Energy & Buildings 273 (2022) 112375

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Polygeneration system optimization for building energy system retrofit: A case of study for TR5 building of UPC-Terrassa

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ARTICLE INFO

Article history:
Received 9 June 2022
Revised 21 July 2022
Accepted 8 August 2022
Available online 20 August 2022

Keywords:
Polygeneration systems
Multiobjective optimization
MILP
2^{nd} life Li-Ion batteries
Energy system retrofit

ABSTRACT

The building sector represents around one-third of the energy related to the EU CO_2eq emissions, which makes it a crucial sector for achieving the EU's energy and environmental goals. Thus, the EU has established a legislative framework to foster, among others, the modernisation of the existing building stock through a better energy system integration. In this sense, bearing in mind the needs of energy system retrofit of the public buildings in Spain, this paper carried out a thorough analysis of different trade-off solutions obtained from the multiobjective optimization of a polygeneration system for the TR5 building of the Polytechnic University of Catalunya. The results highlight the selection of PV panels, cogeneration modules and 2_{nd} life Li-Ion batteries, among others, to achieve cost-effective and sustainable energy systems. By covering the available area, 2000 m^2, the PV panels attend about 23% of the electricity required for the building. On the other hand, considering the current geopolitical tensions, it presents a potential configuration that allows to cut off the natural gas consumption reducing about 6% the current cost. The study was carried out by using a Mixed Integer Linear Programming model maximizing the Net Present Value of the project considering the environmental impact.

1. Introduction

The climate change is a worldwide concern for the humanity that struggles for decreasing the greenhouse gas (GHG) emissions to achieve climate neutrality by mid-century [1]. This concern is based on the serious impacts that would lead to a global warming of 1.5 °C above pre-industrial levels [2]. Different sectors are involved in the climate change; however, in 2020, only the building sector was responsible for about 37% of the global energy-related CO_{2eq} emissions, of which 27% are due to the building operation [3]. This shows the importance of this sector for achieving the EU's energy and environmental goals. Therefore, the EU has established a legislative framework to boost the energy performance in buildings. This updated framework includes, among others, the modernisation of the existing building stock and their systems, and better energy system integration[4]. Focused on the CO_{2eq} emissions due to the building operation, these can be reduced by reducing energy demand working on the building envelope, and/or decarbonizing the power supply, which is the centre of this work. In this sense, the use of polygeneration systems could be considered a suitable alternative to fulfil the EU's energy and environmental goals since they allow both a lower consumption of natural resources and CO_{2eq} emissions reductions with respect to the conventional separate production [5,6]. Polygeneration in buildings generally refers to the combined production of electricity, heat and cooling. 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 [7]. Among them, technologies driven by renewable energies play a key role in the design of sustainable energy supply systems for residential buildings [8]. In fact, when highest energy reductions are required, for instance zero energy buildings (ZEB), they incorporate as many renewable energy technologies as needed, and it is even better when they are hybridized with energy storage systems [9]. Different works have demonstrated their advantages from the economic and environmental point of view; however, most of them are focused on new buildings [10–12]. On the other hand, different technologies have been studied for polygenertaion systems such as cogeneration modules, heat pumps, renewable energy technologies and energy storage, however, these latter could be considered as a key component in the energy transition because they enable both to reach a significant fraction of renewable energy and increase the energy security [13,14]. In this respect, and keeping a wider perspective of the energy systems for buildings, different works have studied the possible integration of thermal and electri-

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https://doi.org/10.1016/j.enbuild.2022.112375
0378-7788/

Nomenclature

Acronyms/abbreviations

ACH	Absorption chiller
ac	alternating current
BAT	Battery
BB	Biomass boiler
CHP	Combined Heating and Power
CM	Cogeneration module
dc	direct current
ESys	Energy System
EU	European Union
GB	Gas boiler
GHG	Green–house gas
HP	Heat pump
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
Inv	Inverter
InvC	Inverter-Charger
MILP	Mixed Integer Linear Programming
MG	Microgrid
Mch	Mechanical Chiller
MCR	Major Component Replacements
NBESS	New battery energy storage system
NG	Natural Gas
NPV	Net Present Value
PIES	Park-level integrated energy systems
PV	Photovoltaic
RES	Renewable Energy Sources
SL-BESS	Second-life battery energy storage system
ST	Solar thermal
TEC	Total Environmental Cost
TES	Thermal energy storage
TSQ	Thermal energy storage for heating
TSR	Thermal energy storage for cooling
UPC	Polytechnic University of Catalunya
VAT	Value-added tax
ZEB	Zero Energy Buildings

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 €
Cap	Installed capacity
$CapEx$	Capital Expenditure, €
CF	Cash Flow, €
COP	Coefficient of performance, –
$CO2$	CO_2 emissions $kgCO_2$
CO_2U	Unit embodied CO_2 emissions/*
cp	Purchase energy price $€/kWh$
$cPct$	unit price of contracted power, €/kW
Cu	Average unit cost
$dist$	Distance, m
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	Maintenance cost factor, %/yr
h	Hour
H	Set of hours
I	Intensity, A
IT	Income tax, €
L	Lenght, m
LT	lifetime, yr
Mte	Maintenance costs, €
N	Number, –
$OpEx$	Operational Expenditure, €
Pct	Contracted power, kW
PL	Partial load, %
Q	Heating, $kWht$
R	Cooling, $kWht$
r	discount rate, $\%$
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

alpha	Efficiency,$\%$
beta	Tilt, ^{o}
Delta	Difference or variation
eta	Efficiency, $\%$
Gamma	Form of energy
lambda	Energy loss factor, %
mu	Open-circuit voltage coefficient, $\%/K$
omega	Weight of a representative day

Subscripts

ac	alternating current
c	cycle
ch	charge
dis	discharge
dc	direct current
e	electrical
fix	fixed
g	conventional fuel/natural gas
gc	grid connected
inf	Inflation
ins	install
min	minimum
ON	operation mode ON/OFF
ope	operational
p	purchased
q	thermal
rep	representative
$repl$	replacements
rt	round trip
v	variable

cal energy storage in buildings, nevertheless, the results so far have demonstrated that the batteries are not feasible in grid connected energy systems for buildings from the economic viewpoint, highlighting the advantage of using thermal energy storage for obtaining more cost-effective energy systems [11,15,16]. Nonetheless, 2^{nd} life Li-Ion batteries have not been considered in those works. This alternative technology has been widely studied in the last years under the circular economy tendency and it has been demonstrated, in theory, its potential use in different applications such as self-consumption, area regulation and transmission deferral, among others [17]. But it has also demonstrated its good performance in practice recently, by the study carried out by Lacap et al. [18] by including it in the design, construction, and operation of a commercial-scale microgrid.

Table 1
Summary of studies about polygenerations systems, 2^{nd} life Li-Ion batteries applications and building retrofit.

Application			Technologies						Retrofit		Year	Ref.
Buildings	MG	PIES	CHP	RES	HVAC	TES	NBESS	SL-BESS	ESys	Envelope		
Polygeneration systems for buildings												
x			x	x	x	x					2019	[10]
x			x	x	x	x	x				2021	[11]
x			x	x	x	x	x				2022	[15]
x			x	x	x	x	x				2018	[19]
x			x	x		x			x		2014	[21]
x			x	x		x					2021	[20]
2nd life Li-Ion batteries in stationary applications												
	x			x			x	x			2022	[18]
		x	x	x	x	x	x	x			2021	[25]
	x							x			2021	[22]
	x										2021	[23]
x				x			x	x			2022	[24]
Buildings retrofit to enhance energy efficiency												
x										x	2018	[27]
x				x	x				x		2022	[26]
x										x	2020	[28]
x			x	x	x	x	x		x	x	2022	[30]
x			x	x	x	x	x		x	x	2017	[29]

The Table 1 summarizes some of the most recent studies carried out about polygeneration systems for buildings, 2^{nd} life Li-Ion batteries (SL-BESS) in stationary applications and buildings retrofit to enhance energy efficiency. Most of the studies about polygeneration systems are carried out for theoretic buildings models, mainly for new projects [19,10,11,20,15], although an existing building like a hospital has also been studied [21]. They usually include technologies such as cogeneration, renewable energy sources (RES), HVAC systems and energy storage systems both thermal and electric, however none of those works have considered SL-BESS. Concerning these latter, there are few studies related to stationary applications, most of them in the last two years. Among them, demonstrations in microgrid (MG) [18,22], applications behind the meter [23], or home energy management applications [24] could be highlighted, focused only on the electricity demand as load. Nevertheless, beyond the electricity demand, some works study the thermal/electrical integration [15,25] as an advantage to increase the energy system efficiency, in particular, Guo et al. [25] demonstrates how a hybrid energy storage system (thermal/electric) planning is beneficial to improving the economy of the park-level integrated energy system (PIES) and delaying second-life battery energy storage system degradation. Therefore, from the authors' viewpoint, more studies including SL-BESS in polygeneration systems should be developed to foster the implementation of this technology and the thermal and electric integration. Regarding the buildings retrofit to enhance energy efficiency, there are several studies about this topic. These studies are focused on the retrofit of the energy system (ESys) [26] or the building envelope [27,28], or both of them [29,30]. Among these studies, it is worthy to highlight the work developed by Petkov et al. [30] which presents a novel optimization framework and model for the long-term investment planning of existing building retrofits, including most of the technologies considered in polygeneration systems. However, none of these studies have considered the use of 2^{nd} life Li-Ion batteries.

