Design of affordable sustainable energy supply systems for residential buildings: A Case Study

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Abstract

The residential sector plays an important role to mitigate climate change due to its high energy consumption. Polygeneration systems are a suitable alternative enabling efficient use of natural resources with low environmental impact. However, their deployment depends, among other factors, on the economic cost and the legal restrictions. This work analyses the potential reduction of greenhouse gases emissions, expressed in CO_2-equivalent emissions (CO_2eq), in residential buildings installing polygeneration systems and considering the current Spanish self-consumption regulation. This is achieved through a multiobjective optimization, applying a Mixed Integer Linear Programming model, considering economic, environmental and legal aspects. Obtained results provide interesting replicable lessons, and show the interest of collective installations, in which remarkable CO_2eq emissions reductions, above 65% with respect to conventional systems, can be achieved at an affordable cost. Technologies such as photovoltaic, reversible heat pumps, biomass and thermal energy storage are competitive when properly integrated. Furthermore, the sale of renewable electricity to the grid under a net-billing scheme, with suitable electricity sale prices, is an appropriate approach, aligned with the European climate and energy policy. Nevertheless, the current Spanish self-consumption regulation is mostly appropriate for small-medium size residential buildings.

Keywords— Multiobjective optimization, Self-consumption framework, Affordable polygeneration systems for buildings, Renewable energy, Greenhouse gas emissions reduction.

1 Introduction

The residential sector represents about 20% of the final energy consumption and 17% of the greenhouse gases emissions, hereinafter expressed in CO_2 equivalent emissions (CO_2eq), of the IEA (International Energy Agency) member countries [1]. Therefore, this sector plays an important role in the policies to mitigate climate change and its impacts [2]. In fact, this is one of the objective sectors in the pathway to limit the global warming according to the special report of the Intergovernmental Panel on Climate Change (IPCC) on the impacts of global warming of 1.5 °C above pre-industrial levels [3].

Consequently, the need of designing buildings with low energy consumption is a matter of research and study since several years ago [4, 5], oriented to reduce the building's energy demand, through the design of high efficient energy buildings with very low energy requirements [6], as well as through the improvement of the energy efficiency of the energy supply systems and the integration of renewable energy technologies in buildings [7, 8]. Recent studies show that the integration of thermal and electrical systems allow to increase the share of renewable energy, and the reduction of CO_2eq emissions [5]. Hence, the use of polygeneration systems for residential buildings can be a suitable alternative to reduce economic costs and CO_2eq emissions with respect to the separate production of energy services, thanks to an adequate energy systems integration [9].

Polygeneration in residential buildings generally refers to the combined production of electricity, heat and cooling [10]. They consist of different energy technologies, which convert renewable and non-renewable energy resources into the energy services required in the building along the time. Among them, technologies driven by renewable energies play a key role in the design of sustainable energy supply systems for residential buildings [11, 12]. Moreover, they can cover multiple energy demands directly (e.g. electricity from photovoltaic or wind turbines, or heat from solar thermal collectors or biomass boilers) or indirectly by coupling absorption and/or mechanical heat pumps [13, 14, 15]. Nevertheless, non-dispatchable energy technologies, such as wind or solar energy, are not able of covering alone in a reasonable and competitive way the full demand of energy services of buildings. In this respect the combination of non-dispatchable renewable energy sources with dispatchable energy sources (e.g. biomass and/or conventional fossil fuels) and with the integration of energy storage (e.g. electric batteries, thermal energy storage –hot water tanks for heating or chilled water for cooling) allow to reach a significant fraction of renewable energy, to increase the energy security, to reduce the installed capacity of some technologies, to increase the environmental benefits and to reduce the operation costs [16, 13]. Thus, polygeneration offers potential to fulfil the ambitious target of zero energy building (ZEB) because of its flexibility to accommodate more renewable energy sources in the system [17]. However, the economic feasibility of polygeneration systems is highly dependent on the applied energy policies and legal framework.

Concerning energy policy, the pathway of energy systems aims, according to United Nations resolutions on sustainable development [18] signed by a vast majority of world's countries, to the decarbonisation of the energy sector with an increased fraction of renewable energies [19, 20]. In this respect, for example, Mathiesen et al. [21] proposed the integration of electricity, heating and transport sectors in order to achieve 100% renewable energy supply systems. Thus, current European directives ask for the Member States to establish their policies and investment decisions, which include indicative national milestones and actions for energy efficiency to achieve very ambitious short-term (2030), mid-term (2040) and long-term (2050) objectives. For instance, by 2030 greenhouse gas emissions should be reduced by at least 55% as compared to 1990, and to have at least 32% share of renewable energy [22]. And by 2050 European Union aims to become the World's first climate neutral region [22]. Therefore, the evaluation of potential solutions which enable significant reduction of CO_2eq emissions at affordable cost is an important task to be carried out by the governments around the world [20].

In this context, the Spanish government has released the Royal Decree RD 244/2019 [23] which establishes the administrative, technical and economic conditions for self-consumption. This decree settles down two categories of self-consumption: i) self-consumption without surplus electricity production, in which electricity injection to the grid is not allowed, and ii) self-consumption with surplus, in which electricity injection to the grid is allowed. Both self-consumption categories can be applied for individual or collective installations. The self-consumption with surplus type is divided in two types: a) surplus subject to compensation in which the primary energy must be renewable and the installed polygeneration system capacity must be equal or lower than 100 kW, and b) surplus no subject to compensation, when do not accomplish the requirements to receive economic compensation or when voluntarily decide do not receive receive it. The later situation can be caused by the additional administrative and technical requirements and the additional fees charged to sell electricity to the grid. Then, if the surplus of electricity is a small amount, it could be more interesting to avoid these technical and administrative issues. Besides, in this way, surplus of electricity can be delivered to the grid, providing more flexibility of operation and avoiding the additional investment in any dissipator or battery required to manage the excess of electricity produced. On the other hand, when the surplus is subject to compensation, according to the current regulation [23], the economic value of surplus electricity sold to the grid should not be greater than the economic value of consumed electricity from the grid in a billing period, which cannot exceed 1 month. In this work the considered billing period is one year, which is less restrictive and allows to reach more general conclusions.

Accordingly, the threefold aim of this work is: i) to evaluate the suitability of the current Spanish legal regulation [23] in the pathway to reach as much CO_2eq emissions reduction as possible in energy supply systems for residential buildings, ii) establishing guidelines for the optimal design of feasible and affordable polygeneration systems oriented to the transition towards decarbonized energy supply systems, iii) considering also the current European Climate Action objectives and legislation [22]. To do this, a multiobjective optimization considering both economic and environmental aspects was applied to several multifamily residential buildings located in Zaragoza (Spain) in order to find different trade-off solutions. Note that, although several works have applied multiobjective optimization considering those aspects [24, 25, 26], it is the first time that this kind of analysis is made to analyse the ability of a regulation, more specifically the current Spanish self-consumption regulation as a case study to promote feasible reduction of greenhouse emissions at the path required by the European Union. Therefore, the obtained solutions of this work could be considered as a starting point for different stakeholders for the design of energy supply systems for residential buildings in Spain, which should consider the legal restrictions to achieve the key targets defined by the European Union [27, 28, 29].

In this work, it is only considered the impact of energy supply systems on the CO_2eq emissions reduction, starting from predefined energy demands of the residential building, which means that the envelope of the building has not been considered.

For the analysis of the energy supply systems, a synthesis problem based on a superstructure which considers different candidate technologies was defined to evaluate suitable configurations for different economic cost/CO_2eq emissions ratios. These configurations were obtained through the optimization of the polygeneration systems by applying Mixed Integer Linear Programming (MILP).

2 Methodology

2.1 Description of the system

The proposed system should provide different energy services to cover the energy demands of electricity, heat for space heating and domestic hot water, and cooling for air conditioning of a set of dwellings in a multifamily residential building located in Zaragoza (Spain). Each dwelling has a surface area of 102.4 m^2 and an average occupancy of 3 people per dwelling. Three cases of study of residential buildings have been considered namely 12, 24 and 50 dwellings. They establish a relation of the scale to the potential of the current self-consumption regulation to reduce CO_2eq emissions at affordable cost. The limit of the installed capacity according to the RD 244/2019 [23] is 100 kW. In this way, the investors can evaluate the scale of the project to be both profitable and sustainable, being aware of the legal restrictions. The residential building can sign-up a collective contract to cover all energy services. The expected contracted power is above 10 kW; therefore, the electric tariffs 2.1 DHS and 3.0A will be applied in this case [30] according to the available normalized powers from the electric grid [31].

2.1.1 Energy demands

Space heating and cooling demands per dwelling are about 41 and 11 kWht/$(m^2 \cdot year)$ [32]. The electricity demand for appliances is about 28.7 kWh/$(m^2 \cdot year)$ [33]. The domestic hot water (DHW) average consumption is about 28 $L/(person \cdot day)$ [34]. The procedure to obtain hourly data is briefly described as follows [35]: For space heating and cooling demands the *degree days* method was applied for obtaining daily data. The considered base temperature for heating and cooling were 15 °C and 21 °C respectively [36] and the ambient temperature was obtained from the meteonorm database [37]. A hourly function was applied on daily data to obtain hourly space heating and cooling demands [38]. Domestic hot water volume was monthly distributed by applying a distribution factor [39]. The energy required to heat the monthly volume of water was calculated considering the water network supply temperature [40] and the DHW set temperature of 60 °C according to the Spanish regulation [34]. Monthly energy was divided by the days of the month and distributed by means of an hourly distribution function [38]. This procedure assumes that the hourly DHW demand is the same for each day of the month. Annual electricity demand for appliances and lighting was monthly distributed by applying a distribution factor. Then, monthly values are divided by the days of the month and distributed by an hourly distribution function [41]. The procedures briefly described above, provide the hourly demand data series of heating, cooling and electricity, where heating demand consists of the space heating and the domestic hot water. A detailed description of the procedure applied is presented in the work developed by Pinto E.S [35].

