Exergy-Rational Utilization of Low-Enthalpy Geothermal Energy Resources and Exergy-Based Limitations

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Abstract. Along with continuing the efforts of decoupling CO₂ emissions from sustainable development, exergy-rational cities are becoming universally important. This statement does not mean that energy rationality and energy efficiency are ignored. But it is a fact that the mission of the First-Law of Thermodynamics has been almost completed in a pretty good rate of success. Because the Second-Law is especially important and often ignored in geothermal energy, especially for low-enthalpy sources, now it is time to analyze such systems in terms of exergy. Within this context, ORC systems, which are touted as useful systems for utilizing low-enthalpy geothermal resources and ground-source heat pumps, are critically analyzed. 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 developed an analytical model, which reveals with case studies and examples that a broad hybridization of combining geothermal energy-based ORC technology, heat pumps, absorption units, thermal storage, and other renewable energy resources, like solar and wind provides sustainable and exergetically rational design solutions. New evaluation and rating metrics based on Rational Exergy Management Model were introduced. The option of incorporating low-enthalpy geothermal energy resources at about 80°C to support the model is evaluated. The Hydrogen City model is applied to a new settlement area with an expected 200,000 inhabitants to find that the proposed model can enable a nearly net-zero exergy district status. The results have implications for settlements using geothermal energy and hydrogen energy together towards meeting net-zero targets. Such an enrichment of the multiple systems even in a simplistic manner in an exergy economy cycle analytically reduces CO₂ emissions by about 66%, when compared to a conventional district energy system utilizing natural gas.

Keywords: ORC technology, Geothermal energy, Hybrid district energy system, Rational Exergy Management Model, CO₂ emissions responsibility, Heat pumps, Cogeneration, Thermal energy storage.

1. Introduction
European Union had initiated a 20+20+20 target for decarbonization, which will end in 2020. The first 20% improvement stands for energy savings, the second 20% stands for renewables, and the third 20% stands for energy efficiency. It must be noted that energy efficiency is only related to the First-Law of Thermodynamics. In the quest of decoupling CO₂ emissions from sustainable development, EU plans to increase the electricity use in the heating and cooling sector by employing electrically-driven heat pumps. Although increasing the use of electricity in the building sector seems to be a reasonable approach for decarbonization, the question of where the electricity comes from, which is mainly a matter of the Second-Law of Thermodynamics (exergy) must be answered first. Therefore, a
separate and fourth 20 term needs to be added to the goals for 2020 in order to characterize the need for improving the exergy rationality in the energy sector. This is indeed a strong parameter in decarbonization-stronger than anticipated. Today, the global average of exergy rationality is less than 30%, which may be increased up to 80% with novel applications like solar cogeneration and trigeneration with biofuels, hydrogen economy etc. Until the concept of exergy is actively embedded into the EU goals, the original 2020 targets may not be met, until the rationality of exergy allocation among different energy resources at the most appropriate demand points is not recognized soon. In other words, unless exergy transition exceeds energy transition by exergy re-wiring of energy resources, the rate of increase of CO₂ emissions may be slowed but not effectively reduced below the 1990 levels.

About 80% of the vast geothermal resources of Turkey are below 100°C. Because the unit exergy of low-temperature heat is quite low compared to electric power exergy becomes an important way of looking to the design and proper applications of such geothermal applications. Based on the Rational Exergy Management Model (REMM), a new analytical tool with new rating metrics for hybrid energy systems and resources, including low-enthalpy geothermal energy towards achieving nearly-zero status of district energy systems was targeted. Another challenge is the high CO₂ emissions attributable to geothermal systems in Turkey. In Turkey, most of the geothermal energy grabens are CaCO₃ based. This means that geothermal wells extract CO₂ 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 CO₂ to the atmosphere, nearly at a rate of 1 kg CO₂/kW-h. To be precise, this rate, symbolized by \( u \) in Equation 1, is almost equal to coal-based thermal plants [1]. CO₂ emissions per unit power generation are 0.034 kg CO₂/kW-h for Iceland, 0.33 kg CO₂/kW-h for Italy, and the world average is 0.122 kg CO₂/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 CO₂/kW-h and 1.3 kg CO₂/kW-h. Other publications also confirm these results [3]. For natural-gas, combined-cycle power plants this value is around 0.42 kg CO₂/kW-h (Based on an average First-Law Efficiency of 0.47 for the power generation in the plant and the CO₂ content of natural gas of 0.2 kg CO₂/kW-h lower heating value). For coal-based power plants is around 1.3 kg CO₂/kW-h [4, 5, 6]. In Equation 1, \( u \) is the unit CO₂ emissions per kW of electrical power generated, \( E \).

