Hittite Journal of Science and Engineering, 2018, 5 (Special Issue: Selected Papers from ULIBTK'17) 59-73
ISSN NUMBER: 2148-4171
DOI: 10.17350/HJSE19030000119

Rational Exergy Management Model for Effective Utilization of Low-Enthalpy Geothermal Energy Resources

Birol Kılkış[1] **Şiir Kılkış**[2]
[1]Başkent University, Bağlıca Campus 06810 Etimesgut, Ankara, TURKEY
[2]TÜBİTAK, Atatürk Bulvarı, 06100, Ankara, TURKEY

Article History:
Received: 2018/04/04
Accepted: 2018/04/12
Online: 2018/09/07

***Correspondence to**: Birol Kılkış, Başkent University, Bağlıca Campus 06810 Etimesgut, Ankara, TURKEY*
E-mail: bkilkis@baskent.edu.tr

ABSTRACT

Within the broad range of sustainability and decarbonization efforts, energy and exergy-rational cities are becoming universally important. Within this context, both ORC systems, which are touted as primarily useful for utilizing low-enthalpy geothermal resources and heat pumps, which are considered as the primary tool for decarbonization are critically analyzed in this study. In this context, two cases regarding an ORC, which is used only for power generation without utilizing its waste heat and a heat pump operating on grid power, were examined and was concluded that they are not exergetically sustainable, if they operate as individual systems. This study instead developed an analysis model, which reveals with case studies and examples that a broad hybridization of combining ORC technology, heat pumps, absorption units, thermal storage, and other renewable energy resources, like solar and wind provides sustainable and exergetically rational design solutions. It is argued and verified that, within practical demand and supply constraints in the built environment, such hybrid systems lead to 4th generation district energy systems and beyond, like nearly-zero energy and exergy cities. In order to arrive such conclusions, new evaluation and rating metrics based on Rational Exergy Management Model were introduced. A novel nearly-zero energy and exergy design about a 20000-inhabitant town having geothermal energy potential at a production well-head temperature of 80°C is presented for a simplified purpose of demonstrating the algorithm of the new model This design incorporates ground-source heat pumps, waste heat utilization, cogeneration units, in addition to ORC system. Such an enrichment of the multiple systems even in a simplistic manner in an exergy economy cycle analytically reduces CO_2 emissions by about 66%, when compared to a conventional district energy system utilizing natural gas. Yet analyses have shown that results are sensitive upon design constraints and local conditions and concludes that the only option of achieving a truly sustainable solution in terms of exergy towards net-zero status is optimum bundling of the energy resources and systems on a case-by-case design with the main aim of balancing the supply and demand exergy.

Keywords:
ORC technology; Geothermal energy; Hybrid district energy system; Rational Exergy Management Model; CO_2 emissions responsibility; Heat pumps; Cogeneration; Thermal energy storage

INTRODUCTION

Based on the Rational Exergy Management Model, the objective of this study is to develop an analytical tool with new design, evaluation, and rating metrics for designing and analyzing hybrid energy systems and resources, including low-enthalpy geothermal energy towards achieving nearly-zero status of district energy systems, based on both energy and exergy performance of new establishments with district energy systems. The main aim is to achieve maximum decarbonization efficiency in these establishments. Another aim is to resolve the conflict between decarbonization and high CO_2 content of the geothermal reservoirs in Turkey by reducing the unit CO_2 emissions per unit exergy output of the hybrid system, in addition of traditional methods of capturing and use of CO_2.

In Turkey, most of the geothermal energy grabens are $CaCO_3$ based. This means that geothermal wells emit CO_2 that needs to be recaptured, which is considered as an expensive process in the sector. That is why most of the applications in Turkey directly release CO_2 to the atmosphere, nearly at a rate of 1 kg CO_2/kW-h. To be precise, this rate, symbolized by *u* in Equation 1, is almost equal to coal-based thermal plants [1]. CO_2 emissions per unit power generation are 0.034 kg CO_2/kW-h for Iceland, 0.33 kg CO_2/kW-h for Italy, and the world average is 0.122 kg CO_2/kW-h according to the recent studies of the World Bank in 2016 [2]. According to the same report this value, particularly for the Gediz graben in the Western Anatolia varies between 0.9 kg CO_2/kW-h and 1.3 kg CO_2/kW-h. Other publications also confirm these results [3]. For natural-gas, combined-cycle power plants this value is around 0.42 kg CO_2/kW-h (Based on an average First-Law Efficiency of 0.47 for the power generation in the plant and the CO_2 content of natural gas of 0.2 kg CO_2/kW-h lower heating value). This value for coal-base power plants is around 1.3 kg CO_2/kW-h [4, 5, 6]. In Equation 1, u is the unit CO_2 emissions per kW of electrical power generated, E.

$$u = \frac{\sum CO_2}{\sum E} \quad \{\text{kg } CO_2/kW_E\} \tag{1}$$

Equation 1 reminds us that the unit emission values, namely u are based only for power generation and therefore is not responsive for low-enthalpy geothermal energy resources, because their electric power generation capacity are limited or none and instead, they need to be utilized in the form of heat, or sometimes in the form of cold through absorption and most likely, through adsorption cycles. Probably that is why the waste heat of ORC systems are indeed wasted without employing it in useful applications in the field or in the city, because they are not recognized in Equation 1 nor appreciated in bank loans.

Fig. 1 further illustrates that only-electric ORC systems for example, may not be rational, especially from an exergetic point of view [7]. Fig. 2 exemplifies this condition better by comparing the ORC and District Energy bundle [7]. In this figure, options are either using ORC alone or directly using the geofluid in district heating. This example shows that, in many cases of low-enthalpy geothermal sources like below 100°C, it is better to utilize the geothermal energy as heat or cold (through absorption or adsorption cycle) rather than trying to generate power with such a low efficiency around 10% in practical terms. See Fig. 3 for several working fluids [8].

According to the example given in Fig. 2, exergy of ORC power output is only 0.08kW/kW while the exergy of the geofluid, which could be directly used for heating is 0.2 kW/kW. The latter is definitely higher. A new criterion has been defined, which is named the Added Value, *AV*. It is a simple product of the First-Law efficiency, η_{ORC} or η_{DE} and the unit exergy, ε_E or ε_H of the power generation by ORC equipment or thermal output of the district energy system at a well-head temperature, T_K, respectively.

$$AV_E = \eta_{ORC} \times \varepsilon_E \approx \eta_{ORC} \qquad \text{,or} \tag{2-a}$$

$$AV_H = \eta_{DE} \times \varepsilon_H = \eta_{DE} \times \left(1 - \frac{283}{273 + T_K}\right) \tag{2-b}$$

Here η_{ORC} is the First-Law efficiency of ORC in electric power generation (ε_E~1 kW/kW) for a given well head temperature of the geofluid, T_K (See Fig. 3):

$$\eta_{ORC} = aT_K + b \tag{2-c}$$

Here, 283 K is the selected reference temperature, T_{ref} for the ideal Carnot Cycle. Equations 2-a, 2-b, and 2-c may be simultaneously solved for a critical T_K value, namely T_{KCR}. Such a solution is the positive root of the quadratic equation:

$$T_{KCR} = \frac{\left(1 - \frac{273a}{\eta_{DE}}\right) \pm \sqrt{\left(1 - \frac{273a}{\eta_{DE}}\right)^2 + 4 \times 273 \left(\frac{a}{\eta_{DE}}\right) \times \left(1 + \frac{b}{\eta_{DE}}\right)}}{2\left(\frac{a}{\eta_{DE}}\right)} \tag{3}$$

In this Example, T_{KCR} is around 100°C. Below this critical temperature ORC system is not feasible. Above the critical temperature ORC is a better option. An even better option is to utilize the waste heat from ORC in a low-exergy district heating system at around for example 40°C.

