EXERGY-RATIONAL UTILIZATION OF LOW TEMPERATURE GEOTHERMAL AND SEWER HEAT IN DISTRICTS

by

Birol KILKIS[*]

OSTIM Technical University, Ankara, Turkiye

Original scientific paper
https://doi.org/10.2298/TSCI2405435K

Aligning with the decarbonization roadmap of the EU and fifth-generation district heating systems, an exergy-based optimization and decision-making model was developed for minimum CO_2 *emission responsibilities. Nine environmental, thermal, and electromechanical constraints were applied. Seven cases are presented, including sewer heat in Bavaria and Toronto, Jincheon eco-friendly energy town, low enthalpy geothermal heat, a data center, waste incineration plant in Amsterdam, waste heat from the stack of a coal-fired power plant, and building-scale utilization of building wastewater. Sample calculations show that the maximum carbon footprint belongs to the sewer heat system, because of the larger temperature peaking requirement. The minimum carbon footprint belongs to the geothermal heat utilization system.*

Key words: *sewer heat, data center, stack heat, geothermal heat, exergy, waste incineration, plumbing heat*

Introduction

According to the EU Directive 2018/2001, waste heat is renewable [1]. The Energy Efficiency Directive mentions uses of waste heat with cost-benefit analyses (CBA) [2], without considering that low temperature waste heat has limited useful work potential. Table 1 lists common urban waste heat resources, their temperature ranges, unit exergy, and applicability in district energy (5 DE) systems, which involves power, heat, and sometimes also cold distribution. In district heating (DH) systems only heat is distributed. Low (< 60 °C) and ultra low (< 40 °C) waste heat resources are about 89% of all waste heat sources in the EU [3].

Concerning waste-to-heat, waste heat sources at temperatures below 100 °C (373 K) are moving closer to urban areas, thus making it feasible to distribute heat in 5 DE systems [4]. An issue yet to be solved is typically, a building connected to 5 DE for heating (DH) with conventional heating terminal units, which operate between 70 °C and 50 °C, requires a unit exergy of 0.058 kWh_{ex} per kWh_{en} according to the ideal Carnot cycle. From the exergy balance viewpoint, all sources in tab. 1 satisfy the unit demand exergy (sewer heat barely satisfies) but none of them satisfy the 70 °C supply temperature demand. Therefore, terminal units for heating must operate at temperatures around 35 °C (40 °C supply, 30 °C return). Then, the unit demand exergy decreases to 0.032 kWh_{ex} per kWh_{en} letting all waste heat sources to be feasible. Yet certain ultra-low supply sources cannot satisfy the demand temperature requirements, such as sewer heat, solar photovoltaic-thermal (PVT), and wind turbine nacelle heat, requiring either

---

[*] Author's e-mail: birol.kilkis@ostimteknik.edu.tr

temperature peaking heat pumps, temperature-compliant heating terminal units [5], or oversizing the conventional terminal units. Furthermore, there is an optimum point about oversizing the heat pump and oversizing the terminal units for minimum emission responsibility [6]. One of the oldest sewer heat utilization systems with heat pumps is in the City of Paris. According to Guo and Hendel [7], this system saves about 30% energy according to the First law of thermodynamics. The authors also mention that effective nitrogen removal with new techniques is possible to recover waste heat down to 13 °C (286 K), but subsequently, the heat pump loads increase due to increased temperature peaking demand. According to a field study by David *et al.*, [8] covering eleven countries, 149 central large heat pumps with capacities above 1 $\mathrm{MW_H}$ comprising 1580 $\mathrm{MW_H}$ were studied. The largest share among these applications, 56%, belongs to sewer systems [9, 10].

Table 1. Thermal properties of typical low and ultra-low waste heat sources, T_{ref} = 283 K, $\varepsilon = (1 - T_{\mathrm{ref}}/T_{\mathrm{f}})$

Source	Supply temperature range, T_{f}, [°C]	Max-min unit exergy, ε [$\mathrm{kWh_{ex}}$ per $\mathrm{kWh_{en}}$]	Applicability	
			5 DE	Decentralized
Sewer heat	25-15	0.050-0.0174	✓	✓ (Before sewer mains charging)
Geothermal heat after ORC	40-30	0.096-0.067	✓	
Low enthalpy geothermal	60-40	0.150-0.096	✓	✓
Solar PVT	35-25	0.081-0.050	✓	✓
Thermal power plant (cooling tower)	40-35	0.096-0.081	✓	
Power plant stack HR (optimum)	55-45	0.137-0.110	✓	
Wind turbine heat (nacelle)	30-20	0.067-0.034	✓	✓
Data center	60-50	0.150-0.124	✓	
Nearly-zero carbon cooling	35-30	0.081-0.067		✓

One of the latest and largest sewer water-sourced heat pump operations in district heating systems is in the city of Malmo [11]. This system has four large heat pumps with ammonia refrigerant. The total thermal capacity is 40 MW. The annual average COP is reported to be 3.5. Typical performance data extracted from their research show that there is always an exergy deficit between the heat delivered and the electricity demand of the heat pumps. In tab. 2, the nearly avoidable CO_2 emissions responsibility (ΔCO_2) is based on one-step offsetting of exergy destructions with a multiplier of 0.63 times destroyed exergy. If the offsetting is extended to further steps in the background, then ΔCO_2 values in the last column need to be modified by a factor of (2.1/0.63) [4]. Besides the utilization of sewer heat, other waste energy sources are also sought and applied. An on-site incinerator in West Amsterdam generates heat around 28300 $\mathrm{MWh_{en}}$ at about 340 K, which corresponds to an estimated peak thermal power of 7000 $\mathrm{kW_{en}}$ [12]. A data center in the city of Espoo in Finland, provides an average thermal power of 10 $\mathrm{MW_{en}}$ at about 330 K for district heating [13]. In another study, Kilkis [14] compared the waste heat utilization of a data center and concluded that it is better to utilize the waste heat within the data center in a closed thermal exergy loop reduces emission responsibilities.

