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Analysis of the integration of micro-cogeneration units in space heating and domestic hot water plants

González-Pino I.[a*], Pérez-Iribarren E.[a], Campos-Celador A.[b], Terés-Zubiaga J.[a]

[a] ENEDI Research Group, Department of Energy Engineering, Faculty of Engineering of Bilbao, University of the Basque Country UPV/EHU, Plaza Ingeniero Torres Quevedo 1, Bilbao 48013, Spain.

[b] ENEDI Research Group, Department of Energy Engineering, Faculty of Engineering of Gipuzkoa, University of the Basque Country UPV/EHU, Avenida. Otaola 29, Eibar 20600, Spain.

[*] Corresponding author. Tel.: +34946017364. Fax: +34946017800. E-mail: iker.gonzalezp@ehu.eus

ABSTRACT

Micro-cogeneration has been recognized as an efficient technology that can contribute to European Union's energy and climate objectives with respect to delivering low-carbon heat and power to citizens and small businesses. For improving the performance of this technology and so take as much advantage as possible of its potential, thermal energy storage plays a key role. This paper presents a techno-economic evaluation and optimization procedure focused on properly sizing and designing a micro-cogeneration residential installation, emphasizing how thermal energy storage is arranged and the different thermal loads prioritized within the plant. Therefore, the proposed methodology can be easily applied to buildings with different conditions and constraints.

The methodology is then applied to a representative case study that consists of a detached house with a 1 kW_e micro-cogeneration plant. Results of the case study show that in small installations DHW accumulation does not provide any significant improvement but a worsening of efficiency. Additionally, it is also proved that the layout of the distribution loop has an importance on the final performance of the plant that must be kept in mind. Moreover, results show that TES systems coupled with micro-cogeneration engines are traditionally highly oversized, thus worsening economic viability of these facilities.

Keywords: micro-CHP; TES arrangement; load priority; transient simulation; techno-economic analysis; optimization.

Nomenclature

E	electric energy (kWh)
Ex	exergy (kWh)
F	primary energy due to fuel consumption (kWh)
H	thermal energy (kWh)
i	sale-price (€/kWh)
I	income or savings (€)
Inv	investment cost of the hot water tank (€)
j	time (min)
LT	lifetime (years)
m	equivalent carbon dioxide emissions (kg)
n	year of operation of the plant
NPV	net present value (€)
NS	annual net savings (€)
PES	primary energy saving (%)
r	ratio of discount
R	retributive complement (€/MW or €/MWh)
$RefE_\eta$	harmonised efficiency reference value for separate production of electricity
$RefH_\eta$	harmonised efficiency reference value for separate production of heat
U	thermal transmittance (W/m^{2}K)
V	volume (L)
YT	full-year time (min)

Superscripts

ab	relative to the auxiliary boiler
CHP	relative to the CHP device

Greek symbols

Δ	variation
ψ	exergy efficiency
μ	CO_2 specific emission factor

Abbreviations

CHP	combined heat and power
CTE	Spanish Technical Building Code
DHW	domestic hot water
EED	Energy Efficiency Directive
EU	European Union
GHG	Greenhouse gas
GWP	Global Warming Potential
IDAE	Institute for Energy Diversification and Saving
LHV	Lower heating value
LFPSE	linear free piston Stirling engine
RD	Royal Decree
SE	Stirling engine
SHTES	sensible heat thermal energy storage
TES	thermal energy storage

Subscripts

c	relative to the network cold water
CHP	relative to the CHP device
e	electric
E	relative to net electricity produced
F	relative to fuel consumed
H	relative to heat supplied
in	relative to the inlet
inv	relative to the micro-CHP investment-cost
O	relative to the operation of the micro-CHP
out	relative to the outlet
t	relative to heat

1. INTRODUCTION

Buildings are responsible for 40% of the total final energy consumption and 36% of the greenhouse gas (GHG) emissions in the European Union (EU) [1]. Consequently, the European Commission highlights the need for energy savings and emissions reductions in residential and commercial sectors to reach its climate and energy objectives. The EU recognizes the implementation of micro Combined Heat and Power (micro-CHP) as a key technology – specially as a source for heating and Domestic Hot Water (DHW) production – for having reached the 2020 objectives (20% increase of the energy efficiency and 20% reduction of CO_2 emissions) and for accomplishing two of the three key targets included in the 2030 climate and energy framework (32.5% increase of the energy efficiency and 40% reduction of CO_2 emissions) [2]. In this sense, Directive 2010/31/EU on Energy Performance in Buildings [3] states that a significant rollout of micro-CHP would reduce emissions attributed to residential and commercial sectors, while the Energy Efficiency Directive 2012/27/EU [4] remarks its potential role in increasing the energy performance of buildings. Both Directives have been recently slightly amended as part of the Clean energy for all Europeans package through Directive (EU) 2018/844 [5].

The evaluation of the potential benefits of micro-CHP is usually performed by comparing its energy and economic performance to that of conventional or alternative installations, as it was the main objective of the IEA EBC Annex 54 on the Integration of Microgeneration and Related Technologies in Building [6]. However, the benefits are not exclusively technology-related, but they depend on how the full installation is designed or how the micro-CHP unit is run and integrated within it. In most of industrial applications, selection of the main generator and operative conditions of the cogeneration plant is a relatively simple procedure, since thermal and electric loads of industrial processes are nearly constant throughout the year. That is why the optimum sizing of the main components is directly derived from the annual mean thermal demand [7]. However, design of small-scale applications in tertiary and residential sectors requires a more complex approach due to the great fluctuations of electricity and thermal demands, which are related to the climate, occupation and other highly stochastic conditions. Thus, one major concern when implementing micro-CHP systems lies in the mismatch between electricity and heat provided by the micro-CHP and electrical and thermal energy required in the household [8]. Moreover, a micro-CHP system operates more efficiently at a constant full load, but thermal and electrical energy demands are hardly ever constant and difficult to forecast.

This problem may be reduced by integrating Thermal Energy Storage (TES) technologies [9]. Thereby, TES will capture thermal energy surplus and then deliver it back when the micro-CHP system is not able to provide as much energy as the building requires. This fact turns into longer periods and a more beneficial operation of the micro-CHP, consequently avoiding the frequent occurrence of transients during start-up and shutdown processes [10]. TES will also allow extending the operational time of the micro-CHP, which turns into larger energy savings and CO_2 reductions. Even the installation of a small TES leads to an important increase of the yearly number of hours of operation [11]. Therefore, TES can be considered as an energy conservation technology, since it allows decoupling production and consumption sides and so, ensuring energy security, efficiency and environmental quality [12].

Amongst the three main techniques existing for TES, sensible heat thermal energy storage (SHTES) systems are the most habitual. These systems consist of warming up or cooling down a certain quantity of mass, commonly water. Hot water SHTES systems are based on the stratification effect that occurs due to the density difference between hot and cold water; hot water flows to the top and cold water remains at the bottom, while the intermediate region forms the thermocline [13].

In the literature, several works dealing with the feasibility of CHP residential plants including hot water storage have appeared so far. Fragaki et al. [14] highlighted the importance of properly sizing TES through the economic study of engine-based cogeneration plants of different size and TES capacities for a district heating in the United Kingdom. Similar conclusions were drawn by Streckienè et al. [15], who carried out a study of a cogeneration unit participating in the German spot market, which worked during those hours when the electricity price was higher, accumulating the heat excess.

Khan et al. [16] developed a techno-economic study of a trigeneration plant, concluding that heat storage not only increases the profitability (especially when the cogeneration also meets the cooling load by means of an absorption chiller), but also allows obtaining a substantial reduction in the peak production. Analogous results were obtained by Bogdan and Kopjar [17] and Verda and Colella [18].

Mongibello et al. [19] analysed, both technically and economically, the integration of a cylindrical hot water tank with a residential micro-CHP system and compared it with the employment of a latent heat thermal energy storage system. The TES was sized based on the operational logic and the thermal and electric loads. Johar et al. described the performance of thermal storage integrated with a diesel engine-based micro-cogeneration system [20]. Their experimental results showed that integrating LHTES is feasible and helps to make a more efficient use of energy resources, since significant (up to 15%) energy savings can be achieved and so improve energy efficiency.

Barbieri et al. [21] presented a model to analyse the effect of the TES size on the energy and economic profitability of residential micro-CHP systems in a single-family dwelling, concluding that this effect is not linear and becomes more important as the thermal power of the prime mover increases.

Rosato et al. carried out a simulation-based research for analyzing the energy, environmental and economic viability of a residential cogeneration system coupled to a combined buffer tank [22,23]. Their evaluation of three different levels of accumulation showed that, whatever the climatic conditions and the operation strategy was, the tank with the largest volume enabled minimizing the primary energy consumption, the equivalent carbon dioxide emissions, as well as the operating costs of the system.

Other studies lie in mathematical models that optimize the size and operation of cogeneration plants and the charging and discharging of the TES. Gustafsson and Karlsson [24] developed a mixed integer program to optimize the running of the plant in order to maximize the economic performance. Ibáñez et al. [25] presented a simple analytical method for sizing DHW tanks fed by CHP systems. In this line, Katulić et al. [26] developed a simplified method for optimizing the capacity of a TES system so that profits obtained in a cogeneration plant in Croatia could be maximized. Lozano et al. [27] developed a cost-optimization study for obtaining the optimal design and operation of a trigeneration plant. Meanwhile, Iturriaga et al. [28] presented a MILP model, based on a general superstructure where all existing technologies for heating, cooling and DHW can be included, that allows selecting the equipment and its operation in order to minimize annual costs according to constraints imposed by the designer. Results obtained for a case-study show, amongst other factors, that integrating TES, whatever the constraints imposed are, leads to reductions in both overall costs and non-renewable primary energy consumption.

Even though all these studies recognize the importance of including thermal storage tanks in these kinds of applications and deal with the energy and environmental impact of the size and operation of storage systems, none of them draws attention to the way TES is arranged within the thermal plant. Therefore, unlike other previous researches, this paper aims to deepen on the importance of how both TES systems and heating and DHW loads are integrated within the micro-CHP plant, so that the optimization approach can be extended, and so help to draw the potential limits of residential micro-CHP. A simple and general methodology is developed for assessing, by means of dynamic modelling, the techno-economical evaluation of TES with different plant configurations, which is implemented in TRNSYS simulation environment to perform annual evaluations. The proposed methodology, which is easily applicable to buildings with different conditions and constraints, is then applied to a representative case study, where the Remeha eVita micro-CHP unit meets the space heating and DHW needs of a detached house located in the surroundings of Vitoria-Gasteiz (northern Spain), performing a full techno-economic evaluation. The selection of a Stirling engine (SE) lies in the potential benefits this technology can provide in terms of multi-fuel capability, low CO_2 emissions and energy efficiency [29].

