Optimization of the design of polygeneration systems for the residential sector under different self-consumption regulations.

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Abstract

Polygeneration systems enable natural resources to be exploited efficiently, decreasing CO_2 emissions and achieving economic savings relative to the conventional separate production. However, their economic feasibility depends on the legal framework. Preliminary design of polygeneration systems for the residential sector based on the last Spanish self-consumption regulations RD 900/2015 and RD 244/2019 was carried out in Zaragoza-Spain. Both regulations were applied to individual and collective installations. Several technologies, appropriate for the energy supply to residential buildings, e.g. photovoltaics, wind turbines, solar thermal collectors, microcogeneration engines, heat pump, gas boiler, absorption chiller and thermal and electric energy storage were considered candidate technologies for the polygeneration system. A Mixed Integer Linear Programming model was developed to minimize the total annual cost of polygeneration systems. Scenarios with and without electricity sale were considered. CO_2 emissions were also calculated to estimate the environmental impact. Results show that RD 900/2015 discourages the investment in self-consumption systems whereas the RD 244/2019 encourages them, especially in renewable energy technologies. Moreover, in economic terms, it is more profitable to invest in collective self-consumption installations over individual installations. However, this does not necessarily represent a significant reduction of CO_2 emissions with respect to individual installations since the natural gas consumption tends to increase as its unit price decreases because of the increase of its consumption level. Thus, more appropriate pricing of natural gas in residential sector, in which its cost would not be reduced when increasing its consumption, would be required to achieve significant CO_2 emissions reduction. In all cases, the PV panels are competitive and profitable without subsidies in self-consumption schemes and the reversible heat pumps played an important role for the CO_2 emissions reduction. In a horizon to achieve cero CO_2 emissions, the net metering scheme could be an interesting and profitable alternative to be considered.

Keywords: Self-consumption regulations, Renewable energy, Polygeneration systems optimization, energy supply systems for buildings

1. Introduction

The residential sector represents about 27% of the energy consumption and 17% of the CO_2 emissions of the world. Therefore, this sector plays an important role in the policies to mitigate climate change and its impacts [1]. Accordingly, it is one of the objective sectors in the pathway to limit global warming to 1.5ºC according to the last report of the Intergovernmental Panel on Climate Change (IPCC) [2].

Design of buildings with low energy consumption has been, during the last two decades, a matter of research and study [3,4]. There are approaches oriented to reduce the building's energy demand, through the design of buildings with very low energy requirements [5], and also through the implementation of efficient energy supply systems considering as well the integration of renewable energy technologies [6,7].

The integration of thermal and electrical systems makes feasible to increase the share of renewable energy and also achieving CO_2 emissions reduction [4]. In this sense, polygeneration systems for residential buildings can be a suitable alternative to reduce economic costs and CO_2 emissions with respect to the separate production of energy services, thanks to an adequate systems integration [8].Therefore, distributed generation (based on polygeneration systems) is considered an alternative to increase the share of renewable energy in energy mix of countries, reducing the environmental impact of the energy generation infrastructure and improving its sustainability [9,10].

Polygeneration in residential buildings generally refers to the combined production of electricity, heat and cooling [11,12]. They consist of different energy technologies, which convert renewable and non-renewable energy resources into the energy services required in the building along the day and the year. Internal combustion engines, gas turbines, micro-turbines or fuel cells may act as prime movers, coupled to an electric generator when required, in which the chemical energy of fossil fuels or biomass is converted into electrical power. The heat released can be used for the production of domestic hot water (DHW) and/or space heating. Further, thanks to the integration of thermally activated technologies such as absorption chillers, cooling production for air conditioning can also be obtained using the available excess of heat produced in periods in which heating space is not required. Mechanical chillers allow also the cooling production thanks to the efficient conversion of electrical energy. In this respect, reversible heat pumps, producing alternatively both, heating or cooling, are also interesting candidate technologies of polygeneration systems in residential buildings that, together with auxiliary boilers, may complement and avoid the oversizing of the prime mover [13]. Technologies driven by renewable energies (e.g. photovoltaic panels, solar thermal collectors, hybrid photovoltaic/thermal, wind turbines, among others) providing higher flexibility and diversification as well as environmental benefits, also play a key role in the design of sustainable energy supply systems for residential buildings [14–16]. They can cover multiple energy demands directly (e.g. electricity from photovoltaic or wind turbines, or heat from solar thermal collectors) or indirectly by coupling absorption and/or mechanical heat pumps [17,18]. Nevertheless, non-manageable 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-manageable renewable energy sources with manageable energy sources (e.g. 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 [19,20]. Another important aspect to be considered in the design of affordable polygeneration systems for residential buildings is the connection with the electrical grid and the possibility of purchasing and/or selling electricity to it, which provides reliability and security to the building energy supply as well as flexibility and economic benefits [21,22].

However, the feasibility of polygeneration systems depends, among others, on the applied energy policies and legal framework. For instance, previous studies have demonstrated how some policies could promote or limit the installation of specific technologies such as cogeneration [23] or photovoltaic technology [24].

In order to encourage a deployment of energy efficient and low carbon grid connected distributed generation, several targets and policies have been proposed by the governments around the world. In particular, regulatory and pricing policies such as feed-in tariffs (FiT), net metering or net billing have been applied to support distributed generation DG [25]. A brief description of those pricing policies schemes are presented in the following paragraphs.

Feed-in Tariff (FiT): In this scheme, electricity consumption and generation must be separated and accounted differently. While electricity from the grid is purchased at retail price, the electricity injected to the grid is compensated at a predetermined tariff notified by the regulator which can be higher than retail electricity price [26]. When the compensation tariff is indeed higher than the retail electricity price, this scheme can be called Buy all, Sell All arrangement [27].

Net metering or Net energy metering: Under this mechanism, the electricity bill for the net electricity consumption from the grid is accounted after netting off the electricity injected by the owner into the grid. This requires bidirectional meters, or net meters, which keep account of the net flow of electricity. In this case, the owner receives a credit in kilowatt-hours and typically is compensated for the injected electricity at the retail electricity tariff [26].

Net billing: In this scheme, the compensation is monetary. The owner can consume electricity generated by renewable energy installation in real-time and export any surplus generation to the utility grid. All net electricity exports are metered and credited at a predetermined sell rate in the moment they are injected into the grid. The sell rate is lower to the retail rate of electricity [27].

Several countries, such as Germany or Canada, have applied FiT mechanisms to encourage the renewable technology investment as Buy All, Sell All arrangement. However, this mechanism has evolved to net billing arrangements as self-consumption (and offer lower rates for exported energy) [27,28].

In the case of Spain, in particular, in the last four years, the Spanish government has implemented two different royal decrees to regulate the self-consumption.

The first of them is the Royal Decree RD 900/2015 [29] which was appropriated in 2015 and defined two types of self-consumption systems: i) Self-consumption type 1: For systems with installed polygeneration system capacity below 100 kW in which energy sale is not allowed and ii) Self-consumption type 2: there was no limit for installed polygeneration system capacity (either lower or upper limit) and energy sale was allowed. The self-consumption type 2 can be considered as a net billing arrangement. In both types, the installed polygeneration system capacity must be lower than or equal to the contracted capacity from the grid. A relevant aspect of this regulation is that it must be applied two types of self-consumption taxes: i) a fix tax proportional to the difference between the charges application power and the contracted power from the grid, in this work this fix tax is applied to the installed polygeneration system capacity; and ii) a variable tax corresponding to the self-consumed energy, depending on time-of-use tariffs. However, for self-consumption type 1 when contracted power from the grid is lower or equal to 10 kW, self-consumption taxes were not applied.

Recently, the Spanish government has released the Royal Decree RD 244/2019 [30] which stablishes the administrative, technical and economic conditions for self-consumption. This decree derogates the previous one, RD 900/2015, and 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 this case, 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: Self-consumption systems that do not accomplish the requirements to be subjected to compensation or that voluntarily decide do not receive any economic compensation. This could happen, because when a client wants to sell electricity to the grid, some additional administrative and technical requirements should be fulfilled, which also could require to pay additional fees 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, he/she can deliver surplus electricity to the grid, with more flexibility of operation and avoiding the additional investment in any dissipater or battery required to manage the excess of electricity produced.

A relevant difference between both regulations is that in the Royal Decree 244/2019 there is neither application of any tax related to self-consumption nor any restriction on the installed self-consumption system capacity with respect to the contracted power from the electric grid. However, in the case of surplus subject to compensation, i.e. produced with renewable energy, the installed capacity must be equal or lower than 100 kW.

This work aims to compare both regulations by evaluating their impacts on the design of polygeneration systems for the residential sector from the economic and environmental points of view. Although collective installations are not mentioned in the RD 900/2015, in this work both individual and collective installations are studied for both regulations, by considering households as a reference for individual installations, and residential buildings as a reference for collective installations. Three scenarios based on the above-mentioned regulations are considered: i) Scenario 1: Electricity sale is not allowed; ii) Scenario 2: Electricity sale is allowed at spot price; iii) Scenario 3: Electricity sale is allowed at 80% purchase price. In addition, Spanish regulation RD 244/2019 establishes that the surplus electricity cannot be greater than the consumed electricity from the grid in economic terms for the billing time, which cannot exceed 1 month [30]; however, in this work due to the procedure applied to select representative days in the optimization model, the considered billing time is one year. This approach is less restrictive and provides higher flexibility to self-consumption arrangements.

Scenarios 2 and 3 are proposed as particular examples of the type 2 self-consumption in both regulations [29,30], and they are, in fact, net billing arrangements under legal restrictions based on the regulations.