2.1.2 Renewable energy production

The hourly photovoltaic energy production per square meter, E_{PV}, was calculated following the procedure described by [42] as a function of the solar radiation over a tilted surface at 36° and azimuth angle 0° [37]. The hourly solar thermal energy production per square meter, E_{ST}, was calculated as a function of the solar radiation over a tilted surface at 36° and azimuth angle 0° as well, and the mean difference temperature between the collector temperature 60°C and the ambient temperature. Space restrictions have not been considered in order to explore how much solar energy could be feasible from a technical and economic point of view. The electrical production of a wind turbine, E_W, depends on the wind speed [37] and was calculated based on the production curve of a wind turbine with nominal capacity of 30 kW [43], following the procedure described by [44].

2.1.3 Input data from the grid

Hourly electricity spot prices [45] in some cases of study are required for the system in order to calculate the revenues for selling surplus electricity to the grid. Moreover, hourly CO_2eq emissions from the grid [46] were considered in order to evaluate the environmental impact of the systems.

2.2 Representative days

The optimization of polygeneration systems considering the entire year data when several time series and binary variables are involved in the model is a computationally demanding task. Therefore, representative days have been widely used in

Table 1: Set of representative days D_{rep}

Month	**day** (d)	**weight** (ω)	**Month**	**day** (d)	**weight** (ω)	**Month**	**day** (d)	**weight** (ω)
February	37	40	June	162	39	August	235	42
March	62	30	June	177	39	October	298	31
April	112	40	July	208	23	December	339	38
April	116	22	August	221	10	December	352	11

several works to tackle this issue [47, 48]. Taking into account that this work considered time series with high variability, such as wind energy production, the kM-OPT method [13] was applied. This method merged two methods, the k-Medoids developed by Domínguez-Muñoz et al. [49] which aims to group the days of the year into clusters so that the cluster members are as similar as possible, and the OPT method developed by Poncelet et al. [50] which consists of fitting the data duration curve obtained from representative periods to the duration curve of the original time series. One of the drawbacks of these methods lies in the non-consecutive order of the selected days, which makes it difficult to carry out monthly analysis in terms of economic billings, therefore, yearly analysis was carried out. Table 1 shows the set of representative days D_{rep} with 12 elements and their respective weights ω. Each representative day consists of a set H of 24 time periods h of 1 hour. Two additional days corresponding to cooling and heating peak demands are considered with weight zero, which have influence in the sizing equipment but not on the operational cost.

2.3 Superstructure

The superstructure depicted in Figure 1 considers the candidate technologies and the feasible connections between them. The system is made up of an electrical and thermal part. The electrical part consists of the electric grid, photovoltaic modules PV, wind turbines *WT*, inverter *Inv*, batteries BAT and inverter-charger *InvC*. The excess of electricity produced by photovoltaic modules or wind turbines that is not sold or stored is wasted by a dissipator. The thermal part consists of biomass boiler *BB*, natural gas boiler *GB*, solar thermal collectors ST, single-effect absorption chiller ACH and thermal energy storage for heating *TSQ* and cooling *TSR*. Components such as cogeneration module *CM* and reversible heat pumps *HP* allow the integration of electric and thermal parts.

2.3.1 Technical, economic and environmental data

The economic investment of the polygeneration system considers an annual interest rate of 5% and a capital recovery factor CRF=0.082 yr^{-1}. Indirect costs were considered by applying a factor of 20% over the total investment cost. This study provides a pre-design of polygeneration systems, therefore, an average unit cost Cu was considered for each technology. A factor Fm was defined to consider the installation and maintenance costs. The VAT (Value-Added Tax) was also applied,

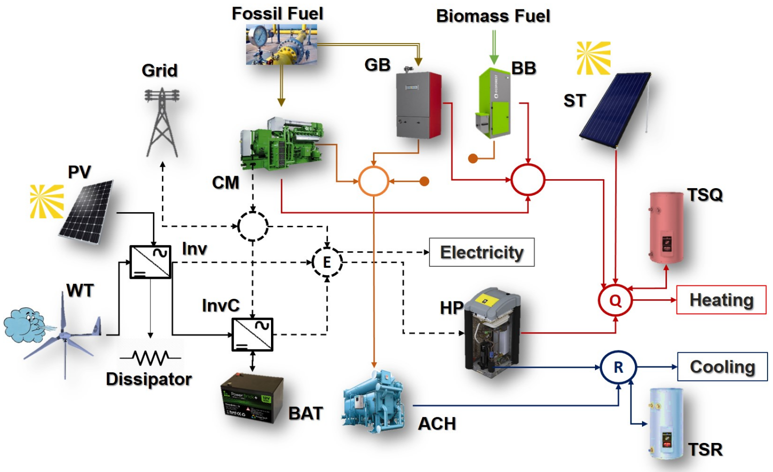

Figure 1: Superstructure

with a value of 21% for Spain (Peninsula). When the lifetime of the component n_{comp} is below the project lifetime, its net present value factor $FNPV$ is calculated in order to take into account the total replacements carried out during the lifetime of the installation. The Table 2 presents the main technical and economic data of the technologies.

The electricity time-of-use tariffs were applied in different scenarios based on economic data of the market, considering the electricity tax $Tax_e = 5.13\%$ and the electricity meter equipment rental cost C_{alq_e} of 16.32 €/yr. In the case of natural gas costs, the contract depends on the annual gas consumption, which is related to the fixed cost C_{f_g}. The variable cost of the natural gas C_{v_g} is proportional to the retail price cp_g. Besides, the gas meter equipment rental cost C_{alq_g} of 7.2 €/yr has been considered. Concerning biomass fuel, the price of the pellets is about 0.04 €/kWht which includes transportation costs [51]. Table 3 and Table 4 summarize the electricity and fuel tariffs.

In order to evaluate the environmental impact, the CO_2eq emissions embodied in every component of the superstructure $CO2_{fix}$ were considered, based on the unit CO_2eq emissions CO_2U of every component (Table 2). Concerning the operational CO_2eq emissions, the CO_2eq emissions released due to the natural gas and biomass combustion were considered, by applying constant values of 0.203 and 0.063 $kgCO_2eq$/kWh respectively [52, 53], and the hourly CO_2eq emissions due to electricity consumption from the grid [46].

2.4 Multiobjective optimization

The aim herein, is to find feasible solutions at an affordable cost, and in turn, it looks for identifying the barriers that impede/limit the reduction of greenhouse gas

Table 2: Technical, economic and environmental data

Component	Technical data (Tech)	Economic data (Econ)			Environmental data (Env)	Based on references		
		Cu	**Fm**	n_{comp}	CO_2U [**kg**CO_2eq**/***]	**Tech**	**Econ**	**Env**
CM	${\alpha_w}^a = 0.28$ ${\alpha_q}^b = 0.56$ $PL^c = 0.15$	1150 €/kWe	0.7	10	65 $kgCO_2eq/kWe$	[54]	[55]	[56]
PV (Polycrystalline)	255 Wp; ${\eta_{mp,sc}}^d = 15.66\%$; $\mu^e = 0.32\%/°C$	113.4 €/m^2	0.9	20	161$kgCO_2eq/m^2$	[57]	[58]	[59, 60]
WT	30 kW Manufacturer curve	2330 €/kW	0.9	20	720 $kgCO_2eq/kW$	[43]	[61]	[62, 63]
ST	${a_0}^f = 0.81$ ${a_1}^g = 3.188W/m^2 \cdot K$ ${a_2}^h = 0.011W/m^2 \cdot K^2$	257 €/m^2	1.5	20	95 $kgCO_2eq/m^2$	[64, 65]		[66]
BB	${\eta_{BB}}^i = 0.90$	240 €/kWt	0.5	20	10 $kgCO_2eq/kWt$	[67]		[56]
GB	${\eta_{GB}}^j = 0.96$	80 €/kWt						
HP	COP^k=3.0 EER^l=4.0	400 €/kWt	0.5	20	160 $kgCO_2eq/kWt$	[68, 69]		
ACH	COP^m=0.7	485 €/kWt	1.5	20	165 $kgCO_2eq/kWt$	[70]		
TSQ	${\lambda_{TSQ}}^n = 1\%$	212 €/kWht	0.1	15	31 $kgCO_2eq/kWht$	[67, 69]		[71, 72, 73]
TSR	${\lambda_{TSR}}^o = 1\%$	257 €/kWht			62 $kgCO_2eq/kWht$			
BAT	${\eta_{rt}}^p = 95\%$ DOD^q=90% ${N_{\phi,failure}}^r = 2000$ ${\lambda_{BAT}}^s = 0.0042\%$	370 €/kWh	0.25	12	160 $kgCO_2eq/kWh$	[74]		[75]
Inv	${\eta_{Inv}}^t = 98\%$	400 €/kW	0	15	191 $kgCO_2eq/kW$	[76, 77]		[59, 60]
InvC	${\eta_{InvC}}^u = 94\%$	774 €/kW	0.25					

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[a] Electrical generation efficiency

[b] Exhaust heat recovery ratio

[c] Partial load

[d] Standard conditions maximum power point efficiency

[e] Temperature coefficient of open circuit voltage

[f] Optical efficiency

[g] First-Order Loss Coefficient

[h] Second-Order Loss Coefficient

[i] Efficiency BB

[j] Efficiency GB

[k] Coefficient of performance HP

[l] Energy efficiency ratio

[m] Coefficient of performance ACH

[n] Hourly energy loss factor for TSQ

[o] Hourly energy loss factor for TSR

[p] Round trip efficiency

[q] Deep of discharge

[r] Number of cycles to failure

[s] Hourly self-discharge

[t] Efficiency Inv

[u] Efficiency InvC

Table 3: Electricity tariffs in Spain (Peninsula)[78, 30].