This way, the article is structured in five sections. After this introduction section, Section 2 presents the methodology, where different design options of micro-CHP plants are investigated, as well as the modelling and simulation approach that allows for its energy and economic assessment. Section 3 introduces the specificities of the case study presented in this paper, which consists of the reference building description, the micro-CHP unit under consideration, as well as the legal and economic framework for the analysis. Results obtained from the evaluation of the case study are then presented and discussed in Section 4, while, finally, the main conclusions and achievements are summarized in Section 5.

2. METHODOLOGY

As indicated, this paper focuses on analysing the design of micro-CHP plants, emphasizing how TES can be arranged within the plant and which the load priority configuration is. Thus, in this section a detailed description of the methodology proposed for evaluating the different design options is presented.

2.1. INTEGRATION OPTIONS FOR DOMESTIC MICRO-CHP UNITS

Domestic micro-CHP plants can be integrated in very different ways to meet the energy needs of a building or dwelling. The different options lead to a different operation and interaction between devices, which determines the actual operation of the plant. In this paper, two separated integration options are investigated: (i) the TES system connection to the micro-CHP plant and (ii) the load priority, considering for both cases different TES volumes.

2.1.1. TES SYSTEM CONNECTION TO THE MICRO-CHP PLANT

Campos-Celador [30] states that any heat storage system can be classified, regarding its connection to the water loop, as: 1 inlet-1 outlet or 2 inlets-2 outlets configuration. In 1 inlet-1 outlet systems, as represented in Figure 1, there is a single loop for both charging and discharging processes, which goes through the storage system from the inlet to the outlet. Likewise, these systems can be implemented by an upstream or a downstream configuration.

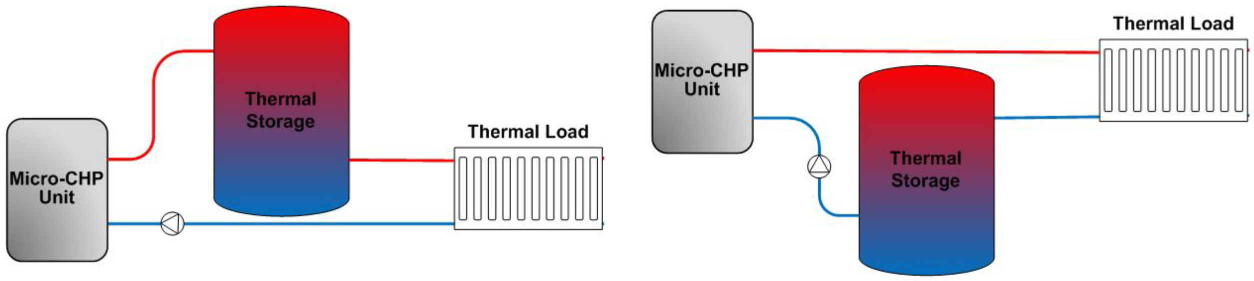


Figure 1 – Basic integration of 1 inlet-1 outlet TES system in a micro-CHP plant: downstream integration (left) and upstream integration (right).

The performance of these storage configurations depends on the operating mode. In the downstream configuration, the storage capacity increases during the charging process, as it is connected at the outlet of the cogeneration unit where the temperature of the fluid reaches its maximum. However, this adds priority to the storage over the load, which can cause deficit in meeting the demand. Under the upstream configuration, although the effective storage capacity decreases, the inlet temperature to the micro-CHP unit during the charging process is reduced, which results in an increase of the CHP performance. Although the selection and operation of this kind of system is hardly dependent on the operation strategy of the micro-CHP and the nature of the heat loads, in small residential applications downstream configuration generally results more suitable.

A typical solution for improving the exchanged power and, therefore, the storage efficiency, is to make the heat transfer fluid enter the storage system on opposite sides during the charging and discharging, respectively, as depicted in Figure 2. Thus, the temperature gradient between the heat transfer fluid and the storage medium increases and simultaneously the heat transfer ratio. However, this solution requires an active piping system governed by a control system that discerns between charging and discharging which, in fact, turns into a more complex and expensive facility.

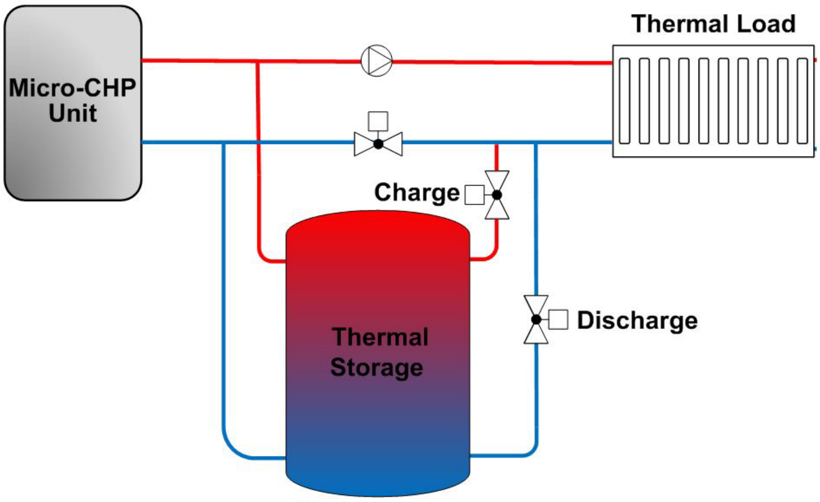


Figure 2 – Advanced integration of 1 inlet-1 outlet TES system in a micro-CHP plant.

On the other hand, in 2 inlets-2 outlets systems, as shown in Figure 3, two different loops can cross the storage system at a certain instant. These systems exhibit two decoupled hydraulic loops, one for the discharging process and the other one for the charging, so being the integration and operation simpler than in the case of the 1 inlet-1 outlet system. Nevertheless, the management of the energy content of the storage system is less flexible than in the previous case.

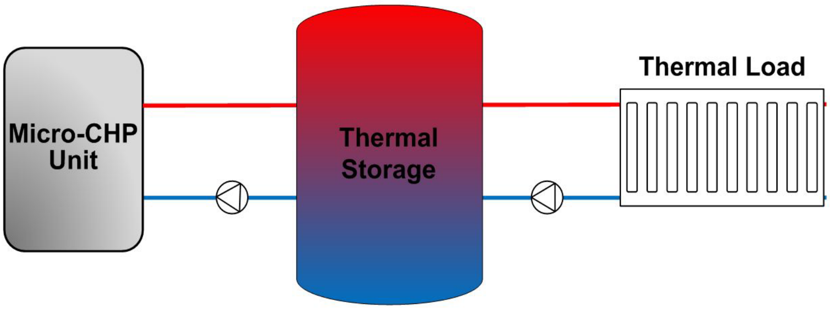


Figure 3 – Integration of 2 inlets-2 outlets TES system in a micro-CHP plant.

2.1.2. LOAD PRIORITY

Most commercial small-scale SE-based micro-CHP units operate similarly to conventional high-performance boilers but also integrate an engine that produces electricity. Thus, these units should meet both space heating and DHW needs, existing two different options to do so: parallel distribution and series distribution (Figure 4). While the parallel distribution makes no distinction between the two thermal demands, in the series distribution priority is given to the DHW demand, afterwards providing heating at a lower temperature.

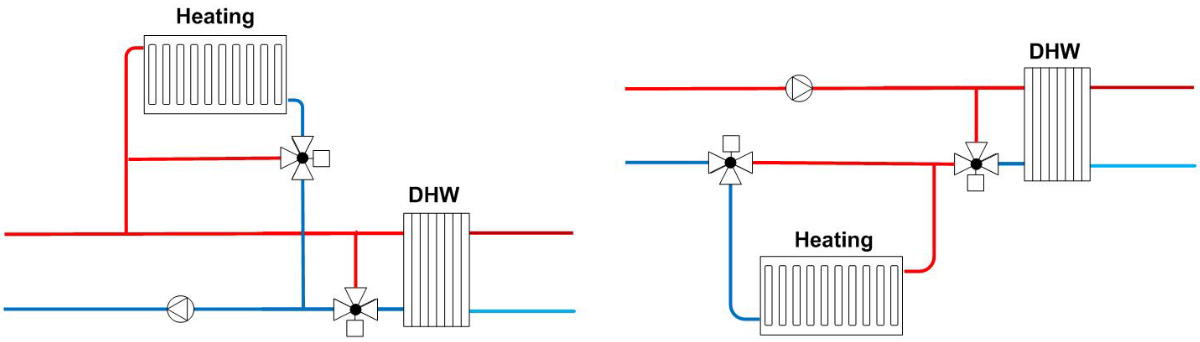


Figure 4 – Different configurations of the distribution circuit: parallel connection (left) and series connection (right).

2.2.MODELING AND SIMULATION OF MICRO-CHP PLANTS

Amongst the different energy simulation environments, TRNSYS is generally the most complete tool for building-scale simulation [31]. This justifies the election of TRNSYS 17 software for the here presented analysis.

The SE-based micro-CHP unit is modelled with a self-tailored Type. This model is generic and adaptable to different gas-fired units available in the market. The modelling is approached in terms of a grey-box, where all the transitory effects that take place are taken into account. For this purpose, as depicted in Figure 5, three control volumes and a control mass were set out for modelling the dynamic thermal performance of the micro-CHP boiler: the head of the engine, the engine block and the heat exchanger corresponding to the SE operation, and the auxiliary burner block when extra heat is required. All the components are supposed to be thermally defined by a unique mean temperature. Additionally, since the model does not attempt to physically model all the actual phenomena that take place, some simplifying considerations were adopted:

- Exhaust gases are replaced by effective heat transfer processes between control volumes.
- Enthalpies of reactants and products are lumped within a combustion efficiency term.
- The fuel input is related to the electricity output by means of the electric efficiency.
- Steady-state performance is related to the cooling water temperature and flow through a multiple regression modelling approach.
- A firing-rate that reduces the fuel input for part-load operation is defined.
- Independent correlations are used for modelling fuel and electric power during transient phases.

Further information about this Type can be found at [32].