\[
u = \frac{\sum CO_2}{\sum E} \text{[kg CO}_2/\text{kW}_E\text{]} \quad (1)
\]

Equation 1 shows that the unit emissions, \( u \) 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. Speaking about absorption cooling, the unit exergy of cold is lower than the source heat, even it is of low-enthalpy type. Therefore low-enthalpy geothermal resources need to be left in the form of heat, if there is sustained and sufficient heat demand, rather that converting it to cold. 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. In the following figure, the heat output of a LEGS (Low-Enthalpy Geothermal Source) at 90°C (363 K) is used in a single-stage absorption cooling machine.

\[
\varepsilon_{\text{sup}} = \left(1 - \frac{273}{363}\right) = 0.247 \text{ W/W}
\]

\[
\varepsilon_{\text{dem}} = \left(1 - \frac{273}{285}\right) = 0.042 \text{ W/W}
\]
Here, the ideal Carnot Cycle compares unit exergy values, \( \varepsilon \), of cold, or otherwise heat. The heat output of the LEGS has 0.247 W/W unit exergy. If it is used for cooling, then REMM efficiency, \( \psi_R \), is 0.17 (See Figure 2 and Equation 1), which is a low value even compared to the general reference value of 0.2.

\[
\psi_R = \frac{\text{Unit Demand Exergy}}{\text{Unit Supply Exergy}} = \frac{0.042 \text{ W/W}}{0.247 \text{ W/W}} = 0.17
\]

If, however, the waste heat of the absorption machine is utilized rather than rejecting, in a useful application, which is seldomly done in practice, then the REMM Efficiency increases:

\[
\psi_{II} = 0.6 + \left(1 - \frac{T_{\text{ref}}}{313}\right) = 0.66
\]

In this example, the Second-Law efficiency is given by the following equation:

\[
\eta_{II} = COP_{\text{abs}} \times \psi_{II} = 0.6 \times 0.17 = 0.102
\]

This simple example shows that even the waste heat from the ABS unit at 313K (if utilized for a useful application) has a higher unit exergy than the unit exergy of the cold produced. This is an early indication that heat produced must be used in the form of heat instead of cold production if there is sustainable and sufficient heat demand. Otherwise, a substantial amount of exergy destruction takes place due to the temperature, thus unit exergy difference between heat and cold. In some specific design cases however, cold production may be exergetically rational if and only if the waste heat of the absorption machine is utilized in useful works. On the other hand, simple economic analyses give quite different results when only market prices of power, heat, and cold in the built environment are considered.

An example using low-enthalpy geothermal energy in an absorption cycle for generating cold and organic Rankine cycle (ORC) for generating power is given below. In this analysis the potential use of waste heat from the organic Rankine cycle is ignored.

The following assumptions were made:

- Design \( COP \) of a single-stage absorption cooling machine is 0.6,
- Annual cooling period is 4500 hours (Mediterranean climate),
- \( COP \) of conventional chiller in cooling period is 2.5,
- ORC uses 45\% of the geothermal source for power generation at an efficiency of 8\%.
- The rest of the geothermal energy is used for cooling.

The simple investment cost recovery of this combined cold and power (CCP) system is calculated in the following simple manner that is generally practiced in the sector for a unit geothermal thermal power input of 1 kW and an electricity price of 0.27 €/kW-h:

Savings in electricity cost per hour from ORC: \( 1 \text{ kW} \times 0.45 \times 0.08 \times 0.27 \text{ €/kW-h} = 0.01 \text{ €/h} \),