Time-of-use tariff (I)	Contracted power [kW]	Time period (i)	Winter (h)	Summer (h)	cPct [€/kW yr]	cp[€/kWh]
Tariff 2.1 DHS	10<Pct<15	P1	14-23	14-23	50.187	0.187157
		P2	1;8-13;24	1;8-13;24		0.11527
		P3	2-7	2-7		0.082849
Tariff 3.0 A	15<Pct<30	P1	19-22	12-15	41.951	0.192699
		P2	9-18;23-24	9-11;16-24	25.17	0.172904
		P3	1-8	1-8	16.78	0.129289
	30<Pct<50	P1	19-22	12-15	41.951	0.188567
		P2	9-18;23-24	9-11;16-24	25.17	0.168758
		P3	1-8	1-8	16.78	0.125166
	50<Pct<100	P1	19-22	12-15	41.951	0.185322
		P2	9-18;23-24	9-11;16-24	25.17	0.165525
		P3	1-8	1-8	16.78	0.121922
	100<Pct<250	P1	19-22	12-15	41.951	0.183892
		P2	9-18;23-24	9-11;16-24	25.17	0.164085
		P3	1-8	1-8	16.78	0.120491

Table 4: Natural gas [30] and pellets [51] tariffs.

Fuel	Tariff	C_{fg} [€/yr]	cp_g[€/kWh]	Annual consumption limit [kWh/yr]
Natural gas	3.1	61.8	0.063125	$\leq$ 5000
	3.2	112.2	0.05845	5000−50000
	3.3	650.64	0.050523	50000−100000
	3.4	971.64	0.046843	>100000
Pellets	N/A	N/A	0.04	N/A

emissions. To do this, two objective functions have been considered for the optimization of the polygeneration system: minimization of total annual economic costs and/or total annual CO_2eq emissions. Thus, multiobjective optimization is used to pursue both criteria simultaneously [79]. The optimization of the polygeneration system is carried out by solving a MILP model developed in the optimizer software Lingo [80]. The optimization model is presented below.

Objective functions:

$$Min\,TAC = Min(CIA + C_{ope}) \tag{1}$$

$$Min\,TCE = Min(CO2_{fix} + CO2_{ope}) \tag{2}$$

Regarding the economic objective, TAC is the total annual cost, CIA is the investment annual cost and C_{ope} is the operational cost. Concerning the environmental objective, TCE is the total annual CO_2eq emissions, composed of a fixed part $CO2_{fix}$ corresponding to the annual CO_2eq emissions embodied in the components and the variable part $CO2_{ope}$ corresponding to the annual CO_2eq emissions due to the fossil fuels and pellets combustion, and/or electricity consumption from the grid.

The operational annual cost C_{ope} is the sum of the annual electricity bill cost C_e and the annual fuel consumption cost C_g.

$$C_{ope} = C_e + C_g \tag{3}$$

Subscript $_e$ indicates electricity and subscript $_g$ indicates conventional and/or biomass fuels.

The objective functions are subject to:
The electricity bill C_e is composed of a fixed part C_{fix_e}, and the variable cost C_{v_e} (Eq. 4). The C_{fix_e} is proportional to the contracted power that must be lower or equal to the hourly purchased and sold power (Eq. 5). C_{v_e} (Eq. 6) is calculated based on the electricity consumption E_{pch} at cp_e price and the sale electricity E_s at cs_e price. Values of cp_e and cs_e in €/kWh depend on the time-of-use electricity tariff.

$$C_e = ((C_{fix_e} + C_{v_e}) \cdot (1 + Tax_e) + C_{alq_e}) \cdot (1 + VAT) \tag{4}$$

For each electric tariff period i:

$$Pct(i) \geq E_{pch}(i,d,h) + E_s(i,d,h) \; \forall \; i \in I, \; d \in D_{rep} \; \wedge \; h \in H \tag{5}$$

$$C_{v_e} = \sum_{d \in D_{rep}} \omega(d) \cdot \left(\sum_{h=1}^{24} (cp_e(i,d,h) \cdot E_{pch}(i,d,h) - cs_e(i,d,h) \cdot E_s(i,d,h)) \right) \tag{6}$$

C_g represents the natural gas bill cost which is composed of a fixed part related to the annual natural gas consumption C_{fix_g}, and a variable part proportional to the fuel consumption C_{v_g}.

$$C_g = ((C_{fix_g} + C_{alq_g}) + C_{v_g}) \tag{7}$$

$$C_{v_g} = \sum_{d \in D_{rep}} \omega(d) \cdot \left(\sum_{h=1}^{24} cp_g \cdot F_g(d,h) \right) \tag{8}$$

Regarding the CO_2eq emissions, the operational CO_2eq emissions (Eq. 9) encompass the annual CO_2eq emissions associated to the combustion of each fuel $CO2_g$ (Eq. 10), and the CO_2eq emissions associated to the electricity from the grid $CO2_{gc}$ (Eq. 11).

$$CO2_{ope} = \sum_{d \in D_{rep}} \omega(d) \left(\sum_{h=1}^{24} (CO2_g(d,h) + CO2_{gc}(d,h)) \right) \tag{9}$$

$$CO2_g(d,h) = \sum_{j \in J} (CO2(j) \cdot F(j,d,h)) \; \forall \; d \in D_{rep} \; \wedge \; h \in H \tag{10}$$

$$CO2_{gc}(d,h) = uCO2_{grid}(d,h) \cdot (E_{pch}(d,h) - E_s(d,h)); \forall \; d \in D_{rep} \; \wedge \; h \in H \tag{11}$$

Installation of technologies: The Installation of the components is determined by the binary variable Y_{ins} taking into account the maximum capacity of each component $max\ Cap$.

$$Cap(j) \leq Y_{ins}(j) \cdot max\ Cap(j)\ \forall j \in J \tag{12}$$

Energy balance: Energy balance is carried out in each node of the superstructure for every day d and hour h. The variable u represents the energy (electricity E/W, heating Q or cooling R) value in/out in each time step.

$$\sum u^{in}(\Gamma, d, h) - \sum u^{out}(\Gamma, d, h) = 0\ \ \forall\ \Gamma \in \{W/E, Q, R\},\ d \in D_{rep},\ h \in H \tag{13}$$

Equipment efficiency: Efficiency of every component of the superstructure has been considered. F represents the fuel consumption of the component.

$$BB : \eta_{BB} \cdot F_{BB} - Q_{BB} = 0 \tag{14}$$

$$GB : \eta_{GB} \cdot F_{GB} - Q_{GB} = 0 \tag{15}$$

$$HPQ : Q_{HP} - W_{HPQ} \cdot COP = 0 \tag{16}$$

$$HPR : R_{HP} - W_{HPR} \cdot EER = 0 \tag{17}$$

$$CM : \alpha_w \cdot F_{CM} - W_{CM} = 0 \tag{18}$$

$$CM : \alpha_q \cdot F_{CM} - Q_{CM} = 0 \tag{19}$$

$$ACH : R_{ACH} - COP_{ACH} \cdot Q_{ACH} = 0 \tag{20}$$

Energy storage: In the case of energy storage, the stored energy at the beginning of the day ($h = 1$) must be equal at the end of the day ($h = 24$) (Eq. 21), due to the use of representative days.

$$S(d, 1) = S(d, 24) \tag{21}$$

The energy stored S is evaluated in each time step taking into account their energy loss factor λ to consider the hourly energy losses. In the case of batteries, λ corresponds to the self-discharge value. For each energy storage technology j:

$$S(j, d, h) = S(j, d, h-1) \cdot \lambda + u^{in}(j, d, h) - u^{out}(j, d, h)\ \forall\ d \in D_{rep}\ \wedge\ h \in H \tag{22}$$

The model of capacity used for the batteries is described by Diorio [81]. Besides the hourly energy losses, the round trip efficiency η_{rt} is also considered. In addition, the number of cycles must be lower or equal to the cycle life of the battery $N_{ø,failure}$ [82].

Renewable energy technologies: For the renewable energy production technology, the aim is to find the surface areas of the PV modules A_{PV} and solar thermal collectors A_{ST}, and the number of wind turbines N_{WT}.

$$PV : W_{PV} = E_{PV} \cdot A_{PV} \tag{23}$$

$$ST : Q_{ST} = E_{ST} \cdot A_{ST} \tag{24}$$

$$WT : W_W = E_W \cdot N_{WT} \tag{25}$$

Installed capacity: For each component, the energy production is equal or lower than its nominal capacity. In the case of energy storage, its stored energy must be equal or lower to their nominal capacity

$$u(\Gamma, d, h) \leq Cap(j) \; \forall \; \Gamma \in \{W/E, Q, R\}, j \in J, \; d \in D_{rep}, \; h \in H \tag{26}$$

$$S(j, d, h) \leq Cap(j) \forall \; j \in J, \; d \in D_{rep}, \; h \in H \tag{27}$$

Operational restrictions: Partial load PL of the engine in the case of the cogeneration module is considered by applying a binary variable Y_{ON} along with the $BigM$ number. In this way, the engine can modulate according to the expression:

$$W_{CM} - PL \cdot Cap_{CM} \geq - BigM \cdot (1 - Y_{ON}) \tag{28}$$

$$W_{CM} \leq BigM \cdot Y_{ON} \tag{29}$$

3 Results

The multiobjective optimization of the polygeneration system was carried out for buildings consisting of 12, 24 and 50 dwellings for three different scenarios: scenario 1 in which electricity sale is not allowed, corresponding to the case of self-consumption type 1; scenario 2 in which electricity sale is allowed at spot price; and scenario 3 in which electricity sale is allowed at 80% purchase price. Scenarios 2 and 3 are proposed as particular examples of the self-consumption type 2 [23]. For comparison purposes, a conventional energy system in which electricity is purchased from the electrical grid, a gas boiler (GB) attends heating demands and a mechanical chiller (MCh) covers only cooling demands, was considered as a reference scenario (Table 5).