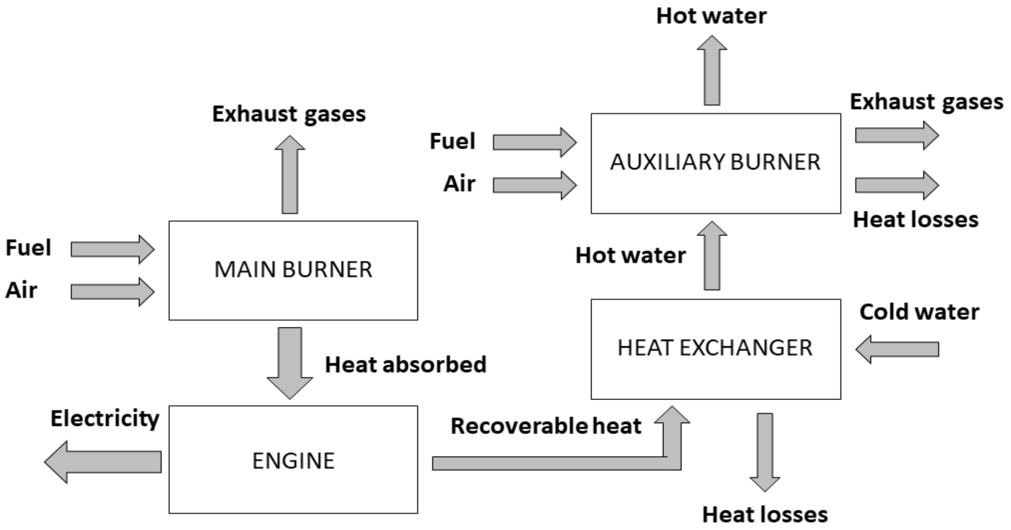


Figure 5 – Simplified mass and energy flows of the Stirling micro-CHP model.

The generation unit is externally governed by a controller that aims to maintain the temperature of the water delivered to the demand above a certain temperature. This control is implemented by Type 2, providing the installation with a hysteresis that avoids repeated on-off cycles of the generation unit, so helping to get a smoother operation of the SE.

Hot water tanks, as well as hydraulic compensators, are simulated using the model developed by Klein et al. [33], implemented in TRNSYS as Type 4. This model, which takes into account all the main effects occurring within a tank, is considered to perform the most realistic behavior amongst the existing modelling approaches with simplicity and good agreement with the experimental results shown by Klein [33]. The model bases on solving a one-dimensional convection equation.

DHW is produced by a plate heat exchanger modelled by Type 91, whether it is instantaneously or tank-through produced. In this zero-capacitance sensible heat exchanger the effectiveness is given as a constant input parameter, and it is independent of the system configuration. Thus, the maximum possible heat transfer is calculated based on the minimum capacity rate fluid and the cold side and hot side fluid inlet temperatures. Additionally, a three-way valve modelled with Type 11 is disposed so that pumping water through the DHW circuit can be avoided for those cases when there is no need for heating up the DHW tank or the occupants of the dwelling do not demand any DHW.

Meanwhile, heating is supplied to each zone by a radiator system which is modelled by a lumped capacity model which exchanges heat (80% convective / 20% radiative) with the air nodes modelled by Type 56. The radiator is modelled through Type 211 using the thermo-physical properties of the commercial series StelRad Elite K2 [34]. Radiators present a bypass controlled by a three-way valve (Type 11), which reduces the need for pumping water through radiators lines when heating is not required. This control can be performed either with a thermostatic valve which maintains the control room temperature within a temperature range, or based on the outdoor temperature; in both cases it is modelled by Type 2.

Finally, pumps are modelled by Type 114, and their operation is linked to the SE operation and DHW and heating demands. This Type models a single-speed pump that maintains a constant fluid outlet mass flow, without considering starting and stopping characteristics, nor pressure drop effects. Additionally, since pipes are located in conditioned spaces, heat losses through them have been ignored, as well as the inner of water circulating within them.

The TRNSYS model scheme for one of the cases simulated is presented in Figure 6, where different colours are employed to represent the different information flows, showing the main components and connections. For the sake of clarity, amongst the 27 zones in which the case-study building is split for modelling (afterwards defined in Section 3.1), only the 3 general floors have been presented.

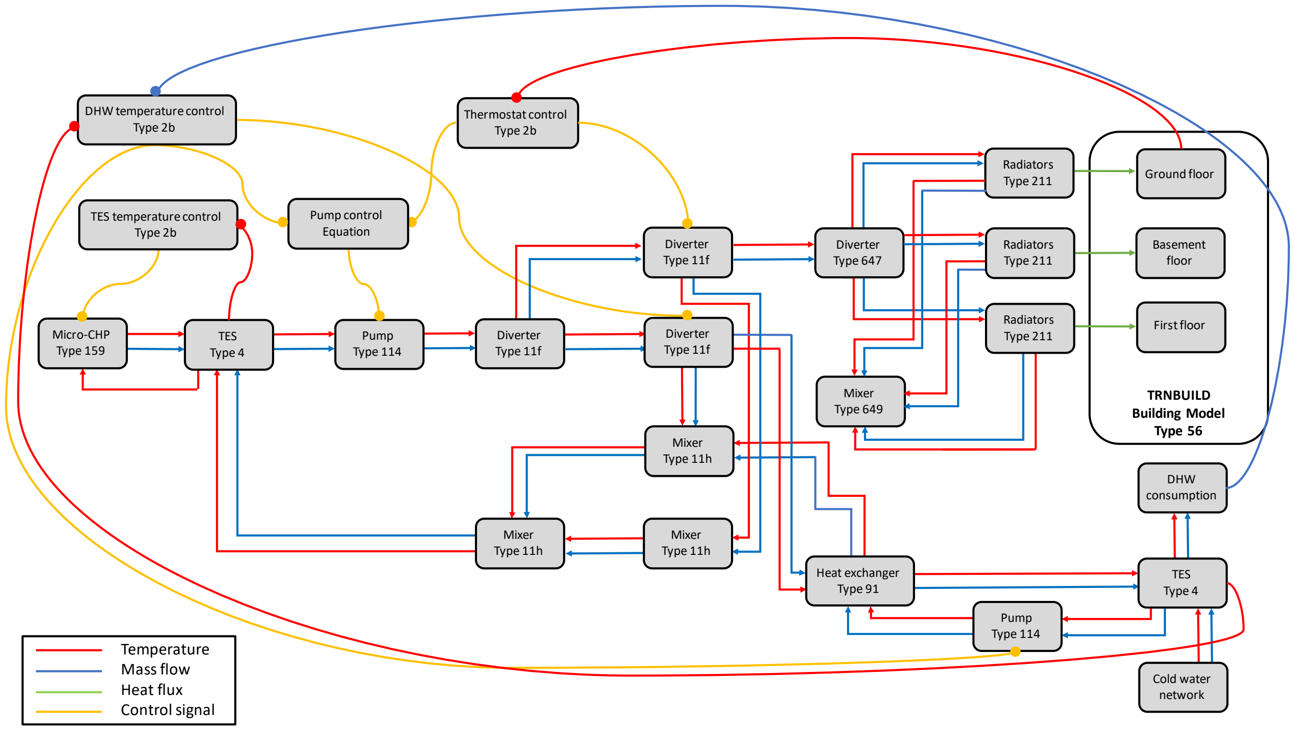


Figure 6 – Simplified scheme of the TRNSYS model for one of the configurations simulated.

All the main TRNSYS Types employed in the simulations are summarized in Table 1, and their mathematical description can be found in [35].

Table 1 – Main components employed in the TRNSYS simulation.

Component	Model	Source
Micro-CHP boiler	Type 159	Self-tailored
Hydraulic compensator	Type 4	Standard
Constant flow pumps	Type 114	TESS
Storage tanks	Type 4	Standard
Flow diverters	Type 11f	Standard
	Type 647	TESS
Flow mixers	Type 11h	Standard
	Type 649	TESS
Differential controller	Type 2b	Standard
Heat exchanger	Type 91	Standard
Radiators	Type 211	Self-tailored

2.3.PERFORMANCE EVALUATION

Energy flows resulting from simulations are used as inputs for the annual energy and economic evaluation, using a set of indicators that are described subsequently.

2.3.1. Energy and environmental analysis

The energy analysis of the installation encompasses an evaluation based on the on-off cycles and the total operation time of the engine, as well as the PES (as shown in Eq. (1)) achievable with the different configurations and the corresponding efficiencies.

$$PES = \left(1 - \frac{F_{CHP}}{\frac{H_{CHP}}{RefH_{\eta}} + \frac{E_{CHP}}{RefE_{\eta}}}\right) \cdot 100 \qquad \text{Eq. (1)}$$

where F_{CHP}, H_{CHP} and E_{CHP} are the respective fuel consumption, useful heat produced and electricity output of the micro-CHP installation, and $RefH_{\eta}$ and $RefE_{\eta}$ are the harmonized efficiencies for separate heat and electricity productions, respectively [4].

For determining the useful heat production of the engine, H_{CHP}, the corresponding heat losses of the TES must be determined and subtracted to the gross thermal production. For that purpose, it must be taken into consideration the previously mentioned fact that Stirling generation devices susceptible of being installed in single-family houses are generally made up of a SE and a condensing boiler working in series. In order to be able to decouple the fraction of heat losses corresponding to each of the generators, an exergy-based assignment procedure is proposed in this article. Since heat transfer is a temperature-dependent phenomenon, this exergy-based assignment method enables taking into account the influence the temperature level at which each technology produces heat has on the heat losses of the TES, defined as follows:

$$H_{CHP} = H_{CHP,gross} - \left(\frac{Ex_{out}^{CHP} - Ex_{in}^{CHP}}{Ex_{out}^{ab} - Ex_{in}^{CHP}}\right) \cdot H_{loss,TES} \qquad \text{Eq. (2)}$$

where $H_{CHP,gross}$ is the gross production of the engine, Ex_{in}^{CHP} and Ex_{out}^{CHP} are the respective exergies of the cooling water at the inlet and outlet of the engine, Ex_{out}^{ab} is the exergy of the cooling water at the outlet of the device and $H_{loss,TES}$ are the total heat losses of the accumulation tank.

For evaluating the performance of the TES itself, the charging-discharging process was assessed, by studying the amounts of energy accumulated per unit of volume for each configuration. Additionally, the efficiency, that is, the ratio between the released and the stored energy, was also calculated.

With respect to GHG emissions, the Global Warming Potential (GWP) defined in the IPCC 2007 method developed by the International Panel on Climate Change was taken as a reference. The GWP is defined as the potential of global warming in a period of 100 years, in kg of carbon dioxide per kg of emission, comparing the effect of the liberation of any GHG with that caused by the CO_2. CO_2-eq emissions are related to primary and final energy consumption through specific emission factors. All emission factors are given in kg of CO_2 equivalent. This way, when assessing and environmental comparative analysis of each micro-CHP plant configuration, CO_2-eq emissions can be calculated taking into consideration the corresponding emission factor of each energy resource utilized.

