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Application of CCHPs in a Centralized Domestic Heating, Cooling and Power Network – Thermodynamic and Economic Implications

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23 1. Introduction

24 Energy plays a key role in connection with the most important concerns of today and tomorrow like
25 food security, sustainable development, climate change, health and environment protection [1].
26 Moving from traditional to smart energy systems (SESs) necessitates designing, analyzing,
27 developing and utilizing transitional solutions to meet the required energy of human in different forms
28 with enhanced performance for better sustainability [2]. In the meantime, secure supply of the
29 dwellings' energy demand is a key element of SESs [3] where there must be a strong relation between
30 district heating/cooling systems (DH/DC) and other energy sectors, especially electricity [4]. 40% of
31 the overall energy usage and 36% of the emitted CO₂ in Europe are referred to buildings [5]. DH and
32 DC systems are introduced as promising solutions to reduce energy consumption and emissions [6].
33 Different categories and the history of the technology development of these systems are described in
34 detail in [7]. DH has a deeper history than DC, being introduced in the USA around 140 years back
35 when steam was the main heat carrier through the pipes. Statistical surveys on the domestic heating
36 and cooling systems show that, in Europe, around 6000 domestic heating networks are in operation
37 delivering 11-12% of the total heat demand, while only 115 DC networks exist delivering 2% of the
38 total cooling demand [5]. DC networks, especially those operated by renewables and waste heat
39 resources, are highly recommended in terms of economy compared to the traditional cooling methods
40 [8]. A wide variety of research works have been reported during the last years focusing on the
41 feasibility of DH and DC networks. The following literature survey addresses some of the most recent
42 publications in this area.

43 Todorov et al. [9] analyzed the integration of an aquifer thermal energy storage and ground-water
44 heat pumps in DH and DC networks in terms of efficiency, techno-economic feasibility and impact
45 on the surrounding groundwater resources. It was shown that combining DH and DC systems with
46 seasonally reversible aquifer thermal energy storage has low impact on the aquifer area and is
47 economically feasible. An index system was determined and visualized via a Geographic Information
48 System (GIS) by Chen et al. [10] for ascertaining both temporal and spatial characteristics of district
49 power loads caused by heating/cooling systems. It was also shown that operation modes and
50 construction type could have great effects on the level and volatility of the district electric load caused
51 by heating. Saberi et al. [11] investigated an improved system in a micro energy grid consisting of an
52 energy hub system as a CCHP-based microgrid running with renewables like photovoltaic and wind.
53 The main aim was to propose a multi-objective model that reduces carbon emission and operation
54 cost in the presence of real-time demand response program. Oró et al. [12] considered waste heat

55 harvesting from urban air cooled data centers to increase energy efficiency of DH networks. It was
56 concluded that some cooling configurations, e.g. rear door cooling systems, are viable economically
57 using waste heat recovery. Peltokorpi et al. [13] focused on defining the design frameworks of an
58 organizational system for applying real-life applicable demand-side management innovations in DH
59 and DC networks. The study revealed that in the organizational design it is needed to make a balance
60 between the assignment of leadership and collaborative governance. Utilizing low-exergy sources for
61 DH and DC networks for establishing sustainable dwellings was reviewed by Hepbasly [14]. Low-
62 exergy systems are those heating or cooling systems that use low-valued energy flows delivered by
63 sustainable energy sources, e.g. waste heat. He introduced different low-exergy heating and cooling
64 systems and used low-exergy relations to estimate buildings' energy and exergy demands. It was
65 observed that the exergy efficiency of utilizing low-exergy sources for DH and DC networks ranges
66 from 0.4% to 25.3%, while it changes between 0.11% and 11.5% for greenhouses usage. Dorotić et
67 al. [15] considered an energy system involving heating, cooling and power sections with the concept
68 of future DH systems. Optimization of DH and DC networks with a multi-objective method and
69 hourly timespan was carried out there. The objective functions of the optimization process were the
70 environmental impacts (CO₂ emission) and the total system cost. The fact that large capital investment
71 cost may limit the implementation of DH and DC networks was claimed by Sommer et al. [16]. Their
72 idea for addressing this problem was to reduce the piping cost via system pressure reduction based
73 on changing the connection of the expansion vessel. Development of a software tool to analyze the
74 feasibility of the 5th generation DH and DC networks in both new and existing districts was published
75 by Rhein et al. [17]. They considered all potential network designs for supplying their demands
76 through the 5th generation DH and DC systems with renewables and waste energy flows as their main
77 energy sources. The obtained results quantified the performance of the 5th generation DH and DC
78 network based on numerous output metrics, including primary energy utilization, CO₂ emissions and
79 network operation cost. Practical and economic benchmarking of sustainable cooling and heating
80 supply options in southern European municipalities was done by Popovski et al. [18]. They concluded
81 that the most competitive solution from a socio-economic point of view is to utilize the excess heat
82 flows of industries. Thermodynamic, economic and environmental assessments of using waste
83 gasification in a polygeneration system were reported by Kabalina et al. [19]. The aim was to supply
84 domestic heating and cooling. It was shown that with a decrease in heating, cooling and electricity
85 loads, the system could supply the demand using refuse-derived fuel or municipal solid waste as the
86 main fuel. Carotenuto et al. [20] investigated low-temperature domestic heating and cooling systems

87 driven by renewable energy sources. The combination of biomass, solar, and geothermal energy
88 sources was considered for Monterusciello, a special location in Italy, as the case study. Although the
89 primary energy ratio of 75% was obtained for the examined system, a long payback period (more
90 than 20 years) showed that the plan was not economically feasible.

91 On the other hand, ORC is a mature technology and can be employed as a power generating system
92 for a wide range of source temperatures [21]. In a recent research, Altun and Kilic [22] presented a
93 thermodynamic evaluation of an operating geothermal driven 3 MWe ORC power plant. The
94 thermodynamic assessment of the system was conducted to evaluate the energy and exergy
95 efficiencies of each component, and the whole plant. Results revealed that the net power output might
96 drop by 36% from winter to summer. In addition, from nighttime and daytime, the net power
97 production may decrease by 5%.

98 In this study, two small-scale CCHPs fueled by geothermal and waste heat are considered in the
99 present study as distributed energy systems. Both CCHPs are also equipped with ORC, single effect
100 LiBr-H₂O absorption chiller and auxiliary heat exchangers to supply electricity, cooling (via chilled
101 water) and heating (both space heating –SPH, and 80 °C for domestic hot water-DHW), respectively.
102 A small residential area in Gaziantep, Turkey was considered as the case study. Since it was almost
103 impossible to have access to high-resolution energy demand profile of the residents at the examined
104 location, it is decided to calculate these profiles. Thermodynamic principles are applied at both
105 component level and system level. In addition, for more reliable results, the economic benefits of
106 using these local energy systems instead of the existing grids are taken into account in terms of
107 household' payment. As the presented literature showed, the sustainable implementation of both
108 supply- and demand-side management for DH and DC networks is often limited because of the
109 existing complexity and the requirements to involve stakeholders. To the best of authors' knowledge,
110 there is no study considering geothermal and industrial waste heat as the local available energy
111 sources to provide energy demand (both thermal and electrical) of a specific neighborhood.

112 **2. Network description**

113 Fig. 1 indicates the connection of the residential area to the case study DH and DC network, in which
114 energy demands are supplied via CCHPs. Considered topology is in such a way that all buildings
115 have a separate access to the electricity, heating and cooling lines. The considered DH and DC
116 network includes two small-scale CCHP units running via geothermal and waste heat sources and a
117 dwelling network. Figs. 2 and 3 illustrate the geothermal and waste heat driven CCHPs, respectively.