Table 2. Environmental performance of the Hammarby district according to the Second law of thermodynamics [15]

T_f	COP_{HP}	$\varepsilon_{sup} = 0.95/COP_{HP}$	ε_{dem}	ε_{des}	$\Delta CO_2 = 0.63\ \varepsilon_{des}$
330	3.5	0.271428571	0.1424242	0.129004	0.0812727
335	**3.1**	**0.306451613**	**0.1552239**	**0.151228**	**0.0952735**
340	2.7	0.351851852	0.1676471	0.184205	0.116049
345	2.3	0.413043478	0.1797101	0.233333	0.147
350	1.9	0.5	0.1914286	0.308571	0.1944

Araz *et al.* [16] performed an exergo-economic analysis concerning a sewer heat recovery system, which is composed of three sub-systems: wastewater, heat pump, and end-user. A solar PVT system supplements the wastewater heat and electrical power. Yet they did not correlate the exergy destructions to ΔCO_2. A district heating company in Stockholm has installed heat pumps with 71 MW_E of electric power demand for the district of Hammarby, delivering 248 MW_{en} of heat at about T_f = 70-80 °C (343-353 K) [15]. This proportion (248 MW_{en} per 71 MW_E) gives a COP of 3.49, which is admissible. The sewer water temperature is 17 °C (290 K). When the Second law of thermodynamics is considered and with the ideal Carnot cycle, there appears an exergy deficit between the power exergy demand and thermal exergy delivered, causing CO_2 emission responsibility. Therefore, the Second law of thermodynamics analysis is a must in such applications. Despite this and in the same token, Kim *et al.* [17] utilized various waste heat sources in apartment blocks for heating and cooling using separate ground source heat pumps, assisted with night-time cooling and seasonal storage and they did not account for the exergy difference between the electric power and thermal power that is generated and consumed.

To show the opposition to their claims by the Second law of thermodynamics, tab. 2 and fig. 1 are presented, showing that there is always an exergy deficit between the heat delivered and the electricity demand of the heat pump, causing a nearly avoidable, ΔCO_2, and the deficit increases at colder outdoor temperatures, causing higher supply temperature demand, T_f from the heat pumps. Despite the claims about mitigation about 60% of CO_2 emissions (direct), by replacing fossil fuels, when the ΔCO_2 emission responsibility and the power exergy demand by the heat pumps are considered, the system is responsible for emissions. If T_f is 335 K:

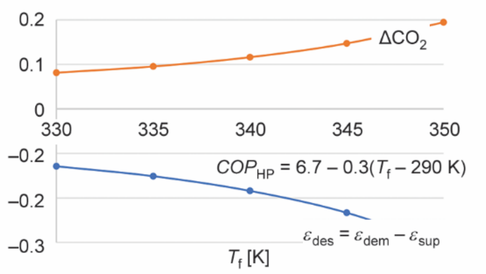


Figure 1. The ΔCO_2 and exergy destructions with T_f for Hammarby district

$$CO_2 + \Delta CO_2 = 0.30645 \times 2.5 \times 0.2\ \text{kg}\ CO_2/\text{kWh}_{en} + 0.0953 = \\ = 0.2485\ \text{kg}\ CO_2/\text{kWh}_{en}\ \text{(from tab. 2)}$$

Here, 2.5 is the average primary energy factor (PEF) for the European countries and 0.2 kg CO_2 per kWh_{en} is the unit CO_2 content of natural gas. The last term is from tab. 2, based on the exergy mismatch, ε_{sup}, and, ε_{dem}. The power exergy demand of the circulation pumps is not factored in yet. Even when fossil fuels are replaced by renewables (without considering their exergy destructions), $CO_2 = -0.2/0.80 = -0.25$ kg CO_2 per kWh_{en}, there remains ΔCO_2 and the district becomes without sufficient mitigation potential. Here, 0.80 is the average First law of thermodynamics efficiency of boilers.

Need for the present study

On the other hand, the stack heat from a coal-fired power plant may be recovered in addition to the entry points to the cooling towers [18]. Despite that the stack heat recovery yields higher temperature, higher exergy waste heat, care must be paid to minimize the efficiency decrease of the power generation requiring stack fan with electricity due to lowered hot gas temperature at the stack exit. Eight major gaps in the literature are given, which miss the exergy rationality.

- The ΔCO_2 terms concerning heat pumps and ancillary equipment are ignored.
- Feasibility studies are based on simple economy, like life-cycle assessment (LCA) and simple payback period (PB) in a cost-to-benefit algorithm (CBA). However, the CBA type of analysis does not consider the environmental cost of exergy destruction and their direct effect of the ΔCO2 terms.
- The distance between a central plant for claiming waste heat or geothermal heat and the district hub is not considered, except for installation costs. In fact, the maximum distance is limited by the pumping power demand and pumping exergy, relating to additional emissions.
- The temperature mismatch between the waste heat source and the terminal heating units are minimized or eliminated by electric heat pumps, leading to power-to-heat exergy losses, thus ΔCO2.
- The EU Directives and all national or international rules and standards are based on the First law of thermodynamics, except limited exergy comparisons based on individual equipment or components. The analyses do not relate exergy destructions to □CO2.
- In low enthalpy geothermal energy resources below but close to 100 °C, power generation, upstream with ORC units is possible, but it is a question of whether using the heat as heat directly in the district or using the reject heat after the ORC operation. An optimization effort also considering the temperature demand of the terminal heating units must be made.
- Exergy-based options concerning the supply of reject heat of heat pumps for summer building cooling to the sewer line for thermal applications downstream are not considered and the PB calculations for heat pumps remains limited by the heating degree.
- The emission equivalent of the ozone depletion potential (ODP) is often ignored. Even if the ODP is claimed to be zero, refrigerants often carry a high GWP. If not ignored they are treated separately and is not related to an equivalent emission responsibility.

Aim of the present study

The primary aim of this research is to respond to all major gaps in theory and practice, needing exergy-rational use of low temperature waste heat with minimum emission responsibilities:

- To develop a rating model using the rational exergy management model (REMM) to introduce the exergy rationality concept to environmental issues by nearly avoidable emission responsibilities, which usually exceed the direct emissions measurable on-site of the source.
- To expand the model to holistically accommodate all aspects of exergy destructions on a system level.

- To apply the model to case studies and show the importance of exergy-based awareness.
- To provide optimization for minimum emissions responsibility.
- To increase the awareness of several constraints, and to provide opportunities for using the waste heat.