Emissions from each case were considered, in terms of natural gas and electricity, while those relative to the extraction and manufacturing of the components were neglected [36]. This way, the differential emissions with respect to the reference case, Δm_{CO_2-eq}, were calculated. The pollutant mass of each plant configuration, m_{CO_2-eq}, can be disaggregated into the different energy sources and be calculated as follows:

$$m_{CO_2-eq} = \mu_F \cdot F + \mu_E \cdot E \qquad \text{Eq. (3)}$$

where μ_f and μ_e are the specific CO_2 emission factors of natural gas and electricity, respectively, and E stands for the net electricity consumption, once discounted that produced by the micro-CHP unit.

2.3.2. Exergy analysis

As underlined by Bejan [37], the objective of any TES system is not only to store energy, but also exergy. Thus, when evaluating their performance, the capacity of storing exergy should also be analyzed. Additionally, as pointed out by Campos-Celador et al. [38], working with stratified tanks has a direct impact in the global performance of any plant, as stratification is not ideal and always implies some mixing. In this sense, an exergy analysis, which takes into consideration the Second Law of Thermodynamics, is considered to be a proper way to analyze this effect.

With data obtained from the simulations, main exergy flows through the micro-CHP plant were obtained and, consequently, as every thermodynamic irreversibility implies an exergy destruction, the effects of the tank volume on the exergy performance of the principal equipment could be assessed, finally calculating the exergy efficiency of the installation, as defined in Eq. (4):

$$\psi = \frac{Ex_H + Ex_E}{Ex_F} \qquad \text{Eq. (4)}$$

where ψ is the exergy efficiency, and Ex_H, Ex_E and Ex_F stand for the exergy of the heat supplied, the exergy of the electricity produced, and the exergy of the natural gas, respectively.

On the other hand, the exergy content of the main components of the plant, as indicated by Campos-Celador et al. [39], can be considered to be negligible.

2.3.3. Economic analysis

The economic feasibility is evaluated through the Net Present Value (NPV), so relating the incomes and outcomes existing through the life-time of the installation to the initial investment, as presented in Eq. (5). As the TES volume is only changed from one simulation to another, a comparative NPV is considered. Thus, departing from the configuration with no accumulation capacity, to which NPV=0 is assigned, variations in the tank investment, as well as natural gas input and electricity output values of the micro-CHP are evaluated, with respect to the aforementioned case.

$$NPV = -\Delta Inv + \sum_{n=0}^{n=LT} \left[\frac{\Delta NS}{(1+r)^n}\right] \qquad \text{Eq. (5)}$$

where ΔInv is the differential cost of the storage tank with respect to the reference case, LT is the lifetime of the plant, r is the discount rate, and ΔNS responds to annual cash flows generated with respect to the reference case, calculated as detailed in Eq. (6).

$$\Delta NS = \sum_{j=1}^{j=YT} (\Delta I_E + \Delta I_F)_j \qquad \text{Eq. (6)}$$

where ΔI_E stands for the differential incomes associated to the electricity produced by the installation (taking into consideration specific retributions, as well as both sales and avoided costs due to self-consumption), ΔI_F is the differential income due to avoided natural gas consumption, and YT is the full-year time in the corresponding time-basis.

3. CASE STUDY

This article deals with the implementation of SE-based micro-CHP devices in detached dwellings. As previously revealed by the authors [40], in Spain, this kind of units may only be profitable in the coldest climatic zones, even if current legislative and remunerative frameworks make payback conditions hardly achievable [41].

3.1.BUILDING SELECTION

The case study under analysis is a detached house sited in a rural area close to Vitoria-Gasteiz, Basque Country (Northern Spain). The dwelling, which was geometrically modelled using Google Sketch Up along with the TRNSYS 3d plug-in (Figure 7), is a typical single-family dwelling in the north-side of the country, built in the 2010s, with 198 m^2 of thermally conditioned surface distributed among three floors (basement, ground floor and first floor).

Figure 7 – Sketch of the building modelled.

Each of the main elements of the envelope was defined for fulfilling its respective referential transmittance value established by the Spanish Building Technical Code (CTE) [42]. Infiltration rates were based on values set by IDAE [43], whilst the main use patterns of the building, i.e. occupancy profiles, internal gains, ventilation rates and heating set-point temperatures were those established by the CTE [42,44].

Bearing all the described parameters of the household in mind, the selected dwelling is susceptible of being considered as representative for Spanish cold climatic zones. Furthermore, it also represents refurbished detached dwellings, as once a deep renovation on a housing is assessed, those requirements for new constructed buildings must also be fulfilled.

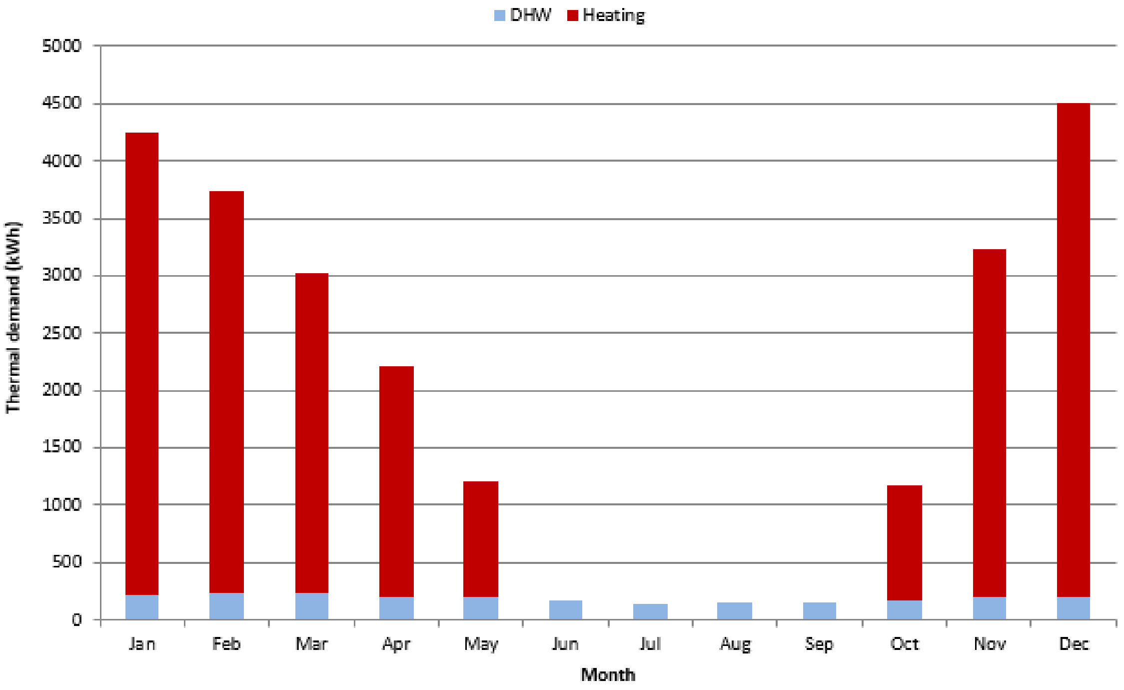


Figure 8 – Monthly distribution of the annual thermal demand.

According to the usage patterns given by Spanish standards, the heating demand of this dwelling on a one-minute basis comes to 22.2 MWh/y, with a power peak of 16.5 kW, while the DHW demand comes to 2,368 kWh/y, both distributed throughout the year as represented in Figure 8.

Concerning DHW, demand values estimated with Spanish standards, being representative of hourly total consumption in the dwelling, do not match accurately the real instantaneous nature of DHW, which is characterized by sharp instantaneous peaks. Thus, when sizing generation devices of the thermal plant, a design margin must be considered in order to deal with these greater peaks. Otherwise, as used in the simulations of this work in order to take into account fairly realistic conditions, 1-minute profiles can be generated with the profile generation tool developed within the IEA Task 26 context [45].

Finally, regarding electricity consumption, it was assumed that the mean demand of a single-family dwelling in Spain is 4,200 kWh [46]. Daily electricity consumption profiles were obtained based on monthly values shown in Figure 9 and hourly multiplication values shown in Figure 10, where summer and winter day-profiles are distinguished. Both profiles are provided by the Spanish operator of the electricity grid [47].

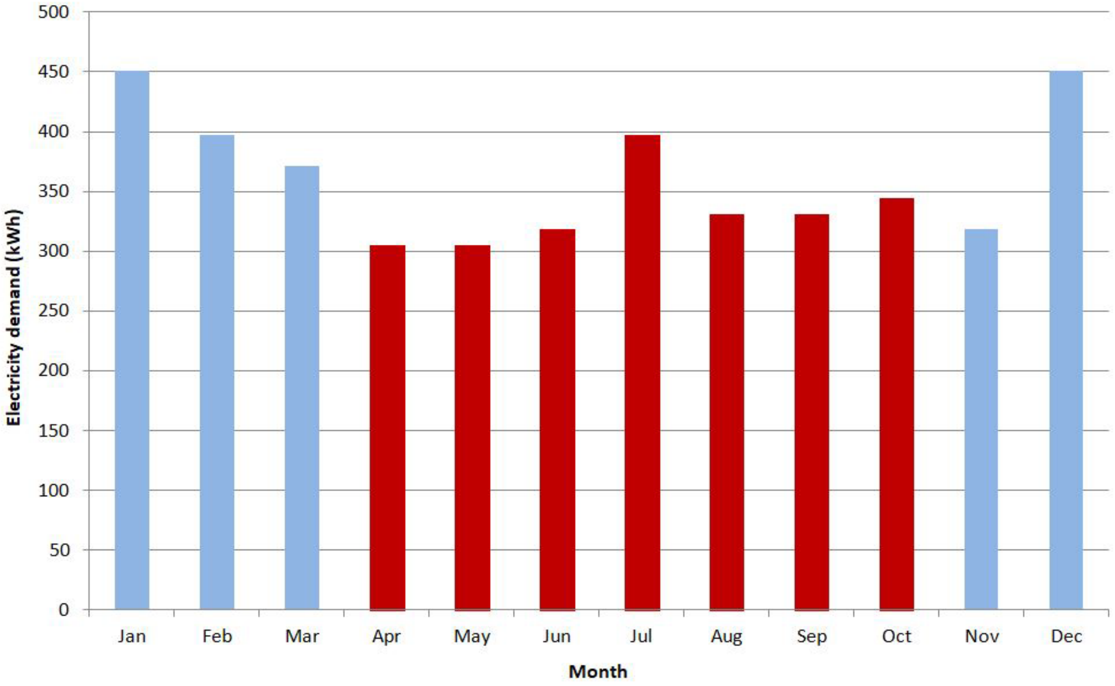


Figure 9 – Monthly distribution of the annual electricity demand.

