A Micro-trigeneration Geothermal Plant for a Smart Energy Community: The Case Study of a Residential District in Ischia

F Ceglia*, E Marrasso, C Roselli and M Sasso

Department of Engineering, University of Sannio, Piazza Roma 21, 82100 Benevento, Italy

*Email: francesca.ceglia@unisannio.it

Abstract. Improvements for islands sustainability subjected to strong anthropogenic pressures could be obtained by innovative solutions for energy supply by using local energy renewable sources. This paper analyses the possible benefits of a geothermal energy community, consisting of residential users, located in Ischia, an island of Naples in South of Italy. The proposed system is mainly based on an Organic Rankine Cycle plant interacting with a medium temperature geothermal source. This system satisfies both community's pure electric load and electricity requests of the electric-driven heat pumps for space conditioning and domestic hot water demands. The entire system and residential users were modelled and dynamically simulated by considering hourly electric, thermal/cooling and domestic hot water loads variation during three reference days for winter, summer and intermediate season. The proposed plant was compared to a traditional system in which the electricity to meet the total community’s electric loads, is taken from the national power grid. The results highlight that the use of proposed system instead of traditional one allows to avoid 29.9 tons per year of CO$_2$ emissions. Furthermore, this proposed system ensures the island-operation of community exploiting local renewable energy source and improving the energy independency.

1. Introduction

The climate change of current century caused, above all, by fossil fuels combustion and deforestation, has been responsible of greenhouse effect [1]. Even though the necessity to reduce the environmental impact of human society evolution, up to 25% growth of global energy demand is expected until 2040 [2]. For more than a decade the political interest has concerned the need to increase the use of all renewable energy resources to supply energy demand and achieve the environmental objectives of reducing greenhouse gas emissions. Nowadays, however, recent legislations on energy efficiency consider new energy solutions such as smart energy districts or communities that exploit renewable energy sources available in the geographic area close to one where the energy demand occurs. Basically, the energy communities represent a user aggregate located in a little area sharing an energy supply service [3]. In particular, the strong attentiveness towards energy sharing and self-consumption is the result of the recent increase in consumption, especially in the civil sector. During 2018 the world global energy consumption of civil sector overcame the industrial energy demand. Thus, the new smart energy communities could determine several advantages such as costs reduction of the energy vectors, improvement of reliability and quality supply and active participation of citizens that suffered the transformation from consumer to user, the use of local energy resources and the reduction of civil sector energy consumption. In addition, the load sharing among smart energy community (SEC) users ensures the electric load peak reduction and the load shifting or the optimization of load trends. As regards to
the specific geographic condition of an island or an island-like system, that needs an external cable connection to the national power grid, the development of energy communities exploiting local renewable energy sources could guarantee the island’s energy independence [4]. In order to balance the energy production and the demand in island system the target is to increase the degree of self-sufficiency or to improve connection with other systems. These objectives are fundamental by considering that the energy costs in rural areas are 19% higher than energy costs in standard residential areas [5]. Thereby, to obtain a higher stability, flexibility and continuous operation in these geographical contests, it seems useful to refer to programmable and locally available renewable energy sources such as geothermal one particularly where this resource is abundant and unused such as in Italy.

On this topic some studies were conducted in South of Italy to assess the feasibility of the geothermal energy district application. In [6] the authors have analysed a geothermal energy-based polygeneration system connected to a district heating and cooling network providing energy for heating, cooling and domestic hot water needs of a residential area in Naples. It has been demonstrated that such system allows avoiding exploitation of 27.2 GWh of primary energy yearly, corresponding to 5490 tons of avoided CO₂ emissions. It has been noticed that some islands present a great low-medium temperature geothermal potential that can be used in different applications such as binary power plants or for industrial, agricultural, district or space heating uses [7]. Indeed, in [8] the Authors consider two issues regarding islands: the waste management and fuels importation that determine strong dependence on the mainland, as well as high economic and environmental costs for small islands. Thus, geothermal energy was considered for thermal drying of wastewater sludge and electricity supply of the whole wastewater treatment by means of an energy conversion system based on an Organic Rankine cycle (ORC) located in Pantelleria, a small island in Southern Italy. The economic profitability of such system was demonstrated by payback period of investment equal to 8.34 year. The ORC technology allows great flexibility in the use of low/medium temperature renewable energies, for this reason, despite its low performance, it is an interesting technology both for industry and for research applications [9][10].