Table 1 summarizes the legal restrictions considered for the design of polygeneration systems in this work which are mainly based on the aforementioned royal decrees.

Table 1. Legal restrictions considered in this work for the design of polygeneration systems

Feature	**Based on RD 900/2015**		**Based on RD 244/2019**	
	Individual	**Collective**	**Individual**	**Collective**
Polygeneration system size	Below or equal to contracted grid power		Unlimited	
Mechanism of compensation	Net billing (optional)		Net billing (optional)	
Sale electricity	Surplus electricity (optional)		Surplus electricity only from renewable resources (Optional)	
Charges over self-consumption	When contracted power is above 10 kW or sale electricity is applied	Yes	No	

Mixed Integer Linear Programming is utilized for the design of the polygeneration systems by applying the superstructure optimization methodology. The feasibility of several candidate technologies are evaluated for the optimal design [31]. The optimization was carried out with the objective to minimize the total annual cost, and CO_2 emissions were also calculated in order to estimate the environmental impact of the system. In this way, the greenhouse gas emissions reduction was verified, which is one of the aims of the new self-consumption policy [32].

The analyses presented in this work provide valuable information for the comparison of the different policies, previously referred, that have been proposed by the governments around the world to support distributed generation DG, such as feed-in tariffs (FiT), net metering or net billing [25].

2. Methodology

2.1 Description of the system

The location of this study is in Zaragoza, Spain (latitude 41.7º). Two cases have been considered for this work:

- Household (Hh): A single dwelling (which belongs to a residential building) occupied by 3 people with a surface area of 102.4 m^2. The expected contracted power is below 10 kW; therefore, the electric tariff 2.0 DHS is applied [33]. The available surface area for photovoltaic panels or solar thermal collectors is 100 m^2.
- Residential building (RB): It consists of a multifamily residential building composed of 50 dwellings (households), each one with 102.4 m^2 of surface area and average occupancy of 3 people per dwelling. The community can sign-up a collective self-consumption contract for all services. The expected electricity contracted power is above 15 kW; therefore, the electric tariff 3.0A is applied in this case [33]. The available area for photovoltaic panels or solar thermal collectors is 2000 m^2.

2.1.1 Energy demands

Energy demands were calculated from annual data. Space heating SH_d and cooling R_d demands per dwelling are about 41 and 11 kWh/(m^2·yr) respectively [34]. The electricity demand for appliances is about 28.7 kWh/(m^2·yr) [35]. The domestic hot water (DHW) average consumption is about 28 L/(person·day) [36]. The procedure to obtain hourly data is described as follows:

For space heating and cooling demands, the *degree days* method was applied for distributing the annual energy demand throughout all the days of the year. The considered base temperatures for heating and cooling were 15 ºC and 21 ºC, respectively [37], and the ambient temperature was obtained from the *meteonorm* database [38]. A hourly function [39] was applied on daily data to obtain hourly space heating and cooling demands.

The domestic hot water volume was monthly distributed by applying a distribution factor [40]. The energy required to heat the monthly volume of water was calculated considering the water network supply temperature [41] and the DHW set temperature of 60 ºC according to the Spanish regulation [36]. Monthly energy was divided by days of the month and distributed by means of an hourly distribution function [39]. This procedure assumes that the hourly DHW energy demand Q_{DHW} is the same for each day of the month.

The annual electricity demand for appliances and lighting was monthly distributed by applying a distribution factor. Then, the monthly values were divided by the days of the month and distributed by an hourly distribution function [42]. In this way the hourly electricity demand E_d was obtained.

The procedures briefly described above, provide the hourly demand data series of heating Q_d, cooling R_d and electricity E_d. Heating demand consists of domestic hot water Q_{DHW} and space heating SH_d, considering a low temperature radiant heating indoor end system, with operation temperatures about of 45 ºC, with the possibility to reach temperatures about 60 ºC for DHW. Therefore, temperature levels of both demands are quite the same.

2.1.2 Renewable energy production

Hourly photovoltaic energy production per square meter, E_{PV}, was calculated following the procedure described by Duffie and Beckman [43], as a function of solar radiation on the surface tilted at 36º and azimuth angle 0º [38]. The PV panels are polycrystalline technology of 255 Wp with a maximum point power efficiency $\eta_{mp,ref}$=15.66% and an open-circuit voltage temperature coefficient μ_{Voc}=-0.32%/ºC [44].

Hourly solar thermal energy production per square meter, E_{ST}, was calculated as a function of solar radiation on surface tilted at 36º and azimuth angle 0º, and the mean temperature difference between the collector temperature 60ºC and ambient temperature. The collector parameters are optical efficiency η_o=80.1% and 1st and 2nd order heat loss coefficients a_1=3.188 W/(m^2·K), a_2=0.011 W/(m^2·K^2) [45].

Restrictions due to shading were considered taking into account both PV panels and solar thermal collectors area [46]. The relation between the required horizontal surface area and the installed area was about 2.5:1 for PV panels and 5:1 for Solar thermal collectors.

The electrical production of the wind turbine, E_W, depends on the wind speed [38] and was calculated based on the production curve of a wind turbine with nominal capacity of 3 kW [47] for small scale (Hh) and 30 kW [48] for medium scale (RB), following the procedure described by Manwell et al. [49].

A summary of annual and peak values of energy demands and renewable energy production is presented in Table 2. The peak demands correspond to the maximum value of each hourly time series.

Table 2. Summary of annual and peak values of energy demands and renewable energy production for households and residential buildings.

Attributes	**Household**				**Residential building (50 dwellings)**			
Energy demands	**Annual Value**		**Peak Value**		**Annual Value**		**Peak Value**	
Heating demand (Q_d)	5832	kWht	5.5	kWt	291607	kWht	274	kWt
Cooling demand (R_d)	1167	kWht	5.9	kWt	58368	kWht	293	kWt
Electricity demand (E_d)	2939	kWh	0.6	kW	146950	kWh	30	kW
Renewable energy production	**Annual Value**		**Peak Value**		**Annual Value**		**Peak Value**	
Photovoltaic production (E_{PV})	285	kWh/m^2	0.16	kW/m^2	285	kWh/m^2	0.16	kW/m^2
Wind energy (E_W)	6397	kWh/ud	3.4	kW/ud	53991	kWh/ud	39	kW/ud
Solar Thermal Production (E_{ST})	995	kWht/m^2	0.79	kWt/m^2	995	kWht/m^2	0.79	kWt/m^2

2.1.3 Input data from the grid

Hourly electricity spot prices [50] were required for the system in order to calculate the revenues for selling surplus electricity to the grid. Moreover, hourly CO_2 emissions from the grid [51] 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 computational demanding task. Representative days have been widely used in several works to tackle this issue [52–54]. Taking into account that this work considered time series with high variability, such as wind energy production and hourly electricity spot prices, herein, the *k*M-OPT method [55] was applied in order to select 12 representative days for the optimization of polygeneration systems. This method combines two methods, the *k*-Medoids [56] 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 [53] which consists of fitting the data duration curve obtained from representative periods to the duration curve of the original time series. By combining both of them, it is possible to reduce the smoothing of typical periods improving the optimization results of the polygeneration systems. One of the drawbacks of this method 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. Tables 3 and 4 show the set of representative days with their respective weights ω (which corresponds to the multiplication factor of each representative day). Two additional days corresponding to cooling and heating peak demands were considered with weight zero, which have influence on the sizing of the equipment but not on the operational cost. Time series considered for households and residential buildings have the same dynamic behaviour, except for the electrical production of the wind turbine. This leads to two different sets of representative days.

Table 3. Set of representative days for household system

Month	**Day (*d*)**	**Weight (ω)**	**Month**	**Day (*d*)**	**weight (ω)**	**Month**	**Day (*d*)**	**weight (ω)**
January	19	16	May	127	36	July	208	23
March	62	29	June	177	43	November	326	22
April	112	34	July	206	22	December	339	37
April	116	27	July	207	46	December	343	30

Table 4. Set of representative days for residential building system

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

2.3 Superstructure

The superstructure depicted in the figure 1 considers the candidate technologies and the feasible connections between them. The system is composed of an electrical and a thermal part. The electrical part consists of the electric grid from which an specific power can be contracted according to the tariff; photovoltaic modules PV whose electrical production W_{PV} is proportional to the E_{PV} and modules area A_{PV}; wind turbines WT whose electrical production W_{W} is the result of the electrical production E_{W} multiplied by the number of turbines; inverter Inv which converts the direct current to alternating current; batteries Bat which can store electric energy and inverter-charger InvC which converts alternating current to direct current and viceversa. The excess of electricity produced by PV or WT which is not sold to the grid is wasted by a dissipator. The thermal part consists of conventional gas boiler GB that consumes fossil fuel F_{GB} to produce heat; solar thermal collectors ST whose heat production Q_{ST} is proportional to E_{ST} and the area A_{ST}; a single-effect absorption chiller ACH that uses heat and a small quantity of electricity to produce cooling R_{ACH}; and thermal energy storage for heating TSQ and cooling TSR, which can charge/discharge thermal energy. Components such as cogeneration module CM, converting the energy of fossil fuels F_{CM} into electricity W_{CM} and heat Q_{CM}, and reversible heat pumps HP, converting the electrical energy E_{HP} into thermal energy either heating Q_{HP} or cooling R_{HP}, enables the integration of electric and thermal parts.