Savings from cooling with respect to operation of a grid electricity-driven conventional chiller:
1 kW x (1-0.45) x 0.60/2.5 x 0.27 € = 0.036 €/h
Total savings per hour per kW of geothermal energy power = 0.01 €/h+0.036 €/h = 0.046 €/h
Total savings in a year = 0.046 €/h x 4500 h/year = 207 € per year for 1 kW geothermal capacity. If the investment cost of a shallow geothermal system is 600 €/kW, a promising result of about 3 years is found for the simple return of the investment. This is a very simplistic calculation just based on electricity tariff prices. It must be noted that this is a geothermal energy case without fuel costs, in principle. Just for comparison purposes, to bring this example closer to a conventional CCP case, imagine that heat was generated in a natural-gas boiler with a First-Law efficiency of 0.80. If the natural-gas price is 0.04/kW-h, then the savings will be reduced by the amount of (0.04/kW-h /0.80), namely 0.05 €/h. This cost is higher than the total gains of 0.046 €/h, which means that the system will never pay back. This simple calculation does not include yet the operating costs and other costs including exergy destruction etc. This example is an early reminder that especially if fossil fuels are used in trigeneration or cogeneration systems, simple economics may not be a conclusive decision maker. Another reminder is that with the greenhouse effect and rising cost of depleting fossil fuels, cogeneration and trigeneration must be directed towards renewable energy resources.

These conflicting conclusions may only be resolved by the Second-Law of Thermodynamics and all these results show the essence of developing exergy-based metrics in order to reveal the actual performance of several options in decision making and optimization processes for the best allocation of energy resources in the built environment, especially in smart cities, which employ cogeneration and trigeneration.

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

From another point of view, Figure 1 further illustrates that only-electric ORC systems may not be rational, especially from an exergetic point of view [7]. Figure 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%. See Figure 3 for several working fluids [8].

According to the example given in Figure 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, \( \eta_{\text{ORC}} \) and the unit exergy, \( \varepsilon_{E} \) or \( \varepsilon_{H} \) of the power generation by ORC equipment or thermal output of the district energy system at a well-head temperature, \( T_{K} \), respectively.

\[
AV_{E} = \eta_{\text{ORC}} \times \varepsilon_{E} \approx \eta_{\text{ORC}} \tag{2-a}
\]

\[
AV_{H} = \eta_{\text{DE}} \times \varepsilon_{H} = \eta_{\text{DE}} \times \left(1 - \frac{283}{273 + T_{K}}\right) \tag{2-b}
\]

Here, \( \eta_{\text{ORC}} \) is the First-Law efficiency of ORC in electric power generation (\( \varepsilon_{E} \sim 1 \text{kW/kW} \)) for a given well head temperature of the geofluid, \( T_{K} \) (See Figure 3):

\[
\eta_{\text{ORC}} = aT_{K} + b \tag{2-c}
\]

---

**Figure 2.** ORC and District Energy Dilemma [7].

**Figure 3.** ORC Efficiencies for Different Working Fluids [8].
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 given in Equation 3 is the positive root of the quadratic equation:

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

(3)

Here, \( T_{KCR} \) is around 100°C. Below this critical temperature ORC system is not feasible. Above this 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.

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. 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):

\[
E_{XR} = \frac{\left(1 - \frac{283}{aT_K + b \times 1}\right) \times \eta_H}{2} > 2
\]  

(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.

Figure 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 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:

\[
u_x = \frac{\sum CO_2}{\sum E_{xE} + \sum E_{xH}} = \frac{\sum CO_2}{\sum E + \sum E_{xH}}
\]  

(5)
The sum of thermal exergy $E_{\text{exH}}$ 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, $E_{\text{xe}}$ (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 $u_{\text{x}}, \text{high CO}_2$ 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, the fuel savings equation of the directive was upgraded by embedding the Rational Exergy Management Efficiency, $\psi_R$ (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:

$$ J = \frac{E_{\text{xe}}}{A} = \left(1 - \frac{T_{\text{ref}}}{T_K}\right) \times \frac{Q}{A} \quad (6) $$

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

Figure 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 $T_K$ value is 107°C (380K) and the geographic area of Turkey is 780,000 km$^2$, then the $J$ value for Turkey is 0.36 kW/km$^2$. 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.

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

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

Figure 5 exemplifies that Turkey has a majority of geothermal reservoirs with low enthalpy. The well-head temperatures in the province of Ankara ranges between 37°C (310K) and 56°C (329K).