Thus, in this work a polygeneration system is proposed to meet the energy demand of residential community in geothermal area of Ischia island (Naples, South of Italy). The ORC module is designed to provide electricity, thermal energy for space conditioning and domestic hot water (DHW) demand of a small community. The electricity produced from ORC is used both to satisfy the pure electric loads and to activates the centralised air to water Electric Heat Pump (EHP) for the DHW production and the air to air EHPs located at each user for space heating and cooling purposes. The proposed system has been modelled and dynamically simulated by considering hourly electric, thermal and cooling loads in each period (winter, summer, intermediate). The novelty of this work is related to a possibility of defining a stand-alone smart energy community on Ischia island thanks to the flexibility of ORC system according to the recent Italian legislation [11]. The ORC can work at partial load following the electric load of the community. In this way the management of sharing plant without connection to power grid provides only energy required minimizing the sea water warming at ORC condenser. The proposed process follows a complete and replicable methodology that can be extended to other renewable local sources to define smart energy communities following recent normative. In the section 2 the users are defined. The layout of the system developed in this work is described in Section 3 while the simulation models are presented in Section 4. In the Section 5 the analysis methods are proposed. The results of proposed case study of Ischia are analysed and reported in Section 6 in which a comparison with a traditional system is reported too. Finally, main conclusions are drawn in Section 7.

2. Geothermal Energy Community

The proposed geothermal energy community is located in Ischia island belonging to the archipelago of the Phlegrean islands (Naples, South of Italy) in Italian climatic zone C and with a value of 1.044 degrees per days. It is the third most populous Italian island, and it is connected to the national power grid via underground cable ducts. Moreover, Ischia has been subjected of strong interest for geothermal studies and applications. The presence of shallow magma bodies produced a well-developed geothermal system, with many surface manifestations (fumaroles and hot springs). These features pushed the SAFEN
Company to investigate the geothermal system of the island for geothermal exploitation aimed to electric production, since 1939 and in 1950 the first 300 kW binary cycle plant worldwide, was installed in the Island, on the Forio beach [12]. Recently a study was conducted for a possible ORC power plant application by using a geothermal brine flow rate of 5400 kg/h at 96 °C experimentally measured in a hotel well in Lacco Ameno [13]. For these reasons, in this study a geothermal-based system has been considered to satisfy the electricity, space heating and domestic hot water demands of a residential energy community located in Ischia. The residential users occupy 12 apartments of 100 m² each in a condominium and they are distinguished in 6 user-types: user 1) two working adults, user 2) two working adults and two children, user 3) two working adults and two students, user 4) two ancient persons, user 5) a single working adult, user 6) five working adults/students in sharing home. The occupation schedules have been defined by considering the different behaviours and activities of user-types. The heating period goes from 15th November to 31st March during which the indoor air temperature is maintained at 20 °C according to the normative [14][15]. The cooling period is from first June to 30th September in which the indoor air temperature is fixed to 26 °C. During the intermediate period (from first April to 14th November) no energy is required for heating and cooling needs. The hourly heating and cooling load of each users have been defined according to previous studies considering the same user-types in the same Italian climatic zone [16][17]. The community energy request for heating and cooling are 39.8 and 31.5 MWh/y respectively. The DHW demand has been scheduled by considering the typical residential activities without exceeding a daily request of 50 l/day for each occupant [18]. The pure daily electricity loads and DHW demands are showed in Figure 1 for each user and for the entire energy community by considering difference use destinations. The data about geothermal source are fixed to 138 °C at 840 m of deep, for geothermal brine availability as reported from ENEL and AGIP campaign and geological cartouches [19].