The results of the reference scenarios have been taken into account to calculate the potential reduction in terms of economic cost and CO_2eq emissions as well as the payback for different optimal configurations along the trade-off solutions of the Pareto curve. The payback is calculated as:

$$Payback[yr] = \frac{CI_{trade-off} - CI_{Reference}}{C_{ope_{Reference}} - C_{ope_{trade-off}}} \tag{30}$$

Table 5: Results of the optimization of the reference systems for 12, 24 and 50 dwellings.

Technology	**12 dwellings**			**24 dwellings**			**50 dwellings**		
	Install Cap	**CIA[€/yr]**	CO_2**fix** [kgCO_2eq/yr]	**Install Cap**	**CIA[€/yr]**	CO_2**fix** [kgCO_2eq/yr]	**Install Cap**	**CIA[€/yr]**	CO_2**fix** [kgCO_2eq/yr]
$Pct_{1,2,3}$ [kW]	$24.2_{1,2}$-17.3_3	-	-	$43.5_{1,2}$-17.3_3	-	-	$110.9_{1,2}$-17.3_3	-	-
HP	70 kWt	5528	562	141kWt	11055	1125	325 kWt	23031	2343
GB	66 kWt	918	33	131 kWt	1836	66	274 kWt	3824	137
	CIA / $CO2_{fix}$	*6445*	*595*	***CIA*** / $CO2_{fix}$	*12891*	*1190*	***CIA*** / $CO2_{fix}$	*26855*	*2480*
Annual operational costs									
Fuel	**Consumption** [kWh/yr]	**Energy cost** [€/yr]	CO_2**ope** [kgCO_2eq/yr]	**Consumption** [kWh/yr]	**Energy cost** [€/yr]	CO_2**ope** [kgCO_2eq/yr]	**Consumption** [kWh/yr]	**Energy cost** [€/yr]	CO_2**ope** [kgCO_2eq/yr]
Electricity	38759	10755	8002	77518	20298	16004	161495	42681	33341
Natural Gas	72901	5253	14901	145813	9449	29804	303757	18401	62088
	C_{ope}/ $CO2_{ope}$	*16008*	*22903*	C_{ope}/ $CO2_{ope}$	*29748*	*45808*	C_{ope}/ $CO2_{ope}$	*61082*	*95429*
	TAC/ TCE	**22453**	**23498**	**TAC/ TCE**	**42638**	**46998**	**TAC/ TCE**	**87938**	**97909**

Where, CI is the total investment cost of the equipment in €, and C_{op} is the annual operational cost in €/yr.

3.1 Multiobjective optimization of the polygeneration systems for residential buildings under legal restrictions

Figures 2-4 show the Pareto curves for the cases of 12, 24 and 50 dwellings and the Table 6 presents the different configurations corresponding to the trade-off solutions along the Pareto curves.

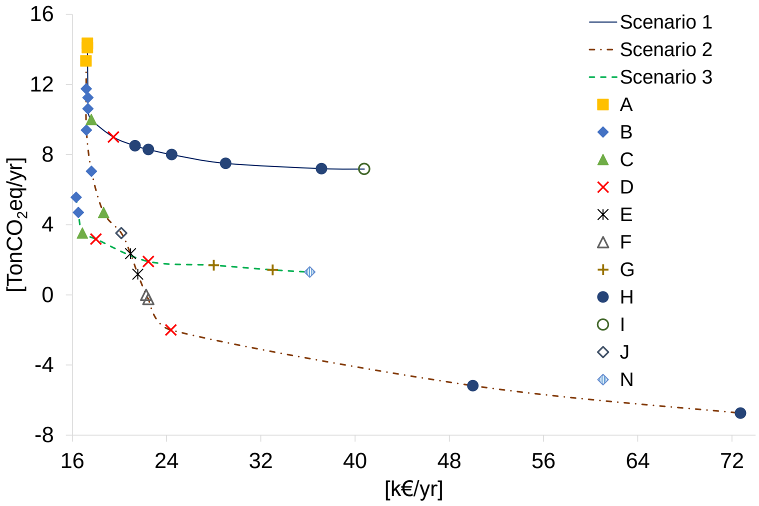


Figure 2: Pareto curves of the different scenarios for 12 dwellings case.

The highest reduction in CO_2eq emissions was obtained in scenarios where selling of electricity was allowed. The more electricity produced with renewable energy was sold, the higher was the reduction of CO_2eq emissions. Note that in all the analysed cases, when it was not allowed the electricity sale, i.e. scenario 1, it was not possible to reach zero CO_2eq emissions. Therefore, in a horizon oriented to achieve zero greenhouse gases emissions (or lower values), selling of electricity produced from renewable energy sources should be allowed. It is noteworthy to remark the Pareto curves shown in figure 4 for the case of 50 dwellings, in which the maximum reduction of CO_2eq emissions is the same for scenarios 2 and 3, because under the current self-consumption regulation [23] the installed capacity of renewable energy technology is limited up to 100 kW. Therefore, the current self-consumption regulation, oriented to foster the implementation of decentralized

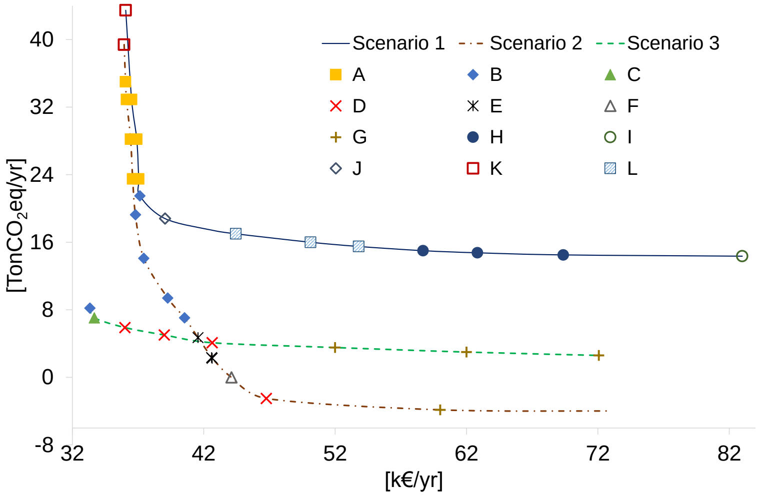


Figure 3: Pareto curves of the different scenarios for 24 dwellings case.

energy supply systems based on renewable energy in buildings, which is also oriented to reach zero CO_2eq emissions, is targeted to small or medium size residential buildings with less than 24 dwellings (based on the considered energy demands). If the regulation would allow higher power capacities than 100 kW [23], the potential of more significant reduction of CO_2eq emissions in big residential buildings would be higher. Therefore, the current self-consumption regulation is not enough to reach long term EU environmental targets on climate neutral by 2050 [28]. Nevertheless, note that as shown in the figures 2-4 in the three scenarios of the three analysed cases there is a sharp reduction of CO_2eq emissions with a relative small increase of economic cost, showing the feasibility of reducing very significantly in an affordable way the greenhouse gas emissions in residential buildings, as it is analysed in more detail in the next subsection. Consequently, the current Spanish self-consumption regulation [23] is nowadays aligned with EU 2030 climate and energy framework targets [28], but from the results obtained in this study the current regulation is not appropriate for reaching long term objective of carbon neutral energy supply systems. Therefore, in the mid-term it would be necessary to modify this regulation when more ambitious objectives on greenhouse gas emissions reduction would be established.

The higher electricity prices encourage electricity sale from renewable energy, which means reducing CO_2eq emissions. However, in the frame of the current regulation [23], there is a point from which the achieved reduction of CO_2eq emissions

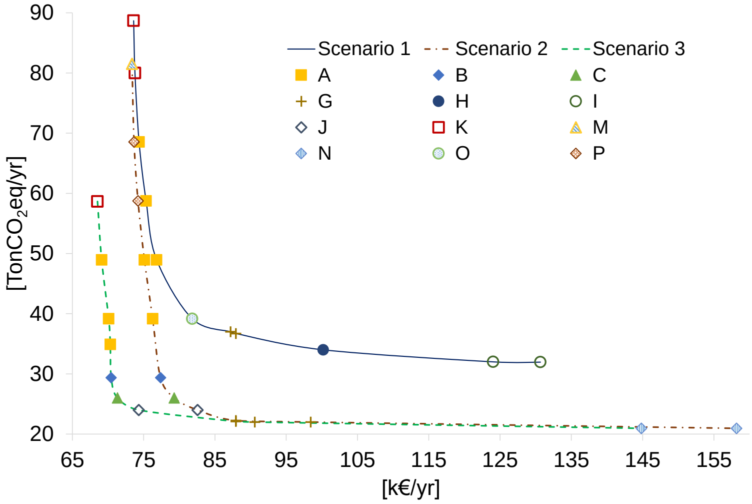


Figure 4: Pareto curves of the different scenarios for 50 dwellings case.

in scenario 2 are higher than those obtained through scenario 3 (Figures 2-3). This is due to the billing time restriction, which establishes that the economic value of surplus electricity cannot be greater than the economic value of consumed electricity from the grid in a billing time, which has been considered a year in this study. Therefore, when net billing restriction is applied, the lower the electricity sale price, the higher the potential amount of electricity produced with renewable energy that could be sold to the grid and the higher the potential of reducing CO_2eq emissions. Obviously, the decentralized electricity produced with renewable energy will be sold to the grid when profitable. From the results shown in figures 2-3, it can be concluded that electricity sold at spot price could be a reasonable and feasible approach. Based on these results, it can be considered that nowadays the scenario 2, providing interesting economic savings with respect to the reference scenario and with the highest potential of CO_2eq emissions reduction, among the considered scenarios, is an adequate approach combining economic profitability and a good alignment with current EU environmental and energy targets [28].