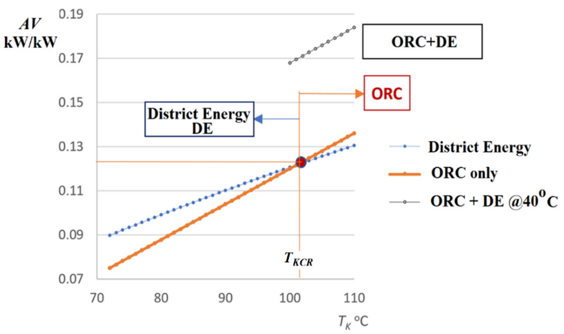


Figure 1. Exergy Rationality of Utilizing Low-Enthalpy Geothermal Energy for R123 Working Fluid [7]

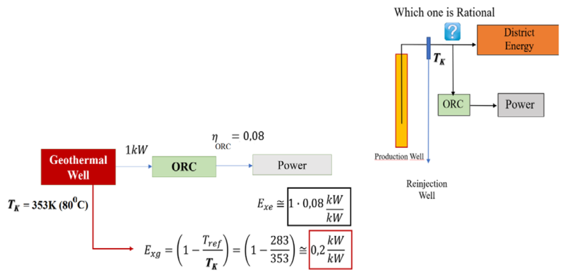


Figure 2. ORC and District Energy Dilemma [7]

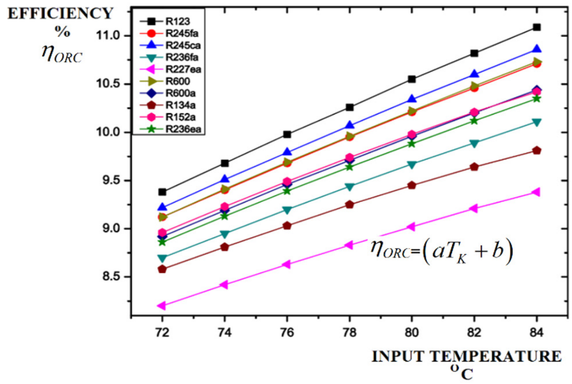


Figure 3. ORC Efficiencies for different working Fluids [8]

In this research, a new evaluation metric, which relates the thermal exergy and power exergy outputs of a geothermal system, named E_{XR} has been derived from the new exergetic approach. The argument of this approach is that the thermal output exergy (Numerator of Equation 4 must be at least 25% more than ORC output exergy):

$$E_{XR}=\frac{\left(1-\dfrac{283}{(273+T_K)}\right)\times\eta_H}{(aT_K+b)\times 1}>2 \tag{4}$$

Low-enthalpy geothermal energy has about 30% share among different heat sources that drive ORC systems for electricity generation [9]. ORC market is rapidly increasing but their expansion mainly depends upon economic incentives, tariffs, and several subsidies [9].

Even today ORC market is relying on the economic benefits of selling the electrical energy based on tariffs and incentives [10]. There are few studies however, which look into their actual benefits, risks, and potential disadvantages from sustainability view at large. One such recent study has revealed that ORC units may not be ecologically sound if used in a stand-alone format and just generate electric power [11]. The same study has shown that ORC systems need to be bundled with other renewable energy resources, systems, and energy storage units in order to be environmentally acceptable from the exergy point of view [11]. In fact, there are few exergy analyses available in the literature that mainly focus on the operation of the ORC units and design without having a holistic approach, that is to say, its connection between the energy source and the demand in the built environment. In fact, without the Second-Law of Thermodynamics, it is not possible to identify and quantify the advantages and disadvantages of using stand-alone ORC units against different bundling alternatives with renewable energy systems.

Fig. 1 at the same time indicates that above a certain well-head temperature, ORC may indeed be a feasible solution, but a better solution is to utilize the so-called waste heat. This is nothing but cogeneration and provides the first signals of hybrid energy systems, moving away from power-only solutions in order to reduce u. Such an application will definitely reduce the above mentioned unit CO_2 emission values. The remaining problem is how to incorporate the thermal output into the power-based equation above, because heat, cold, and power have quite different exergy. At this point the Second Law comes to the rescue such that the denominator of Equation 1 is modified in terms of exergy rather than energy:

$$u_x=\frac{\sum CO_2}{\sum E_{xE}+\sum E_{xH}}=\frac{\sum CO_2}{\sum E+\sum E_{xH}} \tag{5}$$

The sum of thermal exergy E_{xH} includes geothermal heat converted to cold by absorption or adsorption machines. The last term in Equation 5 is based on the widely accepted assumption that electric power has a unit exergy of 1 kW/kW (Actually 0.95 kW/kW at a reference temperature of 283K). Therefore, E_{XE} (Electrical Exergy of a given electrical energy) is replaced by E (Electrical Energy). Thanks to the exergy concept, this equation eliminates the exergy differences between heat and power, because itself is based on exergy and lets large heat and or cold energy potential (if utilized instead of wasted) to be recognized and incorporated in the same domain of exergy with electric power. By this new metric, firstly introduced in this article, namely u_x, high CO_2 emissions from low-enthalpy geothermal energy sources are automatically reduced below other conventional power plants, while these power plants generally do not utilize their waste heat. This new metric is an important incentive towards utilizing the waste heat in useful forms of many different types of applications-not only for geothermal power plants but also for all types of power plants. This is large scale cogeneration according to EU Directive 2004/8/EC [12]. This directive defines the efficiency requirements according to the First Law of Thermodynamics and calculates the primary fuel savings. Although heat and power are discriminated in this equation, it does not recognize the exergy differences in terms of the temperature of the heat provided. In order to resolve this issue Kilkis, S. and Kilkis B. have upgraded the fuel savings equation of the directive in terms of the Rational Exergy Management Efficiency (See Equation 9) [13].

Another important point is the fact that, geothermal potential in terms of thermal quantity, Q that contributes to the added value potential of the associated systems need to be recognized and adjusted according to the quality of geothermal energy potential in terms of exergy, which is defined in terms of the average enthalpy represented by the average reservoir well-head temperature. A new metric, J was defined:

$$J = \frac{E_{XH}}{A} = \frac{\left(1 - \frac{T_{ref}}{\bar{T}_K}\right) \times Q}{A} \tag{6}$$

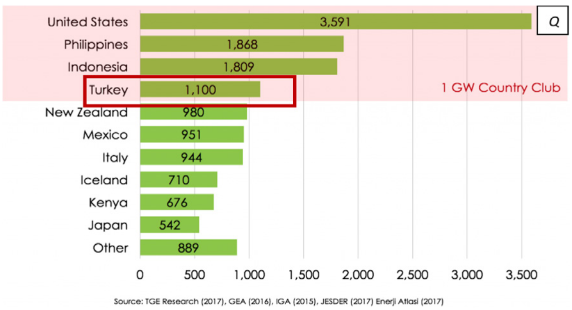


Figure 4. 1 GW Country Club Ratings Based on Reservoir Potential, *Q* [14]

Fig. 4 lists several countries with 1 GW installed capacity and above. This listing is according to the First Law ranking in terms of *Q*. In this list, Turkey ranks fifth in the World. However, if for example the estimated average $\bar{T}_K$ value is 107°C (380K) and the geographic area of Turkey is 780,000 km², then the *J* value for Turkey is 0.36 kW/km². If Equation 6 is applied to all countries given in the Table, then the ranking will definitely shift and the position of Turkey will be quite different.

$$J = \frac{E_X}{A} = \frac{(1{,}100\ \text{MW} \times 1000\ \text{kW/MW}) \times \left(1 - \frac{283}{380}\right)}{780000}$$
$$= 0.36\ \text{kW/km}^2$$

Fig. 5 exemplifies the fact that Turkey is one of the countries in the list, which has a majority of geothermal reservoirs with low enthalpy. According to Fig. 5, the well-head temperatures in the province of Ankara ranges between 37°C (310K) and 56°C (329K). This means that the exergy of the geothermal reservoirs range between (1-283K/310K) *Q* and (1-283K/329K)*Q*, namely 0.087*Q* and 0.14*Q*. This means that the geothermal reservoirs in the province of Ankara the added value of useful work potential ranges only between 8.7% and 14% of the thermal reservoir, *Q*. This is an important step of evaluating of geothermal reservoirs in acknowledging the true quality of geothermal reservoirs instead of the quantity of the reservoirs.

Another metric is related to the investment cost, which is broken to electric power, heat, and cold power services In Equation 7, *i* is the unit investment cost in terms of Turkish Lira, TL investment per unit design power, unit exergy, heating degree hours (HDC), and cooling degree hours, CDH (If included in the project). In Equation 7, *i* is the investment index. I_E, I_H, and I_C are the original investments in Turkish Lira, which are attributable to electric power, heating, and cooling services, respectively to be delivered to human populations receiving power, heat, and cold services N_E, N_H, and N_C, respectively in the district energy system.