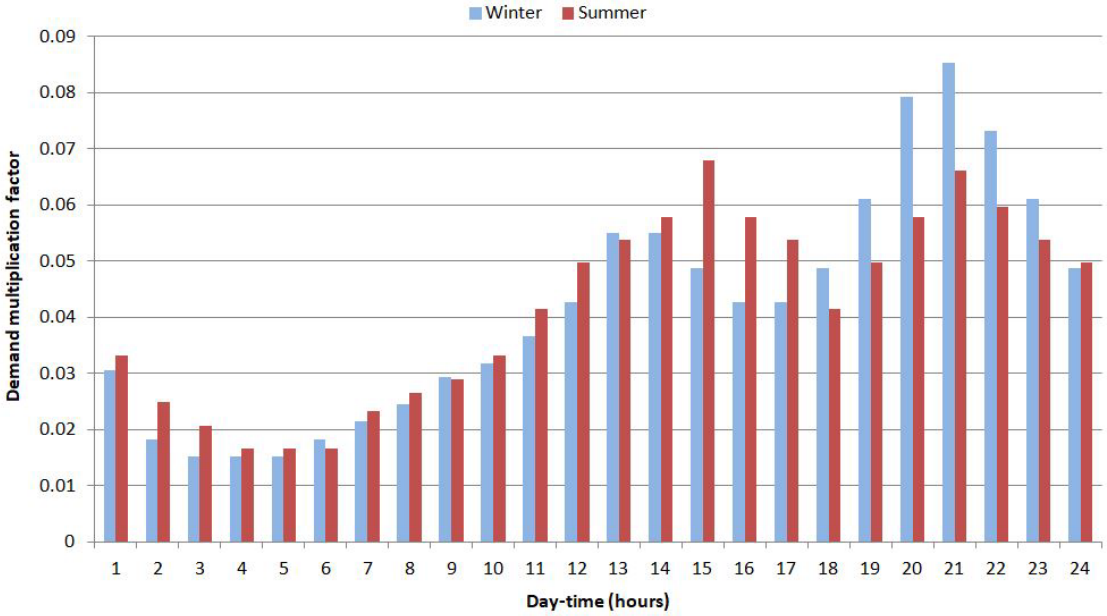


Figure 10 – Daily electricity multiplication factors.

3.2.MICRO-CHP UNIT SELECTION

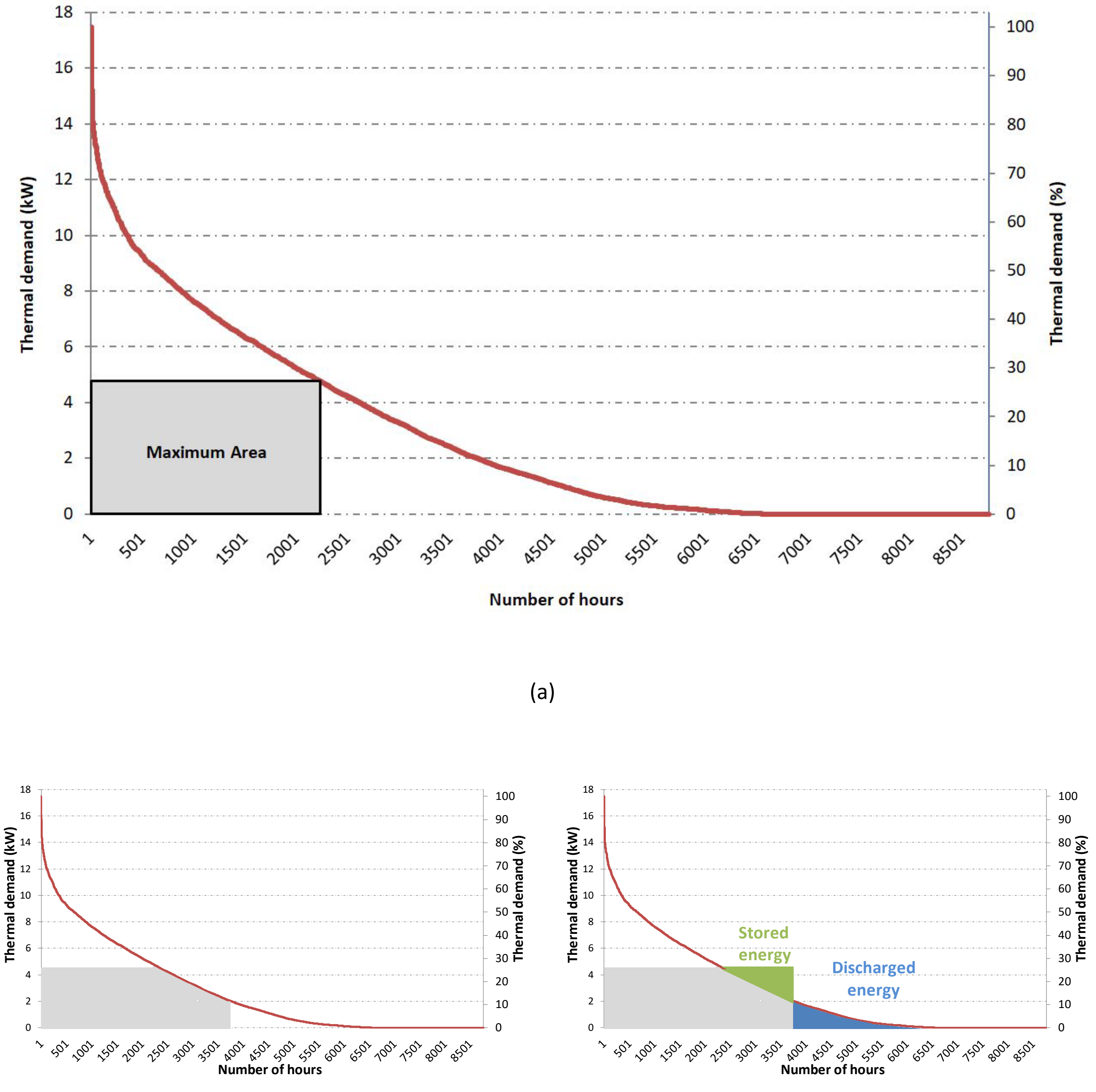
There are several criteria for sizing micro-CHP modules; the most commons are based on maximizing the contribution of the micro-CHP to the thermal demand of the final user. For that purpose, the global demand (space heating and DHW) over a whole year must be determined.

Thereby, once obtained the hourly-basis demand obtained for the reference dwelling, the annual monotonic heat demand curve is built. This curve is a very important tool when sizing micro-CHP modules, as it gives information on the number of hours each demand value is required.

Once built this curve, there are two main criteria for selecting the size of the micro-CHP device:

i. The micro-CHP nominal output remains between 10% and 30% (20% recommended) of the peak thermal demand value.
ii. The micro-CHP nominal output is that power value which allows generating the maximum amount of useful thermal energy at full load.

Even though the second criterion is the most widespread one, it is desirable to fulfil both criteria at the same time, since the first one focuses on avoiding successive warm-up and shutdown periods of the unit, which may damage the unit at the long-run and reduce its useful life considerably [48]. Following these premises, the aforementioned design thermal power is obtained by inscribing the rectangle of maximum area in the monotonic heat demand curve [11], as depicted in Figure 11 (a).



(a)

(b)

(c)

Figure 11 – Maximal area method applied to the monotonic heat demand curve (a) and solutions for incrementing the number of hours of operation: part-load operation (b) and TES (c).

Consequently, a 4.65 kW thermal power value was obtained as optimum (26% of the peak demand), corresponding to 2311 hours per year running at full load, which turns into covering an energy demand of roughly 10.7 MWh/y.

This sizing method, nevertheless, can sometimes present the drawback that the maximum thermal production corresponds to a high thermal power and a low number of running-hours. Amongst the multiple existing possibilities to solve this fact [49,50], part-load operation and TES are, as depicted in Figure 11 (b) and (c), respectively, key in small residential applications.

Table 2 – Available small Stirling micro-CHP units[1].

Model	Engine type	Fuel	Input Power* (kW)	Electric Power (kW)	Thermal Power (kW)
Qnergy QB-3500	LFPSE	Natural gas Propane Wood-pellet Biogas	15	3.5	10
Whispergen EU1	Alpha	Natural gas	9.5	1	8.3
Baxi Ecogen	LFPSE	Natural gas Biogas	7.4	1	6
Senertec Dachs	LFPSE	Natural gas LPG	7.5	1	5.8
De Dietrich Hybris Power	LFPSE	Natural gas	7.3	1	5.8
Viessmann Witowin 350-F	LFPSE	Natural gas	6.5	1	5.3
Remeha eVita	LFPSE	Natural gas LPG	6.3	1	5

* The input power is referred to the LHV

Therefore, among the commercially available units, we should select a micro-CHP unit with a nominal thermal power output immediately below the calculated value and, if possible, that allows load regulation to adapt the production to the demand. In Table 2 some of the commercial Stirling units, with thermal outputs below 10 kW are summarized and, heeding the previously considerations, the Remeha eVita engine might seem to be the one that fits best.

The Remeha eVita micro-CHP device is based on a linear free-piston Stirling engine (LFPSE) developed by Microgen Engine Corporation, which produces around 1 kW_e [51]. Furthermore, the unit also contains a supplementary burner that allows covering peak demands up to 23 kW. This way, being the peak demand of

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[1] Data according to manufacturers

the building around 18 kW, makes no additional generation device necessary. Concerning to its installation, its design and dimensions make of it a suitable device for wall-mounting, as conventional condensing boilers are.

Thus, all these facts make of the Remeha eVita the most appropriate Stirling-based boiler for the case-study and in more global terms, due to the representativeness of the dwelling assessed, for any detached house in the northern half of Spain.

3.3.OPERATIONAL AND ECONOMIC ASSUMPTIONS

In this section, some considerations concerning different aspects of the methodology described in Section 2 are introduced, so that this evaluation procedure can be particularized to analyse the case-study presented.

Before running TRNSYS 17 simulations of the different plant configurations assessed, some assumptions on the operative parameters of the models employed (see Section 2.2) have to be made. In this sense, concerning the generation unit defined for the case-study, the Remeha eVita unit is equipped with a control that enables varying the generation set-point temperature from 30 up to 85 °C. Taking into consideration those cases where DHW is produced through a hot water tank, and that the terminal units considered for the building are traditional high-temperature radiators, the production temperature of the unit was set to 75 °C. The micro-CHP unit is externally governed by a controller that aims to maintain the temperature of the water delivered to the demand side above 60 °C. This control provides the installation with a hysteresis that avoids repeated on-off cycles of the generation unit. Thus, once the unit switches off, it will not turn on again until the bottom temperature of the tank or the hydraulic compensator drops below 62 °C. This helps to get a smoother operation of the SE.