Method

The exergy-based optimization model is based on the simplified diagram given in fig. 2, which shows the fundamentals of a district heating system coupled to the main sewer line. Figure 3 is the exergy flow bar of the rating model. The $\Sigma\dot{E}_{\rm sup}$ term includes power exergy delivered to the heat pump(s) and district pump(s). According to the First law of thermodynamics definition of the coefficient of performance, COP of any process of claiming the waste heat for useful applications like district heating, is given in eq. (1). Equation (2) is the Second law of thermodynamics definition of COP. 0.95 $\rm kWh_{ex}$ per $\rm kWh_{en}$ is the unit exergy of electricity.

$$COP = \frac{\dot{Q}_{\rm WH}}{\dot{E}_{\rm sup}} \tag{1}$$

$$COPEX \geq \dot{Q}_{\rm WH}\frac{1-\dfrac{T_2}{T_1}}{\dot{E}_{\rm sup}}0.95 = COP\frac{1-\dfrac{T_2}{T_1}}{0.95} \quad \{\text{source: electricity}\} \tag{2}$$

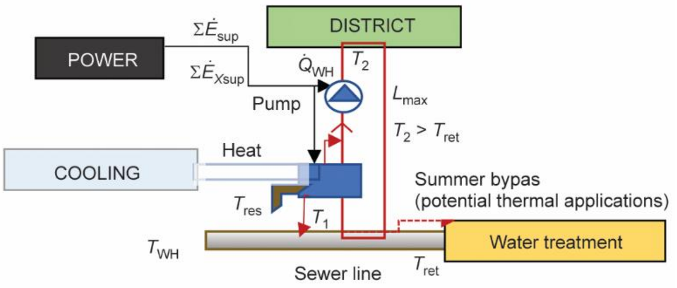


Figure 2. Simplified diagram for sewer waste heat utilization. masked area represents cooling

In eq. (2), $\dot{Q}_{\rm WH}$ includes the power gained by in-line circulation pumps. As a golden rule expressed with the Second law of thermodynamics for the objective function, OF, may be transformation of COP into the exergy domain. The $\dot{E}_{X\rm sup}$ includes thermal, mechanical, hydraulic, and electrical inputs, including the pumping power demand.

$$\mathrm{OF}_1 = COPEX \geq \dot{Q}_{\rm WH}\frac{1-\dfrac{T_2}{T_1}}{\dot{E}_{\rm sup}\varepsilon_i} = \dot{Q}_{\rm WH}\frac{1-\dfrac{T_2}{T_1}}{\sum\dot{E}_{X\rm sup}} \quad \{\text{maximize}\} \tag{3}$$

For slight differences between T_1 and T_2 the exergy-based coefficient of performance COPEX becomes quite small unless COP is very high. Otherwise, emissions responsibility will occur [14]. The objective function, $\rm OF_1$, given in eq. (3) is subjected to the following nine constraints given in eqs. (4) to (24).

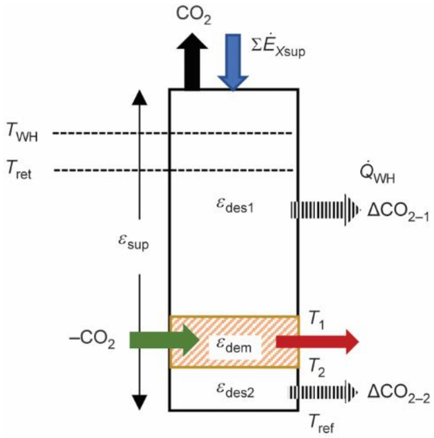


Figure 3. The CO_2 and ΔCO_2 emissions responsibilities of sewer heat utilization due to exergy destructions and CO_2 mitigation by replacing a boiler; this figure corresponds to heating

Constraint 1

After solving COP from eq. (2) for the theoretical condition of COPEX equal to one:

$$COP \geq \frac{0.95}{1-\dfrac{T_2}{T_1}} \quad \{Constraint\ 1, T_2 < T_1\} \tag{4}$$

For example, if T_1 and T_2 are 305 K and 315 K, respectively, then COP in eq. (4) must exceed thirty. Today's applications cannot satisfy this constraint, where practical COP values are below ten. Conventional economy concerning simple payback, claims that much lower COP values are feasible. For example, if the unit revenue of heat claimed is $c_{o,\mathrm{h}}$ [0.16 € per kWh$_{\mathrm{en}}$ from solar PVT at $T_1 = 45$ °C] and the unit cost of electricity consumed $c_{o,\mathrm{e}}$, is 0.25 € per kWh$_{\mathrm{E}}$, then for the investment cost of I, expected PB, average annual operation period H, and known waste heat power claimed, $\dot{Q}_{\mathrm{WH}}$, the economically feasible minimum COP value can be determined:

$$COP_{\min} = \frac{c_{o,\mathrm{e}}}{c_{o,\mathrm{h}} - \dfrac{\dfrac{I}{\dot{Q}_{\mathrm{WH}}}}{PB \cdot H}} \quad \{\text{according to simple payback}\} \tag{5}$$

For example, with a set of sample data with $I/\dot{Q}_{\mathrm{WH}}$ = 1500 € per kW, PB = 5 years, and H = 4000 hours per year, with $c_{o,\mathrm{h}}$ = 0.16 € per kWh based on levelized cost of PVT heat at T_1 = 45 °C, and $c_{o,\mathrm{e}}$ = 0.25 € per kWh [19].

$$COP = \frac{0.25\ €/\text{kWh}}{0.16\ €/\text{kWh} - \dfrac{1500\ €/\text{kW}}{5\ \text{year} \times 4000\ \text{hours per year}}} \tag{5}$$

{according to the First law of thermodynamics and simple payback}

This minimum permissible COP value, which is acceptable today in the energy sector is about 10 times lower than what it should theoretically be for minimum carbon footprint (2.94/30). Despite this fact, many applications, including waste heat from data centers, and sewer systems claim that they are environmentally and economically feasible without referring to the Second law of thermodynamics and considering nearly avoidable emissions. The actual carbon footprint is given by eq. (6) [14], yielding *Constraints 2* and $\mathrm{OF_2}$.