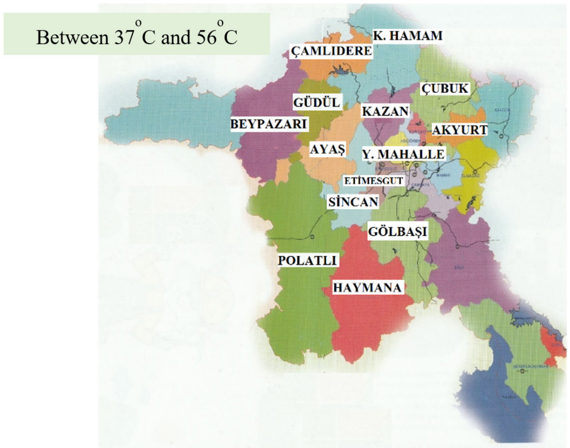


Figure 5. Low Enthalpy Geothermal Energy in the Province of Ankara [15]

$$i = \frac{I_E}{\left[N_E \times P_E \times 1 \times (HDH + CDH)\right]} + \frac{I_H}{\left[N_E \times P_H \times \left(1 - \frac{T_{OH}}{T_K}\right) \times HDH\right]} + \frac{I_C}{\left[N_C \times P_C \times \left(1 - \frac{T_{OC}}{T_K}\right) \times CDH\right]} \tag{7}$$

Here, *P* stands for the design capacities of power, heat, and cold services. *HDH* and *CDH* are the heating and cooling degree-hour values, respectively. Lower the *i* value is, better the economical investment is. The last term drops if any cooling service is not provided in the district energy system. Investment, *I* is rated also for the quality of the services provided in terms of the ideal Carnot Cycle. T_{OH} and T_{OC} are the design outdoor temperatures for winter and summer seasons, respectively. The unit exergy of electricity is taken 1 kW/kW.

LITERATURE SURVEY

Current trend is to isolate any unit from the entirety of the applied system and evaluate it alone. For example, ORC units are sold based on the simple condition of economy to the customer or the power company in terms of electricity prices and subsidies if available and applicable to that particular system. The same also holds true for heat pumps [16]. Investment pay backs and bank loans etc. are always calculated in terms of the simple economy of the customer or the power company. These approaches do not reveal the real performance of the unit and real potential contributions and added value to the energy economy at large and the environment, when coupled to the energy input side and the energy supply side (application).

Another current advancement is the development of geothermal heat pumps in smart cities and communities [17]. However, this project focuses on shallow geothermal heat pumps driven by grid electricity. Therefore, this project needs to be upgraded by novel, integrated solutions, like the ones presented earlier by the Authors [18,19].

Reza Rowshanzadeh [20] has shown that ORC technology has a very wide field of applications and gave a case design for one of the clients of the KTH University in Sweden and pointed out the need for an exergy analysis. Sun, W., Yue, X., and Wang. Y. have investigated the suitable application conditions of ORC-ARC (Absorption Refrigeration-Cycle) and ORC-ERC (Ejector-Refrigeration Cycle) and reported comparative results in terms of their exergy analyses [21]. In their paper, Marini, A., Alexandru, D., Grosu, L. and Gheorghian, A. [22] have analyzed an ORC system driven by solar energy with vacuum-tube collectors, which provides electrical power for a building. They simulated the performance for different working fluids based on the objective of minimizing the exergy destructions in the system. They concluded that such an ORC system may be exergetically feasible if a careful optimization is carried out. A recent study by Kilkis, B. and Kilkis Siir [15] have complemented the idea that the First Law of thermodynamics is not sufficient to evaluate ORC systems for best performance and environmental sustainability, especially when different renewable energy systems and systems are bundled to form a hybrid system. For example, the electric power input to GSHP is utilized to supply heat with a given First-Law *COP* at given operating conditions. But the input side and the supply side have different exergy.

THEORY

Review of the Rational Exergy Management Model

Referring to the *Rational Exergy Management Method* (REMM), developed by Şiir Kilkis [15, 21], it is possible to quantify the exergetic advantages that may also be directly translated to avoidable CO_2 emission calculations one may compare direct geothermal heating versus geothermal ORC power generation also. Fig. 6 and 7 show the so-called *Exergy Flow Bars*, respectively [23].

In Fig. 6, exergy destruction (ε_{des}) takes place both in upstream and downstream. Because exergy is also destroyed upstream, based on ideal Carnot Cycle, the following equation is used to calculate the *REMM Efficiency*, ψ_R [23, 24]:

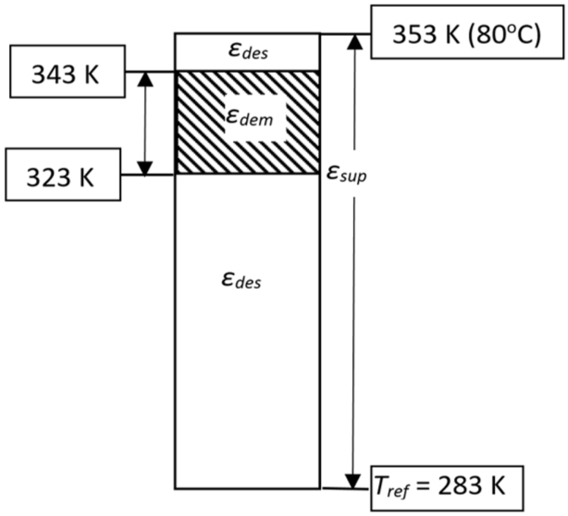


Figure 6. Geothermal District Heating

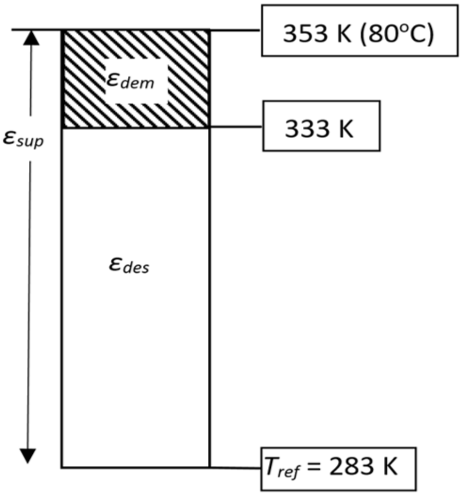


Figure 7. Power Generation with ORC [23]

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{\sup}} = \frac{\left(1 - \frac{323}{343}\right)}{\left(1 - \frac{283}{353}\right)} = 0.294 \qquad (8)$$

Here, ε_{dem} represents the demand exergy of the district heating system between 60°C and 40°C for Low-Exergy buildings connected to the system. Another feature of REMM is the ability of identifying the exergetic effect of the final application. The final application in this case is comfort heating say for example at 20°C indoor air temperature in buildings. Then the ε_{dem} term is replaced by (1-283/293). In this case ψ_R reduces to 0.172.

Fig. 7 shows the Exergy Flow Bar for ORC case for power generation. The un-utilized ORC outlet heat is taken to be at about 60°C (333 K). Because practically no exergy destruction takes place upstream, the following equation is used this time [23]:

B. Kilkis, S. Kilkis / Hittite J Sci Eng, 2018, 5 (Special Issue: Selected Papers from the 21st National Thermal Sciences and Technology Congress) 59–73

$$\psi_R = 1 - \frac{\varepsilon_{des}}{\varepsilon_{sup}} = 1 - \frac{\left(1 - \frac{283}{333}\right)}{\left(1 - \frac{283}{353}\right)} = 0.243 \quad (9)$$

REMM shows that direct geothermal heating is more exergy-rational than just power generation with ORC without other *Geotherm* model applications, which are shown in Fig. 8 and 10.

Optimization Model of Hybrid Thermo Electric Systems- Exergetic Dilemma

The objective of this study was to develop a compound optimization model with a single operational variable, namely the heat supply temperature, T_{out} to a heat demanding building, which is shown in Fig. 8. According to this study, T_{out} must be collectively optimized for a given building heat load, Q_H for a required indoor air comfort temperature, T_a, which is expressed by Equation 10 (See also Fig. 8). Here, the heating demand is satisfied by a certain set of heating equipment installed into the building. The equipment performance is characterized *s* and *n*. The equipment heat output is dependent on T_{out}. Because Q_H is a given input parameter in this model, it is an inequality constraint of optimization. The objective of this new optimization problem is to maximize the total exergy output of the geothermal reservoir at a well head temperature, T_K. Total exergy output is the sum of the electric power exergy, E_{XE} delivered by the ORC unit operating at a First-Law Efficiency of η_{ORC} (T_K) and the thermal exergy supplied to the building, E_{XH}. This objective comprises the following

- ψ_R is to be maximized (Equation 10).
- Compound CO_2 emissions is to minimized (Equation 12),
- *COP* and COP_{EX} are to be maximized (Equations 11 and 13)
- Split of the geothermal energy between an ORC unit (*X*) to produce electric power at a conversion efficiency, η_{ORC} and (1-*X*) to supply heat to the building via the GSHP.