Thus, this work is focused on the optimization of a polygeneration system for a building of the Polythechnic University of Catalunya (UPC) in the Terrassa Campus in order to obtain a more cost-effective and sustainable energy system that allows the reduction of the CO_{2eq} emissions of the building. Likewise, it pretends to evaluate the feasibility of 2^{nd} life Li-Ion batteries for self-consumption applications. Consequently, this study points out three of the Sustainable development goals namely affordable and clean energy, sustainable cities and communities and responsible consumption and production.

On the other hand, besides the high concern about the climate change, this is not the only concern for the mankind nowadays, but the energy security. The current geopolitical tensions have led to reconsider the current energy model. In particular, the war Ukraine-Russia has shown once more the high volatility of the energy prices and the need for EU of leaving the dependency on fossil fuels [31]. Therefore, this work not only evaluates the most cost-effective and sustainable energy systems but also study the feasibility of cutting off the natural gas consumption in buildings.

Thus, the main contributions of this work can be summarized as follows:

- To carry out the optimization of a polygeneration system for a real building to propose alternatives of retrofitting the current installed energy system evaluating the feasibility of 2^{nd} life Li-Ion batteries in this application.
- To find not only cost-effective and sustainable energy systems for a real building, but those which enable cutting off the natural gas consumption at affordable cost.

To this end, a tailored Mixed Integer Linear Programming (MILP) model is developed to carry out a multiobjective optimization to carry out all the above-mentioned studies.

2. Methodology

This study proposes the optimization of a polygeneration system for the energy system retrofit of the TR5 building [1] of the Polytechnic University of Catalunya (UPC) located in Terrassa, province of Barcelona, Spain. The methodology of this study is depicted in the Fig. 1. The first part defines the different hourly time series such as energy demands, renewable energy production, energy prices and unit CO_2 emissions from the grid. Secondly, it is carried out the data processing to reduce the amount of data to deal with

[1] The study considers a set of buildings namely TR4, TR45, TR5 and TR6 (built in 1962) but for the sake of clarity the set is called TR5. The total construction area of the buildings is about 9733 m^2 with three floors. The use is for educational purpose with a daily average use of about 12 h [32].

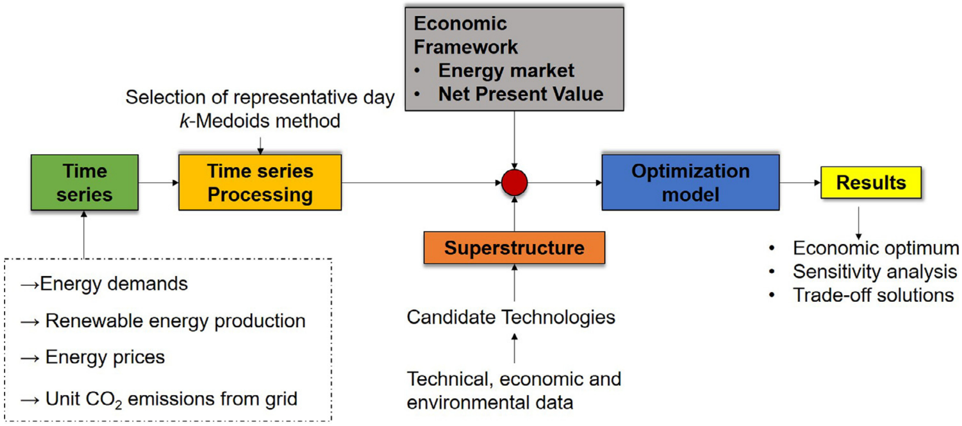


Fig. 1. Description of the methodology carried out in this study.

by selecting representative days through the *k*-medoids method. Thirdly, it is defined the superstructure consisting in the different candidate technologies to consider in the optimization model along with their technical, economic and environmental data. The fourth part describes the economic framework of this study. This includes an analysis of the energy market and the description of the net present value method used for defining the economic objective function of the optimization model. Finally, it is described in detail the optimization model that takes all the data defined previously. The results of the study are presented in the next section consisting in three parts: i) the economic optimization of the energy system, ii) a sensitivity analysis of the electricity prices and iii) a multiobjective optimization to obtain and evaluate different trade-off solutions focused on those which allow the reduction or cutting off the natural gas consumption in a cost-effective and sustainable way.

2.1. Hourly time series

This study starts for the definition of the different hourly time series considered for the optimization process. Thus, the energy demands of the TR5 building, renewable energy production, electricity prices and CO_2 emissions from the grid are defined in this section.

2.1.1. Energy demands

The energy demands for the building are estimated from the real energy consumption data of the year 2017. It corresponds to the most recent year with the best collection data available from the energy and water resources information system (SIRENA) of the Polytechnic University of Catalunya [33]. The Figs. 2a and 2b show the consumption data of the electricity in kWh and natural gas (NG) in kWht[2] in the TR5 building along the year 2017 respectively. Note that is clear the absence of people in vacations, in eastern (April 8–17, 2352–2568 h), August (5089–5832 h) and Christmas (1–200 h and 8592–8760 h) approximately. In these periods, the heating and cooling demands are negligible. On the other hand, there is NG consumption, and hence heating demand, during 8 months, from January to May (0–3081 h) and from October to December (7423–8760 h) Fig. 2b. For the sake of clarity, in this study the heating demand does not include domestic hot water, only space heating. On the other hand, there are individual heat pumps and electric heaters that are accounted for the electricity consumption but not for the heating demand.

To estimate the energy demands namely Electricity, heating and cooling, some assumptions are established. Among them, the efficiency of the equipment is assumed constant. Thus, the average efficiency of the gas boilers to produce heating is 90% and the EER (Energy Efficiency Ratio) of the mechanical chillers to produce cooling is 3.5.

Note that in the electricity consumption (Fig. 2a) there is not a distinction of the final use for the electricity consumption, i.e. electricity for lighting, HVAC, gadgets, etc; however, from the SIRENA system and the maintenance staff of the university, it is known the hourly electricity consumption data of one of the mechanical chillers which capacity is about 90 kWt. Besides, it is also known that the current installed capacity to attend the cooling demands is about 1.8 MWt. Therefore, it is assumed that 60% of the electricity demand in the summer corresponds to cooling demand. This could be considered a good approach to the real demands since the average electricity consumption in the months of April and May (2161–3624 h), when there is no significant heating or cooling demands, is about 40% of the peak demand that takes place on June 19 (day 170, hour 4069). Thus, the Figs. 3a and 3b show the electricity and cooling demands for the TR5 building respectively. On the other hand, the Fig. 3c shows the heating demand and the Fig. 3d shows the set of energy demands of the TR5 building corresponding to the year 2017 in accordance to the above-mentioned assumptions. The heating and cooling demands are presented in kWt.[3]

The Table 2 presents the annual values of the energy demands and peak values. Note that the peak day of electricity demand does not correspond to the electricity consumption because, as mentioned before, the electricity consumption in the summer was divided in electricity demand and cooling demand. In the case of heating demand, the peak day corresponds to the peak day of NG consumption. To take into account the peak days is important to size the energy system properly.

2.1.2. Renewable energy production

The use of some renewable technologies such as PV panels and solar thermal collectors (ST) are considered in this study. However, only the unit production of each technology is required for the optimization model. Thus, the unit electricity production E_{PV} from the PV panels in kWh/m^2 and the unit thermal production E_{ST} from the solar thermal collectors in kwht/m^2 are calculated previously, based on the hourly solar radiation and temperature in the location of the TR5 building [34]. The unit PV production is obtained from

[2] kilowatt-hour of thermal energy

[3] kilowatt of thermal power

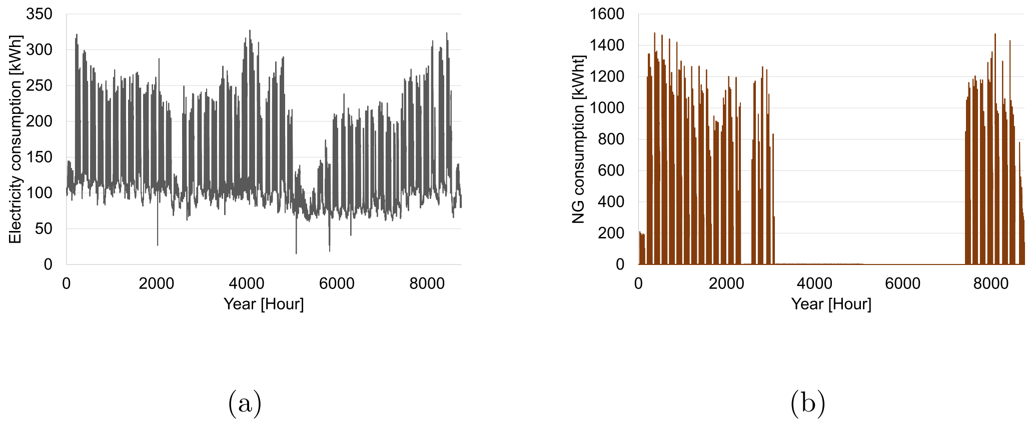


Fig. 2. Energy consumption in the TR5 building in 2017. a) Electricity consumption from the grid in kWh, b) Natural gas (NG) consumption in kWht.