118 A base-load condition is considered for each CCHP. It is also assumed that, under the base condition,
 119 half of the geothermal fluid (state 1 in Fig. 2 for the geothermal-driven CCHP) and half of the ORC
 120 exiting heat source (state 2 in Fig. 3 for the waste heat-driven CCHP) are fed to run the chiller. For
 121 the case of heating delivery, it should be mentioned that the presented system is a combination of the
 122 3rd and the 4th generations of DH systems with the regular operating temperature of around 40 °C for
 123 SPH and 80 °C for DHW. It is supposed that the CCHPs will meet the heating, cooling and electricity
 124 demand of the considered residential area. Here, it is supposed that the considered neighborhood has
 125 an access to the main networks of power, cooling and heating. Therefore, if the peak energy demand
 126 exceeds the supplied value by the utilized CCHPs, then the extra energy will be compensated by the
 127 mains and vice versa. To obtain the energy demand profiles, required databases should be available.
 128 Since there is no access to these databases, the alternative solution is to estimate energy demand
 129 profiles. Therefore, some information according to the energy and comfort principles of the
 130 considered network, i.e. solar energy availability, buildings characteristics, information associated
 131 with the ambient condition, etc. are required. In the considered case study, it is supposed that the
 132 neighborhood contains 100 single-family separate houses, which will be covered by DH and DC
 133 systems. The main characteristics considered for the buildings as well as the environmental conditions
 134 are outlined in Table 1.

Table 1

Characteristics of the buildings as well as the environmental conditions [3,23]

Parameter	Value
Number of buildings with 1 / 2 / 3 / 4 / \geq 5 residents	20 / 20 / 20 / 20 / 20
Living area of each building	150 (m ²)
Buildings shape	rectangular field of 15m \times 10m
Comfort indoor temperature for SPH	20 - 24 °C
Comfort indoor temperature for space cooling (SPC)	24 - 27 °C
Windows area per building shell surface	20%
Walls surface per building shell surface	30%
Roofs area per building shell surface	25%
Floor area (including cold bridges) per building shell surface	25%
Average overall heat loss factor	0.93 W/m ² .K

Needed air exchange rate for ventilation

0.65 m³/h per m³

Effects of inhabitants' metabolism on the average daily internal heat gain of the building