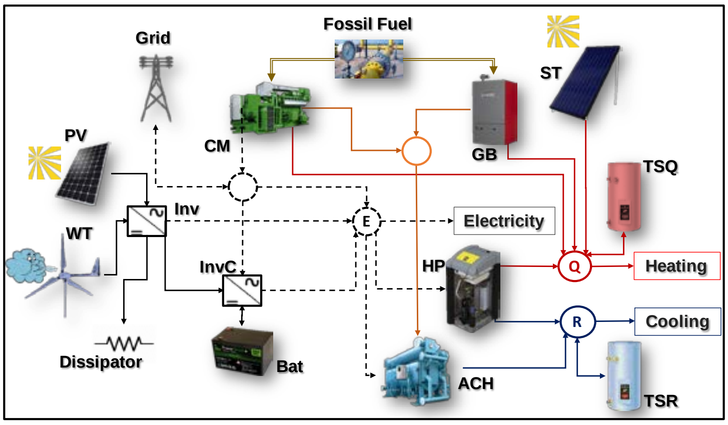

Figure 1. Superstructure containing all considered candidate technologies. Nodes are represented by circles.

Technical data: The components *Comp* of the superstructure are commercially available. The main technical parameters obtained from the manufacturers' catalogues are shown in Table 5.

GB, HP and ACH can be modulated up to nominal capacity. The efficiency η_{GB} of conventional boiler was considered constant. Heat pump operates in heating mode assuming a constant coefficient of performance COP, or in cooling mode considering a constant Energy Efficiency Ratio EER with a constant cooling/heating capacity ratio β. Both COP and EER have been estimated considering the operational temperature of the reservoirs expected for Zaragoza (Spain), about 3ºC in winter and 31ºC in summer; moreover, the maximum operational set temperature for the application, about 60ºC for DHW and 7ºC for cooling water. The single effect absorption chiller operates with a constant $\mathrm{COP}_{\mathrm{ACH}}$.

For the inverter and inverter-charger, an oversizing factor of 20% was applied to size their capacity. Also, a constant efficiency η was considered.

Regarding energy storage, for thermal energy storage tanks, the energy stored S_q and S_r for heating and cooling, respectively, were calculated at each time step (1 hour) taking into account the energy losses by applying a λ factor. In the case of batteries, the technology is Ion-Lithium. The round trip efficiency η_{rt}, determines the energy losses during the charging and discharging process in each time step. Charging and discharging processes are not allowed simultaneously either in thermal energy storage tanks or in batteries. Further, a maximum deep of discharge *DOD* is defined for batteries to avoid premature failures. During the batteries lifetime operation, the number of charge-discharge cycles has to be lower than the maximum number of cycles that that cause failure $N_{c,failure}$, according to the manufacturer. This was verified by applying the equivalent full cycle to failure ageing method [57]. Model of capacity [58] was applied to calculate the dynamic behaviour of Ion lithium batteries which take into account both, the maximum charge current stablished by manufacturer and the charge ratio α_c in A/Ah [59]. Taking into account that this study is based on representative days, for both thermal and electrical storage, the stored energy at the beginning of each representative day must be equal to the stored energy at the end of each representative day.

In the case of the cogeneration module CM, modulation varies depending on the manufacturer, for instance, it can modulate down to 50% [60], and even down to 6% subject to additional components [61]. A common practice to maintain a constant efficiency is to install several units which allow load control to be applied by shutting down individual engines while keeping the others at nearly-nominal load. For instance, when the CM set consists of 2 cogeneration modules, and each CM can modulate up to 50%, the CM set can modulate up to 25%. However, taking into account that modulate up to about 6% is possible, it could be a suitable approach to consider CM set partial load up to 15% for residential buildings applications where 2 or more cogeneration modules can be installed. On the other hand, for household applications, partial load of about 30% could be considered a good approach.

Small and micro cogeneration must provide primary energy savings (PES) to be considered as a high-efficiency cogeneration [62]. Therefore, PES was calculated and verified to accomplish the normative. More information about them can be found in Appendix A.

Economic data: The economic investment of the polygeneration system considers a project lifetime n_{proj} =20 years at interest rate r = 5%. Then, the capital recovery factor $CRF = 0.082\ yr^{-1}$ was applied to set the fixed annual cost of the investment. In addition, indirect costs were considered by applying a factor F_{ind} of 20% over the total investment cost. Economic investment of each component was calculated from the unit cost C_u. A factor F_m was defined to consider the installation and maintenance costs. This study offers an approach for the design of polygeneration systems, therefore average unit costs have been considered for each technology. Nevertheless, there is a difference between the household and the building because of the economy of scale, which have been considered for some components. Moreover, the available minimum capacity is a restriction for the installation of some components at some scales. For instance, absorption chiller was not considered as a candidate technology for household system. The *VAT* (Value-Added Tax) was applied, whose value is 0.21 for Spain (Peninsula). When the lifetime of the component n_{comp} is below to project lifetime, its net present value factor *FNPV* is calculated in order to take into account the total substitutions carried out throughout the installation's lifetime. All economic data are shown in Table 5. The electricity time-of-use tariffs were applied in different scenarios based on economic data of the electricity marketer [33]. Also, it was considered a meter equipment rental cost C_{alq_e} and the electricity tax Tax_e. In the case of natural gas costs, the contract depends on the annual gas consumption, which is related to the fixed cost C_{fg}. The variable cost of the natural gas C_{vg} is proportional to the retail price p_g [33]. Table 6 and 7 summarize the electricity and natural gas tariffs.

Environmental data: In order to evaluate the environmental impact, it was considered the CO_2eq emissions embodied in every component of the superstructure CO_2fix, based on the unit CO_2 emissions CO_2U of every component (Table 5). Further, CO_2 emissions released due to the i) natural gas combustion, considering a constant value of 0.204 kgCO_2eq/kWh [63], and ii) the hourly CO_2 emissions due to electricity consumption from the grid [51] were considered as well.

Table 5. Technical, economic and environmental data

Comp	Technical data (Tech)	Min Capacity [*]	Economic data (Econ)						Environmental data (Env)	References		
			Household			Building						
			Cu [€/*]	F_m	n_{comp} [Years]	Cu [€/*]	F_m	n_{comp} [Years]	CO_2U [$kgCO_2eq$/*]	(Tech)	(Econ)	(Env)
PV	$\eta_{mp,ref}$= 15.66%; μ_{Voc}=-0.32%/ºC	1.6 m^2	113	1.8	20	113	0.9	20	161	[44]	[64]	[65]
WT	Manufacturer curve	1 kWe	2360	2	20	2360	0.9	20	720	[47,48]	[66]	[67–69]
ST	η_0=0.801; a_1=3.188 W/m^2·K; a_2=0.011 W/m^2·K^2	2 m^2	257	1.5	20	257	1.5	20	95	[45]		[70]
CM	α_w=0.28 α_q=0.56	1 kWe	1150	0.7	10	1150	0.7	10	65	[61]	[71]	[72]
GB	η_b=0.96	20 kWt	80	0.5	15	80	0.5	20	10	[73]		[72]
HP	COP=3.0 EER=4.0	3 kWt	500	0.5	20	400	0.5	20	160	[74,75]		[72,76]
ACH	COP=0.7	17 kWt	-	-	-	485	1.5	20	165	[77]		[72,76]
TSQ	λ_{TSQ}=1%	2 kWht	283	0.1	15	212	0.1	15	31	[73,75]		[76]
TSR	λ_{TSR}=3%	1 kWht	325	0.1	15	257	0.1	15	62			
Bat	η_{rt}=0.95; DOD=90%; $N_{c,failure}$=2000	0.5 kWh	370	0.25	12	370	0.25	12	160	[78]		[79]
Inv	η_{Inv}=0.98	0.8 kWe	400	0.00	15	400	0.00	15	191	[80–82]		[83]
InvC	η_{InvC}=0.94	0.8 kWe	774	0.25	15	774	0.25	15	191			

Table 6. Electricity tariffs in Spain (Peninsula) [33,84]

Time-of-use tariff	Contracted power [kW]	Time period	Hours		cPct [€/kW·yr]	cp [€/kWh]
			Winter	Summer		
Tariff 2.0 DHS	Pct<10	P1	14-23	14-23	47.816	0.173941
		P2	1;8-13;24	1;8-13;24		0.099554
		P3	2-7	2-7		0.076838
Tariff 3.0A	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 7. Natural gas tariffs in Spain (Peninsula) [33]

Fuel	Tariff	Fix term [€/yr]	Variable term [€/kWh]	Annual consumption limit [kWh/yr]
Natural Gas (NG)	3.1	61.8	0.063125	≤ 5000
	3.2	112.2	0.05845	5000 - 50000
	3.3	650.64	0.050523	50000 - 100000
	3.4	971.64	0.046843	>100000

2.4 Optimization of the polygeneration system

The design of the polygeneration system is carried out by solving a MILP model developed in the optimizer software Lingo [85]. A single optimization is carried out minimizing the total annual cost *TAC*, expressed in €/yr, which is composed of the investment annual cost *CIA* and operational cost C_{op}.

$$Minimize\ TAC \tag{Eq. 1}$$

$$TAC = CIA + C_{op} \tag{Eq. 2}$$

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

$$C_{op} = C_e + C_g \tag{Eq. 3}$$

The electricity bill C_e is composed of a fixed part C_{fixe}, and the variable cost C_{ve}. C_{fixe} is proportional to contracted power *Pct* at *cPct* price in €/kWe. C_{ve} is calculated based on the electricity consumption *Ep* at cp_e price and the sale electricity *Es* at cs_e price. Values of cp_e and cs_e in €/kWh depend on time-of-use tariff. A specific tariff is applied depending on the day *d* and the hour *h* (Table 6). Besides different taxes and fixed costs such as the electricity tax Tax_e=0.0513 and the equipment rental cost C_{alqe} of 9.72€/yr for households and 16.32 €/yr for buildings. The contract power *Pct* is selected by using binary variable Y_{Pctn}, taking into account that neither purchased electricity nor sale electricity can exceed the contracted power.