1.1 Exemplary Strategies
In this study two case studies are presented in order to show how exergy analysis may help to distinguish the best among many alternative combinations of systems and equipment.

Strategy 1- CHCP with simple CHP coupled to ORC. In this case ORC generates additional power (with low efficiency) with part of the heat generated by the CHP unit. This is a bottoming cycle too given in Strategy 1. In this case however, waste heat from ORC is utilized in an adsorption chiller.
(low \(COP\)) for generating cold. 50% of heat is directed to ORC, which generates electric power at an efficiency of 0.08. The waste heat from ORC is directed to ADS at a low temperature. That is why the efficiency of ADS is lower (0.45) and the output cold temperature is higher (288 K). In order to consider this temperature difference, a factor of \((1-285/288)\) is applied to the unit exergy of the basic ABS operation:
\[
\varepsilon = 0.042 \frac{\text{W}}{\text{W}} - (1 - 285 \text{ K}/288 \text{ K}) = 0.032 \frac{\text{W}}{\text{W}}.
\]

**Strategy 2 - CHCP with CHP+ORC+GSHP+ADS.**
In this strategy, the heat output is partially or completely dedicated to ORC. Power output of ORC partly or completely drives a GSHP unit, which may either generate heat or cold. The waste heat of the ORC unit is utilized in an ADS system. Instead of cold generation, GSHP may only generate heat if there exists high heat demand. Then the system becomes mainly a heat producer, except the small cold output of ADS unit. In this strategy the \(COPc\) of the GSHP is 3. For the unit exergy of the cold output of the GSHP to be even with the unit exergy of power input, then the minimum \(COP_{c_{\text{min}}}\) value should be much higher:
\[
COP_c > COP_{c_{\text{min}}}, \quad \text{where:}
\]
\[
COP_{c_{\text{min}}} = \frac{1}{\varepsilon_{\text{sup}}} - \frac{1}{0.032} = 31.25
\]

This value is even higher than the maximum theoretical limit of 29.9 in cooling and practically impossible. Therefore, it will be more exergetically rational to directly utilize the thermal output of CHP rather than using ORC and GSHP downstream. 0.47 is the power efficiency, \(\eta\) of the LEGS+ORC units.

**Strategy 3 - CHP+Hydrogen Generation+Fuel Cell and ADS.**
This seems quite futuristic but it may make sense if electricity needs to be stored under fluctuating power loads and to keep the CHP unit at a constantly continuous load at peak efficiency. Fuel cell regenerates power at an amount of demand using H\(_2\) gas stored in the tank. Waste heat of the fuel-cell unit is utilized in an ADS unit, which makes this system a trigeneration system.

### 1.2 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 has 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.

Figure 6-a. Geothermal District Heating

Figure 6-b. Power Generation with ORC [23].

2. Theory
Referring to the Rational Exergy Management Model (REMM)[23,24], it is possible to quantify the exergetic advantages that may also be directly translated to avoidable CO₂ emission calculations one may compare direct geothermal heating versus geothermal ORC power generation also. Figures 6 and
show the so-called Exergy Flow Bars, respectively [23]. In Figure 6, exergy destruction ($\varepsilon_{\text{des}}$) 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, $\psi_R$ [23,24].

$$\psi_R = \frac{\varepsilon_{\text{dem}}}{\varepsilon_{\text{sup}}} = \frac{1 - \frac{323}{343}}{1 - \frac{283}{353}} = 0.294$$

(8)

Here, $\varepsilon_{\text{dem}}$ 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 $\varepsilon_{\text{dem}}$ term is replaced by (1-283/293). In this case $\psi_R$ reduces to 0.172. Figure 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].

$$\psi_R = 1 - \frac{\varepsilon_{\text{dem}}}{\varepsilon_{\text{sup}}} = 1 - \frac{1 - \frac{283}{333}}{1 - \frac{283}{353}} = 0.243$$

(9)

2.1 Heat Pump Performance

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

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

(10)

In Equation 10, $\varepsilon_{\text{in}}$ 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, Figure 7 shows that an exergy base is crucial.