The installed capacities of technologies for the different trade-off solutions are presented below. Among the renewable energy technologies, the PV technology is considered in every trade-off solution in all cases that demonstrate the importance of this technology in the energy transition (Figures 5a, 5c,5e). On the other hand, solar thermal collectors and wind turbines are the less competitive and therefore, they appear in a limited number of trade-off configurations (Table 6), when approaching

Table 6: Different configurations of the trade-off solutions obtained along the Pareto curves.

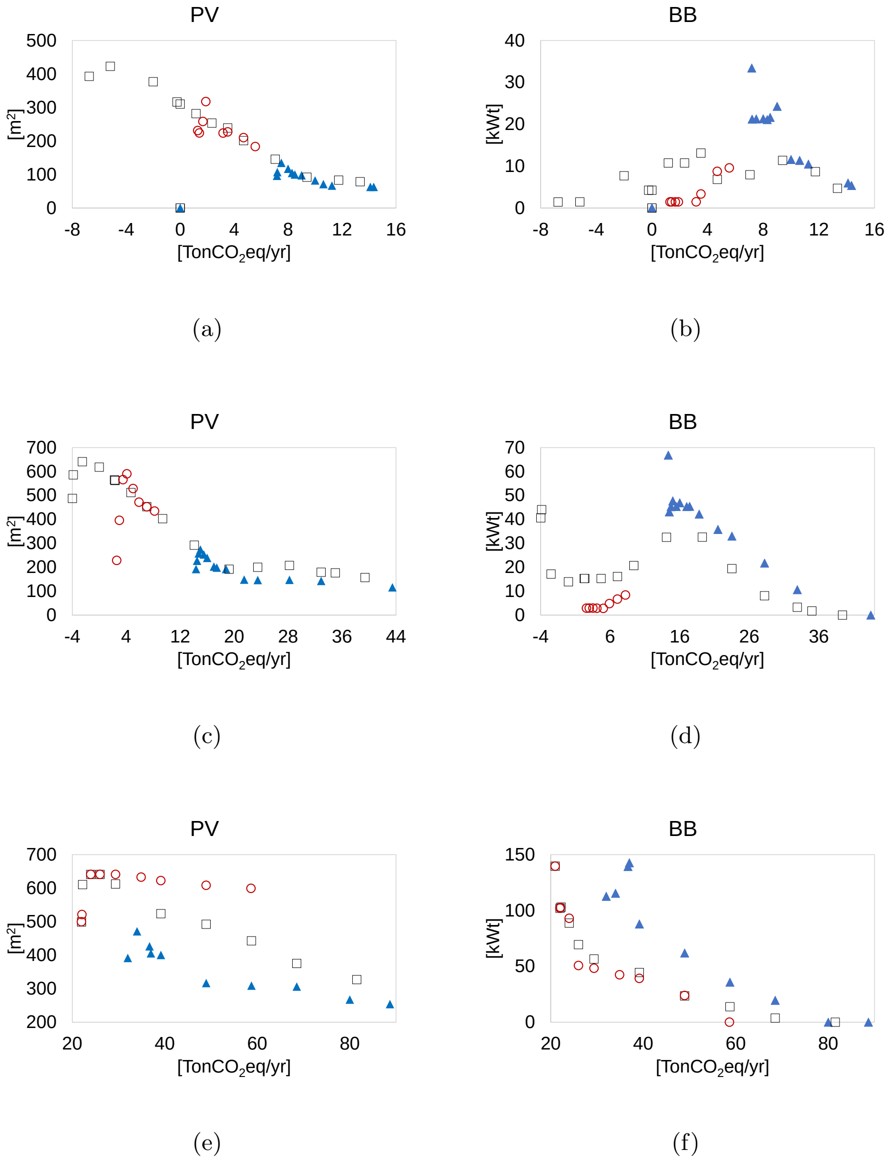
Configuration	**CM**	**PV**	**WT**	**ST**	**HP**	**GB**	**BB**	**ACH**	**TSQ**	**TSR**	**BAT**
A	x	x			x	x	x			x	
B		x			x	x	x			x	
C		x		x	x	x	x			x	
D		x		x	x		x		x	x	
E		x			x		x			x	
F		x		x	x		x			x	
G		x	x	x	x		x		x	x	
H		x	x	x	x		x		x	x	x
I		x	x	x	x		x	x	x	x	x
J		x		x	x	x	x		x	x	
K	x	x			x	x				x	
L		x	x	x	x	x	x		x	x	x
M	x	x			x	x			x	x	
N		x	x	x	x		x	x	x	x	
O		x	x	x	x	x	x		x	x	
P	x	x			x	x	x		x	x	

the environmental optimum and significant reduction of CO_2eq emissions must be achieved. Therefore the graphic of their installed capacity is omitted. In the case of biomass, biomass boiler represents a very interesting alternative to gas boiler and it is selected in most of the configurations (Table 6). Gas boiler technology is the main boiler in the economic optimum. Nonetheless, biomass boiler becomes the main boiler whereas gas boiler tends to disappear in the pathway to reach the environmental optimum (Figure 5b-5f, 6b-6h).

Cogeneration module is not very appropriate in residential buildings for the analysed cases when high CO_2eq emissions reduction must be achieved (Table 6). It appears in configurations close to the economic optimum and its feasibility is higher in bigger collective installations (Figure 6f,6i). In fact, in the case of 12 dwellings, the capacity of the installed cogeneration module is very small (1 kW), and although there are commercial cogeneration module with such a low capacity [83, 84], its feasibility for few dwellings is questionable (Figure 6c).

The heat pump appears in all trade-off solutions (Table 6) with a very significant capacity in the three considered scenarios (Figures 6a, 6d, 6g). It plays a very interesting role in the production of cooling and heating, as well as in the reduction of greenhouse gas emissions because its installation allows the reduction of capacity of gas boiler and cogeneration module. In contrast, the interest of absorption chiller is very limited compared to HP since it is barely selected, and when it does, it is negligible in most of the solutions, therefore the graphic of the its installed capacity is omitted.

The installation of energy storage allows i) the match among energy production and energy consumption when energy resources are non-dispatchable, as it is the

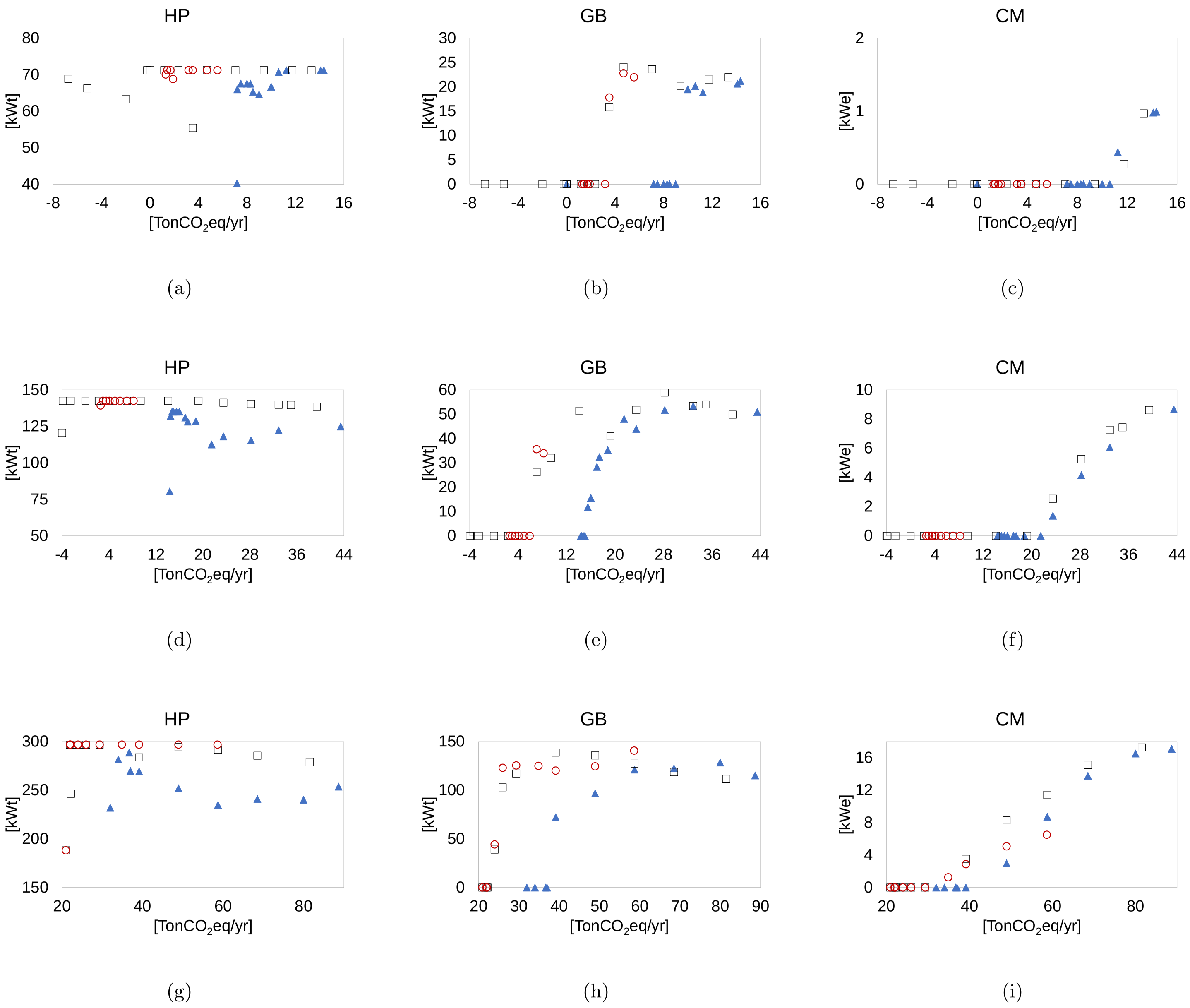


(a) (b)

(c) (d)

(e) (f)

Figure 5: Sizing of the renewable energy technologies, PV and BB, in the trade-off solutions for 12 dwellings (a,b), 24 dwellings (c,d) and 50 dwellings (e,f). Scenario 1 (triangle), scenario 2 (square) and scenario 3 (circle).