These individual objectives may be combined to a grand objective functions with weighing functions to be determined by the designer.

$$Q_H = s\left(T_{out} - T_a\right)^n \quad (10)$$

$$COP = a - b(T_{out} - T_K) - s'\left(1 - \frac{T_K}{T_{out}}\right) \quad (11)$$

$$CO_2 = \left[\frac{c_f}{\eta_I \eta_T}\left(\frac{Q}{COP} + E\right)\right]\left(2 - \psi_R\right) \quad (12)$$

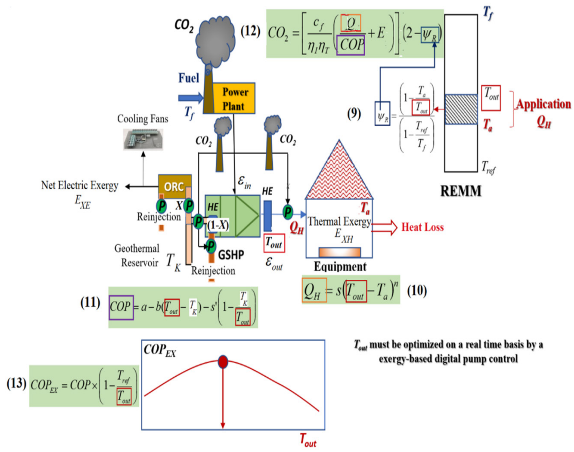


Figure 8. Second Law Model for Low Enthalpy Geothermal Source and a Temperature-Peaking Ground-Source Heat Pump [25]

Heat Pump Performance

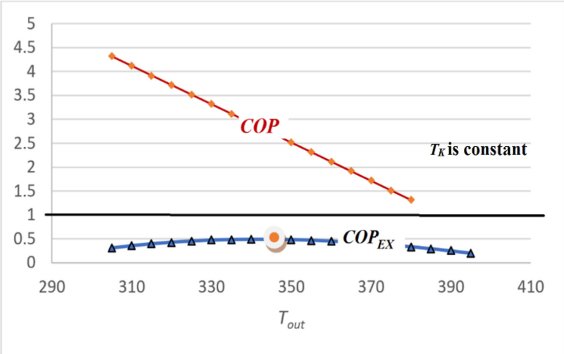
According to Fig. 8, all performance variables are related to T_{out}. For example, Q_H of a given indoor comfort equipment is directly proportional to T_{out}, while the Rational Exergy Management Exergy, ψ_R is inversely proportional to T_{out}. Furthermore, CO_2 emissions responsibility of the geothermal system, which runs on grid power to drive the circulation pumps has a more complex dependence on Tout. For example, in order to decrease the difference between the inlet and outlet temperatures of the heat pump volumetric flow rate needs to be higher. This increases the power need for the circulation pumps and consequently CO_2 emissions responsibility increases. But at the same time *COP* of the heat pump increases resulting on less power demand for the compressor of the het pump. On the other hand, if the temperature difference becomes too small the exergy of the output het at a very low T_{out} decreases. This whole complexity and the conflicting relations show that T_{out} needs to be optimized.

In this study, the performance of the heat pump is expressed in terms of COP_{EX}:

$$COP_{EX} = COP \times \frac{\varepsilon_{out}}{\varepsilon_{in}} = COP \times \frac{\left(1 - \frac{T_{ref}}{T_{out}}\right)}{\varepsilon_{in}} \quad (13)$$

In Equation 13, ε_{in} is the unit exergy of electricity supplied to the heat pump by the power plants through the grid (1kW/kW). It seems that heat pumps play an important role in such clustered, hybrid renewable energy systems and equipment. Furthermore, Fig. 8 shows that an exergy base is crucial.

For a fixed (given) temperature, T_K at the well head of the geothermal reservoir, when T_{out} increases the temperature difference, ΔT between the heat pump inlet temperatu-



$a = 5$, $b = 0.04$ K^{-1}, $T_{in} = 288$ K, $T_{ref} = 283$ K

Figure 9. A Sample Variation of *COP* and COP_{EX} with T_{out} [25]

re (T_K) and the outlet temperature (T_{out}) increases. Consequently, the *COP* of the heat pump decreases. But at the same time, the output unit exergy increases while T_{out} increases (See Fig. 8 and Equations 11 and 13). These equations may be used to determine the maximum COP_{EX} for an optimum T_{out}. According to Fig. 9, although there is a slight maximum for COP_{EX}, its value is below 1. This means that *COP* of commercial heat pumps available today need to be higher, in terms of higher *a* values and smaller *b* values. Fig. 9 shows a sample variation of T_{out} [25].

Distance Constraint

Another constraint for district energy systems, *DE* is the maximum allowable distance between the geothermal source and the district location, namely L_{max} [26]. Height of the buildings in a settlement for a given population determines the L_{max}. In District Energy (DE) systems, the hydronic piping, namely the circuit length has an exergetic and financial limit. Exergetic limit is the requirement that the exergy demand (electric) associated with the pumping energy consumption must be only a small portion of the thermal exergy delivered to the district. Water distribution requires substantial pumping power and piping network is energy/exergy intensive both in embedded and operational forms. Depending upon the amount of thermal power of different forms to be distributed, there are limits on the maximum piping length. Equation 5-a was developed for heating.

$$L_{\max} = a_o + \left(\frac{Q}{1000}\right)^m \times \left(\frac{\Delta T}{20}\right)^{1.3} \quad \{Q>1000\ \text{kW}_H,\ \Delta T \leq 30^\circ\text{C}\} \qquad (14)$$

Q_H is the useful thermal power to be transmitted (kW$_t$), ΔT is the supply return temperature difference, L_{max} is the farthest point that a closed thermal circuit may feasibly reach (km), a_o is an empirical constant, which is generally taken 0.6 km. The power *m* depends on the temperature, thus exergy of the heat supplied. T_{ref} is 283.15 K. 333.15 K is the traditional supply temperature.

$$m = 0.6 \times \left(\frac{\left(1 - \frac{T_{ref}}{T_K}\right)}{\left(1 - \frac{T_{ref}}{333.15}\right)}\right)^{0.33} \quad \{\text{For heating}\} \qquad (15)$$

If cold water is circulated for a cooling demand then:

$$L_{\max} = a_o + \left(\frac{Q}{1000}\right)^m \times \left(\frac{\Delta T}{10}\right)^{1.3} \quad Q>1000\ \text{kW}_H,\ \Delta T \leq 30^\circ\text{C}\} \qquad (16)$$

$$m = 0.6 \times \left(\frac{\left(1 - \frac{T_{ref}}{T_f}\right)}{\left(1 - \frac{T_{ref}}{282.65}\right)}\right)^{-1,23} \quad \{\text{For cooling}\} \qquad (17)$$

CIRCULAR GEOTHERMAL SYSTEM MODEL, GEOTHERM

In order to improve the sustainability awareness in geothermal and ORC industry, a new concept was developed. This concept comprises the idea of combining ground heat and geothermal energy in a circular exergy flow. The concept in heating mode is shown in Fig. 10.

Ground Heat, Geothermal Energy, and Sustainable Systems

Following from the production well to the re-injection well, each unit in the circular exergy flow was analyzed in terms of their expected performance values. Then the following overall performance results (Total output) were obtained:

Total Output = (0.62 kW$_H$ @55°C+0.34 kW$_H$ @90°C
0.04 kW$_H$ @35°C (for preheating of DHW)
= 1 kW$_H$ thermal
+ 0.348 kW$_E$ electric

If the saved natural gas from district heat, which is later consumed in the poly-generation unit is not considered, then the gross *COP* of the circular geothermal loop is 1.348 kW/1 kW of geothermal power input. First-Law *COP* is greater than one, because ground heat is utilized in the GSHP in addition to the geothermal energy. *COP* = 1.348.

In other words, starting from a unit geothermal power at 80°C, the circular geotherm provides 0.348 kW of electric power and 1 kW of thermal power at different supply temperatures. This output favorably compares with 0.08 kW of electric power supplied by the ORC unit without reject heat recovery and 1 kW of thermal power at 80°C supply, if the geothermal power is utilized in the district in the form of heating only (Table 2). For electricity, ε_{in} in may be taken 1 kW/kW. T_{ref} is the environment reference temperature, in this case the average ground temperature (283K).

B. Kilkis, S. Kilkis / Hittite J Sci Eng, 2018, 5 (Special Issue: Selected Papers from the 21st National Thermal Sciences and Technology Congress) 59–73

$$COP_{EX} = \frac{0.62\times\left(1-\frac{283}{328}\right)+0.34\times\left(1-\frac{283}{363}\right)+0.04\times\left(1-\frac{283}{308}\right)+0.348\times(1)}{1\times\left(1-\frac{283}{353}\right)+(0.62/0.8)\times\left(1-\frac{283}{2000}\right)}$$

$$=0.59$$

If only a simple ORC unit would be used, then COP_{EX} would be 0.092.