2.3 °C

135

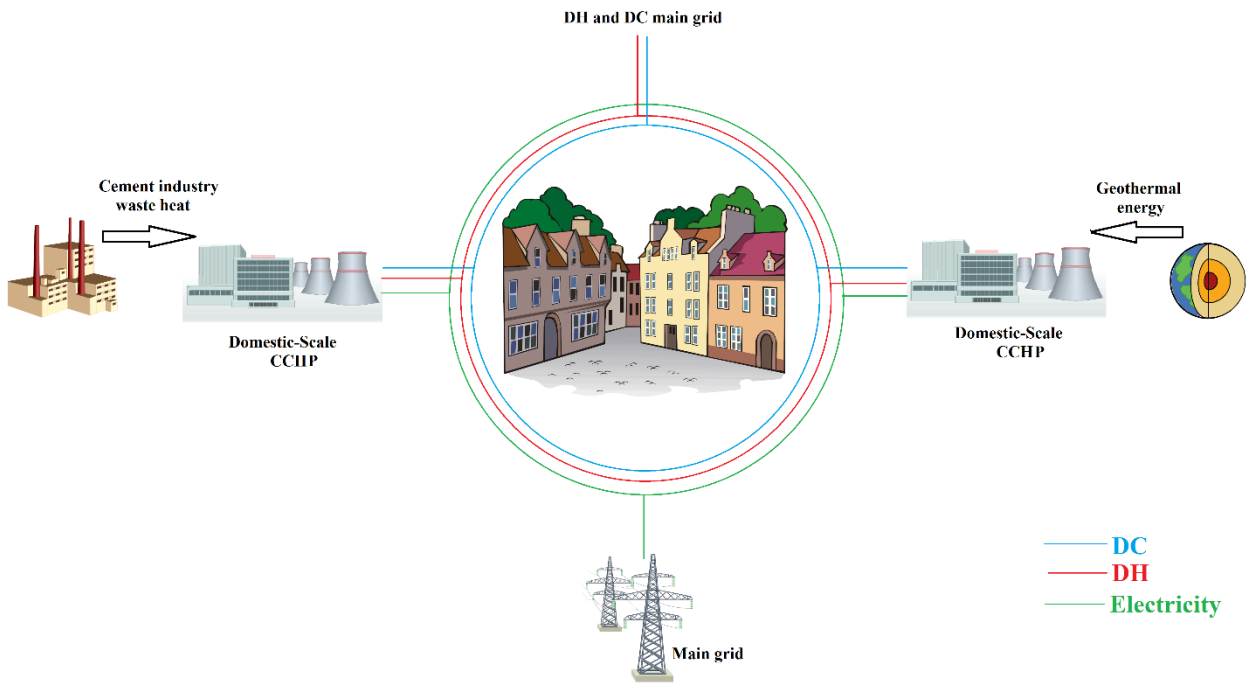


Fig. 1 Main layout proposed in the present study

136

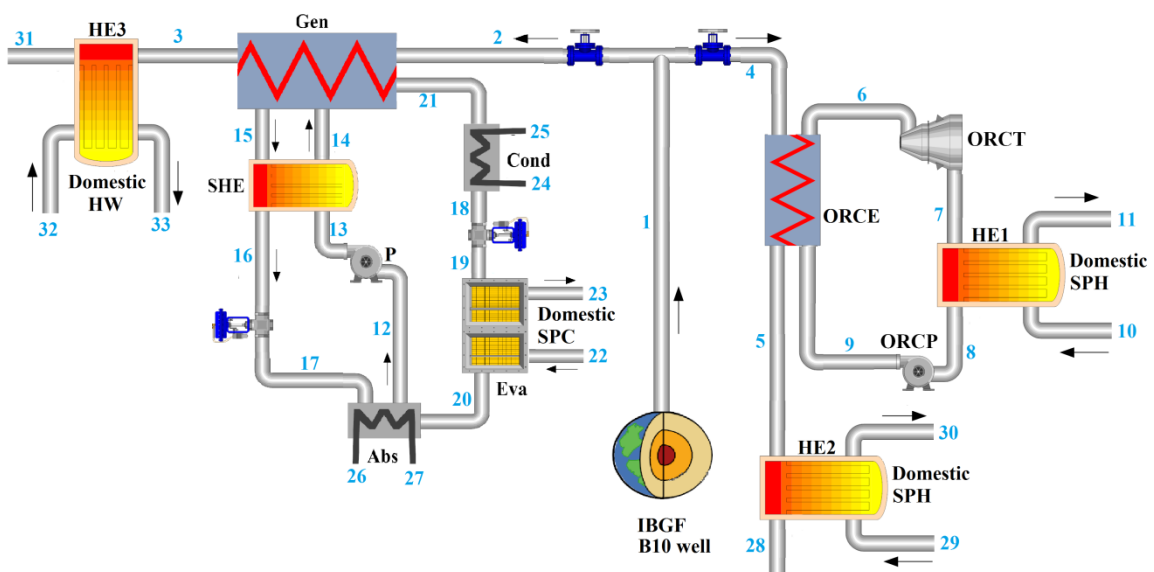


Fig. 2 Schematic diagram of the geothermal-driven CCHP

137

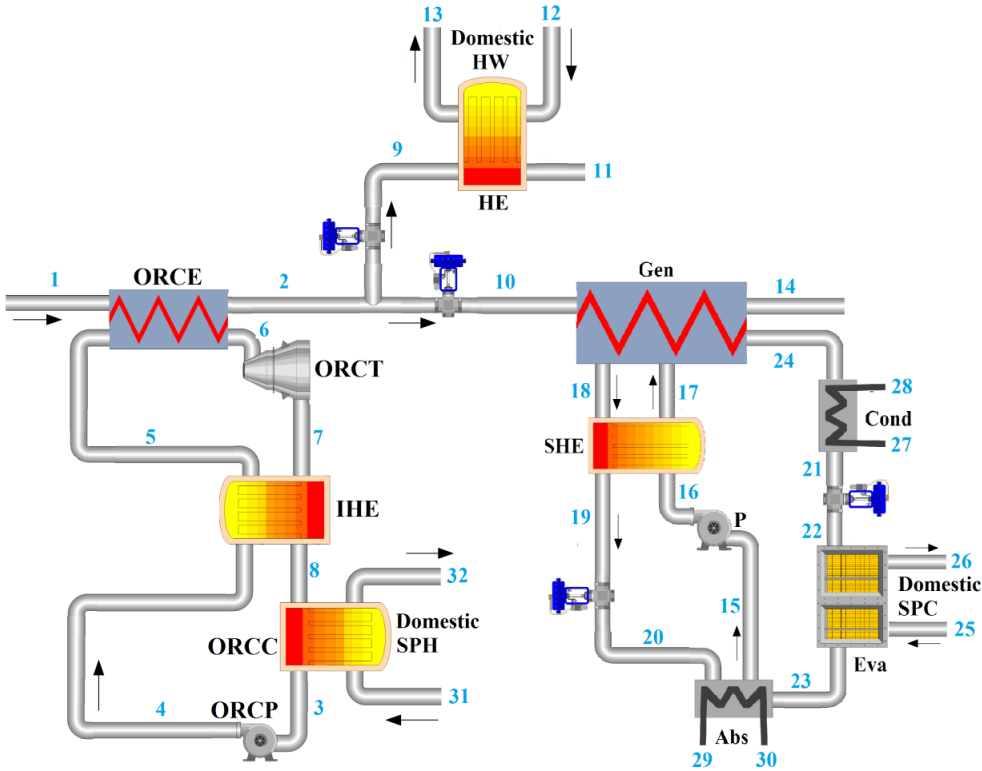


Fig. 3 Schematic diagram of the waste heat-driven CCHP

138

139 It should be noticed that the connection of the DH system to the building is based on the regular
 140 Instantaneous Heat Exchange Unit [23]. Fig. 4 illustrates the configuration of this substation. As the
 141 figure shows, there are two heat exchangers here, one is for hot water preparation and the other one
 142 is for space heating.

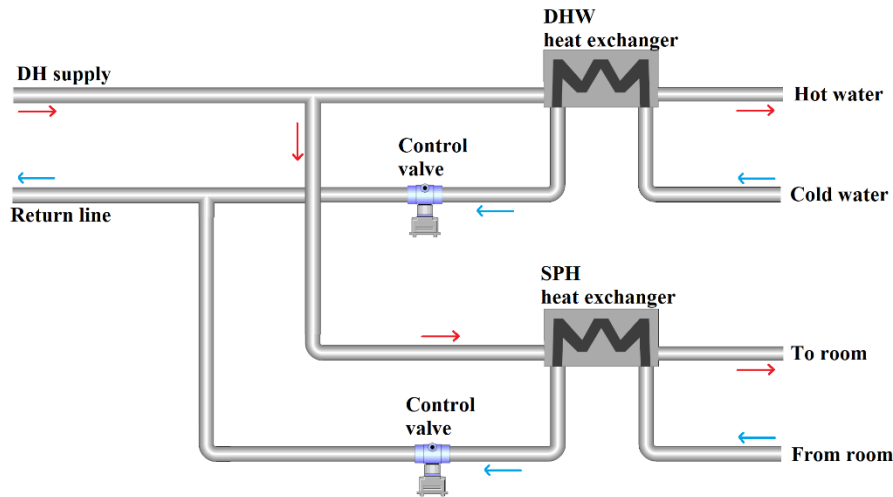


Fig. 4 An instantaneous heat exchange unit.

143

144 3. DH and DC systems mathematical modeling and main assumptions

145 Thermodynamic analysis of the presented DH and DC systems is divided into different subsections
 146 to give the possibility of describing each section in details. Different subsections are presented
 147 hereunder.

148 3.1. Geothermal driven small-scale CCHP

149 As presented in Fig. 2, geothermal driven CCHP is the combination of small-scale ORC, single effect
 150 absorption chiller and different heat exchangers to deliver DH. It should also be highlighted that the
 151 heat rejection within the ORC condenser is harvested to be used as SPH. Part of the geothermal source
 152 runs the ORC, while the rest is used to derive the chiller and after that provide DHW. Designing in
 153 this manner provides the flexibility of changing cooling supply and will adopt the system for different
 154 seasons. Pressurized water is used as the heat transfer fluid for delivering DHW, SPH and SPC. Main
 155 input data used in the geothermal-driven CCHP is listed in Table 2. The use of R123 is expected to
 156 be banned by the Montreal protocol. However, this usage-ban has not been applied yet and for the
 157 time being, not only that is used in a wide spectrum of research and practical works, but also it is
 158 well-proved that this refrigerant performs better than other commercially available refrigerants
 159 [21,24–27].

Table 2

List of input data utilized in the geothermal-driven CCHP modeling

Input data	Value	Unit
Geothermal volumetric flow rate [28]	70-80	m ³ /h

Geothermal source temperature [28]	95-105	°C
Turbine and Pumps isentropic efficiency [29]	90 and 75	%
Temperature of coolant water [30]	20	°C
Temperature of DHW supply / return [31]	80 / 40	°C
Temperature of SPH supply / return [32]	35 / 20	°C
Temperature of SPC supply / return [33,34]	5 / 12	°C
Generator temperature	348 - 358	K
Heat exchangers effectiveness	85	%
Minimum allowed pinch temperature difference in ORCE	5	K
Average ambient temperature	298	K
Minimum allowed pinch temperature difference in Eva and Cond	5	K
ORC working fluid [29]	R123	-
ORCE pressure	250 - 400	kPa

160 In order to assess the geothermal-driven CCHP, thermodynamically, each component is considered
161 as a control volume. Then, energy conservation and mass balance equation are applied as follows
162 [35]:

$$\sum \dot{m}_i h_i + \dot{Q} = \sum \dot{m}_o h_o + \dot{W} \quad (1)$$

$$\sum \dot{m}_i = \sum \dot{m}_o \quad (2)$$

163 Table 3 outlines applied energy conservation equations for the proposed geothermal-driven CCHP
164 components.

Table 3

Energy equations adopted for each component employed in the geothermal-driven CCHP [36]

Component	Equation
ORCT	$\dot{W}_{ORCT} = \dot{m}_6 (h_6 - h_7), \eta_{is,ORCT} = \frac{\dot{W}_{ORCT}}{\dot{W}_{is,ORCT}} \quad (3)$
ORCE	$\dot{m}_4 (h_4 - h_5) = \dot{m}_9 (h_6 - h_9) \quad (4)$
ORCP	$\dot{W}_{ORCP} = \dot{m}_8 (h_9 - h_8), \eta_{is,ORCP} = \frac{\dot{W}_{is,ORCP}}{\dot{W}_{ORCP}} \quad (5)$
HE1	$\dot{m}_{10} (h_{11} - h_{10}) = \dot{m}_7 (h_7 - h_8), eff_{HE1} = \frac{Max\{(T_7 - T_8), (T_{11} - T_{10})\}}{T_7 - T_{10}} \quad (6)$
HE2	$\dot{m}_5 (h_5 - h_{28}) = \dot{m}_{29} (h_{30} - h_{29}), eff_{HE2} = \frac{Max\{(T_5 - T_{28}), (T_{30} - T_{29})\}}{T_5 - T_{29}} \quad (7)$

$$\text{HE3} \quad \dot{m}_3(h_3 - h_{31}) = \dot{m}_{32}(h_{33} - h_{32}), \quad \text{eff}_{\text{HE3}} = \frac{\text{Max}\{(T_3 - T_{31}), (T_{33} - T_{32})\}}{T_3 - T_{32}} \quad (8)$$

$$\text{SHE} \quad \dot{m}_{15}(h_{15} - h_{16}) = \dot{m}_{13}(h_{14} - h_{13}),$$

$$\text{eff}_{\text{SHE}} = \frac{\text{Max}\{(T_{15} - T_{16}), (T_{14} - T_{13})\}}{T_{15} - T_{13}} \quad (9)$$

$$\text{Gen} \quad \dot{m}_2 h_2 + \dot{m}_{14} h_{14} = \dot{m}_3 h_3 + \dot{m}_{15} h_{15} + \dot{m}_{21} h_{21} \quad (10)$$

$$\text{Cond} \quad \dot{m}_{21}(h_{21} - h_{18}) = \dot{m}_{24}(h_{25} - h_{24}) \quad (11)$$

$$\text{Eva} \quad \dot{m}_{21}(h_{21} - h_{18}) = \dot{m}_{24}(h_{25} - h_{24}) \quad (12)$$

$$\text{Abs} \quad \dot{m}_{20}(h_{20} - h_{19}) = \dot{m}_{22}(h_{22} - h_{23}) \quad (13)$$

$$\text{P} \quad \dot{W}_P = \dot{m}_{12}(h_{13} - h_{12}), \quad \eta_{is,P} = \frac{\dot{W}_{is,P}}{\dot{W}_P} \quad (14)$$