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

$$C_{fix_e} = \sum_{i=1}^{3} cPct_i \cdot Pct_i \tag{Eq. 5}$$

$$Pct_{nom} = [Pct_1 \dots Pct_n] \tag{Eq. 6}$$

$$Pct = [Pct_{nom} \cdot Y_{Pct1}\ ;\ Pct_{nom} \cdot Y_{Pct2}\ ;\ Pct_{nom} \cdot Y_{Pct3}] \tag{Eq. 7}$$

$$Pct(n) \geq (Ep(d,h) + Es(d,h))_n \tag{Eq. 8}$$

$$C_{v_e} = \sum_{d=1}^{N_{rep}} \omega_d \cdot \left(\sum_{h=1}^{24} \left(cp_e(h) \cdot (Ep(h)) - cs_e(h) \cdot Es(h)\right)\right)_d \tag{Eq. 9}$$

C_g is the natural gas bill cost which consists of a fixed part related to the annual natural gas consumption C_{fixg} and a variable part proportional to the natural gas consumption C_{vg}.

$$C_g = \left(C_{fix_g} + C_{v_g}\right) \cdot (1 + VAT) \tag{Eq. 10}$$

$$C_{v_g} = \sum_{d=1}^{N_{rep}} \omega_d \cdot \left(\sum_{h=1}^{24} cp_g \cdot F_g(h)\right)_d \tag{Eq. 11}$$

The environmental impact *TCE*, expressed in kgCO_2eq/yr, is evaluated simultaneously for each economic optimum, but *TCE* is not an objective function. It is composed of a fixed part $CO2_{fix}$ corresponding to the CO_2 emissions embodied in the components and a variable part $CO2_{ope}$ corresponding to the CO_2 emissions due to the natural gas consumption and/or electricity consumption from the grid during the operation system.

$$TCE = CO2_{fix} + CO2_{ope} \tag{Eq. 12}$$

$$CO2_{fix} = \sum_j CO_2U_j \cdot Cap_j \cdot \left(1 + Repl_j\right)/n_{proj} \quad \text{(Eq. 13)}$$

$$CO2_{ope} = \sum_{d=1}^{N_{rep}} \omega_d \cdot \left(\sum_{h=1}^{24}\left(CO2_g \cdot F_g(h) + CO2_{grid}(h) \cdot Ep(h) - CO2_{grid}(h) \cdot Es(h)\right)\right)_d \quad \text{(Eq. 14)}$$

$Repl$ is the number of replacements carried out during the lifetime of the installation for every component, $CO2_g$ is the CO_2 emissions associated to the combustion of the natural gas in $kgCO_2eq/kWh$, and $CO2_{grid}$ are the CO_2 emissions associated to the electricity from the grid in each hour, in $kgCO_2eq/kWh$.

Subject to:

Balance equations

Energy balance equations are carried out in each node *m* of the superstructure (Figure 1). *E* represents energy flows of heat *Q*, cool *R* or electricity *W*.

$$\sum_m \left(E_{in}^m - E_{out}^m\right) = 0 \quad \text{(Eq. 15)}$$

Equipment Efficiency

The efficiency of each component of the superstructure has been considered. *F* represents the fuel consumption of the component.

GB: $\eta_{GB} \cdot F_{GB} - Q_{GB} = 0$ (Eq. 16)

HP: $Q_{HP} - W_{HP} \cdot COP = 0$ (Eq. 17)

HP: $R_{HP} - W_{HP} \cdot EER = 0$ (Eq. 18)

CM: $\alpha_w \cdot F_{CM} - W_{CM} = 0$ (Eq. 19)

CM: $\alpha_q \cdot F_{CM} - Q_{CM} = 0$ (Eq. 20)

ACH: $R_{ACH} = COP_{ACH} \cdot Q_{ACH}$ (Eq. 21)

Equipment's capacities:

For renewable energy production components, the aim is to find size of the PV modules A_{PV}, solar thermal collectors A_{ST} and the number of wind turbines N_{WT}

PV: $W_{PV} = E_{PV} \cdot A_{PV}$ (Eq. 22)

ST: $Q_{ST} = E_{ST} \cdot A_{ST}$ (Eq. 23)

WT: $W_W = E_W \cdot N_{WT}$ (Eq. 24)

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

$$E_j \leq Cap_j \quad \text{(Eq. 25)}$$

$$S_j \leq Cap_j \quad \text{(Eq. 26)}$$

Partial load *PL* of CM is considered by applying a binary variable Y_{ON}. Cap_{max} is the maximum capacity allowed for CM. It can work in any time as being required.

$$W_{CM} - PL \cdot Cap_{CM} \geq -Cap_{max} \cdot (1 - Y_{ON}) \quad \text{(Eq. 27)}$$

$$W_{CM} \leq Cap_{max} \cdot Y_{ON} \quad \text{(Eq. 28)}$$

In addition, different legal restrictions were considered.

3. Results

The optimization of the polygeneration system for individual and collective installations was carried out by applying legal restrictions based on both regulations RD 900/2015 and RD 244/2019. Three different scenarios have been studied: i) Scenario 1: Electricity sale is not allowed, which corresponds to the case of self-consumption type 1 in both regulations; ii) Scenario 2: Electricity sale is allowed at spot price; iii) Scenario 3: Electricity sale is allowed at 80% purchase price. As already explained, scenarios 2 and 3 are proposed as particular examples of the type 2 self-consumption in both regulations [29,30].

All runs were performed on an Intel Core i5-6200 CPU @ 2.3 GHz, with a memory of 8 GB and 64-bit system. The runtime was about 7 minutes. The number of variables is 36200, within them, 700 are integer variables.

A conventional energy system consisting of a gas boiler to attend heating demands, a mechanical chiller driven by electricity from the grid to attend only cooling demands, and electricity also purchased from the grid to cover the electrical demand of appliances is considered as a *reference scenario* for both cases. This system was also optimized and their results are presented in each table of results so as to be compared. The rest of scenarios consider reversible heat pump. It was assumed the same unit cost for the mechanical chiller and heat pump.

3.1 Individual installation: Household

3.1.1 Optimization of the polygeneration system for a household based on RD 900/2015

The optimization of the total annual cost of the superstructure for a household was carried out under the legal restrictions based on the RD 900/2015. Tables 8 and 9 show the obtained results for the optimal design of a polygeneration system for a household. Figure 2 shows the optimal configuration. For scenario 1, this includes PV, HP, GB and TSR whereas for scenarios 2 and 3 only HP, GB and TSR were included. The results of scenarios 2 and 3 mean that for a household user, it is not profitable at all to sell electricity (type 2 self-consumption), because in those conditions, the potential electricity bill savings and revenues from electricity sale (from the PV panels) do not compensate the self-consumption taxes to pay.

By comparing the reference scenario with scenario 1, a significant reduction of about 36% in economic operational costs was achieved, but in terms of total annual cost a reduction of about 10% was achieved. The installation of PV panels and TSR enable the contracted power to be reduced up to 50% with respect to the reference scenario. In terms of environmental impact, the total CO_2 emissions were reduced about 50%. In this scenario, the produced PV electricity that is not self-consumed is dissipated at zero cost.

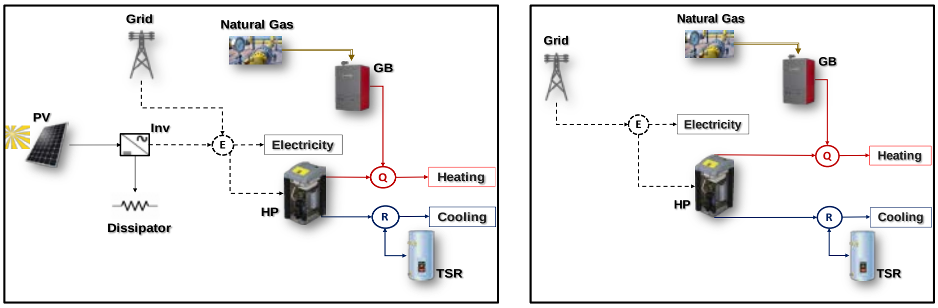

Figure 2. Optimal configuration of a polygeneration system based on RD 900/2015 for a household. Scenario 1 (Left) and Scenarios 2 and 3 (Right)

On the other hand, when the user accepts to sell electricity to the grid, under the application of RD 900/2015, the installation of PV panels is not profitable because the compulsory self- consumption taxes to pay are not compensated with the revenues obtained from the electricity sale, impeding in fact that self-consumption with electricity sale under this regulation could be profitable. Table 9 shows the optimal design of scenarios 2-3. The installation of reversible HP and TSR enable the contracted power to be reduced about 25%. Although a self-consumption system was not installed, there was a reduction in the total economic cost and CO_2 emissions of about 9% and 39% respectively, with respect to the reference scenario. These results show the advantages of using reversible HP to reduce CO_2 emissions as well as its combination with TSR to reduce economic cost. The natural gas consumption decreases about 90% in every scenario with respect to reference scenario thanks to the use of reversible heat pump.