![](image)

Figure 7. A Sample Variation of COP and $COP_{EX}$ with $T_{\text{out}}$ [25].
For a fixed (given) temperature, $T_K$ at the well head of the geothermal reservoir, when $T_{out}$ increases the temperature difference, $\Delta T$ between the heat pump inlet temperature ($T_K$) 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. According to Figure 8, 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. Figure 8 shows a sample variation of $T_{out}$ [25].

### 2.2 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 11 was developed for heating.

\[
L_{max} = a_o + \left( \frac{Q}{1000} \right)^m \left( \frac{\Delta T}{20} \right)^{1.3} \{Q>1000 \text{ kW_h}, \Delta T \leq 30^\circ C\} \tag{11}
\]

Here, $Q_h$ is the useful thermal power to be transmitted (kW), $\Delta T$ 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.

\[
m = 0.6 \times \left( \frac{1 - \frac{T_{ref}}{T_K}}{1 - \frac{T_{ref}}{333.15}} \right)^{0.33} \{\text{For heating}\} \tag{12}
\]

If cold water is circulated in the district in order to satisfy cooling demand then:

\[
L_{max} = a_o + \left( \frac{Q}{1000} \right)^m \left( \frac{\Delta T}{10} \right)^{1.3} \{Q>1000 \text{ kW_h}, \Delta T \leq 10^\circ C\} \tag{13}
\]

\[
m = 0.6 \times \left( \frac{1 - \frac{T_{ref}}{T_f}}{1 - \frac{T_{ref}}{282.65}} \right)^{-1.23} \{\text{For cooling}\} \tag{14}
\]

### 3. 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 Figure 8.
3.1. 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:

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 geothermal 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, $\varepsilon_{in}$ in may be taken 1 kW/kW. $T_{ref}$ is the environment reference temperature, in this case the average ground temperature (283K).

\[
COP_{EX} = \frac{0.62 \times \left(1 - \frac{283}{328}\right) + 0.34 \times \left(1 - \frac{283}{363}\right) + 0.04 \times \left(1 - \frac{283}{308}\right) + 0.348 \times (1)}{1 \times \left(1 - \frac{283}{353}\right) + (0.62/0.8) \times \left(1 - \frac{283}{2000}\right)} = 0.59
\]

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

Figure 8. Combined Heat and Power in Circular Geotherm System: Heating Mode.
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.

| 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$_E$ | -            | -            | -            |

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 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.

$$C_R = \eta_I \times \psi_R \quad \text{or}, \quad (15)$$

$$C_R = COP \times \psi_R \quad (16)$$

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 (15) for geothermal district heating and ORC power-only options to be 0.19 and 0.019, respectively. Here, $\eta_I$ 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 Figure 10, minor exergy destruction in the Circular Geotherm model in heating are neglected.

Then:

$$\psi_R = 1 - \frac{E_{\text{del}}}{E_{\text{sup}}} = 1 - \left( \frac{1}{283} - \frac{1}{353} \right) = 0.827 \quad \text{and from Equation 15:}$$

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

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:

$$R = \frac{(2 - C_R)_{\text{district heating}}}{(2 - C_R)_{\text{geotherm}}} = \frac{2 - 0.19}{2 - 1.114} = 2.04 \quad (17)$$
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. In Figure 9, 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.

![Figure 9. GEOTHERM Case.](image)

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]. Equation 18 is used if there are more than one system with multiple exergy connections [23]:

$$\psi_R = \sum_i \sum_j |\psi_{R_{i-j}}| E_{x_{i-j}}/\eta_{i-j}$$

For thermal links between two nodes $i$-$j$, $E_{x_{i-j}}$ 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), $\psi_{R_{i-j}}$ may be assumed to be approximately 1.

4. Concept Design
A new conceptual 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 (electric) and heat at 90°C are 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 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 2. The return water temperature in the district is 343K.