Hot water tanks employed in the cases set out, according to accumulation capacities traditionally employed, have a volume of 200 and 500 litres for DHW and TES, respectively. In those cases when DHW is produced instantaneously, and the total storage volume (DHW + TES) is to be maintained in a combined single TES system for enabling a comparable comparison afterwards, due to market-availability reasons, the capacity of the combined buffer-tank is 750 litres. These tanks, as well as hydraulic compensators which have a capacity of 15 litres, have a mean heat loss coefficient of 0.25 W/m^2·K (according to several catalogue data obtained from different manufactures), while no heat losses associated to the piping have been considered due to its good external insulation and the fact that it mostly goes by through conditioned spaces. Additionally, when utilizing the model of these deposits, 10 temperature levels have been considered. Concerning the demand side of the installation, the heating control is performed by a thermostat that aims to maintain the control room temperature between 17 and 18 °C from 11 p.m. to 7 a.m. and between 20 and 21 °C during the day. With respect to the heat exchanger responsible of instantaneously or tank-through producing DHW, a constant effectiveness of 90% was assumed.

On the other hand, the different plant configurations implemented in TRNSYS 17 were simulated for a year with a time-step of 1 minute. Doing so, transient effects of the plant, such as start-up and shut-down processes of the SE and filling of hot water tanks, could be taken into consideration avoiding convergence problems [52]. From these simulations, flow rates, temperatures and energy flows were obtained, so enabling the annual evaluation of each configuration.

Concerning the energy analysis described in Section 2.3.1, when calculating the PES value according to Eq. (1), references parameters for separate heat and electricity productions ($RefH_\eta$ and $RefE_\eta$), according to the EED, acquire values of 0.9 and 0.45, respectively.

Regarding GHG emissions, the emission factor considered for the combustion of natural gas, μ_F, was 0.252 kg CO_2-eq per kWh, while that due to the production of a kWh of electricity, μ_E, according to the energy mix shown in Figure 12, was 0.331 kg CO_2-eq per kWh [53].

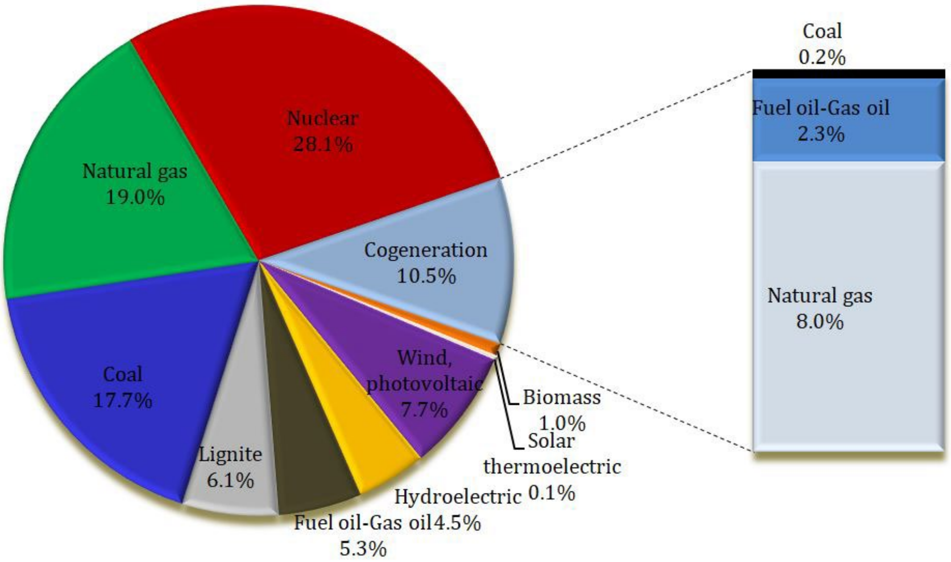

Figure 12 – Spanish energy mix [49].

Additionally, for determining the differential incomes associated to the electricity produced by the installation, Spanish electricity prices and specific retribution were considered. Thus, this term used in Eq. (6) was calculated as indicated in Eq. (7):

$$\Delta I_E = R_{inv} \cdot \dot{E}_{nom} + R_o \cdot E_{grid} + i_e \cdot E_{net} \quad \text{Eq. (7)}$$

where R_{inv} and R_o are the retribution to investment and to operation of the micro-CHP unit, respectively (as explained in [41]), $\dot{E}_{nom}$ is the nominal power output of the micro-CHP unit, E_{grid} stands for the electricity exported to the grid, i_e is the specific income due to sold and self-consumed electricity, and E_{net} is the net electricity production of the micro-CHP unit.

In the current work, R_{inv} was neglected since this complement is attributed to the purchase of the micro-CHP device, while when dealing with electricity and fuel consumptions, only the variable terms are considered, as the fixed terms are common for every case. Therefore, according to RD 413/2014, which regulates the electricity production-activity based on renewable energies and cogeneration in Spain [54], the incentive to operation R_o corresponding to the selected micro-CHP unit is 78.05 € per MWh_e poured into the grid. Additionally, whilst natural gas purchase-price is 5.04 c€/kWh [55], tariff corresponding to purchased electricity, according to the most common taxation modality, is 12.41 c€ [56], while no income corresponding to sold electricity was considered since no guaranteed payment is nowadays established. A discount rate of 5% is considered for the economic assessment.

Finally, for taking into consideration investment costs of tanks, based on various databases and commercial catalogues, an expression proposed by [49] relating investment costs (Inv_{TES}), in €, to the volume of hot water tanks (V_{TES}), in litres, was used (Eq. (8)):

$$Inv_{TES} = 29.968 \cdot V_{TES}^{0.6382} \qquad \text{Eq. (8)}$$

3.4.RESULTING CONFIGURATIONS

According to the different options of arranging TES and the load priority designs discussed in Sections 2.1.1 and 2.1.2, respectively, different simulation cases were obtained. When analysing all the resulting scenarios, each case is named according to the nomenclature explained next: first, the configuration of the TES is referred to (P: parallel, S: series), second the distribution arrangement (load priority) is expressed (P: parallel, S: series), then the TES volume is indicated and, last, the DHW tank volume is specified. The main configurations considered for the current analysis are summarized in Table 3.

Table 3 – Summary of the main configurations contemplated.

Case ID	TES arrangement	Load priority	TES volume	DHW accumulation volume
PP500.200	Parallel	Parallel	500	200
PS500.200	Parallel	Series	500	200
PP500.000	Parallel	Parallel	500	0
PS500.000	Parallel	Series	500	0
PP750.000	Parallel	Parallel	750	0
PS750.000	Parallel	Series	750	0
SP500.200	Series	Parallel	500	200
SS500.200	Series	Series	500	200
SP500.000	Series	Parallel	500	0
SS500.000	Series	Series	500	0
SP750.000	Series	Parallel	750	0
SS750.000	Series	Series	750	0

4. RESULTS AND DISCUSSION

Applying the methodology exposed in Section 2 to the case study, together with the assumptions set in Section 3, results summarized in Table 4 were obtained for each configuration simulated.

First, when analysing results corresponding to the parallel TES arrangement, it can be appreciated that, when dispensing with DHW tank, better results are obtained in general terms, even when the global storage volume is smaller. In this sense, under a similar total volume of accumulation, while both overall efficiency and PES values remain virtually constant, the total operation-time of the engine and the running-hours per on-off cycle, i.e. the mean length of the operation periods, increase substantially.

Table 4 – Summary of the annual behaviour of the micro-CHP plant.

Case	ON/OFF cycles	Hours of operation		Net electricity (kWh)	Net thermal energy (kWh)		Fuel consumption (kWh)		η (%)	PES (%)	ψ (%)
		Total	Part-load		SE	Aux. burner	SE	Aux. burner			
PP500.200	666	3503	310	2859.1	13870.3	8444.9	20135.9	10630.3	81.5	7.5	12.1
PS500.200	866	3174	486	2560.2	12390.5	9962.7	18079.3	12524.4	81.1	7.1	11.3
PP500.000	647	3489	286	2837.4	13804.0	8327.2	20067.8	10490.3	82.2	7.3	12.7
PS500.000	922	3173	487	2537.1	12305.8	9866.0	18051.8	12428.5	81.6	6.5	11.9
PP750.000	520	3720	331	3043.3	14597.9	7520.0	21338.1	9534.5	82.1	7.2	13.2
PS750.000	720	3420	517	2804.5	13250.2	8933.0	19439.9	11335.3	81.5	7.2	12.4
SP500.200	627	3372	103	2726.1	13802.7	9318.9	19629.2	11521.9	79.7	8.2	11.5
SS500.200	613	3530	157	2844.2	14462.3	8128.1	20480.8	10098.1	82.0	8.5	12.2
SP500.000	530	3428	189	2745.4	13397.5	9192.9	19832.7	11353.3	80.0	5.5	12.1
SS500.000	494	3517	175	2827.4	14368.4	8422.5	20375.8	10473.1	81.4	8.4	12.6
SP750.000	446	3653	241	2914.8	14265.2	8384.4	21061.4	10349.3	80.0	5.7	12.5
SS750.000	420	3760	208	3017.0	15346.2	7571.8	21738.4	9382.6	81.3	8.5	13.1

Concerning the load priority, widely better results are obtained with parallel distribution. This fact is directly related to the mass flow of the cold-side of the TES. Since the generation device is controlled with the low-side temperature of the tank and the return temperature to the tank is lower as a consequence of pumping fewer mass flow to the demand side, the return temperature to the tank is consequently lower. Thus, this temperature reduction increases the need for switching generation on, consequently reducing the part-load operation.

In brief, within the parallel arrangement of TES, according to efficiency indicators established, case PP500.000 would be the most suitable. Even if the net energy provided by the SE in PP500.000 is slightly smaller than in case PP500.200, being the global storage volume nearly 30% smaller (so avoiding investment costs in the DHW tank and the pump of the secondary loop of the heat exchanger), the number of hours of operation per on-off cycle is virtually equal.

Regarding to the series layout of the TES, similar conclusions to those of the parallel arrangement are drawn, except for that series connection of the two consumption loops (DHW priority) allows achieving better efficiency results. Although the yearly running-time of the SE is similar in both load-priority configurations (slightly higher when distributed in series), the number of on-off cycles of the engine when giving priority to DHW is lower. As a consequence of these two facts, demand-side distribution in series gives raise to longer operation periods and better energy results, since efficiency losses due to start-up and shut-down periods of the engine are avoided to a greater extent. Consequently, within the series layout of TES, distribution in series and instantaneous DHW production would be the most efficient solution.