3.2. Waste heat-driven small-scale CCHP

165

166 Waste heat-driven CCHP is shown in Fig. 3 and as can be seen it involves a recuperative ORC, a
 167 single effect absorption chiller and a heat exchanger to supply DHW. In the chiller unit, LiBr (lithium
 168 bromide) and water are considered as the absorbent and refrigerant, respectively. Waste heat source
 169 of the cement plant with specified characteristics was selected as the source. Table 4 lists the source
 170 condition. Since the considered waste heat source has a relatively higher temperature, MM as a known
 171 siloxane is considered as the working fluid and as a result recuperative ORC is employed instead of
 172 simple ORC [29]. Assumptions made for the CCHP modeling are the same as those presented in
 173 Table 2. In order to model the presented CCHP in Fig. 3 thermodynamically, all the employed
 174 components are supposed to be operated as a separate control volume and then energy conservation
 175 equations are adopted. Table 5 outlines these equations.

Table 4

Waste heat source properties [37]

Parameter	Temperature (°C)	Mass flow rate (kg/s)	Compositions
Value	250	18.43	0.689 N ₂ , 0.225 CO ₂ , 0.058 H ₂ O, 0.011 O ₂ , 0.01 Ar, 0.007 SO ₂

176

177

Table 5

List of energy equations adopted for the components employed in the waste heat-driven CCHP [38]

Component	Equation
ORCE	$\dot{m}_1(h_1 - h_2) = \dot{m}_5(h_6 - h_5)$ (15)

$$\text{ORCT} \quad \dot{W}_{ORCT} = \dot{m}_6(h_6 - h_7), \eta_{is,ORCT} = \frac{\dot{W}_{ORCT}}{\dot{W}_{is,ORCT}} \quad (16)$$

$$\text{IHE} \quad \dot{m}_7(h_7 - h_8) = \dot{m}_4(h_5 - h_4) \quad (17)$$

$$\text{ORCC} \quad \dot{m}_8(h_8 - h_3) = \dot{m}_{31}(h_{32} - h_{31}) \quad (18)$$

$$\text{ORCP} \quad \dot{W}_{ORCP} = \dot{m}_3(h_4 - h_3), \eta_{is,ORCP} = \frac{\dot{W}_{is,ORCP}}{\dot{W}_{ORCP}} \quad (19)$$

$$\text{HE} \quad \dot{m}_9(h_9 - h_{11}) = \dot{m}_{12}(h_{13} - h_{12}), \text{eff}_{HE} = \frac{\text{Max}\{(T_{13} - T_{12}), (T_9 - T_{11})\}}{T_9 - T_{12}} \quad (20)$$

$$\text{Gen} \quad \dot{m}_{10}h_{10} + \dot{m}_{17}h_{17} = \dot{m}_{14}h_{14} + \dot{m}_{18}h_{18} + \dot{m}_{24}h_{24} \quad (21)$$

$$\text{SHE} \quad \dot{m}_{16}(h_{17} - h_{16}) = \dot{m}_{18}(h_{18} - h_{16}),$$

$$\text{eff}_{SHE} = \frac{\text{Max}\{(T_{17} - T_{16}), (T_{18} - T_{19})\}}{T_{18} - T_{16}} \quad (22)$$

$$\text{Cond} \quad \dot{m}_{24}(h_{24} - h_{21}) = \dot{m}_{27}(h_{28} - h_{27}) \quad (23)$$

$$\text{Eva} \quad \dot{m}_{22}(h_{23} - h_{22}) = \dot{m}_{25}(h_{25} - h_{26}) \quad (24)$$

$$\text{Abs} \quad \dot{m}_{20}h_{20} + \dot{m}_{23}h_{23} + \dot{m}_{29}h_{29} = \dot{m}_{30}h_{30} + \dot{m}_{15}h_{15} \quad (25)$$

$$\text{P} \quad \dot{W}_P = \dot{m}_{15}(h_{16} - h_{15}), \eta_{is,P} = \frac{\dot{W}_{is,P}}{\dot{W}_P} \quad (26)$$

178

179 3.3.Residential area energy demand calculation

180 Thermodynamic model of the energy network (including DH and DC and electricity networks) is
 181 presented in this section. For doing the analysis, one needs to have a database of the loads in each
 182 sector. As there is no access to real users' energy consumption data due to privacy reasons, the energy
 183 consumption profiles (heat, cold and electricity) are estimated according to the number of residents,
 184 buildings' characteristics and standard patterns.

185 For the DH network, the total demand is the summation of DHW and SPH demands. In order to make
 186 a DHW consumption pattern, the randomly obtained profile of a normal single-family house without
 187 bathtub, given in Table 6, is used [3]. In order for making a reasonable simultaneity factor of the
 188 draw-off for the whole network, the given draw-off profile is randomized. With the aim of making
 189 the load profile compatible with a real case, the randomization is carried out in such a way that the

190 distribution of the draw-offs for the periods “6:00-11:59 o'clock” and “18:00-23:59 o'clock” are at
 191 least three times larger than other periods of the day.

Table 6

Draw-off profile of a normal single-family dwelling/apartment without bathtub [3]

Time	Volume (lit)	Temperature (°C)	Duration (min)
10:55	43	40	5
10:55	15	45	2.5
11:05	0	0	0
11:15	42	40	5
11:15	15	45	2.5
11:25	0	0	0
11:35	42	40	5
11:45	0	0	0
11:55	42	40	5
/// ///	/// ///	/// ///	/// ///
22:55	42	40	5
22:55	15	45	2.5
23:05	0	0	0
23:15	42	40	5
23:15	15	45	2.5
23:25	0	0	0
23:35	42	40	5
23:45	0	0	0
23:55	42	40	5

192 On the other hand, several factors, such as the ambient and comfort temperatures and the building
 193 stuck characteristics could affect the energy demand for SPH. Considering all heat transfer terms
 194 between the building and the environment, energy demand in each building for SPH can be written
 195 as [39,40]:

$$\dot{Q}_{sh,b} = \rho_a V_{a,b} (T_{in}^{\lambda+1} - T_{in}^{\lambda}) + \rho_a \dot{V}_{ven} (T_{in} - T_{out}) + UA_{l,b} (T_{in} - T_{out}) + \rho_{bm} V_{bm} (T_{bm}^{\lambda+1} - T_{bm}^{\lambda}) - \sum_{n=1}^M A_n I_T (\tau\alpha)_{avg} \quad (27)$$

196 Where, T , V , ρ , \dot{V}_{ven} , $UA_{l,b}$, A_n , I_T , $(\tau\alpha)_{avg}$ and M are temperature, volume, density, Entering air for
 197 ventilation, building heat loss coefficient, area of each window, solar irradiation through windows,
 198 windows average transmission-absorption coefficient and the inside components of the structure
 199 visible to the sun rays and total number of spaces letting sun rays coming into the structure,
 200 respectively. The superscript λ is the time step counter, while the subscripts *in/out*, *b*, *bm* and *a* refer
 201 to the indoor / ambient condition, the building, the building stuck material and the air within the
 202 building, respectively. The first term in the right side of the equation is the required heat to increase
 203 the indoor temperature. The second and the third terms are the rates of heat losses due to the air
 204 ventilation and to the environment, respectively. Since the rate of energy storage in the building stuck
 205 is supposed to be zero under the steady state conditions, the fourth term is neglected. The last term
 206 indicates the rate of heat absorbed from the sun due to the solar irradiation.