Table 8. Results of the optimization of the polygeneration system for a household based on RD 900/2015. Reference scenario and scenario 1

Technology *j*	**Reference scenario**			**Scenario 1**		
	Installed *Cap*	**CIA*j* [€/yr]**	**[kgCO_2eq/yr]**	**Installed *Cap***	**CIA*j* [€/yr]**	**CO_2fix$_j$ [kgCO_2eq/yr]**
Pct [kW]	*2.3*	-	-	*1.15*	-	-
PV	-	-	-	4.9 m^2	181	39
HP	6.5 kWt	569	52	5.5 kWt	482	44
GB	20 kWt	414	20	20 kWt	414	20
TSR	-	-	-	1.3 kWht	81	8
INV	-	-	-	1.0 kW	63	17
Investment annual cost / Embodied CO_2 emissions		**983**	**72**	**-**	**1221**	**129**
	Consumption [kWh/yr]	**Energy cost [€/yr]**	**CO_2 emissions [kgCO_2eq/yr]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	**CO_2 emissions [kgCO_2eq/yr]**
Purchased electricity	3230	712	668	3653	704	757
Natural gas	6075	542	1242	550	94	112
Operational Economic cost/ Operational CO_2 emissions		**1254**	**1910**	**-**	**798**	**869**
Total Economic cost/ Total CO_2 emissions		***2236***	***1982***	**-**	***2019***	***998***

Table 9. Results of the optimization of the polygeneration system for a household based on RD 900/2015. Scenarios 2 and 3

Technology *j*	**Scenario 2-3**		
	Installed *Cap*	**CIA*j* [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**
Pct [kW]	*1.725*	-	-
PV	0.0 m^2	0	0
HP	5.7 kWt	497	47
GB	20 kWt	414	20
TSR	1 kWht	62	3
INV	0.0 kW	0	0
Investment annual cost / Embodied CO_2 emissions		**973**	**71**
	Consumption [kWh/yr]	**Energy cost [€/yr]**	**CO_2 emissions [$kgCO_2eq/yr$]**
Purchased Electricity	5010	979	1022
Natural gas	524	92	107
Operational Economic cost/ Operational CO_2 emissions		**1071**	**1129**
Total Economic cost/ Total CO_2 emissions		***2043***	***1200***

3.1.2 Optimization of the polygeneration system for a household based on RD 244/2019

The optimization of the total annual cost of the superstructure for a household is carried out. The optimal configuration is shown in the figure 3. This is the same for the three different considered scenarios which includes PV, HP, GB and TSR, the only difference is that an electricity dissipator is not required when sale of electricity is allowed. Tables 10 and 11 show the optimal design of a polygeneration system for a household by applying RD 244/2019.

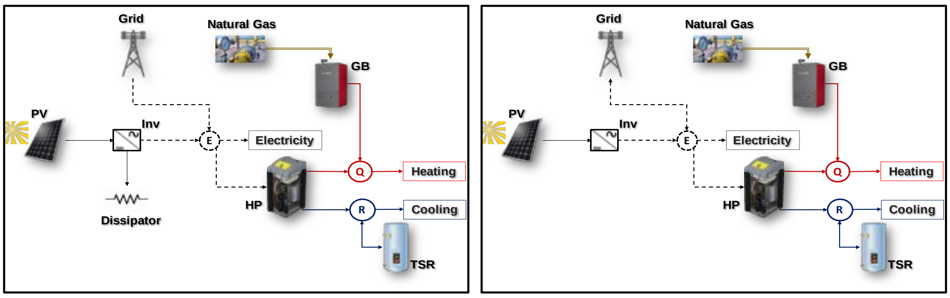

Figure 3. Optimal configuration of a polygeneration system for a household based on RD 244/2019. Scenario 1 (left), scenarios 2 and 3 (right).

The results of scenario 1 based on RD 900/2015 and RD244/2019 are the same, since there is no application of self-consumption taxes in both cases. On the other hand, unlike scenarios 2 and 3 based on RD 900/2015, in this case the installation of a polygeneration system based on PV and HP is profitable. Both scenarios 2 and 3 present the same configuration. The achievements in total economic and environmental costs are quite similar to scenario 1. By comparing scenario 1 with scenarios 2 and 3, the fact of selling electricity increased the PV and HP capacity about 10% and 4% respectively, and decreased the TSR capacity about 23%. However, in absolute terms, these variations were not significant in this size scale. Regarding the installation of PV panels, these covered only about 15% of the total available horizontal surface. The obtained results show that for 1 household the possibility of selling electricity to the grid does not provide a significant economic benefit but operational flexibility without dissipating electrical energy.

Table 10. Results of the optimization of the polygeneration system for a household based on RD 244/2019. Reference scenario and scenario 1

Technology *j*	**Reference scenario**			**Scenario 1**		
	Installed *Cap*	**CIA*j* [€/yr]**	**CO$_2$fix$_j$ [kgCO$_2$eq/yr]**	**Installed *Cap***	**CIA*j* [€/yr]**	**CO$_2$fix$_j$ [kgCO$_2$eq/yr]**
Pct [kW]	*2.3*	-	-	*1.15*	-	-
PV	-	-	-	4.9 m^2	181	39
HP	6.5 kWt	569	52	5.5 kWt	482	44
GB	20 kWt	414	20	20 kWt	414	20
TSR	-	-	-	1.3 kWht	81	8
INV	-	-	-	1.0 kW	63	17
Investment annual cost / Embodied CO$_2$ emissions		**983**	**72**	**-**	**1221**	**129**
	Consumption [kWh/yr]	**Energy cost [€/yr]**	**CO$_2$ emissions [kgCO$_2$eq/yr]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	**CO$_2$ emissions [kgCO$_2$eq/yr]**
Purchased electricity	3230	712	668	3653	704	757
Natural gas	6075	542	1242	550	94	112
Operational Economic cost/ Operational CO$_2$ emissions		**1254**	**1910**	**-**	**798**	**869**
Total Economic cost/ Total CO$_2$ emissions		***2236***	***1982***	**-**	***2019***	***998***

Table 11. Results of the optimization of the polygeneration system for a household based on RD 244/2019. Scenarios 2 and 3

Technology *j*	**Scenario 2-3**		
	Installed *Cap*	**CIA*j* [€/yr]**	**CO$_2$fix$_j$ [kgCO$_2$eq/yr]**
Pct [kW]	*1.15*	-	-
PV	5.4 m^2	199	43
HP	5.7 kWt	497	45
GB	20 kWt	414	20
TSR	1 kWht	62	6
INV	1 kW	70	19
Investment annual cost / Embodied CO$_2$ emissions		**1242**	**134**
	Consumption [kWh/yr]	**Energy cost [€/yr]**	**CO$_2$ emissions [kgCO$_2$eq/yr]**
Purchased electricity	3550	686	726
Sold electricity	52	-5	
Natural gas	550	94	112
Operational Economic cost/ Operational CO$_2$ emissions		**776**	**839**
Total Economic cost/ Total CO$_2$ emissions		***2017***	***973***

3.2 Collective installation: Residential building

By applying the legal restrictions based on the aforementioned regulations, the optimization of the polygeneration systems for residential building leads to the optimal configuration shown in the figure 4, which included CM, PV, HP, GB and TSR, and in some scenarios, TSQ as well. An electricity dissipator was required in scenario 1 when there was a surplus of produced PV electricity that was not self-consumed and in scenario 3 by applying RD 244/2019, due to the technical restriction which does not allow to sell electricity above the contracted power (Eq. 8). Note that only electricity which come from renewable energy can be sold, therefore, the electricity produced by CM is only for self-consumption. In all cases, primary energy savings *PES* were positive.

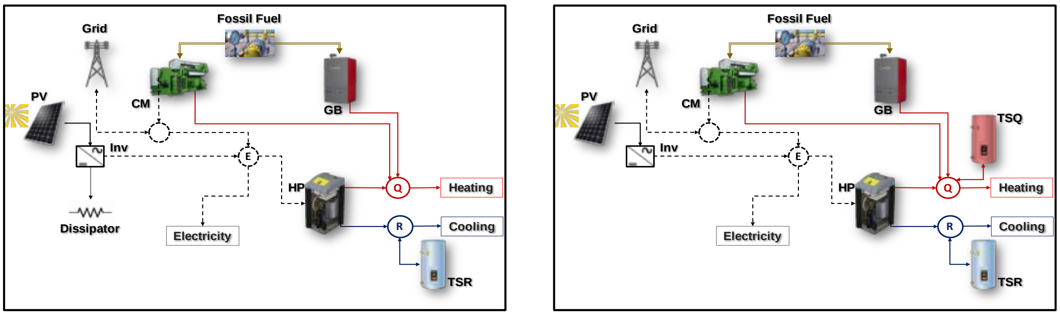

Figure 4. Optimal configuration of a polygeneration system for a residential building based on RD 900/2015 and RD 244/2019. Left: Scenarios 1 and 2 (RD 900/2015) and scenario 1 and 3 (RD 244/2019). Right: Scenario 3 (RD 900/2015) and scenario 2 (RD 244/2019).

3.2.1 Optimization of the polygeneration system for a residential building based on RD 900/2015

Tables 12 and 13 show the optimal design of a polygeneration system for a residential building composed of 50 dwellings, by applying legal restrictions based on RD 900/2015.