Finally, when comparing both TES arrangements to each other when identical storage capacities are disposed (cases PP500.000 and SS500.000), it can be highlighted that, in general terms, installing TES in series provides slightly better results than doing it in parallel. In this sense, this series arrangement enables substantially increasing the annual hours of operation while also drastically decreasing on-off cycles of the unit, so getting longer and smoother operational cycles. This fact turns into a considerable increment of both the percentage of thermal demand covered by the SE (64.7 % versus 61.7 %) and the PES value, while global energy and exergy efficiencies are slightly higher in the parallel arrangement, which is consequence of a better performance of the tank. In this sense, although both arrangements provide similar maximum amounts of energy stored per litre of capacity (1.11 versus 1.12), it is also noteworthy that the efficiency of the tank in the series arrangement is notably lower (94.6% versus 97.5%). This is explained by the fact that charging and discharging processes do not occur simultaneously, unlike it is sometimes the case with the parallel configuration, and therefore, energy losses are more noteworthy. Focusing on the capacity of storing exergy of the TES when arranged in parallel and in series, it turned out annual exergy destructions of 220 kWh and 348 kWh, turning into efficiencies of 94.4 % and 78.7 %, respectively, so demonstrating a better performance of the tank when arranged in parallel. This fact is mainly due to the layout of the inlet-outlet pipes of the tanks since, in parallel, hot and cold flows are always top and bottom-connected, respectively, so maintaining and taking advantage of the different temperature levels reached within the tank. Providing TES with a top-bottom connection when charging and a bottom-top layout when discharging would substantially improve the exergy performance of the TES when arranged in series but, as previously discussed, it would turn into a quite complex and expensive control for such a housing. Taking all the above-exposed considerations, apart from the instantaneous DHW production and the corresponding distribution design determined for each case, it cannot be categorically stated that the optimum operation of this kind of installations would be achieved by arranging a heat buffer in series or in parallel. Consequently, taking previously highlighted cases PP500.000 and SS500.000 as a baseline, a parametric analysis is carried out to determine both the optimum integration and size of the TES, where economic aspects are also introduced.

4.1.Parametric analysis

According to results summarized in Table 4, it seems evident that sizing the TES system is a crucial aspect when designing this type of installations. Thus, for finally defining the optimal configuration, a parametric analysis based on some relevant indicators was also conducted. For determining the optimum storage capacity, technical and economic indicators, both jointly and separated, were assessed for each of the two cases previously selected (PP500.000 and SS500.000).

First, operational indicators were analysed. In this sense, results show that, for both series and parallel arrangement, the sharpest reduction of the number of on-off cycles of the engine per unit of volume of TES occurs when increasing the tank capacity up to 100 litres approximately, afterwards continuing that reduction substantially up to 350 litres, turning into mean operation periods of roughly 5 hours. Such effect almost mitigates with volumes bigger than 400-450 litres. Furthermore, when compared, it was obtained that, averagely, the engine switched on every 4.1 and 5.6 hours, respectively, for cases PP350.000 and SS350.000, becoming into almost 40% on-off cycles less for the series case.

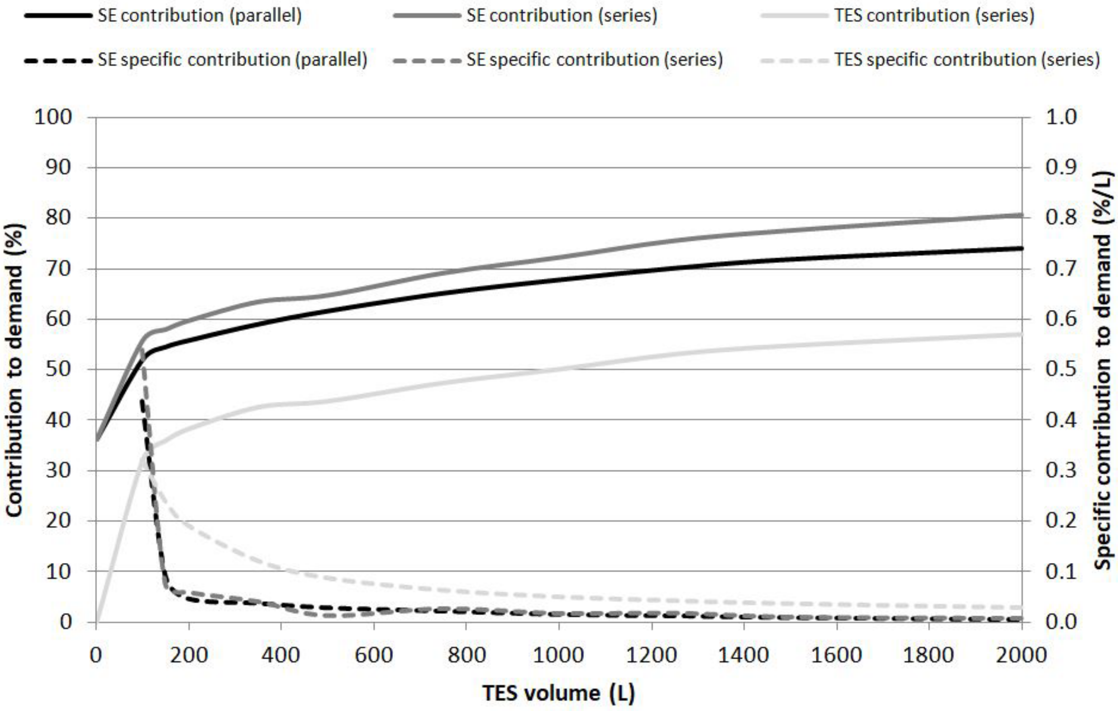

Figure 13 – Variation of the contribution of the SE and the TES to the demand in function of the storage volume.

Concerning energy terms, the percentages of demand covered by both the SE and the TES (in the series case) undergo important increases as the tank gets bigger. However, when analysing these two terms per unit of volume of accumulation of the tank (specific contribution), it is observed that the bigger the tank, the lower this specific contribution. This fact means that adding an extra accumulation unit diminishes the energy each accumulation unit provides. As shown in Figure 13, the greatest agreement between both absolute and specific contributions corresponds to an accumulation capacity of around 105 litres. If the coverage percentage is to be optimized, storage volumes close to 160 litres would be the most suitable. Additionally, it can also be observed that series arrangement does always allow the engine to deliver substantially more thermal energy than the parallel case does.

Something similar happens to PES. In this case, the best agreement between absolute and specific values happens at 130 litres, although the optimum PES value for the series case is achieved at a slightly higher value. Meanwhile, for volumes above 450 litres PES growth lessens due to the higher specific weight of heat losses, up to the point that for big volumes it trends to reduce. Comparing both configurations, PES shows an evolution where two sections can be distinguished: first, up to volumes of 250 litres, parallel arrangement presents slightly better PES values while, from that point on, this trend is reverted and, moreover, parallel connection shows a negative slope. This fact is due to the weight losses in the hydraulic compensator disposed in the series case has on the efficiency of the plant when working with low storage volumes.

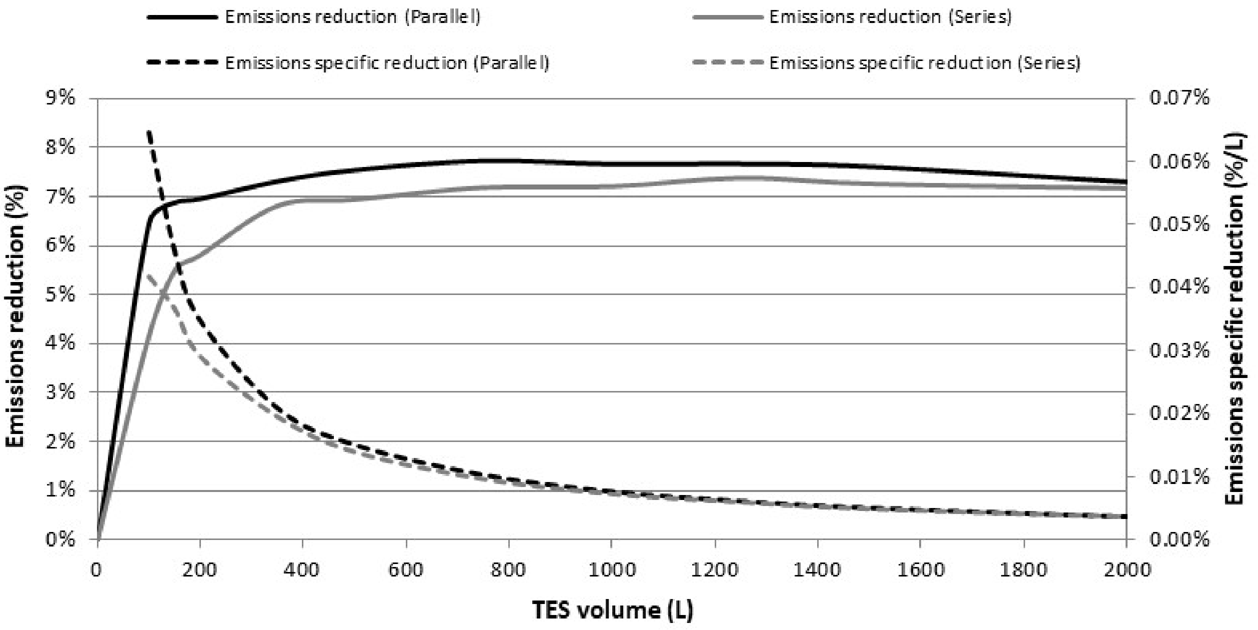

Figure 14 – Variation of the GHG emissions reduction in function of the storage volume.

On the other hand, concerning GHG emissions, it was detected that emitted CO_2-eq is quite similar in both cases. Besides, as depicted in Figure 14, even though emissions per unit of volume keep on reducing as the volume of the tank gets increased, the most pronounced reduction occurs during the 0-150 interval, afterwards keeping relatively flat. As occurs with the PES, high accumulation levels give raise to negative reductions in emissions due to the higher importance of heat losses. Attending to the environmental optimum size of the TES given by the intersection between absolute and specific percentage reductions, this happens for a capacity of 125 litres.

With regards to exergy, even though it is true that overall irreversibilities in the plant get reduced as the size of the tank increases – irreversibilities due to heat losses through the walls of the tank increase, but irreversibilities due to mixture of the water decrease to a greater extent –, these reductions respect to variations on the tank volume are very limited for volumes higher than 150-200 liters, as highlighted in Figure 15. Furthermore, it is noteworthy that, opposite to the PES trend, the exergy efficiency of the plant is slightly better with series arrangements for small storage volumes (up to 300 liters) and, subsequently, the parallel configuration is to reach better results.