![Figure 1. Pure daily electric loads and DHW demands.](image-url)
3. System Layout
The plant layout consists of an ORC activated by direct heat exchange from geothermal brine, a centralised air to water EHP used to satisfy the DHW demand and decentralized EHPs for each apartment meeting space heating and cooling loads. The geothermal brine at 138 °C is withdrawn from geothermal well 1 by using an electric pump (P_geo) (Figure 2). Geothermal fluid interacts with ORC working fluid (R245fa, WF_{ORC}) inside the evaporator. This heat exchanger is an innovative polymeric evaporator (EV_{ORC}) more resistant than metal heat exchanger to fouling phenomenon related to geothermal brine chemical composition [20]. After flowing EV_{ORC} the geothermal fluid is reinjected at 80 °C in the second geothermal well (8) with a temperature higher than 70°C according to law suggestion [21]. The working fluid passes through the expander (EX_{ORC}) that mechanically activates an electric generator (with a fixed efficiency η_{EG}) providing electricity to the energy community (2). The condensation of R245fa takes place in a condenser (CO_{ORC}) by water-cooling process by using sea water. The electricity available from ORC (2) is used to cover energy community’s electric pure load (3) and to feed centralised the EHP_{DHW} for DHW requests (4) and the EHPs for space heating/cooling needs (5). The centralised EHP_{DHW} is an air to water heat pump with an integrated storage tank satisfying energy community’s DHW requirements (6). The considered EHP module present a nominal thermal power of 9.30 kW and a nominal COP of 3.0 when producing hot water 55 °C at air temperature of 7°C [22]. The volume of storage tank is equal to 1000 l. Moreover, decentralised air to air EHPs located at each apartment cover heating (EHP_{th}) and cooling (EHP_{co}) requests (7). The chosen EHP is reversible heat pump which performance at nominal conditions are listed in Table 1 [23].

![Figure 2. Layout plant system.](image)

Table 1. Data sheet for air to air EHP for space heating (inlet air temperature 21°C) and cooling (inlet air temperature 27 °C).

| Season  | Nominal thermal power [kW] | Electric power input [kW] | COP/EER |
|---------|----------------------------|---------------------------|---------|
| Heating | 6.0                        | 1.30                      | 4.41*   |
| Cooling | 5.0                        | 1.36                      | 4.03**  |

* at 7 °C of external air temperature in nominal operating conditions.
** at 35 °C of external air temperature in nominal operating conditions.

4. Simulation Model
In this Section the models used for ORC, EHP_{DHW} and EHP_{th/co} have been introduced. They are implemented in MATLAB environment following the algorithms described in Subsection 4.4 and a dynamic simulation with a one-hour time-step is performed.

4.1. Mathematical Model for ORC Plant
In this section, the model used to determine the performance of an ORC at part-load operation is presented. The calculations consider a 24 kW$_3$ ORC module with a primary geothermal required power about 260 kW. The electricity request of auxiliaries (variable speed pumps of geothermal brine and sea water) amount to 6 - 7 % of the total electricity demand (pure electric load and electricity for EHP$_{DHW}$ and EHP$_{el}$). The R245fa flow rate (m$_{WF,ORC}$) varies to balance the hourly total electric load. At the same time the withdrawal geothermal brine flow rate (m$_{geo}$) is adjusted to meet the evaporator thermal power avoiding the risk of source depletion. This practice permits a not very variable ORC first law efficiency and requires the right corresponding seawater flow rate without excess of seawater heating.

The system components are outlined by single blocks linked each other by connections through energy balance equations and the model is implemented in MATLAB code [24] by using REFPROP [25] library for thermodynamic fluids properties. From these equations it is possible to calculate the parameters of ORC system such as the m$_{geo}$, m$_{WF,ORC}$ and seawater mass flow rate at condenser m$_{seawater}$ for each time step of one hour. The working fluid selected for ORC is R245fa thanks to its good thermodynamic properties and its compatibility with plastic material. The seawater temperature is fixed to 16 °C, 20 °C, 25 °C for heating, intermediate and cooling period, respectively.

4.2. Mathematical Model of Electric Heat Pump for DHW and Storage Tank

The mathematical model of EHP$_{DHW}$ is based on a MATLAB function evaluating its Coefficient Of Performance (COP) by means of two variables: the environmental temperature (T$_{amb,ext}$[°C]) and DHW mass flow rate (ṁ$_{DHW}$ [kg/h]) as reported in Eq.(1) and water network temperature (T$_{NDHW}$, [°C]). The Eq. (1) is a literature correlation and the fitting coefficients a$_i$ are reported in Table 2 [26]. The heat storage was modelled through an energy balance on the control volume between hot fluid and cold fluid taking into account the losses through the shell. Downstream of the heat storage tank a thermostatic mixer mixes mains water and water taken from the accumulation to give hot water to user at 45 °C with a variability of ±2 °C. The environment temperature is dynamically evaluated from weather data file referred to climate zone.

$$\text{COP}_{EHP_{DHW}} = a_1 + a_2 \cdot T_{amb,ext} + a_3 \cdot T_{NDHW} + a_4 \cdot m_{DHW}$$