This Circular Geotherm Model comprises the following units:

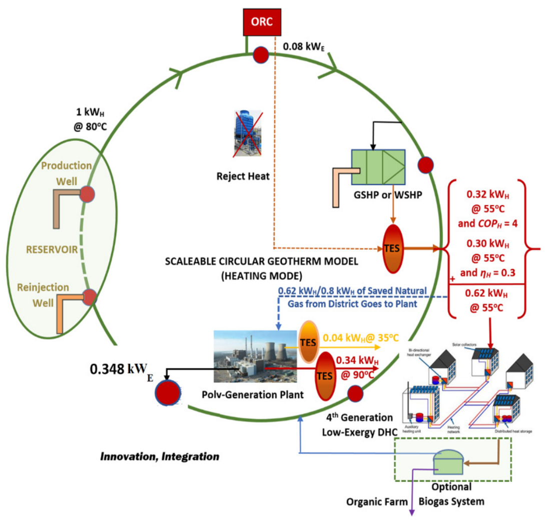


Figure 10. Combined Heat and Power in Circular Geotherm System: Heating Mode

- Geothermal Well(s),
- ORC,
- GSHP,
- District Energy Distribution and Collection System,
- Poly-Generation System,
- Biogas System (Optional), and
- Re-injection well(s).

Geothermal heat drives the ORC system. The electric power generated by the ORC drives the Ground-Source Heat Pumps (GSHP). Heat generated by the GSHP is utilized in the district. This heat is supplemented by the reclaimed reject heat from the ORC system. Buildings in the district are low-exergy type, which permit low temperature heating and high temperature cooling (Cooling Mode is not shown above). For the modeling purposes, the natural gas saved by replacing the heat provided by the ORC system and the GSHP, which otherwise would be spent in conventional boilers for heating purposes, is assumed to be utilized in a local poly-generation system, which generates both heat and electric power. Heat generated is of higher exergy at 90°C and is utilized in the district energy system while the domestic hot water, preheated by the waste heat from the poly-generation system is temperature peaked. Table 1 shows a summary of the performance and compares with other systems.

These results further emphasize that, if a composite index that combines the quantity and quality features of the systems is used. This composite index being developed herein is ***Composite Rationality Index***, C_R. This index gives

Table 1. Comparison of the Circular Geotherm with Natural Gas and ORC only Case.

System	*Output*			
	Electricity	*Heat at 90°C*	*Heat at 55°C*	*Heat at 35°C*
Circular Geotherm	*0.348 kW$_E$*	*0.34 kW$_H$*	*0.62 kW$_H$*	*0.04 kW$_H$*
DH with NG			*0.775 kW$_H$*	
ORC only	*0.08 kW$_E$*			

equal importance to the First and Second Laws of Thermodynamics, namely the First-Law Efficiency and REMM Efficiency. The same expression may also be repeated for applications involving *COP*.

$$C_R = \eta_I \times \psi_R \quad \text{or,} \tag{18}$$

$$C_R = COP \times \psi_R \tag{19}$$

Practical values of C_R in geothermal district energy applications may vary between 0.15 and 0.60. One finds the C_R value from Equation (18) for geothermal district heating and ORC power-only options to be 0.19 and 0.019, respectively. Here, η_I for district heating is taken 0.65 (net after parasitic losses) and for ORC is taken 0.08, respectively. This further shows that power-only ORC system may not be preferable in today's practical conditions and available equipment. This methodology, when applied to the Geotherm Model, further reveals its advantages. In Fig. 10, minor exergy destruction in the Circular Geotherm model in heating are neglected. Then:

$$\psi_R = 1-\frac{\varepsilon_{des}}{\varepsilon_{\sup}} = 1-\frac{\left(1-\frac{283}{293}\right)}{\left(1-\frac{283}{353}\right)} = 0.827$$

and from Equation 19:

$$C_R = COP \times \psi_R = 1.348 \times 0.827 = 1.114$$

After comparing this result with geothermal district heating only case with C_R = 0.19, the CO_2 reduction potential ratio *R* from the carbon stock may also be compared according to REMM:

$$R = \frac{(2-C_R)_{\text{district heating}}}{(2-C_R)_{geotherm}} = \frac{2-0.19}{2-1.114} = 2.04 \tag{20}$$

This calculation shows a double advantage of potential CO_2 reduction from the carbon stock in the built environment.

The major parameter in this achievement is due to the high C_R value obtained in circular geotherm model. The same comparison with power-only ORC case with C_R = 0.09 shows that Geotherm Model has about 2.15 times higher potential.

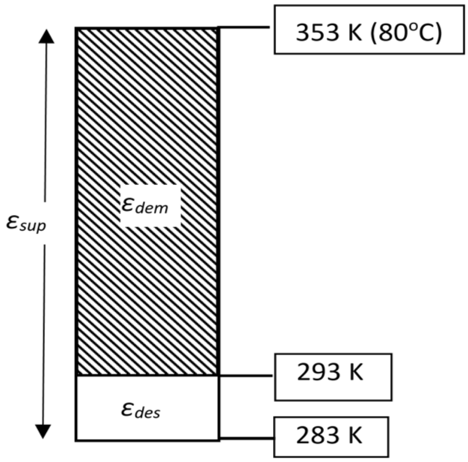


Figure 11. GEOTHERM Case

In Fig. 11, each kW_H of geothermal power and each 0.775 kW_H of the replaced natural gas from original boilers of the district returns to the energy stock by 1 kW_H of thermal power and 0.348 kW_E of electric power. If the geothermal heat is used just in an ORC system, only 0.08 kW_E will be generated and according to the above equation, with a COP_{EX} of 0.092. The *Circular Geotherm* shown above makes use of the ground heat through the GSHP and a complete energy and exergy cycle is obtained, while all types of waste heat are also utilized. Cycle starts at geothermal production well head and ends at the reinjection well. Thermal storage systems suited to two sets of exergy is used to match the loads and shave off the peak loads. A biogas system is an option using municipal wastes.

Biogas is mixed with natural gas saved from the boilers. Electric power generated by the poly-generation system is fed to the district. Optional solar and wind energy systems in the district contribute to peak loads with thermal storage. The entire collection of systems operates in a cascaded form, like a large heat pump. This system couples and mobilizes ground thermal energy with geothermal energy. In small applications, the evaporator side of the heat pumps may be coupled to PV systems (if this option is used in district buildings) to absorb the heat collected by PVs, which further improve the *COP* of the GSHP units. However, the flow rate needs to be dynamically optimized according to instantaneous solar insolation, heat demand, and other operating conditions, in order to maximize the total exergy output (Power and heat) of the PVT system [27, 28]. If there are more than one system with multiple exergy connections, then Equation 21 is used [23].

$$\bar{\psi}_R = \frac{\sum_{i=1}^{u}\sum_{j=1}^{v}\psi_{Ri-j}E_{xi-j}/\eta_{i-j}}{\sum_{i=1}^{u}\sum_{j=1}^{v}E_{xi-j}/\eta_{i-j}} \tag{21}$$

For thermal links between two nodes i-j, E_{Xi-j} is the simple product of Q_{i-j} and $(1-T_{ref}/T_i)$ by definition. For power links if electricity is used in electrical applications (electric to electric), ψ_{Ri-j} may be assumed to be approximately 1.

Other Features

- The same circular model may be applied to other sources of continuous heat, like waste heat from an industrial plant, provided that the supply temperature is equal to or higher than 80°C,
- It is suitable to 4th generation district energy systems (4DE),
- This model represents an integrated, compound power and heat system at large,
- The model may be applied to a single building and scaled up to large district energy systems.
- May be combined with hydrogen economy cycle,
- In terms of exergy, the district may be and in fact should be equipped with exergy meters in order to establish a fair distribution of costs to individual customers
- The Model is equally applicable to district cooling. In this case, cold storage and absorption/adsorption units are also used. See Fig. 12 for a simplified explanation.

EVALUATION AND RATING METRICS

New Metrics

Table 2 lists the new metrics, which were especially developed in this study for rating low-enthalpy geothermal applications. In this table there are thirteen metrics, which rate different aspects of the geothermal system from a holistic point of view.

$$E_{XD} = \frac{E_{XTOT}}{n_D} = \frac{E_{XE}+E_{XH}}{n_D} = \frac{E+E_H\left(1-\frac{T_{ref}}{T_{out}}\right)}{n_D} \tag{22}$$

The number of equivalent dwellings in the district, n_D is based on hypothetical 100m² flats.