207 The space cooling (SPC) demand can be obtained in the same way as that used for SPH demand.

208 The electricity grid considered for the network is a typical grid allowing for bidirectional power flows
 209 between the local facilities/buildings and the distribution network. It is assumed that power
 210 lines/cables are well sized; thus, they could carry the needed power without reaching thermal
 211 constraints. To obtain the electricity demand of the network, the in-building appliances and number
 212 of the residents within the houses should be specified. The nominal electricity consumptions of the
 213 electrical components of the buildings are listed as in Table 7 [41]. To make the results more
 214 generalized, different numbers of residents are considered (see Table 1).

215 Sepehr et al. [41] has described in detail the methodology of calculating the electrical load of
 216 buildings. Based on this methodology, using the equipment listed in Table 7 and the number of
 217 residents in each building outlined in Table 1, the electricity demand of the network can be estimated
 218 over a geographical area. In order to randomize the behavior of the consumers, a bottom-up approach
 219 is developed with a given resolution (e.g. one minute).

Table 7

The list of equipment in each house with the nominal power

Application	Nominal power (kW)	Application	Nominal power (kW)
-------------	--------------------	-------------	--------------------

Refrigerator	0.11	TV 1	0.105
Freezer	0.11	TV 2	0.083
Microwave oven	1.5	Computer / laptop	0.11
Coffee maker	1	Other occasional load	1
Range oven	1.05	Clothes washer	1.2
Hair dryer	1.6	Lighting	0.12

220 In the end, the rate of heat losses/gains, which is vital in thermodynamic modeling of DH/DC systems,
 221 should be calculated. The following correlation is used to obtain the thermal energy losses from
 222 twine-pipes of DH and DC systems [42]:

$$\dot{Q}_l = \frac{7.992}{T_R T_S^2 D_R^{0.5}} - \frac{374.1391}{T_S T_R^{1.5} D_R^2} + \frac{166.9072}{T_R D_R^{1.5}} + \frac{171.3874 T_S T_R}{D_R^2} + 0.28356 T_S^{1.5} T_R^{1.5} D_R^2 - 16.9348 \quad (28)$$

223 The details of how this correlation has been developed could be found in Ref. [42].

224 3.4.Exergy analysis and sustainability index

225 Exergy analysis is a powerful tool to find the exact value of the systems' irreversibility and losses
 226 during the thermodynamic processes [43]. As stated by Bejan et al., exergy can be defined in terms
 227 of four components: physical, kinetic, potential, and chemical exergy [44]. Kinetic and potential
 228 exergy was neglected in the present study and since variations in the compositions of flow streams
 229 did not occur, the chemical exergy was not considered [29]. For comprehensive introduction to the
 230 exergy principle, refer to the textbooks of Kotas [45], Moran et al. [46] or Szargut et al. [47].

231 In the present study, exergy rates associated with the geothermal source and waste heat source are
 232 considered as the fuel exergy for the geothermal-driven and waste heat-driven CCHPs, respectively.
 233 Accordingly, the exergy rates associated with the produced SPH, SPC, DHW and electricity are
 234 considered as the products exergy. Second law efficiency can be written as [48,49]:

$$\eta_{II} = \frac{\dot{E}_{product}}{\dot{E}_{fuel}} \quad (29)$$

235 On the other hand, exergy concept has a tight relation with the sustainable development and
 236 environmental impacts which can be described via a sustainability index [50]. Sustainable

237 development is defined in different ways, but the most frequently used definition refers to “a
 238 development which meets the needs of the present without compromising the ability of future
 239 generations to meet their own needs” [51]. Sustainability index emphasizes the fact that not only
 240 sustainable and renewable energies should be developed and utilized more and more, but also the
 241 available non-renewable energy sources like natural gas or nuclear energy should be used in the most
 242 efficient way. In fact, sustainability index states how exergy destruction reduction can lead to
 243 decreasing the environmental impact and can be defined as [52–54]:

$$SI = \frac{1}{D_p} \quad (30)$$

244 here, D_p is the destroyed exergy divided by input exergy (a depletion number) [55,56]:

$$D_p = \frac{\dot{E}_D}{\dot{E}_m} \quad (31)$$

245 4. Results and discussion

246 Thermal energy and thermomechanical exergy contents of the industrial waste heat and geothermal
 247 energy were calculated to show the energy and exergy that can be harvested for the case study energy
 248 network. Table 8 lists the calculated values. In this table, the available energy/exergy refers to the
 249 difference between the energy/exergy of the energy source at its present conditions and at ambient
 250 temperature.

Table 8

Energy and exergy of the contents of the energy resources

Energy source	Cement factory waste heat	Geothermal
Available thermal energy (kW)	4409	6546
Available thermomechanical exergy (kW)	1133	707.8

251

252 Hereunder, the results of the simulations and analysis carried out on the considered DH and DC
 253 system including both CCHPs will be presented. In this regard, the thermodynamic performance of
 254 the considered CCHPs, and their production capacity of SPH and cooling, DHW and electricity will
 255 be reported initially. As mentioned before, flexibility of supplying different values of SPC was

256 supposed in the CCHPs design due to the fact that heating and cooling demand varies during different
 257 seasons. It should be mentioned that in this section the average ambient temperature is considered to
 258 evaluate the exergy and sustainability performance of the CCHPs. Table 9 lists the systems' capacity
 259 under the base condition and the cost of products, which are obtained using exergoeconomic analysis
 260 [57]. On the other hand, for more general results, different values of cooling load are reported. It is
 261 clear that a change in the cooling capacity of the systems may alter the other products capacity. Table
 262 10 outlines the range of SPH and cooling, DHW and electricity, which would be possible to be
 263 delivered to the network. As can be seen, the proposed local energy systems are designed in such a
 264 way that higher cooling production is favorable for the geothermal-driven CCHP from the
 265 thermodynamics and sustainability points of view while reducing cooling production improves the
 266 waste heat-driven CCHPs' performance.

Table 9

Supplied SPH, SPC, DHW and electricity by each CCHP under the base condition

Parameter	Geothermal-driven CCHP	Waste heat-driven CCHP	Total	Cost (€/MWh)
SPC (kW)	529.7	295.1	824.8	5.688
SPH (kW)	3018	2119	5137	11.811
Electricity(kW)	116.3	608.3	724.6	10.109
DHW (kW)	1744	594.2	2338.2	3.381
η_{II} (%)	49.63	63.6	-	-
SI (-)	1.985	2.747	-	-

267

Table 10

Range of supplied SPH, SPC, DHW and electricity by each CCHP

Parameter	Geothermal-driven CCHP	Waste heat-driven CCHP	Total
SPC (kW)	0 - 1049	0 - 590.2	0 - 1639.2
SPH (kW)	6035 - 0	2119	8154 - 2119
Electricity (kW)	232.6 - 0	608.3	840.9 - 608.3
DHW (kW)	0 - 3454	1188 - 0	1188 - 3454

η_{II} (%)	39.78 - 59.28	67.62 - 59.57	-
SI (-)	1.661 - 2.456	3.089 - 2.473	-

268 The two effective environmental parameters with remarkable effects on the DH and DC system are
 269 the ambient temperature and solar energy availability in the case study. Fig. 5 presents information
 270 regarding these parameters over the entire year. As can be seen from this figure, the ambient
 271 temperature can be low as around -1 °C which would increase the DH demand, while can be high as
 272 35 °C during summertime clarifying the importance of the cooling network. Furthermore, sun
 273 radiation has a considerable effect on the SPC demand, especially in the summer days. As it is
 274 illustrated in detail in Fig. 6, during the sunny days solar radiation reaches to 1kW on a horizontal
 275 surface, while not much solar energy is expected during the cold days as the irradiation decreases to
 276 almost 0.37 kW. Jun 29 and Dec 24 are reported as the days with the highest and lowest solar
 277 radiation, respectively, for the case study.

