frac{T_0 \ln \left(\frac{T_{in}}{T_0} \right)}{T_0 - T_{in}} \quad (8)$$

Fig. 1. Geothermal reservoir thermodynamics.

The enthalpy of the steam is given by Eq. (9) and the total specific exergy is estimated by Eq. (10).

$$h = x_v h_v + x_l h_l \quad (9)$$

$$e_{total} = \eta_{thermal} \delta h \quad (10)$$

3.2. First and second law efficiencies

Although the availability of a geothermal source can be very large, only a fraction of it is actually converted to electric power. Energy conversion and inefficiencies, following the First and Second Law determine the overall conversion efficiency. Several types of efficiencies, concerning different types of geothermal fields and plants, are reported in literature (Kanoglu, 2002; Cerci, 2003; Cengel and Boles, 2017; Edwards et al., 1982; Milora and Tester, 1977; Economides and Ungemach, 1987; Cadenas, 1999; Bettagli and Bidini, 1996) in order to assist the evaluation and comparison of different power conversion processes.

Utilization factor η_u is a Second Law efficiency and constitutes an estimation of the effectiveness of resource utilization. It is defined (Eq. (11)) as the ratio of the net power output of a power plant and the maximum possible work (Edwards et al., 1982; Milora and Tester, 1977).

$$\eta_u = \frac{P}{E} = \frac{P}{\dot{m}(h_i - h_0 - T_0(s_i - s_0))} \quad (11)$$

For a fixed initial temperature of the geothermal fluid T_i , higher values of η_u correspond to lower well flow rates for a given power output.

Cycle efficiency η_{cycle} is a First Law efficiency and is used as a direct measure of how efficiently the transferred geothermal heat is converted to work. If the fluid is cooled to some intermediate temperature T_{out} , the η_{cycle} is given by Eq. (12).

$$\eta_{cycle} = \frac{P}{h_{in} - h_{out}} \quad (12)$$

A correlation for η_u and η_{cycle} derives:

$$\eta_{cycle} = \eta_u \left(1 - \frac{T_0 (s_{in} - s_0)}{h_{in} - h_{out}} \right) \quad (13)$$

When a small amount of heat is extracted from the geothermal fluid (T_{in} is close to T_{out}) η_{cycle} will become proportionally greater than η_u because the resource is utilized poorly.

In order to obtain a value for the desired net power that can be extracted from a power plant, three efficiency factors need to be defined (Edwards et al., 1982). The first factor is an energy recovery factor that must be applied to account for the fact that there is a limitation in the lower rejection temperature mainly because of the rapidly increasing condenser cost. As a result, and in order this study to be realistic, there is a critical temperature below which the production of electricity from a geothermal reservoir ceases to be economical. This value as reported in the literature (Babcock and Wilcox, 1978), is 120 °C. The ideal frac-

tion of energy that can be recovered is given by Eq. (14).

$$\eta_{recovered} = \frac{T_{in} - 120}{T_{in} - T_0} \quad (14)$$

The two other efficiency factors account for the losses of energy associated with the fluid transfer through the pipeline as well as for the losses during the conversion of heat to power. The power plant fraction F_v considers the pressure and temperature losses from the wells to the power plant, the mode of generation and heat exchanger losses in the case of binary cycle turbines. The busbar fraction F_b images the effi-

ciency of conversion of the net available energy delivered to the turbine to electric power at the busbar. Typical values of F_v and F_b fractions based on experience are presented in Table 1.

Since the exergy term of the geothermal fluid has been estimated on the stage of the separator and not at the wellhead, a slightly increased value for F_v (0.75) will be considered. Therefore the desired net output P will be determined by Eq. (15).

$$P = \eta_{thermal} \cdot F_v \cdot F_b \cdot E \quad (15)$$

3.3. Proposed geothermal power plant exergy analysis

A proposed geothermal power plant diagram was designed (Fig. 2) for an exergy evaluation analysis of the different components. Due to further work needed in order to determine the exact final conditions of operation (mass flow rate, pressure, composition, etc.) many assumptions have been taken into account, as shown in Table 2. Saturated steam (geothermal fluid – 16 bar, 5.2 kg/s) will be utilized considering the thermodynamic properties of steam for calculations, and that no other gases (H_2S , CO_2 , etc.) are present. Ammonia (NH_3) will be used

Table 1
Typical values of F_v and F_b fractions for different reservoir types.