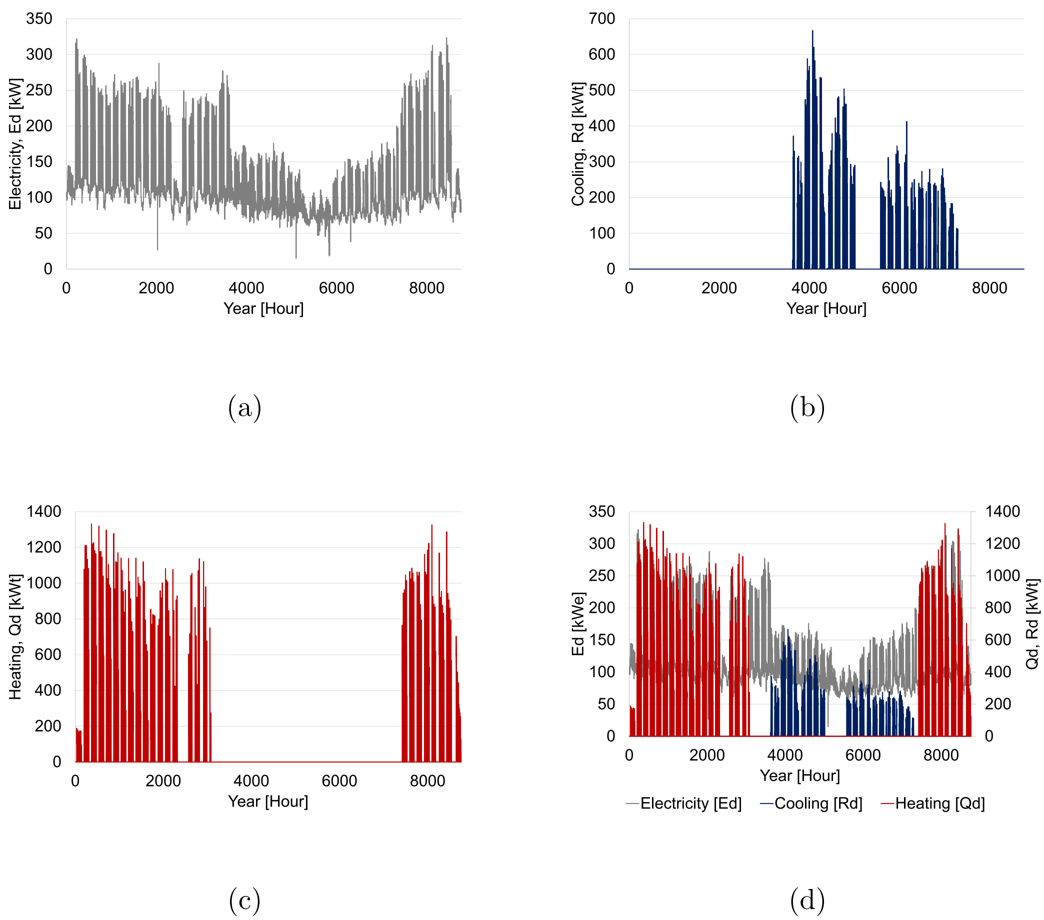


Fig. 3. Hourly energy demands in the TR5 building in 2017. a) Electricity demand in kW, b) Heating demand in kWt, c) Cooling demand in kWt, d) Energy demands.

Table 2
Energy demands and peak values of the TR5 building.

Energy demand	Annual value	Peak value	Day of peak value
Electricity	1080.3 MWh	323.9 kW	352 (December)
Heating	682.1 MWht	1332.1 kWt	16 (January)
Cooling	268.4 MWht	667.2 kWt	170 (June)

PVGis [34] directly for a PV panel with efficiency of 19.2% [35] tilted at 20° with azimuth −14° based on the technical specifications of a current PV project in the TR5 building [36]. On the other hand, the unit ST production is calculated from the technical specifications of the solar thermal collectors such as optical efficiency $a_0 = 0.81$, First-Order Loss Coefficient $a_1 = 3.188 W/m^2 \cdot K$ and Second-Order Loss Coefficient $a_2 = 0.011 W/m^2 \cdot K^2$) [37] tilted at 51.6° with azimuth −14° (taking into account that the heating demand is concentrated in winter [38]) by applying the procedure described by Duffie and Beckman [39].

The available area on the roof for installing PV panels and/or solar thermal collectors is about 2000 m^2. The effect shadow was taken into account by calculating the minimum horizontal distance between rows of PV modules $dist_{min}$ [40]:

$$dist_{min} = \frac{L_{pv} \cdot sin(\beta)}{tan(61 - latitude)} \quad (1)$$

Where L_{pv} is the length of the PV panel or ST collector, β is the tilt of the surface, 20° for PV panels and 51.6° for solar thermal collectors. The latitude of the location is 41.6° (Terrassa-Barcelona, Spain).

2.1.3. Energy prices

Currently, the TR5 building is connected to the grid at tariff 6.1 which includes 6 different hourly electricity prices (cp_e) and 6 potential contracted powers ($cPct$). Regarding these latter, the contracted power Pct in the period n must be lower or equal to the contracted power in the period $n+1$ [41]:

$$Pct_n \leqslant Pct_{n+1} \quad (2)$$

Bearing in mind that the energy prices are already sky-high, as a starting point, the energy prices before the Ukrainian war have been chosen, this means 2021. The Table 3 presents the electricity and natural gas tariff for 2021 and the Table 4 shows the time brands of access tariffs. In the case of the natural gas, there is a fixed cost per year (C_{fix_g}) and the unit price for the natural gas (cp_g).

2.1.4. CO_2 emissions from the electric grid

To quantify the environmental impact, the unit CO_2 emissions from the electric grid are other input data to be considered. In this work, these correspond to the year 2017, and they are collected from the *Red Eléctrica de España* [44] to match the energy demands. It is worthy to say that this is a rough approach because they vary yearly.

2.2. Time series processing

Due to the high computational cost that takes the solution of Mixed Integer Linear Programming (MILP) models, it is advisable to use representative days instead of the whole year data. Thus, the different time series namely energy demands, renewable energy production, electricity prices and CO_2 emissions from the grid are processed by using the k-Medoids method [45] to obtain 10 representative days (D_{rep}). The type of day, working and holidays are identified in order to match their corresponding electricity price properly. The Table 5 presents the set of representative days with their respective weight (ω) and type. Three additional days corresponding to electricity, cooling and heating peak demands days, with weight zero, are also considered to size the energy system properly without any impact on the operational costs.

2.3. Superstructure

The superstructure used for the optimization of the polygeneration system is shown in the Fig. 4. This can be divided into three groups of components depending on the type of energy they pro-

Table 3
Electricity and Natural gas prices 2021 [42,43].

	Electricity tariff		NG tariff	
Time period	cPct [€/kW· day]	cp_e [€/kWh]	C_{fix_g} [€/yr]	cp_g[€/kWh]
P1	0.084	0.235	10655	0.055
P2	0.071	0.219		
P3	0.041	0.199		
P4	0.033	0.190		
P5	0.011	0.174		
P6	0.006	0.158		

Table 4
Time brands of access tariffs. [43].

Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Holidays*
1-8	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
9	P2	P2	P3	P5	P5	P4	P2	P4	P2	P5	P3	P2	P6
10-14	P1	P1	P2	P4	P4	P3	P1	P3	P1	P4	P2	P1	P6
15-18	P2	P2	P3	P5	P5	P4	P2	P4	P2	P5	P3	P2	P6
19-22	P1	P1	P2	P4	P4	P3	P1	P3	P1	P4	P2	P1	P6
23-24	P2	P2	P3	P5	P5	P4	P2	P4	P2	P5	P3	P2	P6

Table 5
Set of representative days (D_{rep}).