(1)

| Table 2. EHP for DHW COP coefficients. |
|----------------------------------------|
| a$_1$ [-] | a$_2$ [°C$^{-1}$] | a$_3$ [°C$^{-1}$] | a$_4$ [h/kg] |
| 2.87 | 0.33 | -5.57 | 1.75 |

4.3. Mathematical Model of Electric Heat Pump for Space Heating and Cooling

The model of the air to air electric heat pumps has been defined by using TRNSYS [27] library based on a normalized performance map. In order to obtain the performance map of the chosen electric heat pump for air conditioning the data sheet provided by the constructor is used as reported in Table 1. A first order polynomial interpolation function is used to simulate the EHP performance as shown in Eq. (2) depending on external air temperature and thermal load for heating and cooling (T$_{amb,ext}$ [°C], $\dot{E}_{th/co}$ [kW]). The polynomial coefficients are reported in Table 3.

$$\text{COP/EE}_{EHP}(T_{amb,ext}, \dot{E}_{th/co}) = p_1 + p_2 \cdot T_{amb,ext} + p_3 \cdot \dot{E}_{th/co}$$

(2)

| Table 3. Polynomial EHP model coefficients. |
|---------------------------------------------|
| Season | p$_1$ [-] | p$_2$ [°C$^{-1}$] | p$_3$ [kW$^{-1}$] |
| Heating | 1.460 | 0.024 | 0.441 |
| Cooling | 2.507 | -0.046 | 0.631 |
4.4. Algorithm Description
The previous models have been implemented in MATLAB environment and the dynamic simulation has been performed following the algorithm schematically represented in Figure 3. In particular, the algorithm is based on a main code and specific functions for each energy conversion model (EHP_{DHW}, EHP_{th/co}, ORC). Depending on the current season, an external file gives the proper users hourly load as input for the energy conversion systems functions. In each time step the electricity demand required by with EHP_{DHW} and EHP_{th/co} is calculated through the corresponding models. The sum of both EHP electricity requests and the pure electricity demand of community represents the global electricity required to the ORC plant. Thus, the main code returns the main operating parameters of ORC such as seawater, working fluid, geothermal flow rates and system efficiency.

![Figure 3. Algorithm simulation procedure.](image)

5. Methodology
The aim of this section is to define both the method used to calculate the load of each energy conversion system dedicated to users energy demand and after to define the method to compare the proposed system to an energy system traditionally used on Ischia island. The proposed system (PS) was modelled as described in previous sections and after it was compared to a traditional system (TS) in which the electricity demand of pure electric load and EHPs loads are covered by power grid. The comparison has been performed by means of an energy and environmental analysis. Considering the thermal energy demand for heating/cooling (E_{th/co}) and DHW (E_{DHW}) of the community by using the model proposed in section 4.2 and 4.3 to evaluate the hourly COP of EHPs dynamically the electric demanded inputs are defined (E_{EHPelth/co}, E_{el,DHW}). These have been added up to electric pure energy (E_{pure,el}) to estimate the total required energy by ORC plant. Thus, the energy analysis is realised by primary energy evaluation in the TS (E_p^{TS}) by using equations (3)-(7) and by considering the electric efficiency indicators defined according to [28], \( \eta^{TS} \), equal to 0.701. For environmental analysis the CO\(_2\) emission (\( CO_2^{TS} \)) connected to TS was evaluated by using Eq. (8) as a function of national CO\(_2\) emission factor for electricity, \( d^{TS} \), equal to 356.02 gCO\(_2\)/kWh that accounts for both RES and fossil electricity production including the losses in 2017. This analysis was completely defined in the absolute terms (Eq. (3)-(4)) because of the PS was 100% renewable-based so it does not determine CO\(_2\) emission and primary required energy during the operation.
\[ E_{p}^{TS} = \frac{E_{el,ORC}^{year}}{\eta^{TS}} \]  
\[ CO_{2}^{TS} = E_{el,ORC}^{year} \cdot \alpha^{TS} \]  

6. Results
The dynamic yearly simulation results split in heating, cooling and intermediate period are reported in Table 4. By considering a yearly analysis, the geothermal energy used to satisfy the energy community requests is 84.1 MWh/y.

The space heating demand (39.8 MWh/y) is higher than the cooling request (31.5 MWh/y) even if Ischia belongs to Italian climatic zone C with mild winters and hot summer. This event is due to the fact that the heating period and the switch-on hours of the plant are higher than cooling one. The ORC efficiency is higher during heating period when the seawater presents the lower value. Moreover, the DHW storage tank losses cover 15% of total DHW demand. In order to evaluate the advantages of proposed system the primary energy saving is calculated respect to TS. By considering geothermal source able to feed the 100% of loads, the proposed system allows to avoid all primary energy required and all CO2 emissions caused by TS; these values are respectively 119.9 MWh/year and 29.9 tons of CO2.