Reservoir type	Power plant fraction F_v	Busbar fraction F_b
Vapor dominated	0.95	0.72
Liquid dominated	0.6	0.72
Hot dry rock	0.6	0.65
Geopressured	0.6	0.75

Fig. 2. Schematic layout of the proposed geothermal power plant.

Table 2
Assumptions made concerning the proposed power plant.

Properties	Geothermal fluid (saturated steam)
$\dot{m}$ (kJ/s)	5.2
T_{in} (°C)	201.41
T_{out} (°C)	70
p_{in} (bar)	16
p_{out} (bar)	1

as the working fluid, circulating in a closed cycle based on the Rankine cycle. Ammonia is the most preferred choice among several working fluids, such as HCFC 123, n-Pentane and PF5050; this is due to the fact that ammonia exhibits the highest ratio of Rankine cycle efficiency to objective function compared to the respective ratios of the other working fluids (Madhawa Hettiarachchi et al., 2007) ().

The proposed power plant is designed for electricity generation of approximately 2.1 MWe net. The plant operates in a closed loop with no environmental discharge and 100% reinjection of the geothermal fluid. The geothermal fluid (saturated steam) is entering the plant at Level 1 and is fed to vaporizer 1 where it condenses. As saturated liquid leaves Level 1 and enters the Level 2 vaporizer where is cooled and reinjected at a temperature of 40 °C. At both Levels, the working fluid (Ammonia, NH_3) circulates through the two cycles. The working fluid enters the vaporizers as saturated liquid where it is evaporated and superheated. Then, it is directed to the turbines, exhausts to the water-cooled condensers where it condenses, and pumped to the preheater pressure. At the preheater, the effluent brine, coming from the separator, is used to raise the ammonia temperature. Finally, the working fluid reaches the vaporizer as saturated liquid as the Rankine cycle is completed. Further detailed description on the operation geothermal power plants of this type as well as on exergy analysis, can be found in literature (Kanoglu, 2002; Babcock and Wilcox, 1978; Bettagli and Bidini, 1996; Franco and Villani, 2009).

Exergy calculations are based on Eqs. (1) and (2). Exergy rate is calculated by Eq. (16). The power that can be obtained by the turbine and the work given to the pump in order to operate and increase the pressure of ammonia are given by Eqs. (17) and (18) respectively. Eqs. (19) to (22) give the exergy efficiencies for the turbine (Eq. (19)), pump (Eq. (20)), vaporizer (Eq. (21)), condenser (Eq. (22)) and preheater (Eq. (23)). The exergetic efficiency of the plant based on total geothermal fluid exergy drop in the cycle can be calculated by Eq. (24). Exergy destruction J can be calculated in each case by the difference between the numerator and denominator. Finally, the first law efficiency can be calculated by Eq. (25) based on energy input to the plant (Kanoglu, 2002). Equations (16)–(22) refer to Level 1 and are applied also to Level 2 by performing the corresponding changes.

$$\dot{E} = \dot{m} \cdot e \quad (16)$$

$$\dot{W}_{st} = \eta_{st} \cdot \dot{m}_{Am} \cdot (h_{in} - h_{out}) \quad (17)$$

Table 3
Exergy calculated values.

Method	Exergy [kW]
T-E charts	2381.6
Steam tables	2293.2
Constant c_p^h, c_p^s assumption	2288
Constant c_p^E assumption	2288
Thermal efficiency	1820

$$\dot{W}_{sv} = \frac{\dot{m}_{Am}}{\eta_{sv} \cdot 1000} \cdot \left(\frac{p_{out}}{\rho_{out}} - \frac{p_{in}}{\rho_{in}} \right) \quad (18)$$