Constraint 2

According to this environment-related objective, $\mathrm{OF_2}$, to minimize the carbon footprint, the net $\mathrm{CO_2}$ emissions in one hour of operation must be less than zero. From fig. 3, where 2.1 is a three-step offsetting factor. The $\mathrm{OF_2}$ includes direct emissions, and upstream and downstream $\Delta\mathrm{CO_2}$ in fig. 3:

$$\mathrm{OF_2} = \left(\mathrm{CO_2} + \Delta\mathrm{CO_{2-1}} + \Delta\mathrm{CO_{2-2}}\right)\dot{Q}_{\mathrm{WH}} - \\ -\left[\frac{0.35(1+r)\dot{Q}_{\mathrm{WH}}}{\eta_{\mathrm{IB}}} + 2.1\left(1-\frac{T_{\mathrm{E}}}{T_{\mathrm{f}}}\right)\dot{Q}_{\mathrm{WH}}\right] < 0 \quad \{\text{minimize}\} \tag{6}$$

The term in square brackets is the emissions savings due to the replacement of boilers. The multiplier 0.35 is the average $\mathrm{CO_2}$ content of fossil fuels considering the renewables in the supply mix with their $\Delta\mathrm{CO_2}$. The term r is the ratio of pumping power to the thermal waste heat power. For a boiler and in-line pump, $T_{\mathrm{f}} = 2235$ K, $\eta_{\mathrm{IB}} = 0.85$, $T_{\mathrm{E}} = 600$ K, $r = 0.05$, and $\dot{Q}_{\mathrm{WH}} = 1$ kW.

$$\left(\mathrm{CO_2} + \Delta\mathrm{CO_{2-1}} + \Delta\mathrm{CO_{2-2}}\right) < 1.97 \text{ kg } \mathrm{CO_2} \text{ per kWh} < 0 \ \ \{\text{in one hour}\} \tag{7}$$

$$\Delta\mathrm{CO_{2-1}} = 2.1\left[\frac{0.95}{COP} - 1 + \frac{T_2}{T_1} - \left(1-\frac{T_{\mathrm{ref}}}{T_2}\right)\right] \ \{\text{upstream}\} \tag{8}$$

$$\Delta\mathrm{CO_{2-2}} = 1.1\left(1-\frac{T_{\mathrm{ref}}}{T_2}\right) \ \{\text{downstream}\} \tag{9}$$

The $\mathrm{CO_2}$ emission per hour is the background emissions responsibility from the origin of power generation and transmission [14]. In this study, it is a given of the problem, depending on the fuel used, type of the power plant, stack temperature T_{E}, grid losses, *etc.*, except COP.

$$\mathrm{CO_2} = c_K PEF\left[\frac{\dfrac{s\dot{V}^2}{\dot{Q}_{\mathrm{WH}}}}{\eta_{1p\text{-}m}} + \frac{1}{COP} + 1.1\left(1-\frac{T_{\mathrm{ref}}}{T_{\mathrm{E}}}\right)\right] \ \{\text{turbulent flow in pipes}\} \tag{10}$$

A simplified expression for total $\mathrm{CO_2}$ emissions combines $\mathrm{OF_1}$ and $\mathrm{OF_2}$ [14]:

$$\sum \mathrm{CO_2} \simeq 2\frac{1-COPEX}{COP} \ \{\text{Minimize}\} \tag{11}$$

Constraint 3

In certain applications, the return temperature, T_2, must be above a certain minimum value, T_{ret}. For example, it is 30 °C (303 K) for sewer heat. For geothermal applications, the reinjection well supply temperature must be above 60 °C (333 K). These constraints also limit the maximum thermal power that may be obtained for a given T_1, volumetric flow rate, and average properties of the heat transfer fluid:

$$\dot{Q}_{\mathrm{WH}} \le \rho C_p (\dot{V})_{\mathrm{WH}} \left(T_1 - T_2\right) \ \{\text{thermal power of waste heat}\} \tag{12}$$

$$(\dot{V})_{\mathrm{WH}} = \frac{\dot{Q}_{\mathrm{WH}}}{\rho C_p (T_1 - T_2)} \ \{\text{flow rate}\} \tag{13}$$

$$T_2 \ge T_{\mathrm{ret}} \ \{\text{in heating}\} \tag{14}$$

Constraint 4

Previous constraints limit the maximum distance of district distribution distance, $L_{\max}$ (one-way) [20]. If this condition does not hold the pumping power demand exergy exceeds the thermal power distributed in the district, causing ΔCO_2:

$$L_{\max} = \left|1 - \frac{T_2}{T_1}\right| \eta_{Ip\text{-}m} \dot{Q}_{\mathrm{WH}}^{1.5} \frac{\frac{h}{c}}{\sqrt{|T_1 - T_2|}} \tag{15}$$

Constraint 5

For practical purposes and to avoid large pressure losses and embodiments concerning pipe size and material use in the district network, the temperature difference must satisfy the following constraint:

$$|T_1 - T_2| \ge 5\ \mathrm{K} \ \{\text{between supply and return}\} \tag{16}$$

Constraint 6

This constraint is given in the literature for sewer heat systems [7]. The multiplier (0.55) converts an ideal COP value to a practical equivalent in the field. The partial load factor (PLF) is the partial load multiplier of the heat pump. The T_1 is the supply temperature from the heat pump and T_{WH} is the source temperature.

$$COP = 0.55 PLF \frac{T_{\mathrm{WH}}}{T_{\mathrm{WH}} - T_2} \ \{PLF < 1\} \tag{17}$$

Contraints 7 and 8

$$T_1 < T_{\mathrm{WH}} \tag{18}$$

$$T_2 > \mathrm{T}_{\mathrm{ret}} \tag{19}$$

All these constraints and the objective functions, OF_1 and OF_2 limit the practical use of low-exergy waste heat below 100 °C, despite their abundance. Therefore, estimates about their potential contributions to climate mitigation and their actual CO_2 footprints must be carefully revised. For example, according to Reyes [21], the contribution of sewer heat in the district heating system in the city of Malmo, the best location for sewer collection was modeled, showing that the location of collection is important for temperature gradients. However, instead of temperature gradients, unit exergy gradients could probably lead to a better solution.

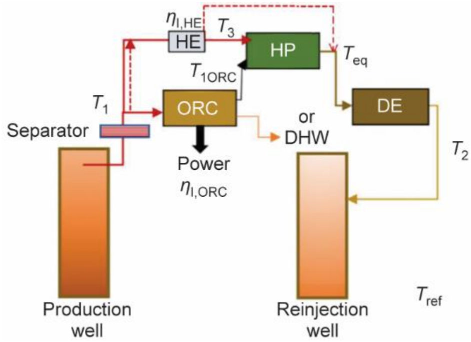
Constraint 9

This constraint concerning the exergy-based optimization inequality is expressed in eq. (20). It states that, if an ORC system is included, the net thermal exergy utilized in a district energy network and the exergy of electric power generated, the left-hand side of eq. (20), must be greater than the alternative case on the right-hand side, which corresponds to the direct use of the geothermal heat with a heat pump in the district without power generation with ORC, fig. 4. In the second case, the COP of the heat pump changes from COP$_{\text{HP-ORC}}$ with ORC system that has an increased COP$_{\text{HP-DE}}$ value due to the higher input temperature supplied directly from the source. In eq. (20), the question is about whether the left-hand-side or the right-hand side is greater, and the question mark represents the is question:

$$\eta_{\text{I,ORC}}0.95 + (1-\eta_{\text{I,ORC}})\left[\left(1-\frac{T_{\text{ref}}}{T_{\text{eq}}}\right)COP_{\text{HP-ORC}} - \left(\frac{0.95}{COP_{\text{HP-ORC}}}\right)\right] >$$

$$> \eta_{\text{I,HE}}\left[\left(1-\frac{T_{\text{ref}}}{T_{\text{eq}}}\right)COP_{\text{DE}} - \left(\frac{0.95}{COP_{\text{HP-DE}}}\right)\right] \tag{20}$$