Day (d)	Type	ω	Day (d)	Type	ω
13	Working day	33	98	Holiday	43
27	Working day	23	139	Working day	46
29	Holiday	40	209	Working day	25
42	Holiday	27	264	Working day	76
75	Working day	32	326	Working day	20

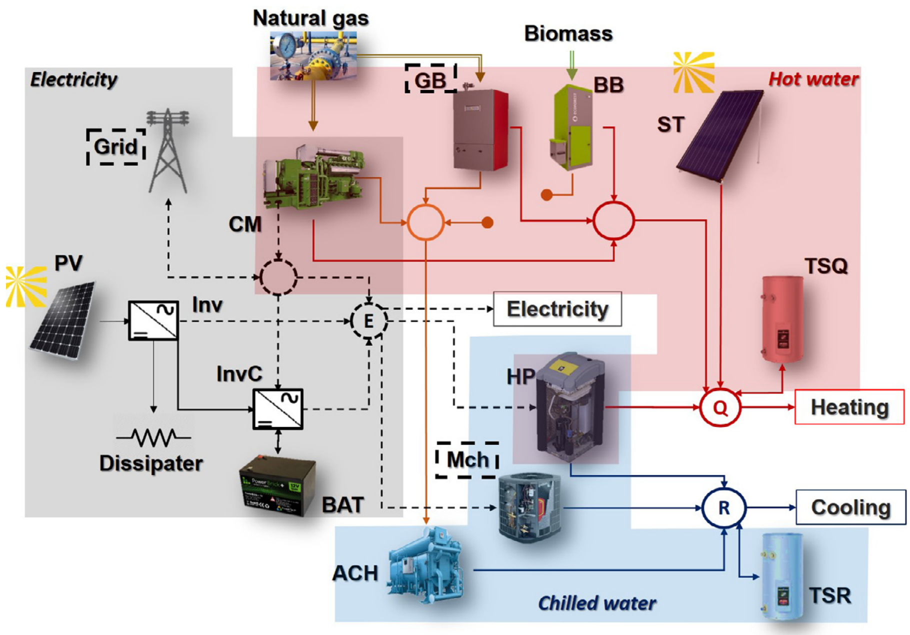


Fig. 4. Superstructure.

Table 6
Parameters of 2nd life Li-Ion batteries (SL-BESS) [46,47] and the new batteries (NBESS) [48].

Parameter	NBESS	SL-BESS
Round trip efficiency [%]	95	95
Self-discharge [%/h]	0,0042	0,0042
DOD [%]	90%	70%
Lifetime [Years]	12	6
Unit cost [€/kWh]	370	76

duce or store, namely: i) Electricity ii) Hot water and iii) Chilled water. However, some components can produce both of them.

i) Electricity: These include the electric grid (already installed in the current energy system of the TR5 building), cogeneration module (CM) fuelled by natural gas, PV panels connected to an inverter (Inv) to produce electricity in alternating current (*ac*) and Li-Ion batteries (BAT) to store electricity from the PV panels, electric grid or from the CM to be used in subsequent periods. To do this, it requires an inverter-charger (InvC) to convert the direct current (*dc*) into *ac* electricity or viceversa.

1. Li-Ion batteries (BAT):Concerning the batteries, due to the internal chemical reactions occurred within them, Li-ion batteries lose capacity with time and use. Thus, in the case of electric vehicle batteries, they are not considered appropriate for traction purposes when they reach about 70–80% of their initial capacity. However, they could have a 2^{nd} life in stationary applications such as self-consumption [46]. Therefore, this study considers 2^{nd} life Li-Ion batteries (SL-BESS) as energy storage alternative. The Table 6 presents a comparison of different parameters between 2^{nd} life Li-Ion batteries and the new ones. Note that the main different between them lies in the depth of discharge (DOD), expected lifetime and unit cost. The technical parameters such as efficiency and self-discharge remain constant approximately.

ii) Hot water: These include the gas boilers (GB) fuelled by natural gas (already installed in the current energy system of the TR5 building), cogeneration module, solar thermal collectors (ST), heat pump (HP) fuelled by *ac* electricity and biomass boiler (BB) fuelled by biomass (pellets) to produce hot water. Besides, the thermal energy storage for heating (TSQ) consisting of a water tank stores the energy that come from GB, CM, ST and HP to be used in subsequent periods to attend the heating demand.

iii) Chilled water: These include the mechanical chiller (MCH) fuelled by *ac* electricity (already installed in the current energy system of the TR5 building), heat pump and absorption chiller (ACH) fuelled by hot water to produce chilled water. It also includes thermal energy storage for cooling (TSR) which consists of a water tank to store the chilled water that come from the Mch, ACH and HP to be used in subsequent periods to attend the cooling demand.

It is important to remark the fact that some components such as the cogeneration module and the heat pump can produce more than one type of energy. Beyond, the connection between different components enables the energy system to increase its energy efficiency, which is one of the advantages of the use of polygeneration systems. The Table 7 summarize the description of the superstructure.

The Table 8 presents a summary of the different technical, economic and environmental data used in this study. Concerning the technical parameters, it was assumed that all the efficiencies of the components remain constant regardless the load. However, in the case of the cogeneration module, it is not allowed to work below 15% of its nominal capacity. Note that several cogeneration modules can be installed to fulfil the demands. On the other hand, the economic data include for each component the unit cost C_u, its maintenance cost in terms of percentage of the investment cost *Fm*, and the expected lifetime in years n_{comp}. Regarding the environmental data, it presents the unit CO_2eq emissions embodied in each component CO_2U. In the case of the natural gas, the CO_2 emissions associated to its combustion are about 0.2 $kgCO_{2eq}$/kWh [49]. It is important to remark that, in this study, for the mechanical chiller (Mch) and the gas boiler (GB) are considered only their maintenance costs, since they are already installed. In general, it is assumed a 3% of the investment costs as maintenance costs [50]. Thus, the maintenance costs for the gas boiler and mechanical chil-

Table 7
Summary description of the superstructure.

Component	Fuel	Fuelled by	Product	Observation
Electric grid (Grid)	-	-	Electricity (ac)	Already installed in TR5 building
PV panels (PV)	Solar radiation	-	Electricity (dc)	To be evaluated for installation
Inverter (Inv)	Electricity (dc)	PV	Electricity (ac)	
Inverter charger (InvC)	Electricity (ac/dc)	PV-Grid-CM-BAT	Electricity (ac/dc)	
2^{nd} life Batteries (BAT)	Electricity (dc)	InvC	Electricity (dc)	
Cogeneration module (CM)	Natural Gas	-	Electricity(ac)-Hot water	
ST thermal collectors (ST)	Solar radiation	-	Hot water	
Gas boiler (GB)	Natural Gas	-	Hot water	Already installed in TR5 building
Biomass boiler (BB)	Biomass (Pellets)	-	Hot water	To be evaluated for installation
Thermal storage for heating (TSQ)	Hot water	ST-GB-BB-CM-HP	Hot water	
Heat Pump (HP)	Electricity (ac)	Inv-InvC-CM-Grid	Hot water/Chilled water	
Mechanical Chiller (Mch)	Electricity (ac)	Inv-InvC-CM-Grid	Chilled water	Already installed in TR5 building
Absorption chiller (ACH)	Hot water	CM-GB-BB	Chilled water	To be evaluated for installation
Thermal storage for cooling (TSR)	Chilled water	HP-Mch-ACH	Chilled water	

Table 8
Technical, economic and environmental data.

Component	Technical data (Tech)	Economic data (Econ)			Environmental data (Env)	Based on references		
		C_u	Fm	n_{comp}	CO_2U [$kgCO_2eq/*$]	Tech	Econ	Env
CM	α_w[a]= 32.5% α_q[b]=55.5% PL[c]=15%	2002 €/kWe	3%	10	65 $kgCO_2eq/kWe$	[53]	[54]	[55]
PV (Monocrystalline)	320 Wp; $\eta_{mp,sc}$[d]=19.2%; μ[e]= −0.28%/°C	290 €/m^2	1%	20	161$kgCO_2eq/m^2$	[35]	[56]	[57,58]
ST	a_0[f]= 0.81 a_1[g]= 3.188$W/m^2 \cdot K$ a_2[h]= 0.011$W/m^2 \cdot K^2$	660 €/m^2	1%	20	95 $kgCO_2eq/m^2$	[52,37]		[59]
GB	η_{GB}[i]= 0.96	–	–	20	–	–	–	–
Mch	EER[j]=3.2	–	–	20	–	–	–	–
BB	η_{BB}[k]= 0.90	292 €/kWt	3%	20	10 $kgCO_2eq/kWt$	[60]		[55]
HP	COP[l]=3.5 EER = 3.5	490 €/kWt	3%	20	160 $kgCO_2eq/kWt$	[61,62]		
ACH	COP[m]=0.7	1074 €/kWt	3%	20	165 $kgCO_2eq/kWt$	[63]		
TSQ	λ_{TSQ}[n]= 0.2%	118 €/kWht	3%	15	31 $kgCO_2eq/kWht$	[52,62]		[64–66]
TSR	λ_{TSR}[o]= 0.5%	235 €/kWht			62 $kgCO_2eq/kWht$			
BAT (2^{nd} life Li-Ion)	η_{rt}[p]= 95% DOD[q]=70% $N_{\o,failure}$[r]= 2000 λ_{BAT}[s]= 0.0042% $V_{dc} = 96 - 192V$	76 €/kWh	3%	12	139 $kgCO_2eq/kWh$	[48]	[47]	[67]
Inv	η_{Inv}[t]= 98%	88 €/kW	3%	15	191 $kgCO_2eq/kW$	[68]		[57,58]
InvC	η_{InvC}[u]= 94%	327 €/kW	3%					

[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 GB
[j] Energy efficiency ratio
[k] Efficiency BB
[l] Coefficient of performance HP
[m] Coefficient of performance ACH
[n] Hourly energy loss factor for TSQ
[o] Hourly energy loss factor for TSR
[p] Round trip efficiency
[q] Depth of discharge
[r] Number of cycles to failure
[s] Hourly self-discharge
[t] Efficiency Inv
[u] Efficiency InvC

ler are about 27 €/kWt and about 225 €/kWt respectively. However, according to the literature, for the PV panels and solar thermal collectors, the maintenance cost is about 1% [51,52].