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

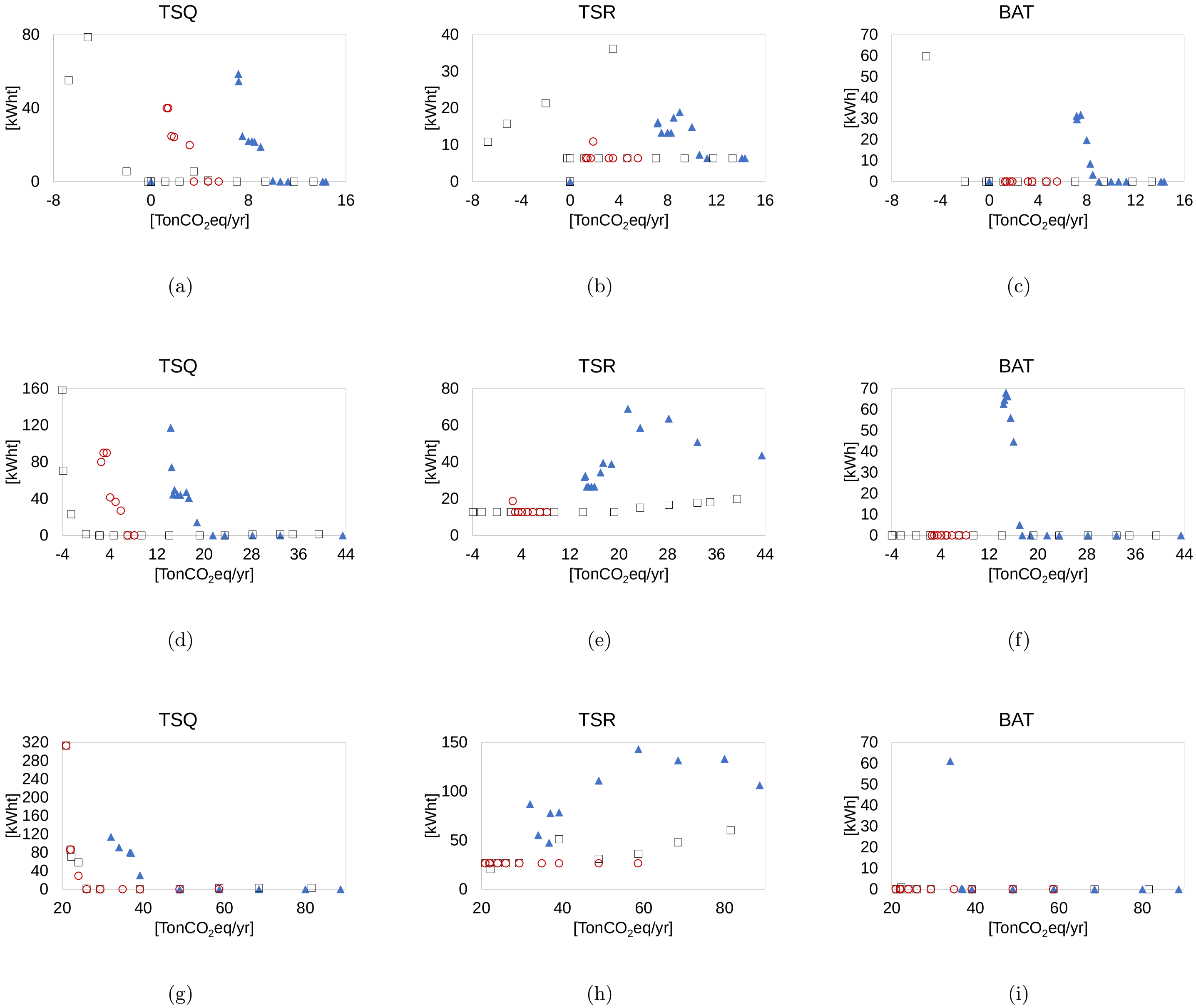
Figure 6: Sizing of the electricity/heating/cooling production technologies in the trade-off solutions for 12 dwellings (a-c), 24 dwellings (d-f) and 50 dwellings (g-i). Scenario 1 (triangle), scenario 2 (square) and scenario 3 (circle).

case of solar (PV and/or ST) and wind energy (WT), and ii) the reduction of the installed capacity of some energy production pieces of equipment, such as heat pump or cogeneration module that thanks to the availability of storing energy they can operate at a high load with lower installed capacity during a longer time period, even when there is not energy consumption, storing the energy produced in order to consume it in the moment where there is a high or peak demand. In this respect batteries appears in a few configurations, due to its high investment cost, when approaching the environmental optimum with a significant production of electricity from non-dispatchable renewable resources (WT and PV) and there is not the possibility of selling it to the grid, as it is the case of scenario 1. In the case of 12 dwellings, batteries are also installed close to the environmental optimum of scenario 2 when there is also installed a significant capacity of photovoltaic modules and wind turbine, and the electricity is sold at spot price, which is a relatively low price. When the electricity price is higher than the spot price (scenario 3), it is more profitable to sell electricity than to store it in the electric batteries (Figure 7c, 7f, 7i). The thermal energy storage for heating, TSQ, which is a quite common technology with a lower investment cost than thermal energy storage for cooling, TSR, appears in less configurations than the latter (Table 6), due to the various different available technological options for the heat production. Furthermore, TSQ is selected in the trade-off solutions close to the environmental optimum (Figures 7a, 7d, 7g). TSR appears in all configurations (Table 6) because its operation is closely coupled with the heat pump, allowing the reduction of the installed capacity, with the corresponding reduction of its investment cost (Figures 7b, 7e, 7h).

Selling to the grid electricity produced with renewable energy technologies offsets greenhouse gas emissions allowing additional CO_2eq emissions reductions. Therefore, the contracted power tends to increase in the pathway towards the environmental optimum in order to enable higher injection of renewable energy to the grid.

3.2 Evaluation of cost and CO_2eq emissions reduction for different trade-off solutions

Different trade-off solutions were obtained along the Pareto curves. Tables 7-9 present, for the different trade-off solutions, the configuration (CFG), payback (PB), cost reduction (CR) and CO_2eq emissions reduction (CO2R) with respect to the reference scenario. Among the trade-off solutions, those at an annual cost equal to the reference scenario are highlighted. In the scenario 1, CO_2eq emissions reductions up to about 65% were achieved, whereas in scenarios 2 and 3, were about 75% - 100%. These results show that nowadays, with the available technology and the current Spanish self-consumption regulation [23], it is possible to achieve remarkable CO_2eq emissions reduction with respect to the conventional systems at an affordable cost. The payback of the aforementioned trade-off solutions is around 10 - 12 years, which could be a reasonable time to recover the investment, taking into account the benefits in the operational costs and environmental aspects. High shares of renewable energy can be considered as an advantage, since the uncertainty



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 7: Sizing of the energy storage technologies in the trade-off solutions for 12 dwellings (a-c), 24 dwellings (d-f) and 50 dwellings (g-i). Scenario 1 (triangle), scenario 2 (square) and scenario 3 (circle).

Table 7: Configuration, payback, total annual cost and CO_2eq emissions reductions for trade-off solutions with respect to the reference scenario in the 12 dwellings case.

Scenario 1				**Scenario 2**				**Scenario 3**			
CFG	**PB [yr]**	**CR**	**CO2R**	**CFG**	**PB [yr]**	**CR**	**CO2R**	**CFG**	**PB [yr]**	**CR**	**CO2R**
A	3.3	-23%	-39%	A	3.9	-24%	-43%	B	5.8	-27%	-76%
A	3.3	-23%	-40%	B	3.8	-23%	-50%	B	6.4	-26%	-80%
B	3.3	-23%	-52%	B	4.0	-23%	-60%	C	7.1	-25%	-85%
B	3.3	-23%	-55%	B	5.8	-22%	-70%	D	8.2	-20%	-86%
C	4.1	-22%	-57%	C	7.6	-17%	-80%	***D***	***12.5***	***0%***	***-92%***
D	7.1	-13%	-62%	J	9.2	-10%	-85%	G	17.8	25%	-93%
H	9.5	-5%	-64%	E	9.4	-7%	-90%	G	22.5	47%	-94%
H	***10.8***	***0%***	***-65%***	E	10.2	-4%	-95%	N	25.6	61%	-94%
H	12.9	9%	-66%	F	11.6	-1%	-100%	-	-	-	-
H	17.4	29%	-68%	***F***	***11.8***	***0%***	***-101%***	-	-	-	-
H	24.9	65%	-69%	D	13.6	8%	-109%	-	-	-	-
I	28.2	82%	-69%	H	38.8	123%	-122%	-	-	-	-
-	-	-	-	H	60.5	224%	-129%	-	-	-	-

on the energy system investment is reduced, due to the lower consumption of fossil fuels, which experience a high variability of their market prices. On the other hand, in the three analysed cases, the payback period corresponding to 50% CO_2eq emissions reduction is significantly lower thanks to the cost reduction with respect to the reference scenario, reinforcing the economic and environmental interest of such systems for the energy supply of buildings.