Figure 4. Power+LT heat option *vs.* MT heat in geothermal district energy (DE) system



The T_{eq} is the demand (supply) temperature of the heating terminal units in the district:

$$COP_{\text{HP-ORC}} = a - b[T_{\text{eq}} - T_{\text{1,ORC}}] \tag{21}$$

$$COP_{\text{HP-DE}} = a - b[T_{\text{eq}} - T_3] \tag{22}$$

$$\eta_{\text{I,ORC}} = e + f\frac{T_1}{T_0} \tag{23}$$

$$T_2 > T_{\text{reinj}} \;\{Constraint\} \tag{24}$$

Constants a, *b*, *e*, and *f* are the equipment-specific values for the heat pump and the ORC unit. The T_{reinj} is the minimum permissible temperature for reinjection.

Clearly, low temperature heating equipment with lower T_{eq} relieves the electric power demand of the heat pumps and therefore a holistic optimization including the type of equipment is necessary. Equation (20) excludes the differences between ozone depletion and global warming potentials due to differences in the heat pump sizes. For example, the following sample data is inserted into eq. (20):

$$0.11\times 0.95 + (1-0.11)\left[\left(1-\frac{283\text{ K}}{320\text{ K}}\right)-\left(\frac{0.95}{4.5}\right)\right]0.85\left[\left(1-\frac{283\text{ K}}{360\text{ K}}\right)-\left(\frac{0.95}{6.0}\right)\right]$$

yielding the following inequality: 0.0195 kWh$_{\text{ex}}$ per kWh$_{\text{input}}$ < 0.047 kWh$_{\text{ex}}$ per kW.

The result of the left-hand side is smaller than the result of the right-hand side. Therefore, the ORC option is not feasible. Note that the left-hand side becomes negative if COP$_{\text{HP}}$ is less than four. This condition puts another constraint on the heat pumps. The ΔCO_2 and CO_2 emissions are analyzed in the results.

Seven case studies that are subjugated to the analysis have different thermal load profiles. Therefore, a common base was established in terms of a unit thermal load of 1 kW thermal power supply. To consider exergy differences, supply temperatures were justified to 60 °C (333 K) to correct the thermal power output in terms of actual temperatures based on the ideal Carnot cycle and a reference temperature of 283 K. For example, if one of the cases listed below delivers thermal power at a temperature T_1 of 40 °C (313 K), then the thermal power is corrected according to the following adjustment formula:

$$\dot{Q}_{\mathrm{WH}_{\mathrm{corrected}}} = Q_{\mathrm{WH}}\left(\frac{T_1}{333\ \mathrm{K}}\right) = 0.862Q_{\mathrm{WH}} \tag{25}$$

Results and discussion

The results are compared according to their environmental footprint concerning ΔCO_2, CO_2, and total emissions responsibility. The COP and COPEX values are analyzed, whenever heat pumps are involved. The seven case studies that are compared in this research work are:

- Sewer water heating in Bavaria and Toronto [22, 23]. The Bavarian Energy Award 2012 went to a sewer water heating project, which satisfies about 65% of the heating load of 102 apartments translating to a thermal energy contribution of 350 MWh per year. A specially designed heat exchanger for low temperature recovery from the sewer heat. A heat pump is used to peak the temperature to meet the temperature requirement of the heating terminal units. A similar project was completed in the City of Toronto [23]. The main drawback of their analysis is the exclusion of the Second law of thermodynamics related to emission responsibility calculations, mainly due to the power-to-heat exergy destructions and the electrical power exergy demand of the district pumps, which also carry CO2 and □CO2.
- Jincheon eco-friendly energy town [17]. This project in North Chungcheong Province in South Korea has combined ground source heat and sewer water heat in their analysis and compared them [18].
- Low enthalpy geothermal heat utilization [24]. A case study was carried out for a nearly zero energy and exergy design for about a 20000 inhabitant town with or without ORC power generation, fig. 4.
- Data center with 20 MW power demand [14]: This case study represents a data center with a nearly-zero carbon data center (nZCDC) features based on a theoretical study using data for an existing data center with the ordinary configuration of grid power and chillers [14]. The nZCDC does not involve any heat pumps and optimally utilizes the waste heat within the data center complex, rather than employing a DH grid for nearby settlements. This eliminates both the DH network and pumping investment, fig. 5.
- Amsterdam waste incineration plant [12]. This case study investigates the waste incineration plant in the City of Amsterdam, which supplies both power and heat. The results that will be given in tab. 3 exclude the emissions due to waste incineration, section *Results*.

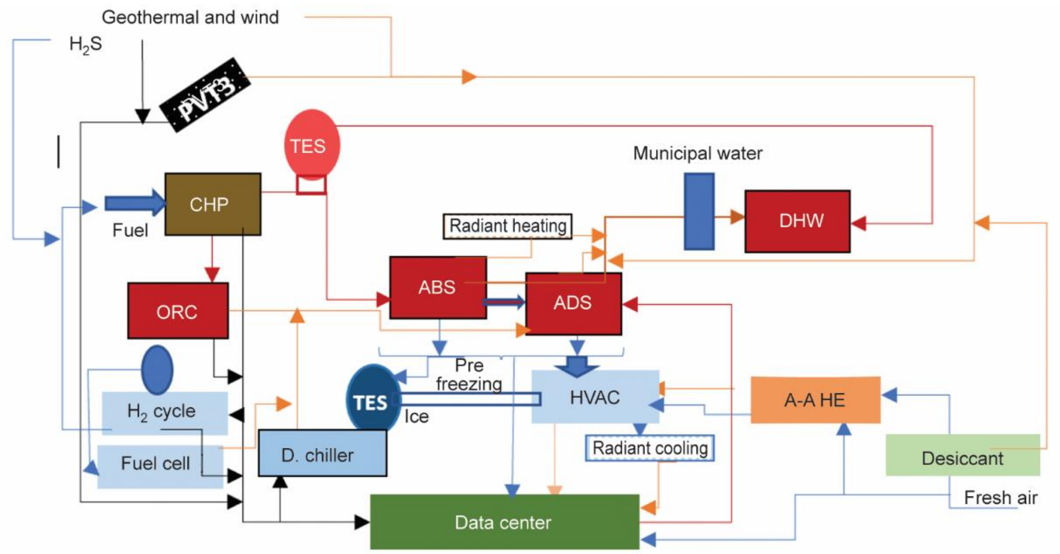


Figure 5. Simplified layout of the next-generation, nearly-zero CO_2 data center design (with PVT)