2.4. Economic framework

This section presents a brief economic analysis of the energy market and the inflation effect. Besides, it establishes the basis of the economic method to be used in the optimization model and subsequent analysis.

2.4.1. Energy market

The current geopolitical tensions have led the EU to face the highest inflation in more than 20 years (Fig. 5). In the EU, the average inflation considering all items has reached values about 8% (Fig. 5a), however, electricity and natural gas have reached values about 30% (Fig. 5 and 40% (Fig. 5c) respectively. In the case of Spain, the average inflation is similar to the EU, however, the electricity inflation has reached values of about 80% (Fig. 5b) and natural gas inflation about 20% (Fig. 5c), the half of the EU value. The lower natural gas price variation regarding the EU could be explained because Spain does not depend on the Russian gas directly. On the other hand, the high increase in the electricity price is due to the way of electricity price is set, strongly affected by the marginal cost of the fossil fuel plants [69]. In this respect, recently, the Spanish government has achieved an agreement with the EU to establish a temporary mechanism that limits the electricity price [70]. However, as just mentioned, it is a temporary measure.

The electricity and natural gas prices tendency from 2007 are shown in the Figs. 6a and 6b respectively. In Spain, during the last 14 years approximately, the electricity and natural gas prices have increased about 54% and 60% respectively. It is worthy to say that is clearer the price tendency to increase in the electricity than in the natural gas, even though, based on the inflation tendency and the energy price volatility, in a 20 years horizon an exponential increase in both electricity and natural gas prices is expected. Thus, aiming to find a cost-effective and sustainable solution, the economic optimization is carried out under the scenario where the electricity and natural gas increase their prices 50% in 20 years. Besides, bearing in mind the energy situation of the EU in reference to the natural gas, it explores solutions in which the natural gas is reduced as much as possible. We are aware that, under this scenario, new technologies based on H_2 should be considered; however, we find interesting to evaluate this scenario considering the most mature technologies in the present due to the rush of the changes.

Pellets market:

Taking into account the aforementioned energy issues [31] and bearing in mind the goal of achieving climate neutrality by mid-century [73], biomass could be considered an interesting alternative fuel. In particular, we consider pellets as an alternative to natural gas for heating, so its economic and environmental aspects must be defined.

The Fig. 7 shows the pellets price (bagged) from 2013–2021 [74]. Note that the highest increase was between 2017 and 2019, about 12%, however, unlike electricity and natural gas prices, during the pandemic period, 2020–2021, the pellet price decreased about 3%. Since pellets are considered an alternative to natural gas, it is worthy to say that the pellet price is not quite connected to the natural gas price, but it is a little affected by the oil price [75]. However, the inflation rate of natural gas and electricity is higher than liquid fuels currently [72]. In this sense, it is assumed that the pellet price increases also exponentially, but the final price

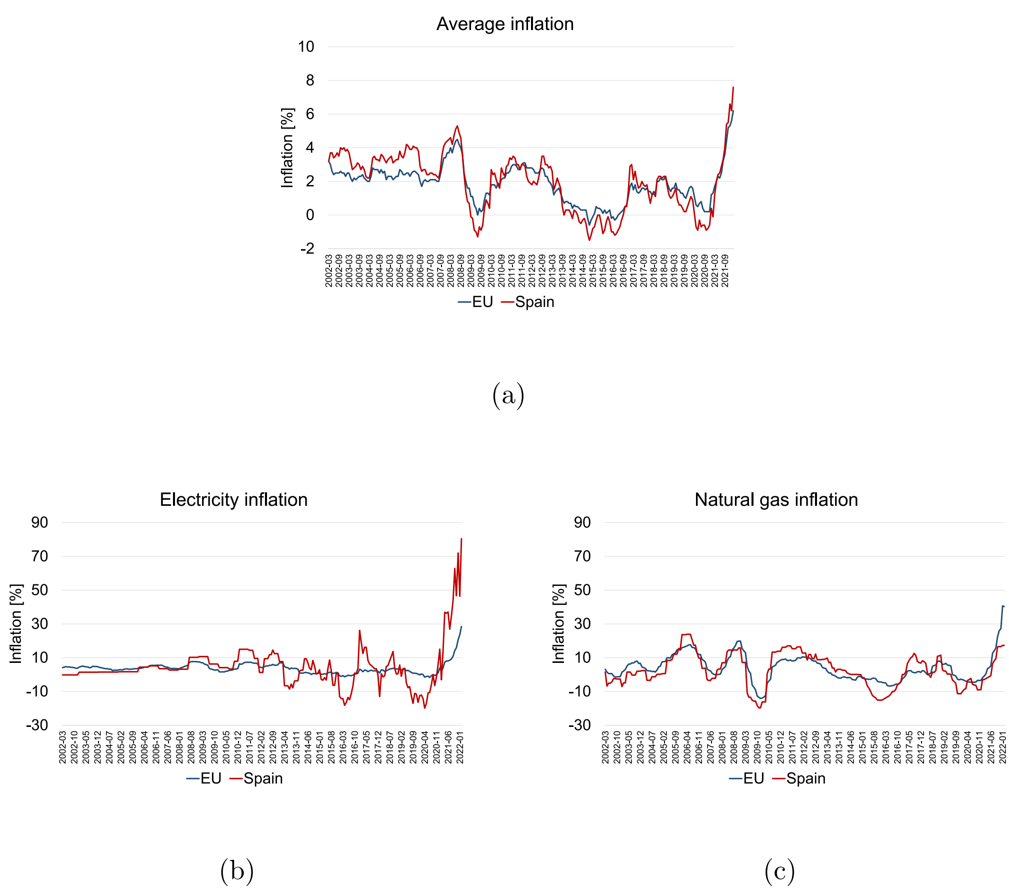
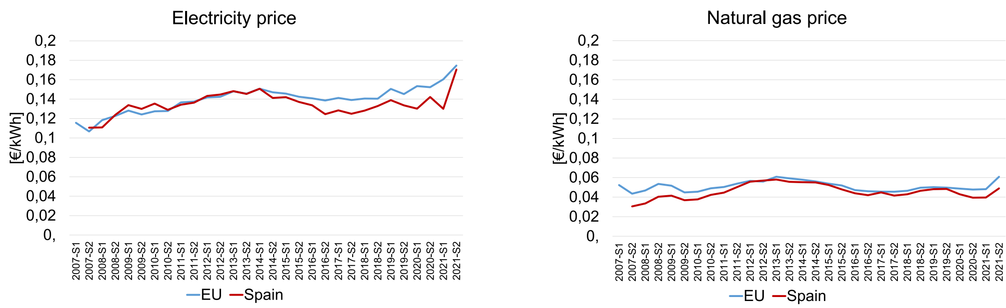


Fig. 5. a) Average Inflation all items b) Electricity inflation c) Natural gas inflation.



(a) (b)

Fig. 6. a) Electricity price from 2007 [71] b) Natural gas price from 2007. Including taxes and levies. [72].

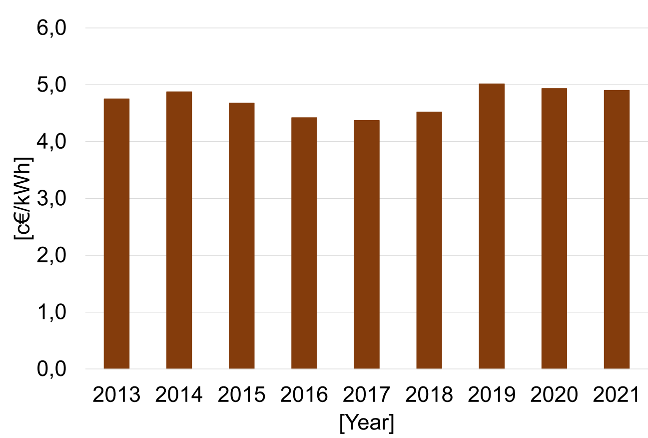


Fig. 7. Pellet price in Spain from 2013 to 2021 [74].

at the end of the 20 years horizon is expected to be 1.2 times the current value.