$$\zeta = \frac{\dot{W}_{ST}}{\dot{E}_4 - \dot{E}_5} \quad (19)$$

$$\zeta = \frac{\dot{E}_7 - \dot{E}_6}{\dot{W}_{SV}} \quad (20)$$

$$\zeta = \frac{\dot{E}_4 - \dot{E}_3}{\dot{E}_1 - \dot{E}_2} \quad (21)$$

$$\zeta = \frac{\dot{E}_5 - \dot{E}_6}{\dot{E}_9 - \dot{E}_8} \quad (22)$$

$$\zeta = \frac{\dot{E}_{18} - \dot{E}_{19}}{\dot{E}_3 - \dot{E}_7} \quad (23)$$

$$\zeta = \frac{W_{net,plant}}{(\dot{E}_1 - \dot{E}_2) + (\dot{E}_{18} - \dot{E}_{19}) + (\dot{E}_2 - \dot{E}_{10}) + (\dot{E}_{20} - \dot{E}_{21})} \quad (24)$$

$$\eta_{plant} = \frac{W_{net,plant}}{\dot{m}_1(h_1 - h_0) + \dot{m}_{18}(h_{18} - h_0) + \dot{m}_{20}(h_{20} - h_0)} \quad (25)$$

where,

$\dot{m}$ = mass flow rate (kg/s)

e = specific flow exergy (kJ/kg)

$\dot{E}$ = exergy rate (kW)

h_0 = restricted dead state enthalpy (kJ/kg)

h_i = enthalpy at the specified state i, see Fig. 2 (kJ/kg)

s_0 = entropy at the restricted dead state (kJ/kg°C)

s_i = entropy at the specified state i, see Fig. 2 (kJ/kg°C)

$\dot{W}$ = power (kW)

ζ = exergetic efficiency

η = first law (thermal) efficiency

4. Results and discussion

4.1. Exergy calculation and efficiencies based on the geothermal fluid collected data

Because of the fact that the composition of the geothermal fluid in the reservoir of the Nis-2 well is not determined, the exergy is calculated using the five methods discussed above, in the separator level.

The separator is assumed to be working under 16 bar pressure, and thus the saturation temperature is 201.41 °C. The stream is constituted of saturated water and saturated steam, the latter having a percentage 40% by weight. The ambient conditions (dead state) are 25 °C and 1 bar. The results of exergy calculations based on the geothermal fluid at the separator level are presented in Table 2.

For an inlet temperature of 201.41 °C and assuming the ambient temperature at 25 °C, the calculated value for energy recovery factor is $\eta_{\text{recovered}} = 0.43$ (Eq. (14)). Cycle and utilization efficiencies are calculated by Eqs. (11)–(13) for a net power 2 MW_e (Institute of Geology and Mineral Exploration (I.G.M.E.), 1981; Public Power Corporation of Greece, Merz – Dal Geothermal Consultants, 1993; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1999; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1985), and their values are 0.42 and 0.216 respectively.

The calculated exergy values are in a relatively good accordance, except for the value estimated by the thermal efficiency method (Table 3). Exergy estimation from the T – E charts method appears higher than the other values; this is due to the deviation caused by the assessment of values in the charts. The use of steam tables for calculating the various terms of exergy is considered to be the most accurate approach because no assumptions or deviations are introduced, and thus, this value can be used for the estimation of the desired net output P. However, the constant c_p assumption does not produce a significant deviation in the exergy calculation compared to the value of exergy resulted in the steam tables method. The net power output that could be achieved from a potential power plant can be estimated at 2.1 MW_e. This value converges at a great extent to the value of the capacity of the power plant estimated in the report given by the Public Power Corporation of Greece (Institute of Geology and Mineral Exploration (I.G.M.E.), 1981; Public Power Corporation of Greece, Merz – Dal Geothermal Consultants, 1993; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1999; Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1985). For the calculation of the cycle efficiency the critical lowest temperature of 120 °C was considered. As can be seen, the utilization efficiency value is relatively satisfactory comparing to other corresponding values given in literature.