In addition to the above metrics, the following pay-back periods may also be calculated and used for additional evaluation:

B. Kilkis, S. Kilkis / Hittite J Sci Eng, 2018, 5 (Special Issue: Selected Papers from the 21st National Thermal Sciences and Technology Congress) 59–73

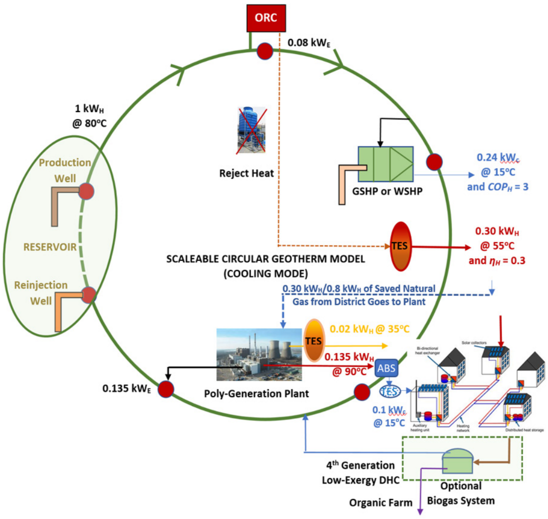


Figure 12. Combined Heat and Power in Circular Geotherm System: Cooling Mode

Table 2. Metrics for Evaluating Hybrid Geothermal Systems with Low-Enthalpy Sources.

Metric	*Explanation (Equation Number)*	*Comments and Criteria*
AV	*Equations 2-a and 2-b, Added Value Index*	*>0.3*
E_{XR}	*Equation 4*	*>2*
u_x	*Equation 5*	*< 0.1kg CO_2/kW-h*
J	*Equation 6*	*Higher is better*
i	*Equation 7*	*Minimize*
C_R	*Equations 18 and 19 Composite Rationality Index*	*>1*
$\overline{\psi}_R$	*Equations 8 and 9, Rational Exergy Management Efficiency*	*Maximize*
R	*Equation 20, CO_2 Reduction Potential Ratio*	*>1.5*
E_{XD}	*Equation 22, kW/kW/number of residences*	*Minimize*
T_{KCR}	*Equation 3*	*Minimize*
nZED	*Nearly-zero Energy District*	$\psi_R \geq 0.80$
nZEXD	*Nearly-zero Energy District*	$\psi_R \geq 0.70$

- CO_2 payback according to embedded CO_2 of material and construction,
- Exergy payback according to embedded exergy of material and construction,
- Energy payback according to embedded energy of material and construction,
- Investment payback according to the tariffs subjected to the service subscribers in the district.

All pay-back periods are important, yet in low-enthalpy geothermal systems CO_2 payback especially in Turkish geothermal fields with high $CaCO_3$ content is critical and must be prioritized in the rating process. Investment returns are also a crucial, because most of the equipment like ORC units get larger and costlier due to lower efficiencies. However, these statements should not mean that exergy and energy paybacks are less important. They influence CO_2 payback and a sustainable economy and grow they are also very important. In essence all these payback definitions must be considered together.

Earlier Metrics

For general geothermal systems, without any distinction between low or high-enthalpy geothermal systems certain rating parameters were defined. For referencing purposes, they are listed in Table 3.

SAMPLE DESIGN STUDY

A new settlement of 20000 inhabitants in the suburbs of Ankara has low-enthalpy geothermal sources at 80°C well-head temperature. The reservoir has sufficient potential to meet the loads. In order to explain the algorithm of the new model, biogas system, wind and solar energy systems, and thermal storage are excluded in this simplistic conceptual design example. Geothermal wells supply heat to the ORC system. The ORC system delivers electricity to the ground-source heat pumps, which generate heat at 55°C to the buildings. In order to bring the design to a common base of comparing the district with a natural gas-based central DE system, the natural gas saved from the district heating system by replacing it with heat supplied by the heat pumps, CHP system is included to the calculations. Power and heat at 90°C is supplied by the CHP system. Power is directly delivered to the district. Part of the heat is delivered to the absorption cooling machines (ABS) first in order to satisfy the coincident cooling loads in the district. Reject heat at 35°C is mixed with the CHP output in order to deliver the heat to the district at the same temperature with the GSHP output. This is not the most feasible solution indeed. The Rational Exergy Management Efficiency would be better if additional useful work was obtained in a process like agricultural or industrial drying in the vicinity of the district for reducing the supply temperature for the

Table 3. Earlier Metrics Defined by the Authors [29, 30].

Metric	*Explanation (Equation Number)*	*Definition*
GE	*U/M, U is the thermal energy claimed in unit time at maximum sustainable geothermal fluid flow rate. M is the mass of geofluid spent in unit time at maximum sustainable geothermal fluid flow rate.*	*Geofluid Effectiveness*
RDR	*f(heat extraction rate-natural recharge rate-re-injection rate).*	*Reservoir Decline Rate*
OF	*Amount of equipment oversizing in order to match supply and demand unit exergies.*	*Equipment Oversizing Factor*
GSE	*Ratio of the district capacity (C_o) in terms of the number of equivalent residences without temperature peaking or equipment oversizing to the district capacity with both temperature peaking and equipment oversizing.*	*Geothermal System Effectiveness*
CBUC	*Capital Cost/C_o*	*Common-base Unit Capital Cost*

thermal grid in the district and utilizing the reject heat separately in a low-temperature application like greenhouse heating. Inputs for coincident design loads of the district with estimated respective diversity applications, are given in Table 4. Fig. 13 gives the sample design that meets the design loads.

RESULTS AND DISCUSSION

Performance Predictions

$\bar{\psi}_R$ is calculated from Equation 21 and the corresponding variables are tabulated in Table 5. Results show that this sample design has a $\bar{\psi}_R$ value of 0.86. Comparing this application with a conventional district heating system with natural gas boilers, with $\bar{\psi}_R$ value of 0.11,

Table 3. Earlier Metrics Defined by the Authors [29, 30].

Load	*Capacities*
Electrical Load	*21000 kW_E*
Heading Load	*52000 kW_E*
Cooling load (Sensible)	*8000 kW_C*

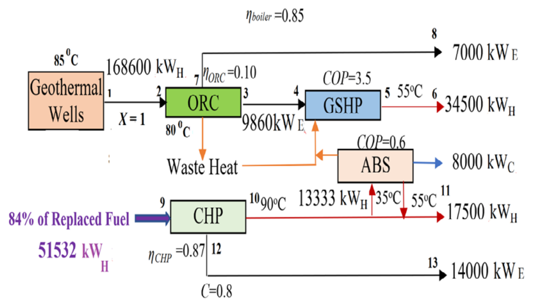


Figure 13. Conceptual System for the new settlement (X=1)

which is calculated from the exergy flow bar shown in Fig. 14. The return water temperature in the district is 343K.

Then, referring to the last term in Equation 20, it is understood that the sample design has a potential of reducing CO_2 emission responsibility by 65.8%:

[(2-0.11)/(2-0.86)-1]x100 =65.8%

Sensitivity Analysis

The effect of the *COP* value of the GSHP on the overall performance was analyzed, while the efficiency of the ORC unit and the capacity and characteristics of the CHP and ABS units were kept fixed. Fig. 15 shows an

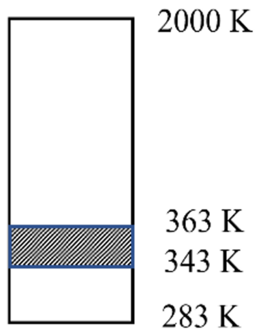


Figure 14. Exergy Flow Bar for District Heating with Central Natural Gas Boilers

unexpected result that *COP* increase does not help in increasing the $\bar{\psi}_R$ value. In this figure, *COP* =1 condition corresponds to `no-GSHP` case, where the geothermal heat is directly used. This result agrees with the argument shown in Fig. 2. This result actually shows the

Table 5. Results for the Sample Design Study. COP=3.5, Q_{5-6}/η_{5-6}=34500 kW.