Table 3. Emissions responsibility comparison of Cases for 1 kW of corrected thermal power supply

Cases	Emission variables						
	ΔCO_2	CO_2	ΔCO_2+CO_2	$\Delta CO_2/CO_2$	COP	COPEX	Eq. (10)
1 [23, 24]	0.05	0.04	0.09	1.25	4	0.5	0.10
2 [18]	0.06	0.05	0.11	1.2	4.5	0.6	0.12
3 [25]	0.03	0.06	0.09	0.5	3.5	0.4	0.11
4 [14]	$0.156\cdot10^{-3}$	0.0229	0.0244	0.0064	na	na	na
5 [12]	0.07	0.03	0.10	2.33	na	na	na
6 [17]	0.02	0.01	0.03	2	4	0.14	0.035
7	0.178	0.1	0.278	1.78	2.85	0.085	na

- Stack heat claimed from a coal-fired power plant [18]. This case study is based on a theoretical study that involves a thermal supply from a coal-fired power plant with heat claimed from the stack.
- Building-scale plumbing wastewater. An open-loop arrangement, part of the low temperature heat from the waste warm water collected from the building, may be recovered before discharge, and then the temperature peaked by a heat pump, fig. 6. While the heat pump output temperature is kept low for higher COP, further peaking may require a boiler to avoid Legionella risk.

According to the First law of thermodynamics, this claim makes sense because the COP is greater than one and waste heat is recovered, although Q_H/COP amount of electricity, Q_E is used from the grid. If the origin of the electricity is not questioned, this claim holds. Even in terms of the First law of thermodynamics, this system is not feasible when the fuel-to-plug efficiency, $\eta_{I,T}$, CO_2 emissions from the thermal power plant, water vapor release from its cooling towers, and refrigerant-related ODI from the heat pump are considered. The ODI is a composite index of ODP and GWP [25]. Water vapor released into the atmosphere has a greenhouse effect of almost twice the CO_2 emission effect. After ignoring the latter effect, the heat recovery has an environmental cost of $CO_2 = 0.1$ kg CO_2 per $\text{kWh}_{\text{heat recovered}}$. If an on-site boiler is used to deliver the heat recovered, its direct CO_2 emissions would be 0.05, less than the claimed heat recovery system. The system claims unit exergy between temperatures of T_2 and T_1, 45 °C and 25 °C, respectively. The heat pump uses grid electricity with a COP of 3. An advanced tandem heat pump system with a COP of 6, could resolve the problem. However, when the exergy is brought in, the claim proves to be inadmissible. The total CO_2 emissions are almost three times more than the First law of thermodynamics predicts. Here are the calculations:

$$\varepsilon_{\text{des}} = \frac{0.95}{COP} - \left(1 - \frac{T_1}{T_2}\right) = \frac{0.95}{3} - \left(1 - \frac{288\text{ K}}{298\text{ K}}\right) = 0.283\text{ W/W}$$

$$COP = 3\eta_{\text{I,B}} = 3 \times 0.85 = 2.55$$

$$COPEX = COP\left(1 - \frac{T_1}{T_2}\right) = 0.085 \ll 1$$

$$\Delta CO_2 = 0.63\varepsilon_{\text{des}} = 0.178\text{ kgCO}_2\text{/kWh},$$

$$\Sigma CO_2 = CO_2 + \Delta CO_2 = 0.1 + 0.178 = 0.278\text{ kgCO}_2\text{/kWh} \tag{26}$$

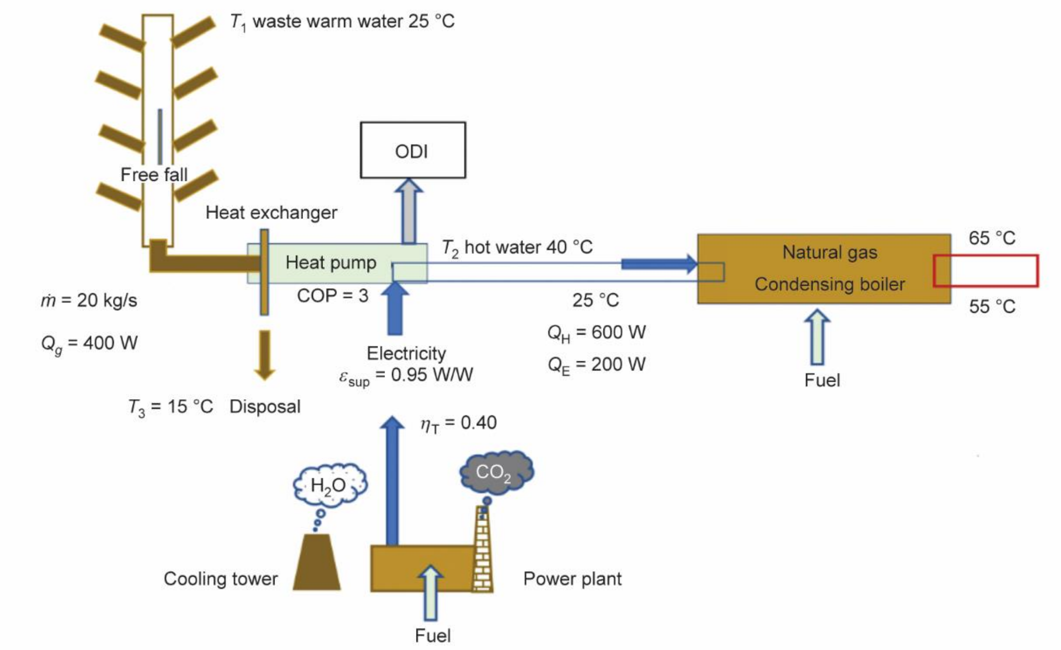


Figure 6. ***Free heat*** **from the plumbing system in a building**

Consequently, low temperature waste heat sources must be connected to low temperature heating terminal units without heat pumps whenever possible. By doing so, the electrical input exergy is eliminated while temperature peaking becomes unnecessary. Accordingly, the lowest total CO_2 emissions responsibility value belongs to *Case 4* (nZCDC) as indicated in the results, tab. 3 and fig. 8.