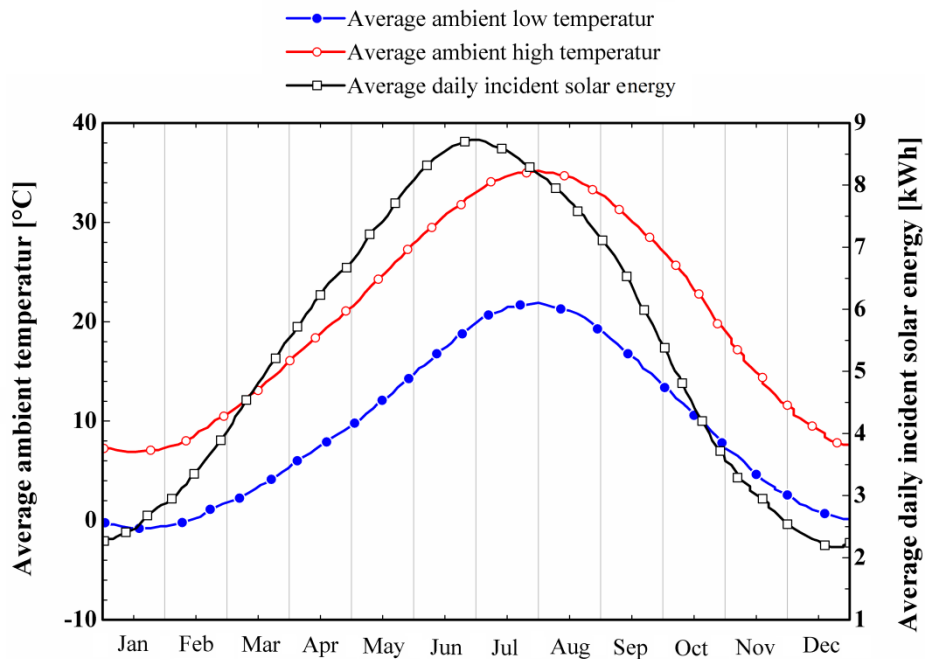


Fig. 5 Average ambient high and low temperature and average daily incident solar energy of the considered residential area in Gaziantep, Turkey over an entire year

278

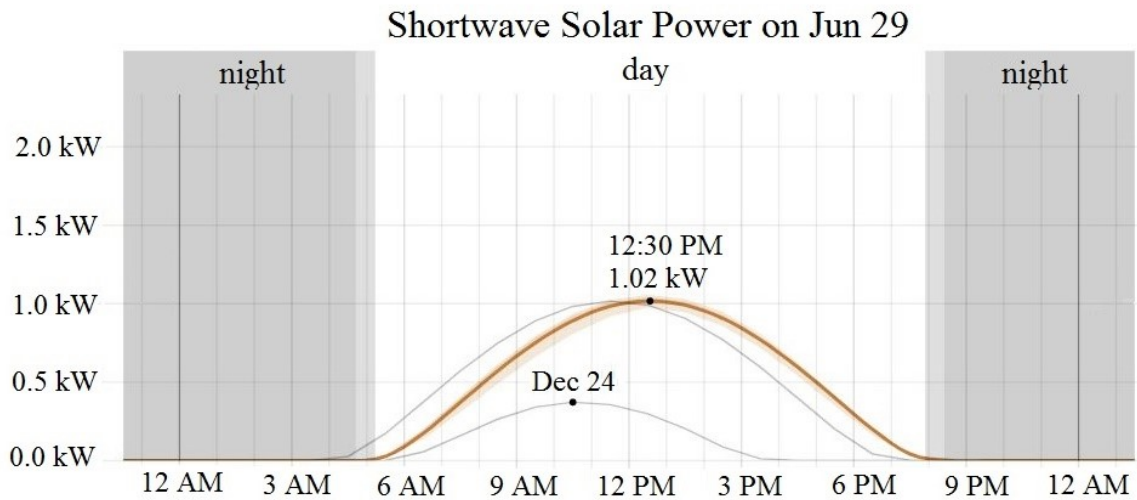


Fig. 6 Solar radiation in the considered residential area in Gaziantep, Turkey over Jun 29 and Dec 24

279 Before analyzing the consumers' consumption pattern and its interaction with the proposed CCHPs
 280 within the DH and DC network, we investigate the effects of the ambient temperature on the exergetic
 281 and sustainability performance of the CCHPs. Figs. 7 and 8 illustrate exergy efficiency and
 282 sustainability index of the geothermal- and waste heat-driven CCHPs, respectively, under the base
 283 condition. As it was expected, during summertime, exergy efficiency and sustainability index of the
 284 both systems decrease mainly due to a reduction in the exergy rate associated with the supplied DH.
 285 In fact, during the cold days, as the ambient temperature decreases, temperature difference between
 286 dead state (which is of importance from the exergy point of view) and delivered DH increases and
 287 results in DH higher exergy rates. During the entire year, exergy efficiency of the geothermal- and
 288 waste heat-driven CCHPs varies between 40.6-53.46% and 62.28-64.1%, respectively. Moreover,
 289 sustainability index of 1.586-2.148 and 2.651-2.785 are obtained for the geothermal- and waste heat-
 290 driven CCHPs, respectively.

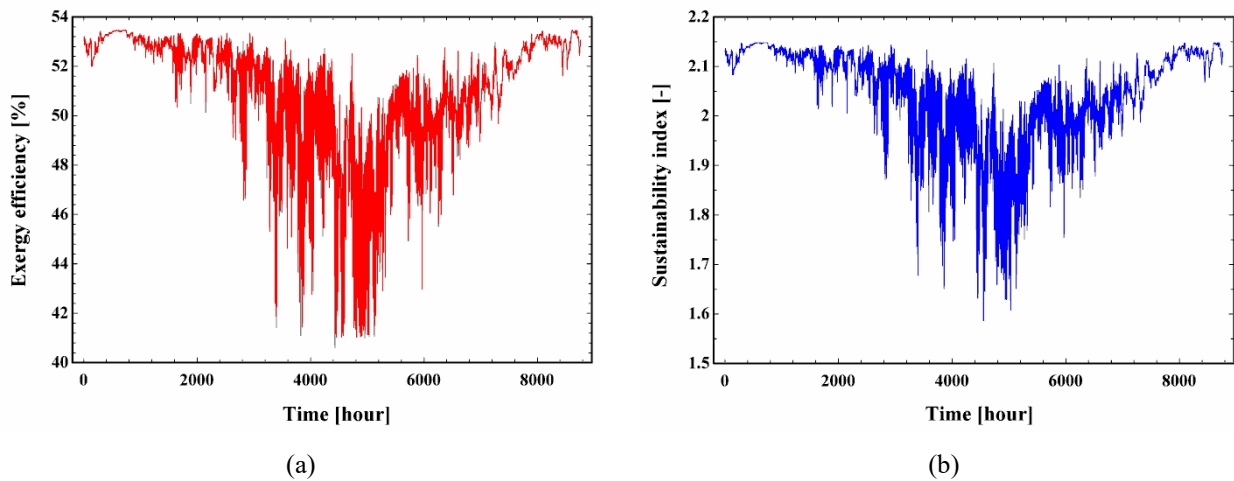


Fig. 7 Exergetic and sustainability performance of the geothermal-driven CCHP with ambient temperature over the entire year