3.3 Feasible configuration to achieve remarkable reduction of CO_2eq emissions at affordable cost

The simplicity of the configuration is an advantage to be considered as investment criteria. In this sense, among the different trade-off solutions, configuration B (Figure 8) has been chosen for its simplicity and convenience in the transition to achieve sustainable energy systems, since allows the gradual replacement of the conventional fuels (natural gas, electricity from the grid) by renewable energy sources. Besides, this configuration was one of the optimal configurations selected in almost all Pareto curves (the only exception is the scenario 1 for 50 dwellings as shown in Table 9) and it allows, in some cases, very significant CO_2eq emissions reductions up to 82%, with a little increase of cost, about 13%, with respect to the economic optimum (see figures 2-4). For the scenario 3, in the case of 24 dwellings, the economic optimum corresponds to the configuration B.

The Table 10 presents the results of the design of the configuration B for the different number of dwellings and scenarios, corresponding to the lowest CO_2eq emission value of configuration B within the Pareto curves (Figures 2-4). In the particular case of the 50 dwellings for the scenario 1, it is presented the economic optimum of the configuration B, which is very close to the Pareto curve. In all the selected designs of configuration B shown in the Tables 7-9, the additional

Table 8: Configuration, payback, total annual cost and CO_2eq emissions reductions for trade-off solutions with respect to the reference scenario in the 24 dwellings case.

Scenario 1				**Scenario 2**				**Scenario 3**			
CFG	**PB [yr]**	**CR**	**CO2R**	**CFG**	**PB [yr]**	**CR**	**CO2R**	**CFG**	**PB [yr]**	**CR**	**CO2R**
K	6.2	-15%	-8%	K	6.7	-16%	-16%	B	7.2	-22%	-83%
A	5.9	-14%	-30%	A	6.7	-15%	-26%	C	7.8	-21%	-85%
A	5.7	-13%	-40%	A	6.7	-15%	-30%	D	9.1	-16%	-87%
A	4.8	-13%	-50%	A	6.7	-15%	-40%	D	10.6	-9%	-89%
B	4.4	-13%	-54%	A	5.8	-14%	-50%	***D***	***12.4***	***0%***	***-91%***
J	7.1	-8%	-60%	B	4.9	-14%	-59%	G	17.5	22%	-92%
O	***10.1***	***0%***	***-63%***	B	6.7	-12%	-70%	G	23.1	45%	-94%
L	11.4	4%	-64%	B	8.7	-8%	-80%	G	28.9	69%	-94%
L	15.0	18%	-66%	B	9.7	-5%	-85%	-	-	-	-
L	17.0	26%	-67%	E	10.5	-3%	-90%	-	-	-	-
H	19.5	38%	-68%	***E***	***11.2***	***0%***	***-95%***	-	-	-	-
H	21.6	47%	-69%	F	12.3	3%	-100%	-	-	-	-
H	24.9	63%	-69%	D	13.7	10%	-105%	-	-	-	-
-	-	-	-	G	21.2	41%	-108%	-	-	-	-
-	-	-	-	N	28.9	71%	-108%	-	-	-	-

Table 9: Configuration, payback, total annual cost and CO_2eq emissions reductions for trade-off solutions with respect to the reference scenario in the 50 dwellings case.

Scenario 1				**Scenario 2**				**Scenario 3**			
CFG	**PB [yr]**	**CR**	**CO2R**	**CFG**	**PB [yr]**	**CR**	**CO2R**	**CFG**	**PB [yr]**	**CR**	**CO2R**
K	6.1	-16%	-9%	M	6.5	-17%	-17%	K	6.7	-22%	-40%
K	6.3	-16%	-18%	P	6.7	-16%	-30%	A	6.2	-21%	-50%
A	6.1	-15%	-30%	P	6.7	-16%	-40%	A	6.1	-20%	-60%
A	5.7	-14%	-40%	A	6.9	-15%	-50%	A	6.0	-20%	-64%
A	5.1	-13%	-50%	A	6.7	-13%	-60%	B	5.8	-20%	-70%
O	7.4	-7%	-60%	B	6.9	-12%	-70%	C	6.4	-19%	-73%
G	9.7	-1%	-62%	C	7.8	-10%	-73%	J	7.1	-15%	-75%
G	***10.0***	***0%***	***-63%***	J	8.9	-6%	-75%	***G***	***10.6***	***0%***	***-77%***
H	14.0	14%	-65%	***G***	***10.0***	***0%***	***-77%***	G	11.3	3%	-78%
I	20.5	41%	-67%	G	13.3	12%	-78%	N	26.6	65%	-79%
I	22.5	49%	-67%	N	37.9	80%	-79%	-	-	-	-

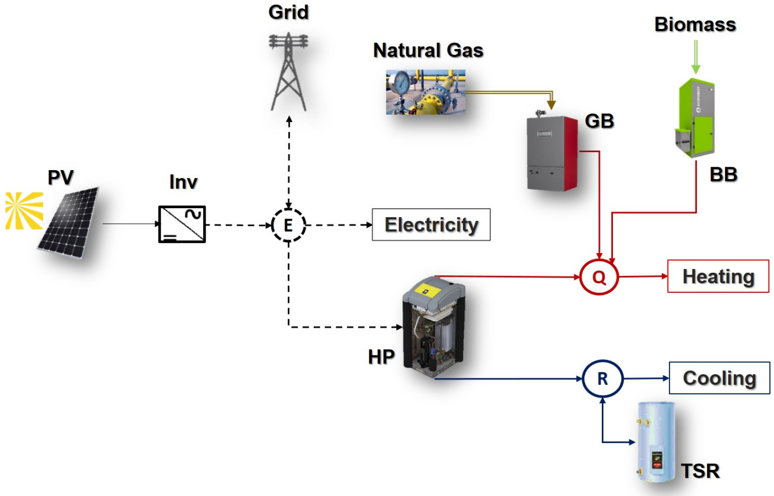


Figure 8: Energy system technologies corresponding to the configuration B.

investment in the polygeneration system (with respect to the reference scenario) is compensated with a remarkable reduction in the operational cost which leads to a total annual cost reduction. The operational cost reduction is proportional to the reduction of electricity consumption from the grid and the fossil fuel consumption. Hence, a remarkable reduction of CO_2eq emissions is also achieved. In the case of 12 dwellings, the gas boiler technology was selected only to cover heating peak demands, i.e. it was selected as an auxiliary boiler. In these cases, the natural gas cost corresponds to the fixed cost of the natural gas contract, so this is the cost for the availability of this service. In the case of 24 dwellings, the natural gas consumption by the GB technology is always lower than the biomass consumption, therefore, gas boiler works as an auxiliary boiler as well. A similar situation occurs in the case of 50 dwellings for scenarios 2 and 3; however, in scenario 1 does not. For this scenario, as aforementioned, the economic optimum of the configuration B is presented, which is close to the economic point of this pareto curve. In this particular case, gas boiler is the main boiler, since the natural gas consumption is higher than the biomass consumption. This is due to the natural gas tariff is lower than the biomass price. Note that the natural gas tariff depends on the natural gas consumption and its unit cost decreases when the gas consumption increases. This fact impedes to achieve higher CO_2eq emissions reduction [85].

Table 10: Results of the design of the configuration B for residential buildings of 12, 24 and 50 dwellings.