Regarding the pellets CO_{2eq} emissions, these are about 0.0468 $kgCO_{2eq}/kWh$ [75].

2.4.2. Net present value

The Net Present Value (*NPV*) is a commonly used method to evaluate the economic viability of an investment project. It is based on the principle that the value of the money is a function of the time of receipt or disbursement of the cash [76]. Bearing this in mind, in this study, the *NPV* consists of the capital expenditure *CapEx* associated with the initial equipment investment outlay and the sum of the discounted cash flows that represent the present value of the different input/output cash flows *CF* during the lifetime of the project *LT*. The real discount rate r is calculated based on the nominal discount rate r_{nom} and the inflation r_{inf}. Last year, 2021, in Spain, the average consumer credit was about 7.5% [77], this is assumed as the interest rate for the evaluation of the project $r_{nom} = 7.5\%$. On the other hand, the average inflation was about $r_{inf} = 3\%$ [72]. Thus, the real discount rate is $r = 4.4\%$.

$$NPV = -CapEx + \sum_{i=1}^{LT} \frac{CF_i}{(1+r)^i} \tag{3}$$

$$r = \frac{r_{nom} - r_{inf}}{1 + r_{inf}} \tag{4}$$

The *CapEx* is proportional to the equipment capacity *Cap*, the unit cost and Value-added tax *VAT*. The unit cost C_u encompasses both acquisition and installation costs. On the other hand, the cash flows *CF* include the operational expenditures *OpEx* and income tax *IT*. Usually, revenues are also considered within the cash flows, however, in this study there are no revenues to take into consideration. Therefore, as there are no revenues, income tax is assumed 0.

$$CapEx = \sum_{j=component} C_u \cdot Cap(j) \cdot (1 + VAT) \tag{5}$$

$$CF_i = -OpEx_i - IT_i \tag{6}$$

Operational expenditure (OpEx):

The operational expenditure *OpEx* encompasses the major component replacements *MCR* and the operational and maintenance costs *O&M*. For the former, it is assumed that the initial investment cost is the same as the replacement cost in the year *i*. On the other hand, in the case of the *O&M*, it consists of the operational costs including the electricity bill C_e, natural gas bill C_g, biomass costs C_b and the maintenance costs of the equipment *Mte*. This latter is calculated by applying a percentage *Fm* (%/yr) on the equipment investment cost.

The maintenance costs are affected by the inflation in the year *i*.

$$OpEx_i = MCR_i + O\&M_i \tag{7}$$

$$O\&M_i = Mte_i + C_{e_i} + C_{g_i} + C_{b_i} \tag{8}$$

$$C_e = \sum_{n=1}^{6} (cPct_n \cdot Pct_n) + \sum_{d \in D_{rep}} \omega(d) \cdot \left(\sum_{h=1}^{24} cp_e(d,h) \cdot E_p(d,h) \right) \tag{9}$$

$$C_g = C_{fix_g} + \sum_{d \in D_{rep}} \omega(d) \cdot \left(\sum_{h=1}^{24} cp_g(d,h) \cdot F_{NG}(d,h) \right) \tag{10}$$

$$C_{pellets} = \sum_{d \in D_{rep}} \omega(d) \cdot \left(\sum_{h=1}^{24} cp_{pellets}(d,h) \cdot F_{pellets}(d,h) \right) \tag{11}$$

$$Mte_i = \sum_j \left(C_u \cdot Cap(j) \cdot (1 + VAT) \cdot Fm(j) \cdot (1 + r_{inf_i}) \right) \tag{12}$$

The electricity bill includes eventual revenues for electricity sale when it applies; however, based on the current Spanish regulation, it is not allowed the electricity bill to be negative [78]. For the sake of clarity, the present value of the annual bills NPV_{bill} of the electricity, natural gas and pellets are calculated based on the value of the first bill as follows:

$$NPV_{bill} = C_{bill} \cdot \sum_{i=1}^{LT} b^i = C_{bill} \cdot \left(\frac{b^{LT+1} - 1}{b - 1} - 1 \right) \tag{13}$$

$$b = \frac{F_{bill}^{(1/LT)}}{1 + r} \tag{14}$$

The subscript ^{bill} refers to electricity, natural gas or pellet bill. Thus, according to the scenario of study, the value of F_{bill} is 1.5 for the electricity and natural gas bills whereas for the pellet bill is 1.2.

Note that as there are no revenues, the *NPV* expected is always negative, so the best option to choose is the lower in absolute terms.

2.5. Optimization model

A Mixed integer Linear Programming (MILP) model has been developed in the software Lingo [79] to carry out this study. The objective function is to maximize the Net Present Value *NPV*:

$$max\ NPV = max\left(-CapEx + \sum_{i=1}^{LT} \frac{CF_i}{(1+r)^i}\right) \tag{15}$$

However, the environmental impact is also evaluated simultaneously by calculating the total CO_2eq emissions per year *TEC* (Eq. 16). It includes both the embodied $CO2_{fix}$ and the operational CO_2eq emissions $CO2_{ope}$. The former are proportional to the equipment capacity, taking into account the number of replacements n_{repl} (Eq. 17) and the latter are proportional to the unit CO_2eq emissions *uCO2* according to the consumption of electricity from the grid ($_{gc}$), natural gas and pellets (Eq. 18–20).

$$TEC = CO2_{fix} + CO2_{ope} \tag{16}$$

$$CO2_{fix} = \sum_{j \in J} \frac{Cap(j) \cdot CU_2U(j) \cdot (1 + n_{repl}(j))}{LT} \tag{17}$$

$$CO2_{ope} = \sum_{d \in D_{rep}} \omega(d)\left(\sum_{h=1}^{24}(CO2_{gc}(d,h) + CO2_g(d,h))\right) \tag{18}$$

$$CO2_g(d,h) = uCO2_{NG} \cdot F_{NG}(d,h) + uCO2_{pellets} \cdot F_{pellets}(d,h) \tag{19}$$

$$CO2_{gc}(d,h) = uCO2_{gc}(d,h) \cdot E_p(d,h)\ \forall\, d \in D_{rep}\ \wedge\ h \in H \tag{20}$$

Subject to:

- Installation of technologies: The Installation of the components is determined by the binary variable Y_{ins} considering the maximum capacity of each component *max Cap*. Then, the technology can or cannot be installed according to the expression:

$$Cap(j) \leqslant Y_{ins}(j) \cdot max\ Cap(j)\ \forall j \in J \tag{21}$$

- 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:

$$\sum u^{in}(\Gamma,d,h) - \sum u^{out}(\Gamma,d,h) = 0\ \ \forall\, \Gamma \in \{W/E, Q, R\},\ d \in D_{rep},\ h \in H \tag{22}$$

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

$$BB : \eta_{BB} \cdot F_{BB} - Q_{BB} = 0 \tag{23}$$

$$GB : \eta_{GB} \cdot F_{GB} - Q_{GB} = 0 \tag{24}$$

$$Mch : R_{Mch} - W_{Mch} \cdot EER_{Mch} = 0 \tag{25}$$

$$HP : Q_{HP} - W_{HP} \cdot COP_{HP} = 0 \tag{26}$$

$$HP : R_{HP} - W_{HP} \cdot EER_{HP} = 0 \tag{27}$$

$$CM : \alpha_e \cdot F_{CM} - W_{CM} = 0 \tag{28}$$

$$CM : \alpha_q \cdot F_{CM} - Q_{CM} = 0 \tag{29}$$

$$ACH : R_{ACH} - COP_{ACH} \cdot Q_{ACH} = 0 \tag{30}$$

- 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. 31), due to the use of representative days:

$$S(d,1) = S(d,24) \tag{31}$$

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*:

$$S(j,d,h) = S(j,d,h-1) \cdot \lambda + u^{in}(j,d,h) - u^{out}(j,d,h)\ \forall\, d \in D_{rep}\ \wedge\ h \in H \tag{32}$$

The model of capacity used for the batteries is described by Diorio et al. [80]. Besides the hourly energy losses, the round trip efficiency η_{rt} is also considered and modelled by applying a charge efficiency η_{ch}, and discharge efficiency η_{dis} to the charge I_{ch} and discharge I_{dis} currents, and the charge $E_{BAT_{in}}$ and discharge $E_{BAT_{out}}$ energies. In addition, the number of cycles $N_ø$ must be lower or equal to the cycle life of the battery $N_{ø,failure}$. The number of cycles $N_ø$ is the ratio between the total amount of energy discharged by the battery along its lifetime and its nominal capacity [81]:

$$\eta_{rt} = \eta_{ch} \cdot \eta_{dis} \tag{33}$$

$$E_{BAT_{in}}(d,h) \cdot \eta_{ch} - I_{ch}(d,h) \cdot V_{dc} = 0\ \forall\, d \in D_{rep}\ \wedge\ h \in H \tag{34}$$

$$E_{BAT_{out}}(d,h) - \eta_{dis} \cdot I_{dis}(d,h) \cdot V_{dc} = 0\ \forall\, d \in D_{rep}\ \wedge\ h \in H \tag{35}$$

$$N_ø \leqslant N_{ø,failure} \tag{36}$$

It is worthy to say that as this study deal with 2^{nd} life Lithium-Ion batteries, the different technical data such as depth of discharge, the number of cycles and therefore the number of replacements are determined previously based on previous studies of 2^{nd} life batteries for self-consumption [17].