Table 4. Results of dynamic simulation.

| Period     | ORC  | EHP air conditioning | EHP DHW | STORAGE TANK |
|------------|------|----------------------|---------|--------------|
|            | \( E_{el,net,SEC} \) [MWh] | \( E_{th,geo} \) [MWh] | \( \eta \) [%] | \( E_{el} \) [MWh] | \( E_{user} \) [MWh] | \( E_{in,TANK} \) [MWh] | \( E_{loss,TANK} \) [MWh] |
| Heating    | 36.5 | 310.5                | 11.3    | 13.1         | 39.8         | 4.2                 | 8.8                 | 10.1                | 1.3                |
| Cooling    | 29.5 | 286.6                | 9.9     | 9.2          | 31.5         | 3.0                 | 8.0                 | 9.2                 | 1.2                |
| Intermediate | 18.1 | 163.4                | 10.6    | 2.8          | 7.0          | 8.1                 | 1.1                 |
| Year       | 84.1 | 760.5                | 22.3    | 10.0         | 23.8         | 27.4                | 3.6                 |

In Figure 4 the results regarding the daily analysis, considering three reference days (heating, cooling and intermediate), are reported. In particular, electricity requested to activate EHP_DHW and EHP_hc/W and pure electricity demand are showed. Moreover, the seawater flow rate and geothermal brine flow rate are reported too. A different seawater temperature is considered in each period.

The maximum total electricity load is recorded in the reference cooling day corresponding to 24 kW at midday. Instead, the maximum electricity load demand for air conditioning is 10.4 kW and 9.9 kW for heating and cooling period, respectively. The maximum electric power required by the domestic hot water heat pump is 3.4 kW in the reference winter day. The seawater flow rate has the same trend ranging from 3877 kg/h (during an night hour of intermediate day) to 41,526 kg/h (during morning hours of summer day). As shown in Figure 4 the required sea water flow rate is lower than 10,000 kg/h for the most of the operating hours. The maximum value of geothermal flow rate is about 3,688 kg/h referred to midday of summer day.
Figure 4. Main results for reference days.

7. Conclusion
An energy and environmental analysis of a geothermal polygeneration system satisfying thermal, cooling, domestic hot water and electricity demands of an energy community in Ischia island has been conducted. The entire system is based on a geothermal activated organic Rankine cycle module, and electric heat pumps has been modelled and implemented in MATLAB environments. The results of dynamic simulation have been used to compare the proposed system to a traditional one in which the electricity request of energy community is satisfied by taking electricity from the national power grid. Thus, the proposed system allows to avoid 29.9 t/year of CO₂ emissions and to save 119.9 MWh/year of primary energy with respect to traditional system. Future studies could consider different energy conversion system solution such as direct use of geothermal energy for district heating/cooling network and/or coupling of other renewable source for such as biomass or solar-geothermal plant.

References
[1] Trenberth KE, 2018. Climate change caused by human activities is happening and it already has major consequences. Energy Nat. Resour. 36, 463-481.
[2] IEA, International Energy Agency. Date and Statistic. Explore energy data by category, indicator, country or region. Available online: https://www.iea.org/data-and-statistic. [Last accessed 5 October 2020].
[3] Ceglia F, Esposito P, Marrasso E and Sasso M. 2020. From smart energy community to smart energy municipalities: Literature review, agendas and pathways. J. Clean. Prod. 254, 120118.
[4] Osti G, 2018. The uncertain games of energy transition in the island of Sardinia (Italy). J. Clean. Prod. 205, 681-689.
[5] Zhang D, Li J and Han P. 2019. A multidimensional measure of energy poverty in China and its impacts on health: an empirical study based on the China family panel studies. Energy Policy 131, 72-81.
[6] Ceglia F, Macaluso A, Marrasso E, Roselli C and Vanoli L. 2020. Energy, Environmental, and Economic Analyses of Geothermal Polypower System Using Dynamic Simulations. Energies 13, 4603.
[7] Arnórsson S, Thórhallsson S and Stefánsson A. 2015. Utilization of geothermal resources. In: Economic Benefits and Cultural Aspects of Volcanism. (Oxford: Elsevier) p. 1240.
[8] Calise F, Di Fraia S, Macaluso A, Massarotti N and Vanoli L. 2018. A geothermal energy system for wastewater sludge drying and electricity production in a small island. Energy 163, 130-143.
[9] Quoilin S, van den Broek M, Declaye S, Dewallef P and Lemort, V. 2013. Techno-economic survey of Organic Rankine cycle (ORC) systems. Renew. Sustain. Energy Rev. 22, 168–186.
[10] Larjola Jaakko AU and Turunen-Saaresti T. 2011. Background and summary of commercial ORC development and exploitation. *Proceedings of the First International Seminar on ORC Power Systems*, (Delft, Netherlands, 22-23 September 2011)