4.2. Proposed geothermal power plant exergy analysis

Results concerning exergy values as well as all other properties (mass flow rates, temperatures, pressures, etc.) at all points of the power plant are given in Table 4. Calculations were conducted assuming saturated steam was used initially as the geothermal fluid at a pressure of 16 bar. Table 5 presents the exergy destruction and the exergetic efficiencies of the power plant and of the different components ($\eta_{\text{st}} = 0.85$, $\eta_{\text{sv}} = 0.75$). The estimated thermal efficiency of the plant is 12.8% and the actual power output for the total level I–II cycle resulted is 2117.884 kW (or 2.1 MW approx.). Fig. 3 illustrates the exergy flow diagram of the proposed geothermal power plant, where exergy losses are given as percentages of the total exergy input to the plant. It is noted that the causes of exergy destruction in the plant include vaporizer-preheater losses, turbine-pump losses, the exergy of the brine reinjected, and the exergy lost in the condenser. The exergetic efficiencies of Level I vaporizer-preheater and Level II vaporizer-preheater are 60.2% and 94.6%, respectively. These percentages indicate the high performance of the heat exchange system. In binary geothermal power plants, heat exchangers are important components and their individual performances have a significant effect on the overall performance of the plant. The exergetic efficiency of the vaporizer is significantly greater than that of the preheater, because the average temperature difference between the brine and the working fluid is smaller in the vaporizer than in the preheater.

The goal of an exergy analysis, in the case of a geothermal power plant, is to identify the points where the highest exergy losses occur. As presented in Fig. 3, the highest exergy losses correspond to vaporizers I and II, while the other components have relatively very low exergy losses. In specific, the largest exergy losses take place at Vaporizer I (38.2%) and Vaporizer II (4.7%), while the smallest ones are observed at the pumps I & II (0.5% & 0.2%, respectively). The exergy losses at Turbines I & II are at particularly low levels (3.3% & 1.2%, respectively). These relatively low efficiencies, together with the significant exergy loss associated with its operation, indicate that performance of the turbines can be improved. The comparison with similar studies involving binary geothermal power plants using Rankine cycle shows

Table 4
Exergy rates and other properties at the power plant locations; state numbers refer to Fig. 2.

State No.	Fluid	Phase	T	T	p	h	s	$\dot{m}$	e	$\dot{E}$
			[°C]	[K]	[bar]	[kJ/kg]	[kJ/kgK]	[kg/s]	[kJ/kg]	[kW]
1	gf	Sat. Vapor	201.41	474.56	16	2793.9	6.423	5.2	913.998	4752.789
2	gf	Sat. Liquid	201.41	474.56	16	858.33	2.343	5.2	174.484	907.316
3	NH ₃	Sat. Liquid	78.3	351.45	40	752.69	6.93	8.796	328.020	2885.399
4	NH ₃	Sup. Vapor	150	423.15	40	1895.5	10.114	8.796	537.528	4728.323
5	NH ₃	Sat. Vapor	40	313.15	11.67	1678.22	10.067	8.796	333.875	2936.91
6	NH ₃	Liquid	30	303.15	11.67	503.6	6.184	8.796	297.561	2617.472
7	NH ₃	Liquid	30	303.15	40	504.6	6.176	8.796	300.906	2646.897
8	Water	Liquid	20	293.15	1	83.86	0.2963	165	0	0
9	Water	Liquid	35	308.15	1	146.48	0.5047	165	1.517	250.228
10	gf	Liquid	70	343.15	16	168.86	0.5715	5.2	4.337	22.552
11	NH ₃	Sat. Liquid	78.3	351.45	40	752.69	6.93	3.076	328.02	1009.009
12	NH ₃	Sup. Vapor	150	423.15	40	1895.5	10.114	3.076	537.528	1653.47
13	NH ₃	Sat. Vapor	40	313.15	11.67	1678.22	10.067	3.076	333.875	1027.022
14	NH ₃	Liquid	30	303.15	11.67	503.6	6.184	3.076	297.561	915.316
15	NH ₃	Liquid	30	303.15	40	504.6	6.176	3.076	300.906	925.606
16	Water	Liquid	20	293.15	1	83.86	0.2963	55	0	0
17	Water	Liquid	35.7	308.85	1	149.55	0.5146	55	1.7	93.488
18	brine	Liquid	99.63	372.78	1	417.51	1.3027	9	38.624	347.615
19	brine	Liquid	41.8	314.95	1	175.022	0.5961	9	3.276	29.48
20	brine	Liquid	99.63	372.78	1	417.51	1.3027	3.5	38.624	135.183
21	brine	Liquid	47.7	320.85	1	199.461	0.6729	3.5	5.201	18.203
Dead	NH ₃	Dead state	20	293.15	1	1719	11.34	–	0	–
Dead	Water	Dead state	20	293.15	1	83.86	0.2963	–	0	–

Table 5
Exergy destruction and exergetic efficiencies.