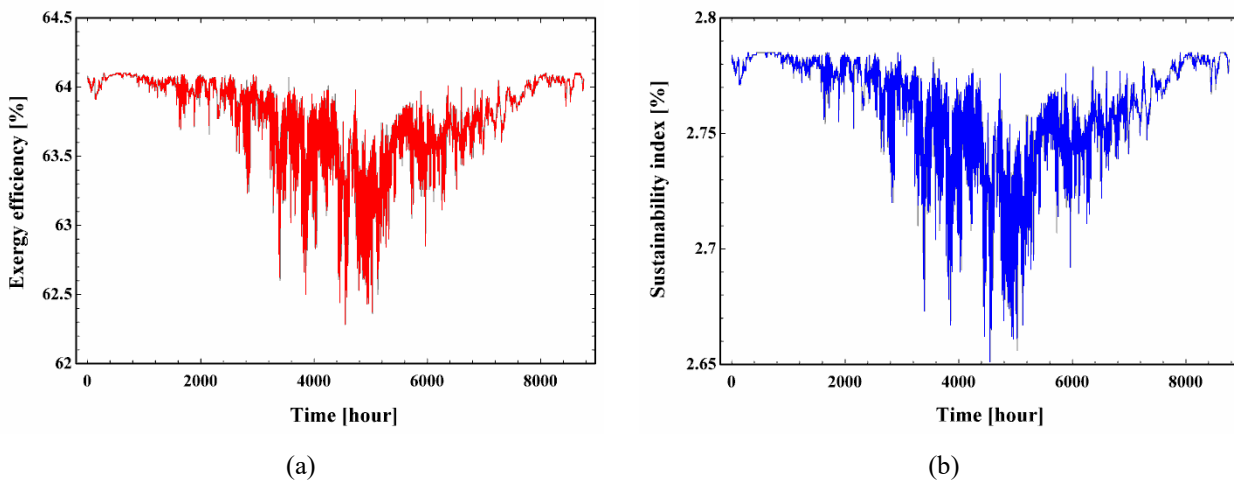


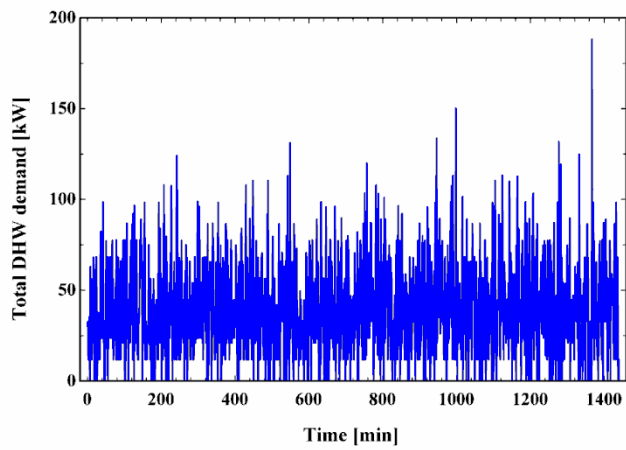
Fig. 8 Exergetic and sustainability performance of the waste heat-driven CCHP with ambient temperature over the entire year

291 Fig. 9 illustrates total energy demand by the case study and overproduced energy by the considered
 292 local CCHPs, which can be transferred to the main grid. Fig. 9(a) presents the DHW draw-off pattern
 293 of a couple of randomly selected houses in the network and the overproduced hot water over a day
 294 (Fig. 9(b)), which can be transferred to the hot water grid. It is supposed that the daily pattern is
 295 repeated over the entire year. Then calculations are reported just for one day with a time granularity
 296 of one minute. As can be seen from Fig. 9(a), DHW consumption by the case study varies between 0
 297 and 188 kW and this amount of demand can be completely fed by the proposed local energy system.
 298 In this way, an extra 2830-3018 kW hot water can be supplied to the main grid of DHW supply.

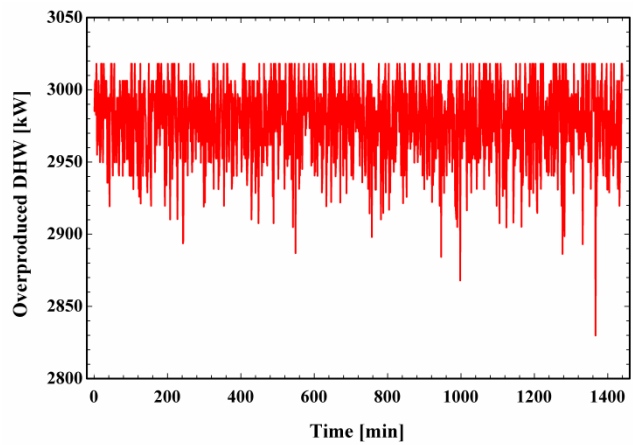
299 Fig. 9(c) indicates the electricity consumption profile by the subscribers in a typical day. Since no air
300 conditioning is needed for the considered buildings and seasonal changes do not affect electricity
301 consumption pattern considerably, then the demand profile will be repetitive during the entire year.
302 Based on Fig. 9(d), the local energy system supplies the electricity demand and feeds the main grid
303 by its surplus power most of the time. However, for the time span of 830-850 and 1330-1430 minutes
304 (i.e., the peak period) the overall electricity consumption is beyond the capacity of the local system
305 thus necessitates power import from the mains. The maximum electricity that is needed to be fed by
306 the main grid is almost 387 kW. During the off-peak period, however, the local energy system is able
307 to charge the main grid with a maximum electric power of 677.6 kW.

308 Since a range of indoor comfort temperature is considered for the winter days, there will be a lower
309 and upper boundary for the required heat. Fig. 9(e) and (f) show the SPH demand by the case study
310 and surplus heating produced by the local designed CCHPs as the SPH. Overproduced SPH can be
311 injected to the main heating grid via pressurized medium-temperature water. As can be seen from the
312 Fig. 9(e), the maximum heat demand changes between 717 and 861 kW within the first months of the
313 year for the comfort temperature of 20 and 24 °C, respectively. It is clear that the lowest value of the
314 required SPH belongs to the summer days. In this condition, designed local CCHPs not only supplies
315 the required heat, but also provides more than 5100 kW extra heating to the main grid, as Fig. 9(f)
316 represents.

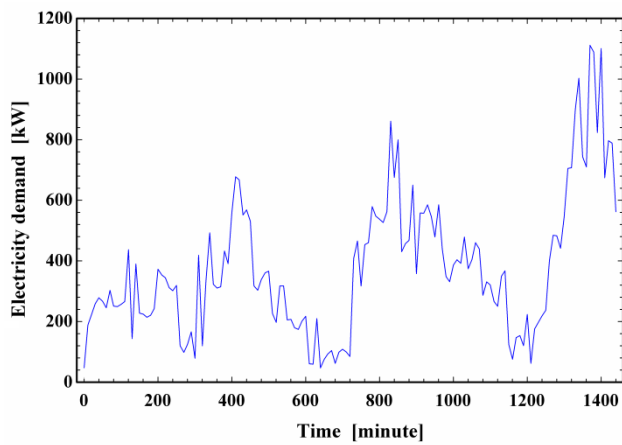
317 Similarly, required cooling for the SPC is calculated for the entire year and it has lower and upper
318 boundaries due to considering a range of comfort temperature. Fig. 9(g) indicates the obtained values
319 of the SPC demand of the examined system, while the surplus cooling produced by the CCHPs is
320 shown in Fig. 9(h). SPC demand touches the maximum value of 526.8 and 631 kW for the indoor
321 comfort temperature of 27 and 24 °C, respectively. This high value of cooling demand is mainly due
322 to the high ambient temperature and solar radiation for the summer days as illustrated in Fig. 5. Based
323 on the obtained results, proposed local CCHPs have a surplus of 193.8 – 824.8 kW cooling energy,
324 which can be delivered to the main grid.



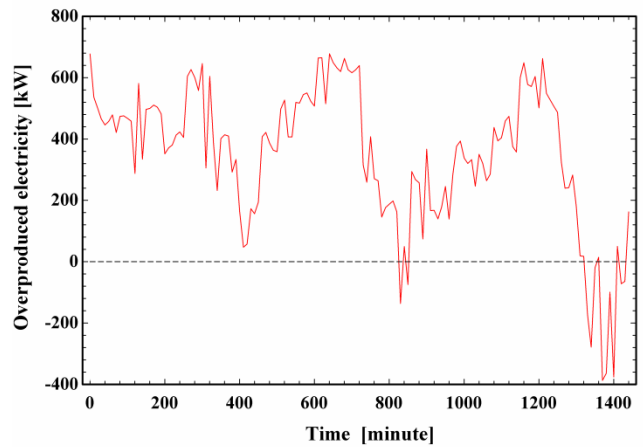
(a)



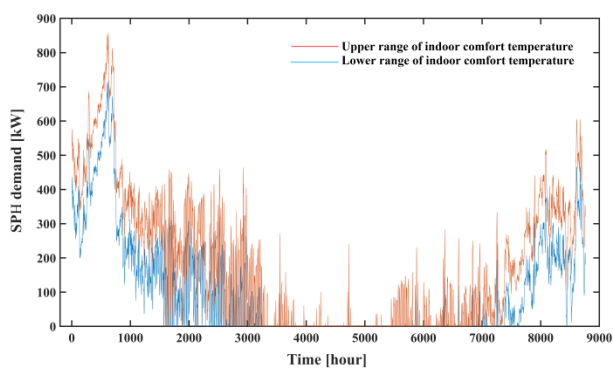
(b)