Node	*T_i*	*T_j*	*ψ_{Ri-j}*	*Q_{i-j}/η_{i-j}*	*E_{xi-j}*	*Numerator of Equation 21*	*Notes*
							T_{ref} = 283
i-j	*(K)*	*(K)*		*(kW)*	*(kW)*	*(kW)*	*K*
1-2	*358*	*353*	*0.95*	*168600*	*35321.23*	*33433.43*	
2-3	*na*	*na*	*0.90*		*9860*	*8913.44*	*T_E = 313 K*
3-4	*na*	*na*	*1.00*		*9860*	*9860.00*	
4-5	*na*	*328*	*0.48*	*9860*	*1352.744*	*649.56*	
5-6	*328*	*323*	*0.90*	*34500*	*4733.232*	*4269.38*	*Demand at 50°C*
6-6	*dummy*				*0*	*0.00*	
7-8	*na*	*na*	*1.00*	*na*	*7000*	*7000.00*	
9-10	*2200*	*363*	*0.26*	*51532*	*11356.91*	*2907.37*	
10-11	*363*	*328*	*0.62*	*24907*	*3417.12*	*2125.45*	
12-13	*na*	*na*	*1.00*		*14000.00*	*14000.00*	
13-14	*363*		*0.92*	*13333*	*2938.40*	*2703.33*	*T_c is 15°C*
14-14	*dummy*					*0.00*	
					99839.64	*85861.96*	
					Σ	*Σ*	
							ΣEq. 21/
						0.86	*ΣE_{Xi-j}*

B. Kilkis, S. Kilkis / Hittite J Sci Eng, 2018, 5 (Special Issue: Selected Papers from the 21st National Thermal Sciences and Technology Congress) 59–73

strength of the Model such that the optimum result is the no GSHP case, which could not be concluded from the First Law. One main reason for this result is the fact that current ORC technology has very low efficiency. Instead, low enthalpy geothermal resources may be supported by solar and wind energy. In this token, PVT systems indeed cover both CHP and heat pump technology. Therefore, before envisioning rather conventional technologies like ORC and classical heat pumps, one need to try solar and wind technology. This approach will indeed stay in heat pump technology without ORC units, unless their efficiencies are substantially improved.

This conclusion however is not universal and shows that every design, every load, and load distribution as a function of time during operation is important and the results are sensitive to these parameters too. For example, if the de-

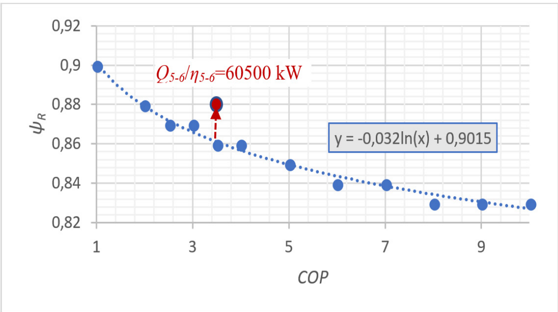


Figure 15. Sensitivity of $\bar{\psi}_R$ on the COP Changes. $Q_{5\text{-}6}/\eta_{5\text{-}6}$=34500 kW

sign value $Q_{5\text{-}6}/\eta_{5\text{-}6}$ is increased to 60000 kW (GSHP heat load) instead of 34500 kW, then $\bar{\psi}_R$ value at a *COP* value of 3.5 becomes 0.88 instead of 0.86 and the trend shown in Figure may also reverse. These results show that both the design, selection, and sizing of the systems and equipment are quite complex and a thorough analysis is essential on an hourly basis of the building loads besides developing and applying an exergy-based load allocation and control software.

CONCLUSION

All the above-mentioned case studies and sample calculations show that ORC, heat pump, district heating and similar energy conversion and distribution systems alone and only based on economic decisions may not be effective in reaching the CO_2 reduction targets of Paris Agreement. Avoidable CO_2 emissions, which are mainly a function of the rational exergy efficiency, namely the ψ_R term must be minimized first of all by maximizing the ψ_R term. Unfortunately, in all CO_2 mitigation strategies, only the Firs-Law rules are applied. In addition, hybrid system designs are quite handful, which has been shown here that they are a requirement in order to meet the CO_2 emission reduction goals. In order to optimize required hybrid system alternatives, new objectives need to be recognized and new evaluation metrics need to be defined based on exergy. *COP* term for example, needs to be modified in terms of exergy. COP_{EX} then shows that first of all heat pumps need to be re-designed for higher design *COP* values.

Using these new objectives and metrics, a careful circular hybridization may be made with rather engineering ease, which is only limited by imagination. In this quest heat pumps also play a major role in the advent of developing smart (or Rational) cities provided that their *COP* are high enough from exergy point of view. This requirement brings a necessary condition of combining low enthalpy energy resources like geothermal reservoirs and waste heat with low-exergy/low-energy buildings and district energy systems so that the temperature difference between the source and the demand is minimal. This leads to holistic design and analysis approaches like given in Fig. 10 [25].

In conclusion, it seems to be an absolute requirement that in low enthalpy resource utilization, we need to investigate the most rational way of utilizing low-exergy resources coupled with low-exergy demands like nZED and nzEXD (nearly-zero energy and exergy districts, respectively) for future settlements and retrofit districts [31]. In the same token, installation of nZEB and nZEXB (nearly-zero energy and exergy buildings, respectively) in order to improve the *COP* values of heat pumps. Last but not least, thermal energy storage systems (TES) are also very crucial for shaving off the peak loads, thus reducing the investment costs attributable to power, heat, and cold generation and improving the rational energy management efficiency [32].

NOMENCLATURE

A	Land area of a country, km^2
AV	Added Value,
a_o	Constant term in Equation 14, km
a, b, s`	Performance factors of the heat pump
A_v	Added value
CDH	Cooling Degree Hour, K·h
C	Power-to-heat ratio of CHP
CBUC	Capital unit Cost, TL/(kW_H/number of equivalent residences)
c_f	Unit CO_2 content of the fuel, based on lower heating value, kg CO_2/kW-h
C_o	District capacity in terms of the number of equivalent residences without temperature peaking or equipment oversizing, number of residences, kW_H/number of residences
COP	Coefficient of Performance
COP_{EX}	Exergy-Based *COP*

B. Kilkis, S. Kilkis / Hittite J Sci Eng, 2018, 5 (Special Issue: Selected Papers from the 21st National Thermal Sciences and Technology Congress) 59–73

C_R Composite Rationality Index
E Electric power, kW
E_X Exergy, kW
E_{XD} Total exergy delivered in the district for each dwelling, kW/dwelling
E_{xh} or E_{XH} Thermal exergy, kW
E_{xg} or E_{XE} Power exergy, kW
E_{XR} Thermal exergy and power exergy output ratio of a geothermal system
GE Geofluid Effectiveness, kW-h/kg
GSE Geothermal System Effectiveness
HDH Heating Degree Hour, K·h
i Unit investment cost of the geothermal system, TL/(person·K·h)
I Investment cost, TL
J Thermal exergy of the geothermal well output per km^2 of a country, kW/km2
N Population receiving district energy service (in the form of heat, cold, and power individually)
OF Equipment Oversizing Ratio
P Installed power capacity, kW
Q Thermal (in the form of heat or cold) power, kW
R CO_2 Reduction Potential Ratio
RDR Reservoir Decline Rate, kWH-h/h
s Equipment performance constant (Equation 10)
T Temperature, K
u Unit CO_2 emissions per kW of electrical power generated, E
u_x Exergy-based unit CO_2 emissions per kW of electrical power generated, E
X Split ratio of the geothermal fluid heat between ORC and the heat pump

Greek Symbols

ε Unit exergy, kW/kW
ψ_R Rational Exergy Management Efficiency
η_I First-Law Efficiency
ΔT Temperature difference, K

Subscripts and Superscripts

a Indoor air design temperature related variable
$_{boiler}$ Boiler
C Cooling, summer related
$\mathcal{D}$ District
DE District energy system
dem Demand
des Destroyed
E Electric
f Fuel
H Heat, heating, winter related
in Inlet to the heat pump
I First Law
K Geothermal well head
KCR Critical well-head temperature for equal power and heat exergy
L_{max} Maximum allowable distance between the geothermal source and the district location, km
n Power of the equipment thermal performance equation (Equation 10)
m Power of Equation 14
in Inlet to the heat pump
orc ORC system
out Outlet from the heat pump
o Outdoor design condition
ref Reference
sup Supply
T Transmission
TOT Total
u, v Summation limits in Equation 21.