Table 2. Loads of the 20000-Inhabitant Settlement Near the City of Ankara.

| Loads                        | Capacities   |
|------------------------------|-------------|
| Electrical Load              | 21000 kW_E  |
| Heating Load                 | 52000 kW_H  |
| Cooling Load (Sensible)      | 8000 kW_C   |

5. Results and Discussion

Computed Results show that this sample design has a $\eta_R$ value of 0.86. Comparing this application with a conventional district heating system with natural gas boilers, with $\eta_R$ value of 0.11, it is quite high. This value in fact directly translates into CO$_2$ emissions responsibility, according to the following Equation:

$$\sum CO_2 \propto (2 - \eta_R)$$  \hspace{1cm} (19)
Here the compound CO$_2$ emissions responsibility is related to the avoidable (indirect) emissions, which are possible to be eliminated with better allocation of the geothermal potential in the built environment, simply by improving the $\psi_R$ efficiency. According to this relationship, it is understood that the sample design has a potential of reducing CO$_2$ emission responsibility in the district energy system by 65.8%:

$$[(2-0.11)/(2-0.86)-1]\times100 = 65.8\%$$

6. 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 $\psi_R$ term must be minimized first of all by maximizing the $\psi_R$ 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.

By using the new objectives and metrics described herein, 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 Figure 8 [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. 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.

7. 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/(kWh/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/number of residences
\( \text{COP} \) \quad \text{Coefficient of Performance}

\( \text{COP}_{EX} \) \quad \text{Exergy-Based COP}

\( C_R \) \quad \text{Composite Rationality Index}

\( E \) \quad \text{Electric power, kW}

\( E_X \) \quad \text{Exergy, kW}

\( E_{XD} \) \quad \text{Total exergy delivered in the district for each dwelling, kW/dwelling}

\( E_{th} \) or \( E_{XH} \) \quad \text{Thermal exergy, kW}

\( E_{pr} \) or \( E_{XE} \) \quad \text{Power exergy, kW}

\( E_{XR} \) \quad \text{Thermal exergy and power exergy output ratio of a geothermal system}

\( GE \) \quad \text{Geofluid Effectiveness, kW-h/kg}

\( GSE \) \quad \text{Geothermal System Effectiveness}

\( HDH \) \quad \text{Heating Degree Hour, K·h}

\( i \) \quad \text{Unit investment cost of the geothermal system, TL/(person·K·h)}

\( I \) \quad \text{Investment cost, TL}

\( J \) \quad \text{Thermal exergy of the geothermal well output per km}^2 \text{ of a country, kW/km}^2

\( N \) \quad \text{Population receiving district energy service (in the form of heat, cold, and power individually)}

\( OF \) \quad \text{Equipment Oversizing Ratio}

\( P \) \quad \text{Installed power capacity, kW}

\( Q \) \quad \text{Thermal (in the form of heat or cold) power, kW}

\( R \) \quad \text{CO}_2 \text{ Reduction Potential Ratio}

\( RDR \) \quad \text{Reservoir Decline Rate, kW-h/h}

\( s \) \quad \text{Equipment performance constant (Equation 10)}

\( T \) \quad \text{Temperature, K}

\( u \) \quad \text{Unit CO}_2 \text{ emissions per kW of electrical power generated, } E

\( u_x \) \quad \text{Exergy-based unit CO}_2 \text{ emissions per kW of electrical power generated, } E

\( X \) \quad \text{Split ratio of the geothermal fluid heat between ORC and the heat pump}

\textbf{Greek Symbols}

\( \varepsilon \) \quad \text{Unit exergy, kW/kW}

\( \psi_R \) \quad \text{Rational Exergy Management Efficiency}

\( \eta \) \quad \text{First-Law Efficiency}

\( \Delta T \) \quad \text{Temperature difference, K}

\textbf{Subscripts and Superscripts}

\( a \) \quad \text{Indoor air design temperature related variable}

\( boiler \) \quad \text{Boiler}

\( C \) \quad \text{Cooling, summer related}

\( D \) \quad \text{District}

\( DE \) \quad \text{District energy system}

\( dem \) \quad \text{Demand}

\( des \) \quad \text{Destroyed}

\( E \) \quad \text{Electric}

\( f \) \quad \text{Fuel}

\( H \) \quad \text{Heat, heating, winter related}

\( in \) \quad \text{Inlet to the heat pump}

\( I \) \quad \text{First Law}

\( K \) \quad \text{Geothermal well head}

\( KCR \) \quad \text{Critical well-head temperature for equal power and heat exergy}

\( L_{max} \) \quad \text{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
CCP
Combined Cold and Power
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
LEGS
Low-Enthalpy geothermal system
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

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