- 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:

$$u(\Gamma,d,h) \leqslant Cap(j)\ \forall\ \Gamma \in \{W/E, Q, R\}, j \in J,\ d \in D_{rep},\ h \in H \tag{37}$$

$$S(j,d,h) \leqslant Cap(j) \forall\ j \in J,\ d \in D_{rep},\ h \in H \tag{38}$$

- 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:

$$W_{CM} - PL \cdot Cap_{CM} \geqslant -BigM \cdot (1 - Y_{ON}) \tag{39}$$

$$W_{CM} \leqslant BigM \cdot Y_{ON} \tag{40}$$

3. Results

The objective of this study is to find a cost-effective and sustainable energy system for the TR5 building through the economic optimization of the superstructure described in the Section 2.3. To this end, the current energy system installed in the building is taken as a reference system for the evaluation. Therefore, the first step in the evaluation is to define the economic and environmental costs of the current installed energy system (Table 9). The O&M costs of the electricity grid and natural gas are proportional to their consumption, in this case, 1164.2 MWh/yr and 757.9 MWh/yr respectively.

Table 9
Technical, Economic and Environmental results of the reference energy system.

Technology	Cap [*]	Economic data (NPV)			Environmental data	
		CapEx [€]	MCR [€]	O&M [€]	$CO2_{fix}$ [kgCO_{2eq}/yr]	$CO2_{ope}$ [kgCO_{2eq}/yr]
Electric grid	324_{1-2}; 345_{3-6} kW	-	-	**5041204**	-	**285360**
Natural gas	-	-	-	**1008701**	-	**153102**
GB	1332 kWt	-	-	52422	-	-
Mch	667 kWt	-	-	173820	-	-
Total	-	-	-	**6276146**	-	**438462**
	$\|NPV\|$	***6276146***			**TEC**	***438462***

3.1. Economic optimization of a polygeneration system for the TR5 building

The Table 10 presents the results of the economic optimization of the polygeneration system for the TR5 building. The optimal configuration includes the gas boiler, mechanical chiller, cogeneration module, PV system (PV panels plus Inverter), and 2nd life battery with its respective inverter charger. The GB capacity reduces about 18% with respect to the reference system, whereas the mechanical chiller capacity is the same. Regarding renewable energy, the PV capacity of 335 kW corresponds to about 1047 m^2 of panels that in turn cover all the available surface, 2000 m^2, taking into account the respective distance considering the shadow effect. Concerning economic and environmental aspects, although there is a reduction of the $|NPV|$ of about 14%, the environmental impact increases about 18% in regard to the reference system. This is due to the increase in natural gas consumption by the cogeneration module.

The Fig. 8a shows the electricity from the grid, natural gas consumption and PV electricity of the optimal polygeneration system and the reference energy system. As mentioned before, there is a significant increase of the natural consumption regarding the reference scenario of about 160%, whereas the electricity from the grid reduces about 66%. On the other hand, regarding the electricity in the optimal polygeneration system, the Fig. 8b shows the electricity breakdown used by the TR5 building. According to this, the installed PV capacity cover about 23%, the cogeneration module about 43% and 34% comes from the electric grid.

On the other hand, at the first sight, a very interesting result in reference to previous works [11,15,16] is the feasibility of the batteries, in this case the 2nd life batteries. There is no doubt that the optimal configuration strongly depends on the electricity price. Therefore, a sensitivity analysis of the electricity price based on the 2021 tariff is carried out to evaluate the different configurations obtained as a function of the electricity price cp_e. According to the Fig. 9, the higher electricity price cp_e, the higher the PV capacity and the lower the contracted power from the electric grid *Pct*. Likewise, the higher electricity price cp_e, the higher the GB and Mch capacity and the lower the HP capacity. Note that at 30% of the 2021 tariff, the PV panels are not profitable at all. They as well as the 2nd life batteries BAT only starts to be profitable at about 40% of the 2021 tariff. Regarding the CM, this starts to be profitable at about 90% of the 2021 tariff. It is important to remark that the configurations obtained above 75% of the 2021 tariff are subjected to the area restriction since it has been achieved the maximum PV capacity for the available area.

These results demonstrate the high profitability of the PV technology nowadays, and also, the feasibility of the 2nd life batteries which is a very interesting result to foster this business model in the interest of the circular economy. Likewise, this sensitivity anal-

Table 10
Technical, Economic and Environmental results of optimal polygeneration system from the economic point of view.

Technology	Cap [*]	Economic data (NPV)			Environmental data	
		CapEx [€]	MCR [€]	O&M [€]	$CO2_{fix}$ [kgCO_{2eq}/yr]	$CO2_{ope}$ [kgCO_{2eq}/yr]
Electric grid	143_{1-6} kW	-	-	**1564123**	-	**99395**
Natural gas	-	-	-	**2304996**	-	**400150**
PV	335 kW	367262	0	64129	8425	-
Inv	335 kW	35662	18778	18682	6397	-
GB	1091 kWt	0	0	42937	0	-
Mch	667 kWt	0	0	173820	0	-
CM	141 kWe	341903	222941	179104	917	-
BAT 2nd life	86 kWh	7946	14585	4163	2402	-
InvC	28 kW	11252	5924	5894	543	-
	Total	**764026**	**262229**	**4357847**	**18685**	**499545**
	$\|NPV\|$	***5384102***			**TEC**	***518230***
	$\%\Delta\|NPV\|_{Reference}$	***-14%***			$\%\Delta TEC_{Reference}$	***18%***

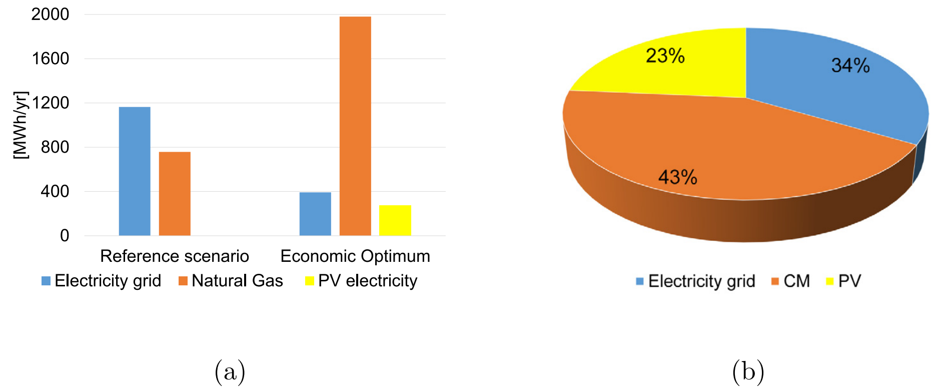


Fig. 8. a) Electricity from the grid, natural gas consumption and PV electricity; b) Electricity breakdown of the polygeneration system.

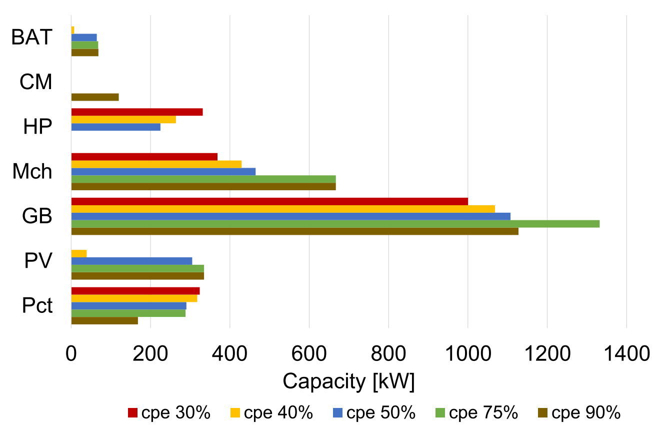


Fig. 9. Results of the optimal configuration of the polygeneration system based on the sensitivity analysis of the electricity price cp_e.

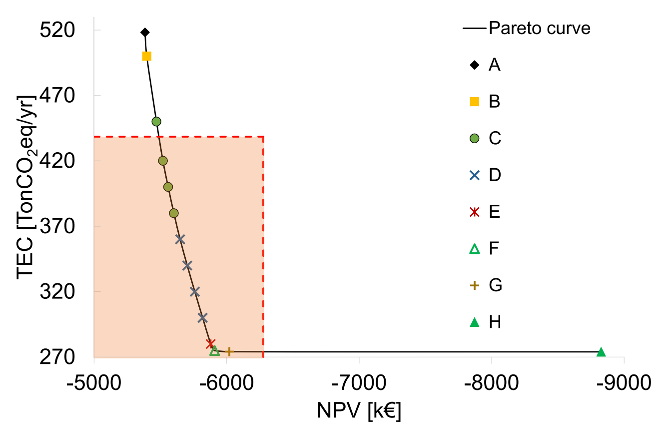


Fig. 10. Pareto curve of the multiobjective optimization of the polyegenration system.

ysis shows how the making decisions, in regard to investment in certain technologies, strongly depend on the decision time due to the energy price volatility.