The contracted power for the collective installation was the same for scenarios 1, 2 and 3, with a significant reduction of about 50% with respect to the reference scenario. This is mainly due to the installation of the CM and PV panels. Regarding equipment capacity, the installation of reversible HP instead of a mechanical chiller enables the reduction of the GB capacity. Likewise, the installation of TSR enables the HP capacity reduction. In economic terms, from the reference scenario to scenario 1 there was a reduction of about 27% and 10% in the operational and total annual costs, respectively. From scenario 2 to scenario 3 there was a reduction of about 10% and 1% in the operational and total annual costs, respectively. On the other hand, from the environmental point of view, from reference scenario to scenario 1 there was a reduction of about 16% and 14% in the operational and total CO_2 emissions respectively. From scenario 1 to 2 there was a reduction below 1% in both operational and total CO_2 emissions. From scenario 2 to 3 there was a reduction of about 4% and 2% in the operational and total CO_2 emissions, respectively. In scenario 1, there was no dissipation of PV electricity, which means that all produced PV electricity was self-consumed. Under this regulation there is an important limitation to reach significant economic and environmental savings due to the self-consumption taxes to pay and to the fact that the installed capacity of the renewable energy and cogeneration technologies cannot exceed the contracted power from the grid.

Table 12. Results of the optimization of the polygeneration system by applying the RD 900/2015 for a residential building. Reference scenario and scenario 1

Technology j	**Reference scenario**			**Scenario 1**		
	Installed Cap	**CIA_j [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**	**Installed Cap**	**CIAj [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**
Pct_i [kW]	*$110.851_{1,2}/20.785_3$*	-	-	*$55.426_{1,2,3}$*	-	-
CM	-	-	-	8 kWe	2941	52
PV	-	-	-	199 m^2	*5006*	*1605*
HP	325 kWt	22747	2603	287 kWt	20083	2298
GB	274 kWt	3824	137	98 kWt	*1375*	*49*
TSR	-	-	-	44 kWht	*2170*	*276*
INV	-	-	-	37 kW	2576	713
Investment annual cost / Embodied CO_2 emissions		**26571**	**2740**	**-**	**34152**	**4993**

	Consumption [kWh/yr]	Energy cost [€/yr]	CO_2 emissions [$kgCO_2eq/yr$]	Consumption [kWh/yr]	Energy cost [€/yr]	CO_2 emissions [$kgCO_2eq/yr$]
Purchased electricity	*161495*	*42681*	*33341*	*84905*	*26275*	*17972*
Natural gas	*303757*	*18189*	*62088*	*302829*	*18136*	*61898*
Operational Economic cost/ Operational CO_2 emissions		**60869**	**95429**	**-**	**44411**	**79870**
Total Economic cost/ Total CO_2 emissions		***87440***	***98169***	**-**	***78563***	***84863***

Table 13. Results of the optimization of the polygeneration system by applying the RD 900/2015 for a residential building. Scenarios 2 and 3.

Technology j	**Scenario 2**			**Scenario 3**		
	Installed Cap	**CIA_j [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**	**Installed Cap**	**CIAj [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**
Pct_i [kW]	$55.426_{1,2,3}$	-	-	$55.426_{1,2,3}$	-	-
CM	8 kWe	2941	52	6 kWe	2206	39
PV	202 m^2	5060	1623	317 m^2	7954	2551
HP	288 kWt	20134	2304	297 kWt	20751	2375
GB	98 kWt	1375	49	106 kWt	1488	53
TSQ	0.0 kWht	0	0	2 kWht	80	6
TSR	43 kWht	2103	267	27 kWht	1292	164
INV	38 kW	2604	721	58 kW	4094	1133
Investment annual cost / Embodied CO_2 emissions		**34218**	**5016**	**-**	**37865**	**6321**
	Consumption [kWh/yr]	**Energy cost [€/yr]**	**CO_2 emissions [$kgCO_2eq/yr$]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	**CO_2 emissions [$kgCO_2eq/yr$]**
Purchased electricity	84687	26260	17654	82873	26699	11173
Sold electricity	1046	-92		33994	-6008	
Natural gas	303441	18171	62023	319647	19089	65336
Operational Economic cost/ Operational CO_2 emissions		**44339**	**79678**	**-**	**39780**	**76509**
Total Economic cost/ Total CO_2 emissions		***78557***	***84694***	**-**	***77645***	***82830***

3.2.2 Optimization of the polygeneration system for a residential building based on RD 244/2019

Tables 14 and 15 show the optimal design of a polygeneration system for a residential building based on the RD 244/2019. The contracted power for the collective installation varies for each scenario, achieving reductions of up to about 69% in scenarios 1 and 2, and up to about 58% in scenario 3 with respect to the reference scenario. The reduction in contracted power is mainly due to the installation of CM and PV panels. Regarding equipment capacity, TSQ capacity is negligible taking into account the size scale. The replacement of the mechanical chiller for a reversible HP enables the GB capacity to be reduced, and the installation of TSR enables the reversible HP capacity to be reduced. In economic terms, from reference scenario to scenario 1 there was a reduction of about 46% and 16% in the operational and total annual costs, respectively. From scenario 1 to scenario 2 there was a reduction of about 8% in the operational cost but it was negligible in the total annual cost. From scenario 2 to scenario 3 there was a reduction of about 37% and 7% in the operational and total annual costs, respectively. From the environmental point of view, from reference scenario to scenario 1 there was a reduction of about 13% and 10% in the operational and total CO_2 emissions respectively. From scenario 1 to 2 there was a reduction about 10% and 8% in operational and total CO_2 emissions respectively. From scenario 2 to 3 there was a significant reduction of about 35% and

28% in the operational and total CO_2 emissions respectively. This is mainly because in scenarios 1 and 2 the exploited area for PV panels is about 32% and 41% respectively, whereas in scenario 3 is about 74%. The available area for installing PV panels is a key factor for the reduction of CO_2 emissions. The limit value of 2000 m^2 for the available area is an assumption only to evaluate how much PV panels could be installed in the different scenarios.

Table 14. Results of the optimization of the polygeneration system for a residential building by applying RD 244/2019. Reference scenario and scenario 1

Technology *j*	**Reference scenario**			**Scenario 1**		
	Installed Cap	**CIA_j [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**	**Installed Cap**	**CIA_j [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**
Pct_i [kW]	$110.851_{1,2}/20.785_3$	-	-	$34.641_{1,2,3}$	-	-
CM	-	-	-	17 kWe	6250	111
PV	-	-	-	256 m^2	6416	2057
HP	325 kWt	22747	2603	254 kWt	17738	2030
GB	274 kWt	3824	137	116 kWt	1618	58
TSR	-	-	-	118 kWht	5254	668
INV	-	-	-	48 kW	3302	914
Investment annual cost / Embodied CO_2 emissions		**26571**	**2740**	-	**40578**	**5837**
	Consumption [kWh/yr]	**Energy cost [€/yr]**	**CO_2 emissions [$kgCO_2eq/yr$]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	**CO_2 emissions [$kgCO_2eq/yr$]**
Purchased Electricity	161495	42681	33341	44151	11523	9427
Natural gas	303757	18189	62088	358411	21286	73259
Operational Economic cost/ Operational CO_2 emissions		**60869**	**95429**	-	**32809**	**82686**
Total Economic cost/ Total CO_2 emissions		***87440***	***98169***	-	***73387***	***88524***

Table 15. Results of the optimization of the polygeneration system for a residential building by applying RD 244/2019. Scenarios 2 and 3

Technology *j*	**Scenario 2**			**Scenario 3**		
	Installed Cap	**CIA_j [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**	**Installed Cap**	**CIA_j [€/yr]**	**CO_2fix_j [$kgCO_2eq/yr$]**
Pct_i [kW]	$34.641_{1,2,3}$	-	-	$43.648_{1,2,3}$	-	-
CM	17 kWe	6349	112	7 kWe	2411	43
PV	327 m^2	8210	2633	599 m^2	15037	4822
HP	279 kWt	19497	2231	297 kWt	20751	2375
GB	112 kWt	1560	56	141 kWt	1970	70
TSQ	3 kWht	115	9	0.0 kWht	0	0
TSR	60 kWht	2942	374	27 kWht	1292	164
INV	61 kW	4225	1169	112 kW	7740	2142
Investment annual cost / Embodied CO_2 emissions		**42897**	**6584**	-	**49201**	**9616**
	Consumption [kWh/yr]	**Energy cost [€/yr]**	**CO_2 emissions [$kgCO_2eq/yr$]**	**Consumption [kWh/yr]**	**Energy cost [€/yr]**	**CO_2 emissions [$kgCO_2eq/yr$]**
Purchased Electricity	42888	11276	6815	73650	18635	517
Sold Electricity	10463	-878		77127	-13957	
Natural gas	333248	19860	68116	237516	14434	48548
Operational Economic cost/ Operational CO2 emissions		**30258**	**74931**	-	**19112**	**49065**
Total Economic cost/ Total CO_2 emissions		***73155***	***81515***	-	***68312***	***58681***

3.3 Individual and Collective installations comparison

The total annual cost and CO_2 emissions per dwelling were calculated for the case of the residential building consisting of 50 dwellings. These results were compared with individual installations in order to evaluate the advantages and disadvantages of both types of installations from the economic and environmental point of view. It is noteworthy in reference scenario (see tables 16 and 17) that in collective installations the cost per dwelling is lower than in individual installations. The reason is the reduction of natural gas cost when its consumption is increased (See table 7), which is a common feature in most of countries [86].

Table 16 presents the total annual cost and CO_2 emission of the optimal design of a polygeneration system for a residential building by applying legal restrictions based on the RD 900/2015. According to these results, the use of collective installations enables the reduction of the total annual cost per dwelling about 22% with respect to individual installations. However, apart from reference scenario, CO_2 emissions per dwelling increase by using collective installations in every scenario, about 70% in scenario 1, and about 40% in scenarios 2 and 3, with respect to the emissions corresponding to the individual installations.

Table 16. Total annual cost and CO_2 emissions per dwelling based on RD 900/2015.