[11] ARERA 4 AGOSTO 2020 318/2020/R/EEL Online available on https://www.arera.it/it/docs/20/318-20.htm [last accessed 21 October 2020].

[12] Carlino S, Somma R, Troiano A, Di Giuseppe MG, Troise C and De Natale G. 2014. The geothermal system of Ischia Island (southern Italy): Critical review and sustainability analysis of geothermal resource for electricity generation. *Renewable Energy* 62, 177-196.

[13] Buonomano A, Calise F, Palombo A and Vicidomini M. 2015. Energy and economic analysis of geothermal–solar trigeneration systems: A case study for a hotel building in Ischia. *Applied Energy* 138, 224–241.

[14] UNI TS 11300–2. Energy Performance of Buildings. Part 2: Evaluation of Primary Energy Need and System Efficiencies for Space Heating and Domestic Hot Water Production; 2008.

[15] D.P.R. August 26, 1993, n. 412. Regulation for the design, installation, operation and maintenance of heating system in building for the purpose of reducing consumption energy [in Italian].

[16] Marrasso E, Roselli C, Sasso M and Tariello F. 2018. Global and local environmental and energy advantages of a geothermal heat pump interacting with a low temperature thermal micro grid. *Energy Convers. Manag.* 172, 540–553.

[17] Marrasso E, Roselli C, Sasso M. 2020. Energy and environmental performance of a heat pump in different power grid scenarios. *Int. J. Energy Res.* 1–23.

[18] Hervás-Blasco E, Navarro-Peris E and Corberán JM. 2019. Optimal design and operation of a central domestic hot water heat pump system for a group of dwellings employing low temperature waste heat as a source. *Energy* 188, 115979.

[19] AGIP. Geologia e geofisica del sistema geotermico dei Campi Flegrei. 1987. Technical report. Settore Esplor e Ric Geoterm Metodol per l’Esplor Geotermica. San Donato Milanese, Italy; p.23.

[20] Ceglia F, Macaluso A, Marrasso E, Sasso M and Vanoli L. 2020. Modelling of Polymeric Shell and Tube Heat Exchangers for Low-Medium Temperature Geothermal Applications. *Energies* 13, 2737.

[21] Franco A and Villani M. 2009. Optimal design of binary cycle power plants for water-dominated, medium-temperature geothermal fields. *Geothermics.* 38, 379–391.

[22] AERMEC. datasheet On line available: https://global.aermec.com/it/products/?select-catalogue=CAT_50HZ_UE [last accessed 13 October 2020]

[23] Data sheet, MITSUBISHI. On line available: https://www.mitsubishithermal.it/prodotto/monosplit-full-dc-kireia-plus/ [last accessed 6 October 2020].

[24] The MathWorks, Inc., 2018. MATLAB and Statistics Toolbox Release. (Natick, Massachusetts, United States)

[25] McLINDEN Mark, 2002. Reference Fluid Thermodynamic and Transport Properties, Nist 709. Standard Reference Database 23, version 9.1. Physical and Chemical Properties Division, NIST, 710, USA.

[26] Tammaro M, Montaguad C, Corberán JM, Mauro AW and Mastrullo R. 2017. Seasonal performance assessment of sanitary hot water production systems using propane and CO2 heat pumps. *Int. J. Refrig.* 74, 224–239.

[27] TRNSYS 17, a TRaNsient System simulation program. Solar Energy Laboratory; University of Wisconsin-Madison; 2010.

[28] Marrasso E, Roselli C, and Sasso M. 2019. Electric efficiency indicators and carbon dioxide emission factors for power generation by fossil and renewable energy sources on hourly basis. *Energy Convers. Manage.* 196, 1369–1384.