12 dwellings residential building									
Technology	**Scenario 1**			**Scenario 2**			**Scenario 3**		
	Install Cap	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**	**Install Cap**	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**	**Install Cap**	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**
Pct	13.9 kW	-	-	13.9 kW	-	-	13.9 kW	-	-
PV	71 m^2	1789	574	146 m^2	3654	1172	210 m^2	5272	1691
Inv	13 kW	921	255	27 kW	1881	520	39 kW	2713	751
HP	71 kWt	4944	566	71 kWt	4980	570	71 kWt	4980	570
GB	20 kWt	282	10	24 kWt	330	12	23 kWt	319	11
BB	11 kWt	477	6	8 kWt	333	4	9 kWt	367	4
TSR	7 kWht	358	45	6 kWht	310	39	6 kWht	310	39
	CIA */* $CO2_{fix}$	*8770*	*1456*	***CIA*** */* $CO2_{fix}$	*11488*	*2317*	***CIA*** */* $CO2_{fix}$	*13961*	*3067*
Annual operational costs									
Fuel	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**
Electricity (Purchased)	35236	7131	7399	30044	6201	3436	2760	5609	4
Electricity (Sold)	-	-	-	14784	-1131		28537	-4387	
Natural Gas	0	71	0	0	71	0	0	71	0
Biomass	27939	1352	1760	20547	994	1294	25847	1251	1628
	C_{ope}/ $CO2_{ope}$	*8554*	*9159*	C_{ope}/ $CO2_{ope}$	*6137*	*4731*	C_{ope}/ $CO2_{ope}$	*2543*	*1632*
	TAC/ TCE	**17324**	**10615**	**TAC/ TCE**	**17625**	**7048**	**TAC/ TCE**	**16504**	**4699**
24 dwellings residential building									
Technology	**Scenario 1**			**Scenario 2**			**Scenario 3**		
	Install Cap	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**	**Install Cap**	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**	**Install Cap**	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**
$Pct_{1,2,3}$ [kW]	$20.8_{1,2,3}$	-	-	43.6_1-$34.6_{2,3}$	-	-	$34.6_{1,2,3}$	-	-
PV	148 m^2	3727	1195	453 m^2	11369	3646	435 m^2	10909	3498
Inv	28 kW	1918	531	85 kW	5852	1619	81 kW	5615	1554
HP	113 kWt	7875	901	142 kWt	9961	1140	142 kWt	9961	1140
GB	48 kWt	672	24	26 kWt	366	13	34 kWt	474	17
BB	36 kWt	1501	18	16 kWt	676	8	8 kWt	352	4
TSR	69 kWht	3363	427	13 kWht	620	79	13 kWht	620	79
	CIA */* $CO2_{fix}$	*19056*	*3096*	***CIA*** */* $CO2_{fix}$	*28843*	*6505*	***CIA*** */* $CO2_{fix}$	*27931*	*6292*
Annual operational costs									
Fuel	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**
Electricity (Purchased)	48536	12122	10331	51304	14375	-2594	56972	15070	-196
Electricity (Sold)	-	-	-	68461	-5158		62795	-11354	
Natural Gas	3752	358	767	0	71	0	83	77	17
Biomass	115754	5603	7293	49812	2411	3138	33188	1606	2091
	C_{ope}/ $CO2_{ope}$	*18082*	*18390*	C_{ope}/ $CO2_{ope}$	*11700*	*544*	C_{ope}/ $CO2_{ope}$	*5400*	*1912*
	TAC/ TCE	**37138**	**21486**	**TAC/ TCE**	**40543**	**7049**	**TAC/ TCE**	**33331**	**8204**
50 dwellings residential building									
Technology	**Scenario 1**			**Scenario 2**			**Scenario 3**		
	Install Cap	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**	**Install Cap**	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**	**Install Cap**	**CIA[€/yr]**	CO_2**fix [kg**CO_2eq**/yr]**
$Pct_{1,2,3}$ [kW]	$43.6_{1,2,3}$	-	-	$43.6_{1,2,3}$	-	-	$43.6_{1,2,3}$	-	-
PV	309 m^2	7764	2490	613 m^2	15377	4931	641 m^2	16092	5160
Inv	58 kW	3996	1106	115 kW	7914	2190	120 kW	8283	2292
HP	236 kWt	16513	1890	297 kWt	20751	2375	297 kWt	20751	2375
GB	167 kWt	2331	83	117 kWt	1638	59	125 kWt	1754	63
BB	7 kWt	292	3	57 kWt	2373	28	48 kWt	2025	24
TSR	141 kWht	6865	873	27 kWht	1292	164	27 kWht	1292	164
	CIA */* $CO2_{fix}$	*37761*	*6444*	***CIA*** */* $CO2_{fix}$	*49345*	*9747*	***CIA*** */* $CO2_{fix}$	*50196*	*10078*
Annual operational costs									
Fuel	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	CO_2**ope [kg**CO_2eq**/yr]**
Electricity (Purchased)	100897	24229	21242	103127	25041	9530	104686	25311	6210
Electricity (Sold)	-	-	-	62260	-4756		81330	-14692	
Natural Gas	189521	11926	38738	1012	149	207	6560	608	1341
Biomass	48184	2332	3036	156804	7589	9879	186390	9021	11743
	C_{ope}/ $CO2_{ope}$	*38487*	*63016*	C_{ope}/ $CO2_{ope}$	*28023*	*19615*	C_{ope}/ $CO2_{ope}$	*20249*	*19294*
	TAC/ TCE	**76248**	**69460**	**TAC/ TCE**	**77368**	**29362**	**TAC/ TCE**	**70446**	**29372**

4 Conclusions

The potential of reduction of CO_2eq emissions in residential buildings has been studied thanks to a Mixed Integer Linear Programming (MILP) multi-objective optimization model applied to find the optimal configuration of different polygeneration systems covering the energy demands of different multifamily buildings.

The legal restrictions in accordance to the current Spanish self-consumption regulation [23] was taken into account to evaluate the potential of reduction of CO_2eq emissions at an affordable cost, as well as to check its alignment with the European objectives on greenhouse gases emissions reduction [28]. Different scenarios were studied in residential buildings (12, 24 and 50 dwellings) located in Zaragoza (Spain), with and without selling of electricity to the electric grid. It was demonstrated in all the analysed cases, the feasibility of using polygeneration systems for the energy supply for buildings to reduce both the economic costs and the environmental impact. It is highlighted the remarkable CO_2eq emissions reduction (above 65% with respect to conventional systems) at an affordable cost.

Although under a self-consumption scheme only, without allowing electricity sale to the electrical grid, was achieved a significant reduction of CO_2eq emissions, it was not possible to offset 100% of greenhouse gas emissions. This objective, zero CO_2eq emissions, only could be reached allowing also the sale of electricity produced with renewable energy sources.

The effect of implementing, in addition to the self-consumption possibility, a net billing mechanism for the sale of electricity produced from renewable energy was analysed. In this respect, although high prices of electricity sale foster the investment in renewable energy technologies, the potential reduction of CO_2eq emissions is limited because of the net billing restriction. Therefore, good signals of electricity sale prices must be considered to overcome this issue. In the analysed cases, the sale of electricity at spot price provided high potential of CO_2eq emissions reduction obtaining also economic benefit. This means that the production of electricity from renewable energies can be competitive, without any subsidy, allowing a very important reduction of CO_2eq emissions in buildings at an affordable cost and aligned with short term European Union objectives on climate change. On the other hand, the obtained results have shown that, due to the power limitation established by the current Spanish regulation, the highest potential of CO_2eq emissions reductions is achieved for small or medium size residential buildings, being limited the potential of CO_2eq emissions reduction for big residential buildings. This limitation should be progressively removed in coordination with the technological improvement of the electrical network as well as with the proposed objectives to combat global warming.

A detailed analysis was carried out on an energy system made up of the following technologies: photovoltaic panels, heat pump, gas boiler, biomass boiler and thermal energy storage for cooling. This configuration B was one of the most selected along the Pareto curves obtained from the different scenarios analysed. Besides it was demonstrated as an interesting alternative to evaluate the transition to achieve remarkable CO_2eq emissions reductions with respect to conventional systems. Note that this configuration B has shown to be feasible and very appropriate for the different scenarios and cases of study analysed in this work. Its interest is beyond the analysed cases and could be considered an appropriate configuration for different Mediterranean countries. Obviously the capacity of each installed technology and design criteria should be determined for each specific place considering the climatic conditions, energy demands, socio-economic and legal framework.

Based on the obtained results, a concluding remark from the lessons learnt from the Spanish self-consumption regulation is that the installation of i) polygeneration energy supply systems based on photovoltaic panels, heat pumps, thermal energy storage for cooling, and biomass, properly integrated, under ii) self-consumption scheme, with iii) net billing of renewable electricity sale, iv) at an appropriate electricity price (spot market price in the analysed cases), with v) an adequate limitation of the installation of renewable electrical power in vi) collective energy supply systems, is an interesting approach properly oriented to reach carbon neutral energy supply for buildings.

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Nomenclature

Acronyms/abbreviations

ACH Absorption chiller

BAT Battery (Ion Lithium)

BB Biomass boiler

CFG Configuration

CM Cogeneration module

CRF Capital recovery factor

DHW Domestic hot water

EU European Union

GB Gas boiler

GHG Green-house gas

HP Heat pump

HPQ Heat pump for heating

HPR Heat pump for cooling

IEA International Energy Agency

Inv Inverter

InvC Inverter-Charger

IPCC Intergovernmental Panel on Climate Change

MILP Mixed integer linear programming

PV Photo-voltaic

RD Royal decree

ST Solar thermal

TAC Total annual cost

TSQ Thermal energy storage for heating

TSR Thermal energy storage for cooling

WT Wind turbine

VAT Value-added tax

Latin symbols

A Surface area, m^2

a_0 Optical efficiency, $-$

a_1 First heat loss coefficient, $W/(m^2 \cdot K)$

a_2 Second heat loss coefficient, $W/(m^2 \cdot K^2)$

$BigM$ Very large number (i.e 10^6)

C Cost €

CIA Investment annual cost e/yr

CI Investment cost €

cp Purchase energy price $€/kWh$

cs Sale energy price $€/kWh$

Cap Installed capacity, *

Cu Average unit cost, $€/*$

COP Coefficient of performance, $-$

$CO2$ CO_2 emissions $kgCO_2$

$CO2R$ CO_2 emissions reduction $kgCO_2$

CO_2U Unit embodied, CO_2 emissions/*

CR Annual total cost reduction, €/yr

d Day

D Set of days

DOD Allowable depth of discharge, %

E Energy/Electricity, kWh

EER Energy Efficiency Ratio, $-$

F Fuel/natural gas consumption kWh

Fm Installation costs, €

h Hour

H Set of hours

I Intensity, A

N Number, $-$

PB Payback yr

Pct Contracted power, kW

PL Partial load, %

Q Heating, $kWht$

R Cooling, $kWht$

S Stored energy, kWh

$uCO2$ Unit CO_2 emissions, $kgCO_2/kWh$

V Voltage, V

W Electricity, kWh

Y Binary variable, [0,1]

Greek symbols

α Efficiency,%

η Efficiency, %

λ Energy loss factor, %

μ Open-circuit voltage coefficient, $\%/K$

ω Weight of a representative day

Subscripts

alq rental equipment

$\o$ cycle

ch charge

dis discharge

dc direct current

e electrical

fix fixed

g conventional fuel/natural gas

ins install

$\textsc{on}$ operation mode ON/OFF

ope operational

pch purchased

q thermal

rep representative

rt round trip

s sale

v variable

w electrical

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