Scenarios	**Individual Installation**		**Collective installation**	
	Total Annual cost [€/yr]	**Total CO_2 emissions [kgCO_2eq/yr]**	**Total Annual cost [€/yr]**	**Total CO_2 emissions [kgCO_2eq/yr]**
Reference scenario	2236	1982	1749	1963
Scenario 1	2019	998	1571	1697
Scenario 2	2043	1200	1571	1694
Scenario 3			1553	1657

Table 17 presents the total annual cost and CO_2 emissions of the optimal design of a polygeneration system for a residential building by applying legal restrictions based on the RD 244/2019. The use of collective installations enables the reduction of the total annual cost per dwelling about 27% in scenarios 1 and 2 and about 32% in scenario 3. In contrast, CO_2 emissions per dwelling were increased by using collective installations about 77%, 68% and 21% in scenarios 1, 2 and 3 respectively.

Table 17. Total annual cost and CO_2 emissions per dwelling based on RD 244/2019.

Scenarios	**Individual Installation**		**Collective installation**	
	Total Annual cost [€/yr]	**Total CO_2 emissions [kgCO_2eq/yr]**	**Total Annual cost [€/yr]**	**Total CO_2 emissions [kgCO_2eq/yr]**
Reference scenario	2236	1982	1749	1963
Scenario 1	2019	998	1468	1770
Scenario 2	2017	973	1463	1630
Scenario 3	2015	973	1366	1174

The obtained results are remarkable taking into account that the CO_2 emissions reduction is a very important factor to be considered in the energy policy. Encouraging the collective installations should lead to decrease both the total annual cost and the CO_2 emissions per dwelling, but it does not. In the three scenarios, the CO_2 emissions per dwelling in residential buildings are higher than the obtained from individual installations.

This increase of CO_2 emissions per dwelling is partly due to the natural gas consumption of the cogeneration module. In order to evaluate the impact of the cogeneration in the CO_2 emissions, the energy system is optimized not allowing the installation of this technology. Figures 5 and 6 present the obtained results for a household (Hh), residential building per dwelling considering cogeneration (RB-CM), and residential building per dwelling without cogeneration (RB-Not CM) for both regulations.

The economic and environmental impact of the optimization of polygeneration system per dwelling based on the RD 900/2015 is shown in the Figure 5. There is a CO_2 emissions reduction of about 7-9% when CM technology is not part of the optimal configuration with respect to RB-CM. However, CO_2 emissions results in residential building per dwelling remain higher than household results in every scenario.

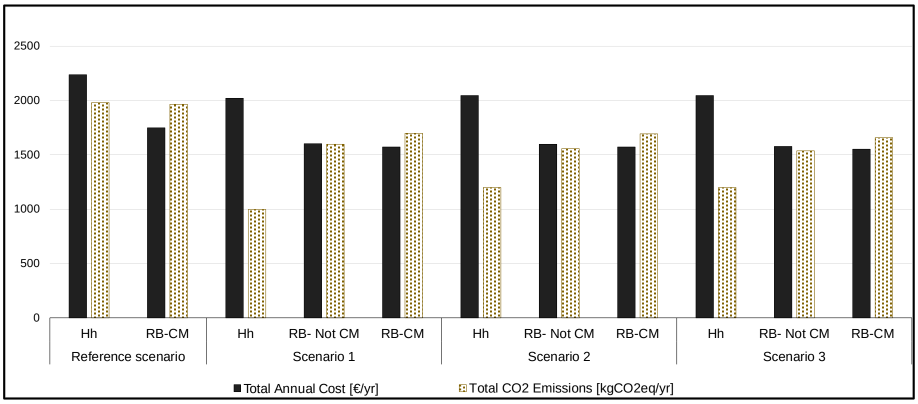

Figure 5. Economic and environmental impact of the optimization of polygeneration system per dwelling based on RD 900/2015

The economic and environmental impact of the optimization of polygeneration system per dwelling based on the RD 244/2019 is shown in the figure 6. There is a CO_2 emissions reduction of about 15-20% when CM technology is not part of the optimal configuration with respect to RB-CM. However, the CO_2 emissions results in residential building per dwelling remain higher than household results. Unlike RD 900/2015, the RD 244/2019 does not have restrictions on installed self-consumption system capacity, which allows the installation of as much PV panels as possible in scenario 3, leading to reduce the CO_2 emissions significantly.

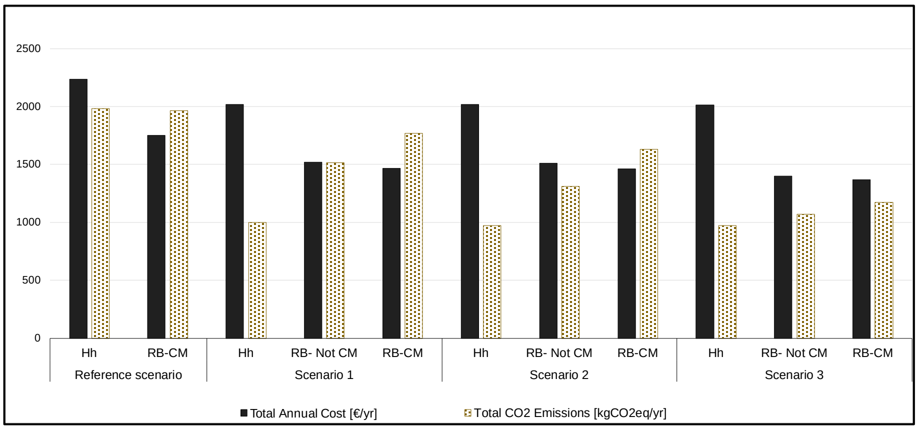

Figure 6. Economic and environmental impact of the optimization of polygeneration system per dwelling based on RD 244/2019

The fact that the CO_2 emissions per dwelling in residential buildings remain higher than household is because the natural gas consumption increases significantly whereas purchased electricity decreases in the residential building per dwelling as depicted in the figure 7. This is because under the current natural gas prices structure, the higher the natural gas consumption, the lower the natural gas price. Based on the obtained results, this prices structure should change in order to do not favour a larger consumption of fossil fuels (natural gas), at least for the residential sector (residential buildings-collective installations). In this way, more environmental-friendly technologies based on renewable energies that could be competitive and profitable would not be penalised and higher reductions of CO_2 emissions would be achieved. (See table 7).

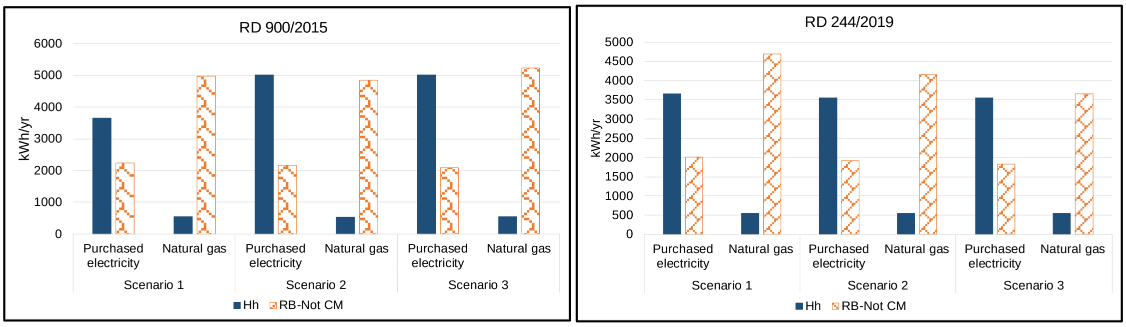

Figure 7. Natural gas consumption and purchased electricity per dwelling based on RD 900/2015 (Left) and RD 244/2019 (Right)

Thus, the natural gas price for residential building (Tariff 3.4) is 26% lower than for household (Tariff 3.1). On the other hand, the electricity price is higher for residential building than household. Therefore, based on the data shown in the table 18, the increase in the natural gas consumption results in a proportional increase in CO_2 emissions.

Table 18. Electricity and natural gas prices and unit CO_2 emissions

Fuel		**Household [€/kWh]**	**Dwelling-Building [€/kWh]**	**Unit CO_2 emissions [kgCO_2eq/kWh]**
Natural gas		0.063125	0.046843	0.2044
Electricity	**P1**	0.173941	~0.189	Variable (0.0633-0.3811) Annual Average 0.208
	P2	0.099554	~0.169	
	P3	0.076838	~0.125	

3.4 Comparison of results of the optimization of polygeneration systems under RD 900/2015 and RD 244/2019

The use of polygeneration systems with respect to conventional systems (reference scenario) provides economic and environmental benefits in all analysed cases. In individual installations (households), economic benefits were about 10%, whereas CO_2 emissions reductions of about 50%, when PV technology was selected, for both regulations. The main reason of this difference in this case was the taxation imposed to self-consumption in RD 900/2015, which represented a barrier to its development. In collective installations (residential buildings), the economic benefits were about 10% and 20% based on the application of RD 900/2015 and RD 244/2019 respectively. On the other hand, the CO_2 emissions reduction was only about 14% for both regulations with respect to the reference system, except for the scenario 3 based on RD 244/2019, which enables CO_2 emissions reduction about 40%, thanks to the installation of a significant capacity of PV, which is profitable due to the economic revenues obtained with self-produced electricity sale at 80% of the retail price.

When comparing collective versus individual installations, it was observed that both regulations enable economic benefits of about 25% when using collective installations. However, promoting collective installations could lead to an increase of the CO_2 emissions up to about 77% with respect individual installations in some scenarios. Therefore, promoting collective installations does not necessarily lead to accomplish the targets of CO_2 emissions reduction, on the contrary, it could lead to increase the environmental impact under the current conditions.