Component	Exergy destruction [kW]	Exergetic efficiency [%]	Heat transfer/Power [kW]
Vaporizer I	2002.549	47.9	10052.64
Preheater I	79.544	75	2182.393
Condenser I	69.210	78.3	10332.419
Turbine I	166.790	89	1624.624
Pump I	26.040	53.1	55.466
Level I cycle	2344.133	37.7	1569.158
Vaporizer II	240.304	72.8	3515.356
Preheater II	33.547	71.3	763.171
Condenser II	19.318	82.7	3613.193
Turbine II	58.326	89	568.122
Pump II	9.106	53.1	19.396
Level II cycle	360.601	54.8	548.726
Level I-II cycle	2704.734	41	2117.884

that the proposed unit exhibits substantially smaller losses at turbines and pumps, but considerably larger ones at vaporizers (Kanoglu, 2002; Franco and Villani, 2009). The parasitic power loss is 5.45% in total, which is considered as relatively low (Franco and Villani, 2009).

The exergetic efficiencies of the geothermal plant components were determined, as well as the corresponding one for the whole system. The proposed power plant has a very high exergetic efficiency value of 41% which is comparable to the best efficiencies reported for other ex-

isting plants in previously published research (Table 6). The vast majority of geothermal plants have achieved exergy efficiencies that vary between 20% and 35%. In any case, exergetic efficiencies of more than 40% have been achieved in just a few plants with geothermal fluids having specific exergies of 200 kJ/kg or lower (Yari, 2010). Thus, the construction of a plant for the exploitation of Nisyros geothermal field is supported by the technical data.

5. Conclusion

The current study has revealed that a binary geothermal plant based on a Rankine cycle is a feasible project from a technical point of view. All exergy indicators and efficiencies emerging from a series of calculations provide strong support to the implementation of the proposed 2.1 MW binary geothermal plant in Nisyros that could reach up to 10 MW of total installed power in the future (Theodosiou et al., 2014). This particular power generation plant would supply the Dodecanese interconnected power system with a very substantial amount of electricity, thus reducing the dependence of the system to the diesel power unit installed in Rhodes, Greece. Hence, the gain from an environmental point of view would be great.

As it has been already stated, this is a proposed power plant and the exact properties of the geothermal fluid in order to be utilized must be determined, thus further design and analysis (considering the financial parameter as well) is required; however, it provides a very clear picture of the satisfying utilization level that can be achieved. Furthermore, future research should nonetheless attempt to replicate this study using alternative working fluids, so as to improve the confidence in the findings about feasibility geothermal unit. We hope that our findings will motivate authorities of Greece and those of European Union to take advantage of this special renewable energy field, located in the Southeastern part of Mediterranean, to the benefit of the environment.

Fig. 3. Exergy flow diagram of the proposed geothermal power plant.

Table 6
Exergy efficiencies comparison.

Power plant	Exergetic efficiency [%]
Nisyros NIS-2	41
Kavala, Greece (Al-Dabbas, 2009)	33.3
Denizli Turkey (Mendrinis et al., 2010)	20.8
Nothern Nevada, USA (Institute of Geology and Mineral Exploration (I.G.M.E.), 1981)	
• Based on the exergy input to isopentane cycles	34.2
• Based on the exergy input to the plant	29.1
Case study (Greek Institute of Geology and Mineral Exploration (I.G.M.E.), 1999; Institute of Geology and Mineral Exploration (I.G.M.E.), 1981)	
• Based on the exergy input to the plant	22.6
• Based on the Rankine Cycle	34.8
Case study (Cerci, 2003; Institute of Geology and Mineral Exploration (I.G.M.E.), 1981)	
• Based on the exergy input to the plant	20
• Based on the Rankine Cycle	33.5
Case study (Bodvarsson and Eggers, 1972)	
• Single flash cycles	38.7
• Double flash cycles	49

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