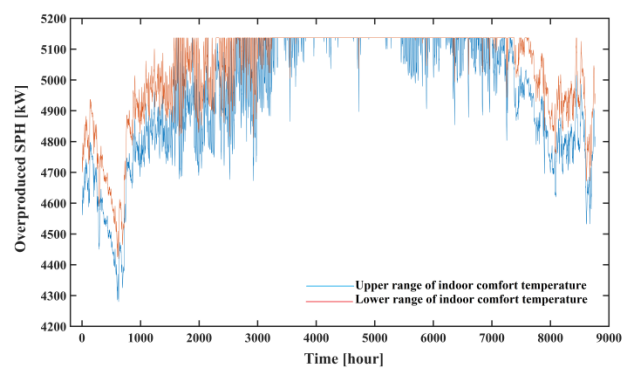
(c)



(d)



(e)



(f)

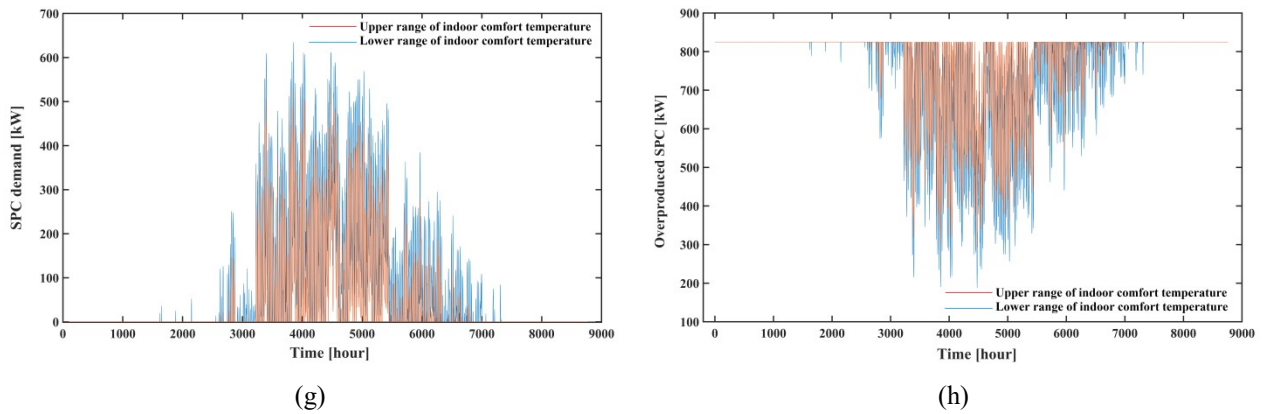


Fig. 9 Total demand of (a) DHW, (c) electricity, (e) SPH, (g) SPC of the examined system and overproduced (b) DHW, (d) electricity, (f) SPH, (h) SPC by the proposed CCHPs

325 As it is obtained, the local energy system based on geothermal and waste heat-driven CCHPs is able
 326 to supply the energy demand of the considered residential area in terms of DHW, SPH, SPC and
 327 electricity. In addition, most of the time, this local energy system produces surplus energy, which will
 328 be transferred to the main grid. However, in analyzing an energy conversion system, not only
 329 thermodynamic and sustainability should be considered, but also enough attention should be paid on
 330 the economic criteria. The latter is of a great significance from the end-users' perspective as the
 331 energy consumption cost can be substantially decreased through use of local energy systems instead
 332 of main grids. To further investigate the economic aspect, Table 11 shows simulation results
 333 regarding annual households' payment for their energy demand (as shown in Fig. 9) supplied by the
 334 main grid and the designed local energy systems. In these calculations, it is assumed that cost of the
 335 electricity supplied by the main grid is 20 €/MWh [58], while cost of heating and cooling is almost
 336 15 €/MWh. Cost of energy provision by the local energy system is also listed in Table 8. As proved
 337 by Table 11, the highest payment belongs to the SPH, while the highest economic benefit refers to
 338 the SPC. This is because the unit cost of SPC supplied by the designed energy system is much lower
 339 than that the one by the main grid. Considering all types of energy demand in the case study, almost
 340 15687 € will be saved for the households with employing the proposed local energy system.

Table 11

Households' payment for their energy demand supplied by the main grid and the designed local energy system

Different forms of energy	SPH	SPC	DHW	Electricity	Total
Cost of energy supplied via the main grid (€/year)	18168	7315	5206	6569	37258

Cost of energy supplied via designed local CCHPs (€/year)	14304	2774	1173	3320	21571
Economic benefits of households (€/year)	3864	4541	4033	3249	15687

5. Conclusions and Recommendation

Energy systems are moving towards integrated designs for supplying electricity, space conditioning and DHW via power, heat and cold distribution grids. Distributed energy systems are promising due to reducing the production and transportation costs and enabling to use free/cheap low quality energy sources (e.g. low- and medium-temperature geothermal, waste heat from different industries, etc.). Utilizing low quality energy sources is such important that has been addressed as one of the 17 sustainable development goals of the UN.

This study investigated the use of waste heat and low-medium temperature geothermal heat sources to run small-scale CCHPs for domestic heating, cooling and electricity applications in a case study in Turkey. A residential neighborhood was considered as the case study in which the energy demands of buildings (electricity, hot water and space conditioning) were mainly supposed to be supplied by the designed CCHPs. The CCHPs are equipped with ORC, single effect LiBr-H₂O absorption chiller and auxiliary heat exchangers. Both supply- and demand-side were analyzed in detail using energy and exergy principles to dig into deep thermodynamic time-dependent performance of the network. Then, energy demand of the buildings in the case study was determined over an entire year. The main conclusions out of the thermodynamic and economic simulations of the CCHPs are as:

- Under the base condition, exergy efficiency / sustainability index of 49.63 % / 1.985 and 63.6 % / 2.747 were obtained for the geothermal and waste heat-driven CCHP, respectively.
- The designed energy system was able not only to feed the whole energy demand of the case study, but also to provide a considerable value of surplus energy to the main grid.
- In terms of payment value by the end user consumers for their energy demand, the proposed system could bring a significant benefit. Since the supplied energy by the proposed system has lower cost compared to that of the main grid, it was possible to save around 15687 € per year for the case study.

In addition, the following subjects are suggested for future extension of this work:

- Employing different kinds of renewable energy sources and comparing the thermodynamic and economic results with those reported in the present study.

- 368 • Exergoeconomic and exergoenvironmental analyses of the presented system using the energy
 369 concept as developed by Aghbashlo et al. [59].
- 370 • Environmental analysis of the proposed energy network and comparing the findings with the
 371 existing conventional energy systems.

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Nomenclature

Abbreviations

CCHP	combined heating, cooling and power
Cond	condenser
DC	district cooling
DH	district heating
DHW	domestic hot water
Gen	generator
HE	heat exchanger
HW	hot water
IHE	internal heat exchanger
ORC	organic Rankine cycle
ORCC	ORC unit condenser
ORCE	ORC unit evaporator
ORCP	ORC unit pump
ORCT	ORC unit turbine
P	pump
SHE	solution heat exchanger
SPC	space cooling
SPH	space heating

Latin letters

e	specific physical exergy (kJ/kg)
eff	effectiveness
\dot{E}	exergy flow rate (kW)
h	specific enthalpy (J/kg)
\dot{m}	mass flow rate (kg/s)
\dot{Q}	heat transfer rate (kW)
s	entropy (kJ/kg K)
T	temperature (K)
V	volume
\dot{W}	power (kW)

Greek letters

η	energy efficiency (-)
η_{II}	exergy efficiency (-)
η_{is}	isentropic efficiency
ρ	density
ε	exergy efficiency (-)

Subscripts

<i>ch</i>	chemical
<i>cv</i>	control volume
<i>D</i>	destruction
<i>e</i>	outlet
<i>i</i>	inlet
<i>o</i>	outlet
<i>ph</i>	physical
<i>ven</i>	ventilation
<i>0</i>	ambient conditions

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