Acronyms

ABS Absorption system
CHP Combined Heat and Power
DHC District heating and cooling
DE District energy system
4DE Fourth-generation district energy system
GSHP Ground-source heat pump
nZED Nearly zero-energy district
nZEB Nearly zero-energy building
nZEXD Nearly zero-exergy district
nZEXB Nearly zero-exergy building
ORC Organic Rankine Cycle system
REMM Rational Exergy Management Model
TES Thermal energy storage
WSHP Water-source heat pump

B. Kilkis, S. Kilkis / Hittite J Sci Eng, 2018, 5 (Special Issue: Selected Papers from the 21st National Thermal Sciences and Technology Congress) 59–73

References

1. Baba. A. 2017. Hydro–Geochemical Properties of Geothermal Systems and its Effect on the System in Turkey, IGC 2017 Conference, Oral Presentation, 22–24 May, 2017.
2. ESMAP, 2016. Energy Sector Management Assistance Program, Greenhouse Gases from Geothermal Power Production, Technical Report 009/16, The World Bank Group, Washington DC, USA.
3. Niyazi A., Özge S., Halim M., and Gizem K. 2015. CO_2 Emission from Geothermal Power Plant in Turkey, Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015.
4. Aslan, H. 1996. Kömüre Dayalı Termik Elektrik Santrallarında Verim ve Kapasite Kullanım Oranı Düşüklüğünün Nedenleri ve Bunların Yükseltilmeleri İçin Alınması Gerekli Tedbirler, TMMOB 1. Enerji Sempozyumu, 12–14 Kasım 1996, Ankara.
5. Marta R.K., Olafur P.P., and Halldor P. 2010. Factors for Primary Energy Efficiency and CO_2 Emission of Geothermal Power Production, Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25–29 April 2010.
6. Halldór Á. 20013. CO_2 Emission from Geothermal Plants, S12 Paper 103, pp: 56–62, International Geothermal Conference, Reykjavík, Sept. 2003.
7. Kılkış, B. 2017Jeotermal Enerjimiz, CO_2 Salımları ve Organik Rankin Çevrimli Santraller, Yeni Enerji, 61: 40–44.
8. Shengjun, Z., Huaixin, W. and Tao, G. 2011. Performance Comparison and Parametric Optimization of Subcritical Organic Rankine Cycle (ORC) and Transcritical Power Cycle System for Low– Temperature Geothermal Power Generation, Applied Energy, (88), 2011, 2740–2754.
9. Quoilin, S. and Lemort, V. 2009. Technological and Economical Survey of Organic Rankine Cycle Systems, 5th European Conference Economics and Management of Energy in Industry, 14–17 April 2009, Portugal: http://orbi.ulg.ac.be/bitstream/2268/14609/1/ECEMEI_PaperULg_SQVL090916.pdf
10. Mathew A., Brian A. Chris U. 2011. Performance Analysis of the Chena Binary Geothermal Power Plant. Applied Thermal Engineering, Elsevier, 2011.
11. Kilkis B. and Kilkis, San, 2014. Energy and Exergy Based Comparison of Utilizing Waste Heat of a Cogeneration System for Comfort Cooling Using ORC Driven Chillers or Heat Pumps Versus Absorption/Adsorption Cycles, ASME ORC 2013, Conference Proceedings, 7–8 October, De Doelen, Rotterdam, the Netherlands.
12. EU, 2004/8/EC. 2008. Directive 2004/8/EC of The European Parliament and of The Council of 11 February 2004 on the Promotion of Cogeneration Based on a Useful Heat Demand in The Internal Energy Market and Amending Directive 92/42/EEC.
13. Kilkis, B., Kilkis, Ş. 2007. Comparison of Poly–generation Systems for Energy Savings, Exergetic Performance, and Harmful Emissions, Proceedings of ES2007, Energy Sustainability, Paper No: ES 2007–36262, June 27–30, Long Beach, California
14. TGE Research. 2017. Top 10 Geothermal Countries– 1 GW Installed Capacity Country Club.
15. Güven, Ö. 2015, Ankara'nın Jeotermal Potansiyeli ve Ankara'daki Jeotermal Projeleri, Jeotermal Kaynaklar Birliği Ekim Olağan Toplantısı, 2015, Haymana.
16. Kilkis, B., Kilkis, Siir, Kilkis, San. 2017. Optimum Hybridization of Wind Turbines, Heat Pumps, and Thermal Energy Storage Systems for Near Zero–Exergy Buildings (NZEXB) Using Rational Exergy Management Model, Paper No. 2, 12th IEA Heat Pump Conference, 15–18 May, Rotterdam 2017. Papers on line, https://www.eiseverywhere.com/ehome/index.php?eventid=165152&tabid=558494 Also, abstracted in print, pp: 179–180.
17. EGEC. 2015. Developing Geothermal Heat Pumps in Smart Cities and Communities, EU REGEOCITIES, Project Publication, Brussels, June 2015, www.regeoocities.eu
18. Kilkis, B. 2017. Analysis of Fourth–Generation District Energy Systems with Renewable Energy Cogeneration by Using Rational Exergy Management Model, World Sustainable Built Environment Conference 2017 WSBE17, Invited Paper, Paper no: 5693, 5–7 June 2017, Hong Kong.
19. Kilkis, B. 2016. Analysis of Fourth–Generation District Energy Systems with Renewable Energy Cogeneration by Using Rational Exergy Management Model, Paper No. 103, Proceedings, pp: 512–522, SBE 16 Smart Metropoles Conference, Istanbul, 13–15 October, 2016.
20. Rowshanzadeh, R. 2010. Performance and Cost Evaluation of Organic Rankine Cycle at Different Technologies, Master Thesis, Department of Energy Technology, KTH, Stockholm, Sweden.
21. Sun, W., Yue, X., and Wang. Y. 2017. Exergy efficiency analysis of ORC (Organic Rankine Cycle) and ORC–based combined cycles driven by low– temperature waste heat, Energy Conversion and Management, Vol. 135, 1 March 2017, Pages 63-73.
22. Marini, A., Alexandru, D., Grosu, L. and Gheorghian, A. 2014. Energy and Exergy Analysis of an Organic Rankine Cycle, U.P.B. Sci. Bull., Series D, Vol. 76, Issue 4, 2014 ISSN 1454–2358.
23. Kılkış, B. ve Kılkış, Ş. 2015. Yenilenebilir Enerji Kaynakları ile Birleşik Isı ve Güç Üretimi, (Combind Heat and Power With Renewable Energy Resources), TTMD Pub. No: 32, First Ed., ISBN: 978–975–6263–25–9, 371 pages, Doğa Pub. Co., İstanbul, 2015.
24. Kilkis, Ş. and Kilkis, B. 2017. A Simplified Exergy Methodology for Net–Zero Buildings Using Rational Exergy Management Model, Seminar 72 Low Energy Building Design Using Exergy Modeling, ASHRAE Winter Meeting, 27 January–1 February, Las Vegas.
25. Kılkış, B., Kılkış, Şiir, Kılkış, Şan. 2017. Hydrogen Economy Based Net–Zero Exergy Cities of The Future with Water–Energy Nexus, The 12th Conference on Sustainable Development of Energy, Water, and Environment Systems–SDEWES Conference, 4–8 October 2017, Dubrovnik.
26. Kılkış, B., Kılkış, Ş. 2018. An Urban Planning Algorithm for Optimizing the Height of Buildings To Maximize the Share of PV Electricity Generation in a Nearly–Zero Exergy District, Proceedings of the 1st Latin American Conference on Sustainable Development of Energy, Water, and Environment Systems, LA. SDEWES 2018.0340, pp. 1–28.
27. Kilkis, B., Kilkis, Şiir, Kilkis, Şan. 2016. Next– Generation PVT System with PCM Layer and Heat Distributing Sheet, Solar TR2016 Conference and Exhibition, 6–9 December, 2016, Paper No: 0006, Proceedings, pp. 20–28, Istanbul.
28. Kilkis, B. 2016. Optimum Operation of Solar PVT Systems: An Exergetic Approach, Solar TR2016, Paper No: 0025, Proceedings, pp. 72–79, Istanbul Conference and Exhibition, 6–9 December, 2016.

B. Kilkis, S. Kilkis / Hittite J Sci Eng, 2018, 5 (Special Issue: Selected Papers from the 21st National Thermal Sciences and Technology Congress) 59–73

29. Kilkis, I. B. 1996. Closed Loop Versus an Open Loop District System: A Techno–Economical Assessment, Geothermal Resources Council, Transactions, Vol. 20. pp: 95–102.
30. Kilkis I. B., Evaluation of the Proposed Geothermal District Energy System for the City of Aydin with New Rating Parameters, ASHRAE Transactions, Vol. 108, Part 2, pp.595–600, 2002.
31. Kilkis, B, Kilkis, Ş. 2017. New Exergy Metrics for Energy, Environment, and Economy Nexus and Optimum Design Model for Nearly–Zero Airport (nZEXAP) Systems, Energy Journal, 140 (2017) 1329–1349, Advanced Technologies in Aviation, Special Issue.
32. Kilkis, B. 2017. Exergetic Comparison of wind energy storage with ice making cycle versus mini–hydrogen economy cycle in off–grid district cooling, International Journal of Hydrogen Energy 42 (2017) 17571–17582.