Table 3 gives the performance data of the seven cases. The first four columns report the nearly avoidable CO_2 emissions due to exergy mismatches, the direct CO_2 emissions, their total, and their ratio, respectively. This is followed by COP and COPEX and the results of eq. (10). Any missing values concerning the original data from the cited literature are estimated values. According to the results in tab. 3 and fig. 8, the least emissions responsibility value belongs to *Case 4* (nZCDC). Case 4 does not involve any heat pump but uses an ORC unit for additional power generation.

Referring to fig. 5, the central unit is a combined heat and power system (CHP). The waste heat of CHP and ORC are separately utilized. A deep chiller is used for ice storage as thermal energy storage (TES) to shave off the cooling demand. In the same *Case 4*, about 10% of the power and heat (at low exergy) is supplied by a PVT system on site.

The $\Delta CO_2/CO_2$ ratio is the smallest. In other cases, the ratio is greater than one, showing that this model can identify unrecognized emissions responsibilities as the primary root cause. On a building scale, *Case 7* has the highest ΔCO_2. For an additional overview, the system claims unit exergy between temperatures of T_2 and T_1, namely 45 °C and 25 °C, while the heat pump uses grid electricity with a COP of 3. An advanced heat pump with a COP of 6, which may be possible at such low temperature differences, could resolve the problem with a cascading arrangement. However, when the exergy is considered, the claim becomes inadmissible. The total CO_2 emissions are almost three times more than the First law of thermodynamics predicts. According to fig. 7 the exergy deficit between the electrical power exergy input to theheat pump and the final thermal exergy of the plumbing heat after the temperature peaking increases with peaked temperature, thus ΔCO_2 increases unless a higher COP is achieved. Figure 8 compares the total CO_2 emissions responsibility for the seven large-scale cases. The results for *Case 4* followed by *Case 6* indicate the lowest total ΔCO_2 emissions responsibility, which contradict *Case 7* and others. The heat recovery from the sewer line may be challenged by the option of heat recovery at the treatment plant for producing biogas and syngas for power generation at two points [26]. Heat may be recovered at two points. The first one is after the sludge processing step and the second one is after the production of biogas, which is used in a combined heat and power system. This step generates thermal power at about 360 K, which has a much higher unit exergy than the sewer line. Power is also generated such that these alternatives gain a higher exergy efficiency and REMM efficiency. This option needs to be analyzed in future designs.

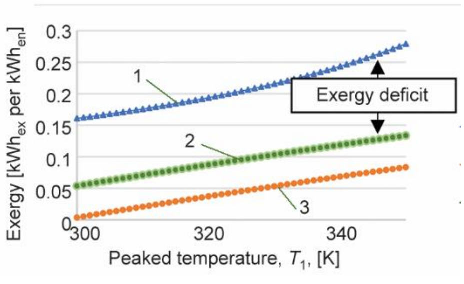


Figure 7. Exergy deficit increases with temperature peaking from 298 K (plumbing or sewer heat); *1 – input energy, 2 – peaking exergy, 3 – exergy after peaking*

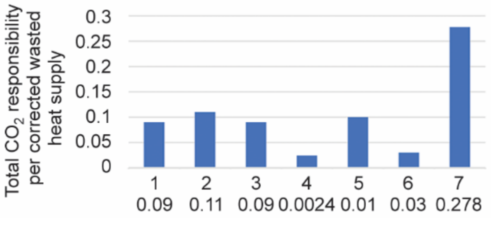


Figure 8. Comparison of total CO_2 emissions responsibility for seven large-scale cases

Conclusion

This paper has provided a complete set of optimization functions for minimizing the total CO_2 emissions responsibility regarding low temperature waste heat utilization with several unidentified design and operation constraints in the present literature. The rating model also provides clues and robust analysis formulae about correcting sampled systems in this paper for better performance and minimum CO_2 emission responsibilities. The best results for *Case 4* also hint that instead of distributing heat to outside customers, the first attempt should be to use the waste heat internally in the plant like data centers and power plants. It is also recommended to consider the cooling potential of the heat pumps installed for temperature peaking. This study further shows that simple economic analyses are far surpassed by the environmental issues of today against global warming. Examples have shown that actual minimum COP requirements for lower CO_2 emissions footprints cannot be revealed by simple economics, which gives underestimated values. There are some exergo-economic and energo-economic studies in the literature, all of which ignore the direct relationship between exergy destructions and nearly avoidable emission responsibilities. Therefore, it is concluded that all rules and directives need to be revised to accommodate the nearly avoidable emission responsibilities to derive the correct CO_2 emissions footprints toward decarbonization. Such a move will also reveal potential solutions that have been kept hidden so far. After all, heat extraction from the sewer line upstream of the water treatment may not be an exergy-rational option when heat recovery at the water treatment facility is an option.

Nomenclature

c, h	– constants in eq. (15)
c_o	– unit cost, [€ per kWh_{en}]
CO_2	– CO_2 emission, [$kgCO_2$ per kWh_{en}]
ΔCO_2	– nearly avoidable CO_2 emission responsibility, [kg CO_2 per kWh_{en}]
C_p	– specific heat at constant pressure, [kWh_{en} per kgK]
E_x	– exergy, [kW_{ex}]
$\Sigma\dot{E}_{sup}$	– power exergy supplied, [kW_{ex}]
H	– average annual operating hours, [hours per year]
I	– unit investment cost, [€ per kW_{en}]
L_{max}	– maximum one-way distance between the central plant and the district hub, [m]
$\dot{Q}_{WH}$	– thermal power of waste heat, [kW_{en}]
r	– ratio of pumping power of in-line pumps to the thermal power of waste heat
s	– constant for relationship between pumping power and volumetric flow rate
T_1	– supply temperature, [K]
T_2	– return temperature, [K]
T_E	– reject (exhaust) temperature, stack temperature, [K]
T_f	– adiabatic flame temperature of fuel, or supply temperature (from the heat pump), [K]
T_{ref}	– reference environment temperature, [K]
T_{res}	– ambient resource temperature, [K]
T_{ret}	– return temperature (to water treatment)
$\dot{V}$	– volumetric flow rate, [m^3h^{-1}]