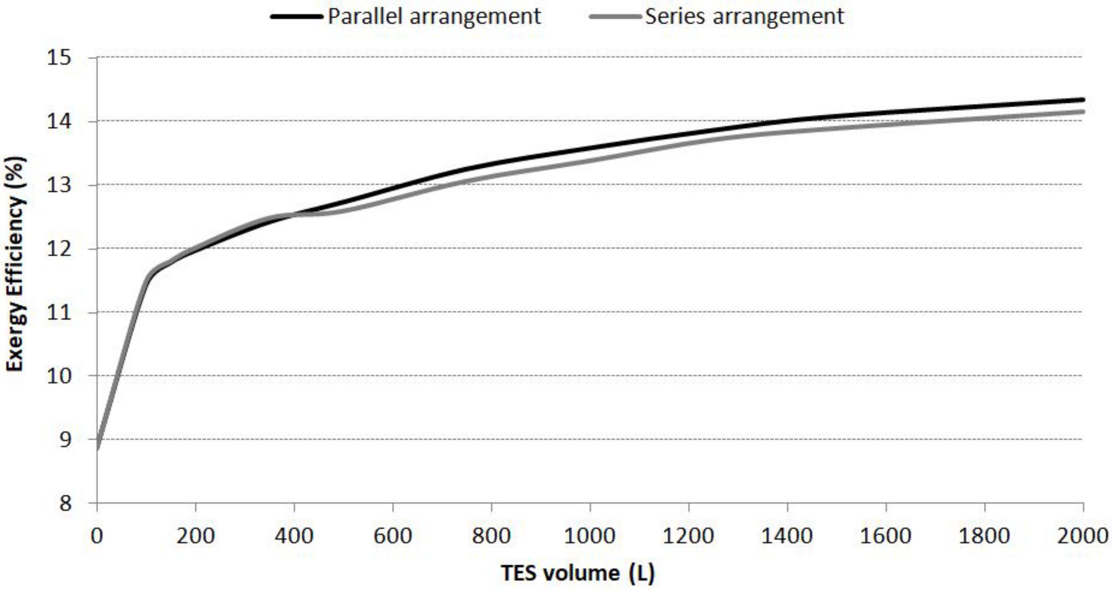

Figure 15 – Overall exergy efficiency of the installation with respect to the TES volume.

From the economic point of view, it was observed that the optimum volume is far from those traditionally installed (500 litres for generation units with similar sizes to that considered), being the most appropriate around 120 and 150 litres for the parallel and the series arrangements, respectively, for the case-study, as plotted in Figure 16. In any case, the NPV of the parallel arrangement of the TES is virtually always slightly higher than that of the series one.

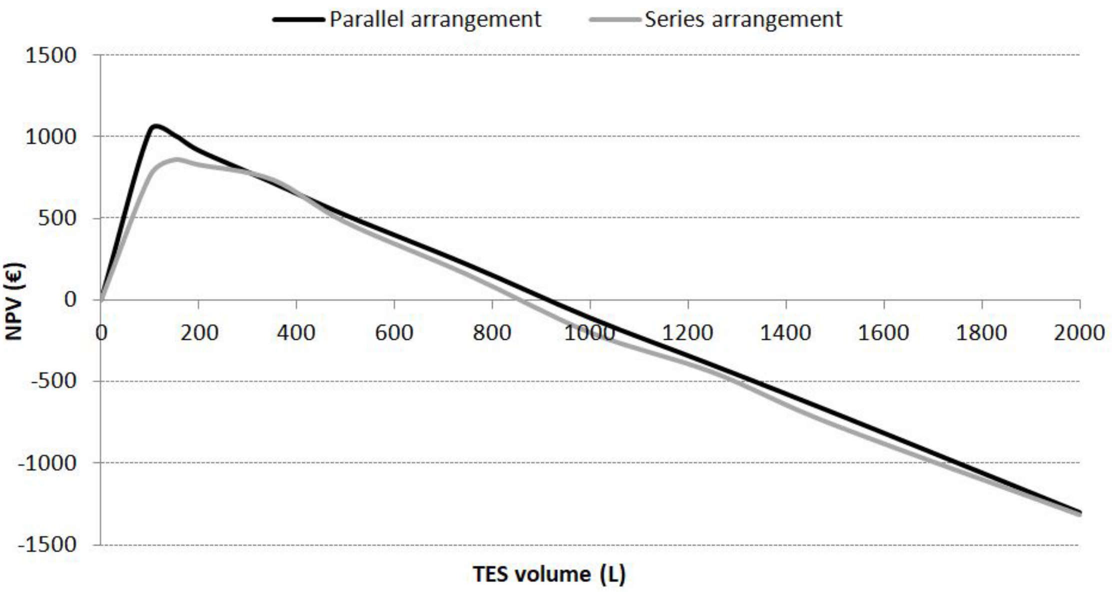

Figure 16 – Net Present Value of the tank investment with respect to its volume.

Taking into consideration all the aforementioned issues, it can be stated that, in general, for small accumulation volumes, installing TES in parallel with both the generation and the demand, as shown in Figure 17, provides better global results. Even though energy and exergy results are slightly worse, as no significant difference is got between both arrangement options, the economic criterion unequivocally sets the best design. Thus, it is concluded that the optimum TES system for such an installation should be installed in parallel, with a storage capacity of 120 litres, corresponding to an accumulation factor of approximately 25 litres of TES per nominal thermal power of the SE.

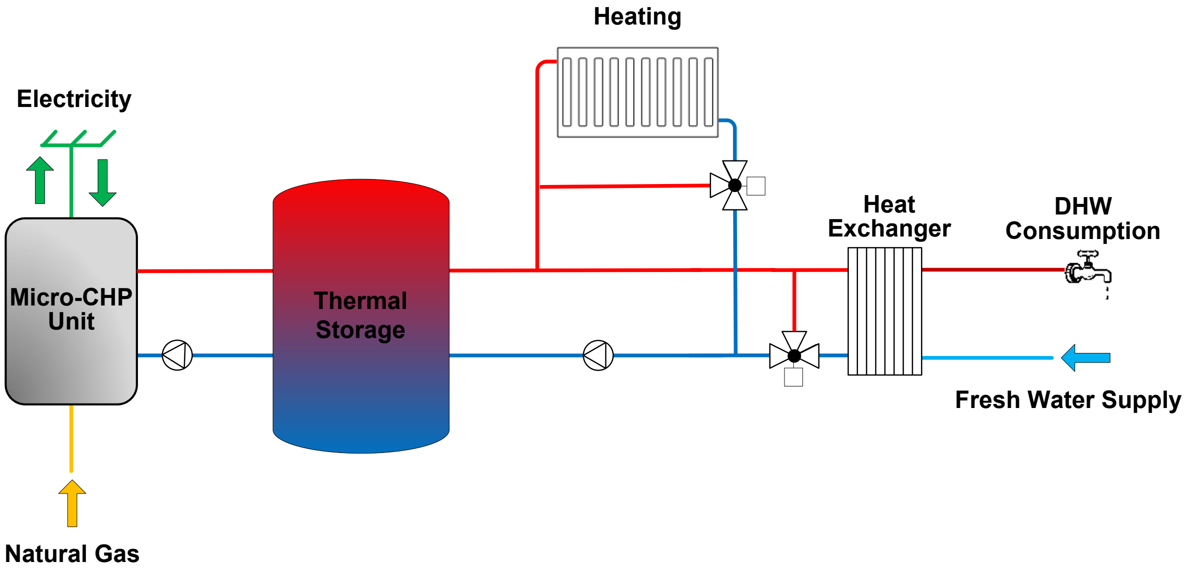

Figure 17 – Schematic diagram of the optimum configuration of the SE-based micro-CHP installation.

Finally, it must be pointed out that, if larger volumes are to be employed in order to increase the operation hours of the engine while diminishing the number of on-off cycles, results show that series connection of the TES will provide much better overall results for accumulation volumes above 300 litres.

5. CONCLUSIONS

This paper has focused on the importance of correctly sizing and designing a micro-CHP residential installation including a TES system. Based on previous works by the authors, how TES should be arranged within the plant has been firstly considered (parallel or upstream / downstream series). Additionally, the need of DHW accumulation has also been assessed. These issues have been combined with the way thermal loads (heating and DHW) are included within the plant, that is load priority, which gave rise to a variety of configurations.

A complete evaluation methodology has been introduced. The energy performance of the micro-CHP has been assessed accordingly to the EED, getting the PES obtained from each case in relation to the separate production of heat and electricity. To assess this PES in cases when both the micro-CHP and the traditional back-up source are integrated within the same device, an exergy-based assignment has been proposed in order to decouple heat losses of the TES associated to each generator. Additionally, the number of on-off cycles and hours of operation of the engine (so giving raise to the mean duration of operation periods) have been considered, since they can have a significant influence on the lifespan of the micro-CHP unit. Not only the performance of the SE has been assessed, but also the performance of the TES, so that the effectiveness of the charge and discharge processes can be maximised. This has been complemented with the economic yield each solution provides, evaluated in terms of NPV at the end of the lifetime of the micro-CHP unit.

The presented methodology has been applied to the analysis of a case study, with a micro-CHP properly sized for its integration in the considered representative dwelling. Results of the case study show that, in small installations suitable for detached houses, where simplicity is a key factor, it is preferable to directly produce DHW instead of using a tank, as no significant improvement is achieved but efficiency deterioration and higher investment costs. Additionally, it has also been proved that the layout of the distribution loop has an importance on the final performance of the plant that must be kept in mind: increments from 12-13% up to 50% in the PES can be reached if correctly disposing the load priority, depending on if the TES is arranged in parallel or in series.

The case study has been completed with a parametric analysis of the influence the size of TES has on both the performances of the tank itself and the SE and the global functioning of the plant, so that its size can be optimised. Results extracted from this analysis show that TES systems coupled with small-scale micro-CHP engines are traditionally oversized (storage capacities between 2.5 and 5 times higher than the optimum are normally disposed). This oversizing allows slightly incrementing the number of hours of operation of the generation unit at the expense of an important worsening of the economic viability. For those accumulation-volume intervals suitable for installations in single-family dwellings, it is observed that, parallel arrangement of the TES requires slightly lower accumulation values. This way, an optimum size of the tank that allows obtaining better economic results while keeping virtually equal technical indicators when compared to the optimum series arrangement, and, consequently, from a multi-objective perspective, can be achieved.

Finally, it must be remarked that, even though the selected case study can be considered as representative of those detached houses with strong thermal requirements, the performance of any thermal plant is heavily dependent on both the thermal demand profile and the type of control that governs the operation of it. Consequently, for those conditions that may not be represented by the current case study, the proposed methodology could be easily used out of these conditions and constraints in order to widen the results.

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