Obtained results presented in this Section 3 are consistent with the work developed by other authors, although a direct comparison is not possible due to the specificity of the work presented in this paper. Thus, Huang et al. [21] designed several hybrid energy systms for grid-connected net zero energy buildings in Hong Kong and concluded that hybrid systems integrating PV and CM where more robust than the other three hybrid energy systems under the same design conditions. Sigarchian et al. [18] optimized a grid connected polygeneration system for a residential complex located in the north of Italy, operating under a net billing scheme, consisting of similar components as considered in this paper (CM, HP, ACH, WT, TSQ, TSR, Bat, etc.) and obtained considerable cost reduction (about 20%) and CO_2 emissions reduction (about 40%) compared to conventional separate heat and power production. Finally, Pina et al. [22] developed a multiobjective framework for the synthesis of polygeneration systems and applied to a residential multifamily building consisting of 100 dwellings in Spain, and reached also the conclusion of the important role of HP in the reduction of CO_2 emissions, as well as the economic interest of installing PV at the expense of CM when additional CO_2

reduction was required. Moreover, the installation of TSR was also preferred to TSQ. It is also shown in this work the role of the electrical grid and the interest of purchasing and/or selling electricity to it, providing economic benefit as well as reliability and security to the building energy supply.

4. Conclusions

Aiming to evaluate the effect of different regulations in the optimal configuration of polygeneration systems in residential sector, the application of two recent regulations in Spain was studied. The study encompasses the individual installations (households) and residential buildings. A comparison between the regulations in economic and environmental terms were carried out.

The obtained results for individual households show that polygeneration systems based on PV are competitive and profitable without subsidies in self-consumption schemes, even in the case of net billing that limits the amount of renewable electricity that can be sold. In these conditions, in which the technology is competitive without subsidies, is not necessary the application of incentives, such as feed-in tariff, that were applied in the past for the promotion and development of promising technologies. Another interesting result is the competitive role of reversible HP in the provision of energy services with a low environmental impact and with a significant reduction of CO_2 emissions with respect to the current conventional schemes (reference scenario).

In the case of collective installations (Residential buildings), both regulations lead to significant economic savings: around 10 % when RD 900/2015 is applied and up to 24% when RD 244/2019 is applied. In both cases, the optimal configuration includes PV, CM, HP, GB and TSR. The obtained results show that the main drawback of the RD 900/2015 to achieve economic savings, is the installed capacity restriction of the renewable technologies and cogeneration. On the other hand, although there is no limit to the installed capacity of generation equipment according to the RD 244/2019, this regulation stimulate only the electricity sale generated from renewable primary energy, which discourage to some extent the cogeneration technology.

Attending to the comparison of the individual vs collective installations results, the collective ones are more economically profitable than individual installations in the application of both regulations. However, from the environmental point of view, polygeneration systems for collective installations based on both regulations lead to increase CO_2 emissions with respect to individual installations. In scenarios 1 and 2, the use of polygeneration systems in the individual installations enabled CO_2 emissions reduction about 40-50% with respect to conventional systems (reference scenario), whereas by using collective installations the reduction of CO_2 emissions per dwelling was only about 9-16%. This is because the higher the natural gas consumption, the lower the natural gas price. The idea of promoting collective installations lies in part, in the fact of taking advantage the more efficient energy systems; however, according to the obtained results, if the design of energy systems remains based on minimizing the economic cost, under the current natural gas prices structure, the best solutions from the economic point of view are those with a high natural gas consumption. Therefore, the legal restrictions for residential buildings should take into account this fact, in order to avoid the increase of CO_2 emissions.

In scenario 3, the increase of the potential revenues from electricity sale from renewable technology lead to higher CO_2 emissions reductions in residential buildings. In this sense the obtained results show that, in a horizon to achieve cero CO_2 emissions, the Net Metering scheme could be an interesting and profitable alternative to be considered, since it encourages the free exchange of electricity with the electric grid.

In general, by promoting collective installations, the RD 244/2019 encourages the investment in different renewable energy technologies unlike RD 900/2015, which established a specific taxation to self-consumption installations higher than 10 kW, in spite of that they were profitable.

This taxation represented a barrier to competitive distributed generation. However, the current Spanish regulation is not enough to achieve a significant reduction of CO_2 emissions with respect to the individual installations. Based on the obtained results, through the optimal configuration of individual installations it is possible to achieve higher CO_2 emissions reduction than those obtained by using collective installations. Therefore, more appropriate regulations with a wider perspective leading to further CO_2 emissions reduction in collective installations should be evaluated. The obtained results provide conclusions that are also valid for most of European countries, where the natural gas price for household consumers decreases when increasing the level of consumption. A more appropriate pricing of natural gas, in which its cost was not reduced when increasing its consumption, and in which greenhouse-gas emissions were considered, would lead to the design and installation of energy systems for building providing the required energy systems (polygeneration systems) with significant reduction of CO_2 emissions at reasonable and even profitable costs.

The Spanish example, that presents some common features with other countries, presented herein, highlights that inappropriate regulations and/or energy pricing may lead to results which may differ from the pursued objective of, for instance, promoting decentralized energy production and/or reduction of CO_2 emissions. Therefore, future efforts should be devoted to improve self-consumption regulation, with a broader perspective than the current policy, oriented to a more significant reduction of CO_2 emissions at an affordable cost.

Acknowledgment

This work was developed in the frame of the research project ENE2017-87711-R, partially funded by the Spanish Government (Energy Program), the Government of Aragon (Ref: T55-17R), Spain, and the EU Social Fund (FEDER Program 2014-2020 "Building Europe from Aragon"). Thanks are extended the mobility program for Latin-Americans offered by Unizar-Santander Universities.

Appendix A. Primary energy savings *PES* for cogeneration

Primary energy savings PES are calculated as follows:

$$PES = 1 - \frac{F_{cogen}}{\frac{E_{cogen}}{Ref_E} + \frac{Q_{cogen}}{Ref_Q}} \qquad \text{(Eq. A1)}$$

E_{cogen}: CM Electricity production [kWh/yr].

F_{cogen}: CM Fuel consumption [kWh/yr]

Q_{cogen}: CM useful heat production [kWh/yr]

Ref_q: Reference Efficiency value to produce heat (for domestic hot water) in a conventional system, 0.92 [87].

Ref_E: Reference Efficiency value to produce electricity in a conventional system, 0.53 [87].

Moreover, some correction factors must be applied on Ref_E [87], as follows:

- Correction factors relating to the average climatic situation (F_{cz}): For Zaragoza, average temperature is about 15 ºC [88], therefore, the correction factor is 0.
- Correction factors for avoided grid losses (F_{gl}): This study is for low voltage (below 450 V). The correction factors to apply are: 0.888 for electricity exported to the grid and 0.851 for electricity consumed on-site, according to the Spanish version of the establishing harmonised efficiency reference values [87].

$$Ref_E^{\,*} = (Ref_E + F_{cz}) \cdot F_{gl} \qquad \text{(Eq. A2)}$$

Nomenclature

Hh: Household
RB: Residential building

Energy demands
Q_d: Heating demand
R_d: Cooling demand
E_d: Electricity demand

Renewable energy production
E_{PV}: Hourly photovoltaic energy production per square meter
E_{ST}: Hourly solar thermal energy production per square meter
E_W: Hourly electrical production of a wind turbine

Equipment
PV: Photovoltaic panels
WT: Wind turbine
ST: Solar thermal collectors

Inv: Inverter
InvC: Inverter-Charger
GB: Gas boiler
HP: Heat Pump
ACH: Absorption Chiller
TSQ: Thermal energy storage for heating
TSR: Thermal energy storage for cooling
CM: Cogeneration module

Data Cost
CIA: Annual investment cost [€/yr]
C_{op}: Annual operational cost [€/yr]
C_e: Electricity bill cost [€/yr]
C_g: Annual cost of fuel consumption [€/yr]
C_{fix}: Fixed cost bill [€/yr]
C_{alq}: Meter equipment rental cost [€/yr]
CRF: Capital Recovery Factor 0.0802
Cu: Unit Cost [€/*]
cp: Purchase electricity/natural gas price [€/kWh]
cs: Electricity sale price [€/kWh]
F_{ind}: Indirect cost factor
$FNPV$: Net Present Value factor
F_m: Installation and maintenance cost factor
Pct_{nom}: Nominal power from the grid [kW]
Tax_e: Electricity tax 0.05113
VAT: 0.21 in Zaragoza, Spain.

Energy flows
Ep: Purchased electricity [kWh]
Es: Sold electricity [kWh]
F: Fuel consumption [kWh]
E: Energy [kWh]
W: Electricity production [kWh]
Q: Heating production [kWh]
R: Cooling production [kWh]

Variables
A: Area [m^2]
Cap: Nominal capacity
N_{WT}: Number of wind turbines
S: Store energy [kWh]
Y: Binary variable

Technical parameters
α_w: Electric efficiency engine
α_q: Thermal efficiency engine

COP: Coefficient of performance
EER: Energy Efficiency ratio
η: Efficiency
λ: Energy losses factor for thermal energy storage
η_{rt}: Round trip efficiency of the battery
DOD: Maximum deep of discharge of the battery
$N_{c,failure}$: Maximum number of cycles that provoke the failure in the battery
α_c: Battery charge ratio [A/Ah]

Sub-indexes $_e$ and $_g$ indicate electricity and natural gas, respectively

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