Greek symbols

ηI	– First law efficiency
ε	– unit exergy, [kW_{ex} per kW_{en}]

Subscripts

0	– design (rated) value
B	– boiler
dem	– demand
des	– destroyed
e, E	– electricity
en, ex	– energy, exergy, respectively
eq	– heating equipment
h	– Heat (cost)
input	– input
p-m	– pump and motor (efficiency)
ref	– reference
reinj	– reinjection (geothermal well)
res	– ambient resource
ret	– return
sup	– supply

Acronyms

A-A	– air-to-air
ABS	– absorption cooling
ADS	– adsorption cooling
CBA	– cost benefit analysis
CHP	– combined heat and power
COPEX	– exergy-based coefficient of performance

D. Chiller – deep chiller
DE, 5 DE – district energy, fifth generation DE
DHW – domestic hot water
HE – heat exchanger
HP – heat pump
HR – heat recovery
LT – low temperature
MT – medium temperature
nZCDC – nearly zero-carbon data center
ODP – ozone depletion potential
OF – objective function
PB – pay-back period, year
PEF – primary energy factor
PLF – partial load factor (<1)
PVT – photovoltaic-thermal
REMM – rational exergy management model
TES – thermal energy storage
WH – waste heat

References

[1] ***, EU. 2023. Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015. https://eur-lex.europa.eu/eli/dir/2023/2413/oj, accessed August 31, 2024

[2] Navarro, J., *et al.*, Efficient District Heating and Cooling, EUR 30986 EN, Publications Office of the European Union, Luxembourg, 2022

[3] Mauro, L., *et al*., An Estimate of the Ultralow Waste Heat Available in the European Union, *Energy, 238* (2022), Part C 121967

[4] Kilkis, B., Optimum Urban Land-Use Model for Minimum CO_2 Responsibility Under Energy and Exergy-Based Constraints, *Proceedings,* SDEWES 5th SEE Conference, Vlore, Albania, 2022

[5] Kilkis, B., *et al.,* Energy Benefits of Heat Pipe Technology for Achieving 100% Renewable Heating and Cooling for Fifth-Generation, Low temperature District Heating Systems, *Energies, 14* (2021), 17, 5398

[6] Kilkis, B., An Exergy-Based Minimum Carbon Footprint Model for Optimum Equipment Oversizing and Temperature Peaking in Low temperature District Heating Systems, *Energy, 236* (2021), 121339

[7] Guo, X., Hendel, M., Urban Water Networks as An Alternative Source for District Heating and Emergency Heat-Wave Cooling, *Energy. 145* (2017), Feb, pp. 79-87

[8] David, A., *et al*., Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems, *Energies, 10* (2017), 4, 578

[9] Averfalk, H. *et al.*, Large Heat Pumps in Swedish District Heating Systems, *Renewable & Sustainable Energy Reviews, 79* (2017), Nov., pp. 1275-1284

[10] Wang, F. *et al.,* A Novel Ammonia-Based CO_2 Capture Process Hybrid Ammonia Absorption Refrigeration, *Energy Procedia, 142* (2017), Dec., pp. 3734-3740

[11] ***, E.ON. 2021. E.ON Turns Sewage into a Valuable Resource With GEA Heat Pump Technology,

[12] McCarthy, T. 2004. Waste Incineration and The Community-The Amsterdam Experience, in: *Waste Management World,* ISWA, September-October Issue, <https://consult.environment-agency.gov.uk/psc/hu9-5pb-hull-bulk-handling-limited/supporting_documents/NDM%20Response%20%20IBAA%20source%20%20Amsterdam%20EfW%20%20McCarthy_WTE_experience.pdf> Accessed August 30, 2024

[13] Wahlroos, M., *et al*., Utilizing Data Center Waste Heat In District Heating- Impacts On Energy Efficiency And Prospects For Low temperature District Heating Networks, *Energy, 140* (2017), 1, pp. 1228-1238

[14] Kilkis, B., Rational Utilization of Thermal Exergy of Cogeneration in Data Centers, *Proceedings,* 3rd LA SDEWES Conference, Paper no: LA. SDEWES2022.0003, Sao Paulo, Brasil, 2022

[15] ***, IEA, HPT. Heat Pumps in Combination with District Heating Increases Energy Efficiency at Hammarbyverket, Annex 47: Heat Pumps in District Heating and Cooling Systems, 2018

[16] Araz, M., *et al*., Exergo-Economic And Exergo-Environmental Assessment of A PV/T Assisted Wastewater Source Heat Pump System for a Sustainable Future, *Int. J. Exergy, 35* (2021), 4, pp. 503-526

[17] Kim, M.-H., *et al.,* Ground Source and Sewage Water Source Heat Pump Systems for Block Heating and Cooling Network, *Energies, 14* (2021), 5640

[18] Kilkis, B., Development of an Exergy-Rational Method and Optimum Control Algorithm for the Best Utilization of the Flue Gas Heat in Coal-Fired Power Plant Stacks, *Energies, 12* (2019), 760

[19] ***, Eurostat. 2023. Electricity Price Statistics

[20] Kilkis, B., An Exergy-Rational District Energy Model for 100% Renewable Cities with Distance Limitations, *Thermal Science, 24* (2020), 6A, pp. 3685-3705

[21] Reyes, D. G., Modelling Heat Recovery from Urban Wastewater Systems-Case Study from Malmö, Master Thesis Number: 2019-2, Lund University, Lund, Sweden, 2019

[22] ***, Huber, Thermal Heat From Sewers: Bavarian Energy Award 2012 In The Category Energy Concepts And Initiatives Goes To HUBER SE!
[23] ***, Huber, World's Largest Project For Energy Recovery From Wastewater
[24] Kilkis, B., Kilkis, Ş., Rational Exergy Management Model for Effective Utilization of Low-Enthalpy Geothermal Energy Resources, *Hittite Journal of Science and Engineering*, *5* (2018), July, pp. 59-73
[25] Kilkis, B., Exergy-Optimum Coupling of Heat Recovery Ventilation Units with Heat Pumps in Sustainable Buildings, *Journal of Sustainable Development of Energy, Water and Environment Systems, 8* (2020), 4, pp. 815-845
[26] Enebe, N. L., *et al.*, Biogas and Syngas Production from Sewage Sludge: A Sustainable Source of Energy Generation, *Methane, 2* (2023), 2, pp. 192-217

Paper submitted: March 22, 2024
Paper revised: September 1, 2024
Paper accepted: September 16, 2024