Nonetheless, focused on the results obtained for the 2021 tariff, as the study aims to obtain cost-effective and sustainable solutions, it proceeds to carry out a multiobjective optimization for the purpose of finding different trade-off solutions which allow the selection of a cost-effective and sustainable polygeneration system for the TR5 building. We must be aware of the fact that all the trade-off solutions will be limited by the available area, since in the economic optimum it has been already covered by the PV panels.

3.2. Multiobjective optimization of polygeneration systems for the TR5 building

The Fig. 10 shows the pareto curve obtained through the multiobjective optimization of the polygeneration system for the TR5 building by using the ϵ-constraint method. The highlighted area encompasses the trade-off solutions that offer the most cost-effective and sustainable polygeneration systems in respect of the reference energy system.

On the other hand, the Table 11 presents the components of the different configurations of the Pareto curve. Note that along the Pareto curves, there are two technologies which have not been selected in any case: solar thermal collectors and thermal energy storage for cooling. The former has not been selected because it competes with the area of the PV panels. This result demonstrates the advantages of PV panels over solar thermal collectors in the energy system integration since besides of attending the electricity demand, they can drive the heat pump to produce either heating or cooling (configurations E-H). On the other hand, the thermal energy storage for cooling is not selected because this study starts from the already installed mechanical chiller. It is worthy to say that several works present the thermal energy storage for cooling as a good alternative to reduce indeed the equipment capacity for cooling, heat pump or mechanical chiller, but these have been carried out for new building projects [10,11,15], however this study is for an energy system retrofit project instead.

The Fig. 11 shows the energy consumption of the different trade-off solutions along the pareto curve. In the economic optimum exists the highest natural gas consumption and the minimum electricity consumption. The lower environmental impacts are achieved when the natural gas consumption decreases and the consumption of both electricity from the grid and biomass increase. Note that, it is possible to cut off the natural gas consumption at affordable cost (NPV = 5880 k€).

Bearing in mind one of the objectives of this study, *to evaluate the feasibility of* 2^{nd} *life batteries for self-consumption applications*, the results shows indeed the feasibility of this business model, and therefore confirm this application to improve the circular economy of this technology that aim to one of the sustainable development goals, *responsible consumption and production*. Other objective of this study aim to find a cost-effective and sustainable polygeneration system for the TR5 building. In this sense, two trade-off solutions have been selected:

Table 11
Optimal configurations of trade-off solutions of the Pareto curve.

Configuration	CM	PV	ST	Mch	HP	GB	BB	ACH	TSQ	TSR	BAT
A	x	x		x		x					x
B	x	x		x		x		x			x
C	x	x		x		x	x	x			x
D	x	x		x		x	x	x			x
E		x		x	x		x		x		x
F		x		x	x		x		x		
G		x		x	x		x	x			
H		x		x	x	x	x	x			

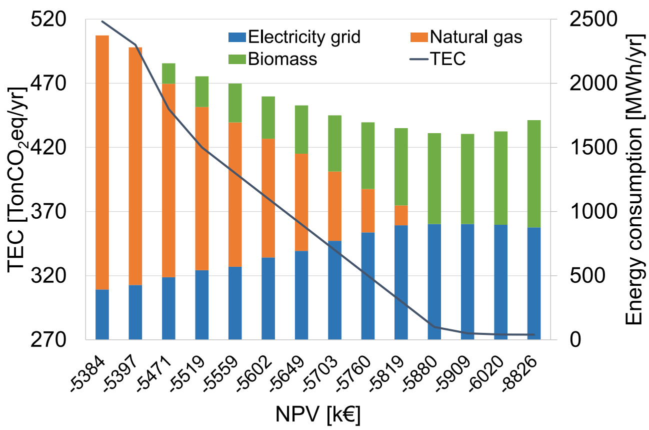


Fig. 11. Energy consumption along the Pareto curve.

1. **Configuration C:** Since the economic aspect is one of the most important drivers for making-decision, configuration C is selected since it is the most cost-effective among the highlighted solutions on the pareto curve.
2. **Configuration E:** This configuration is within the cost-effective and sustainable solutions highlighted in the Pareto curve. This is selected because enable the reduction of the natural gas consumption as much as possible at affordable cost. Besides, it also includes the 2nd life batteries.

3.3. Cost-effective and sustainable polygeneration system: Configuration C

The Fig. 12 shows the optimal configuration of the polygeneration system corresponding to the trade-off solution C. This includes cogeneration module, PV panels, mechanical chiller, natural gas and biomass boilers, absorption chiller and batteries. The Table 12 presents the technical, economic and environmental data of this configuration. The electricity demand is covered by the electric grid, PV panels, and cogeneration module. As mentioned before, the PV capacity corresponds to the maximum possible capacity. The contracted power is reduced about 42% in respect of the reference system. Regarding the heating demand, this is covered by the cogeneration module and the natural gas and biomass boilers. In this case, the gas boiler capacity decreases about 35% with respect to the reference system. This means that part of the current energy system can be used as a backup, allowing the reduction also of the maintenance costs and increasing the reliability of the energy system. Concerning the cooling demand, the mechanical chiller capacity decreases about 4% in respect of the reference system thanks to the installation of the absorption chiller. In general, this configuration is a good example of the benefits of using polygeneration systems, where from different resources such as solar energy, biomass, electricity from the grid and natural gas, different products namely electricity, heating and cooling are obtained in a cost-effective and sustainable way. In this case, the polygeneration system offers a reduction of about 11% in the *NPV* and 13% in the environmental impact concerning the reference energy system.

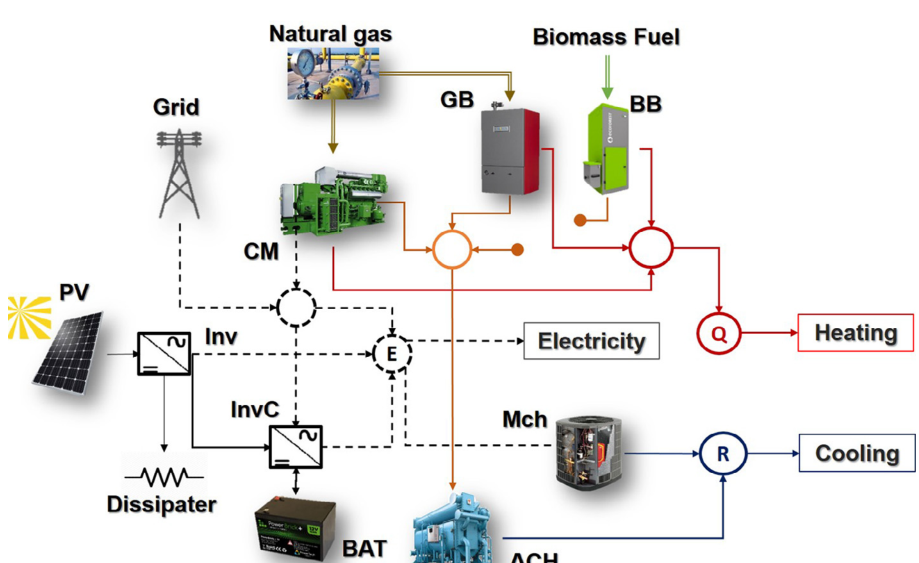


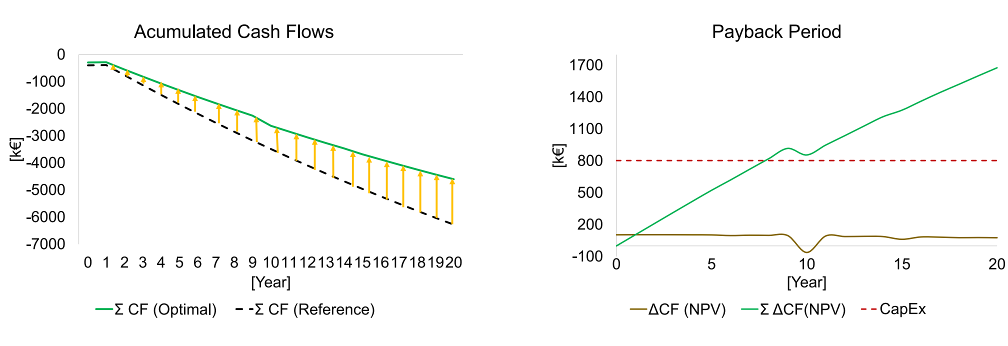
Fig. 12. Optimal configuration of the polyegenration system C.

Table 12
Technical, Economic and Environmental results of Cost-effective and sustainable polygeneration system: Configuration C.

Technology	Cap [*]	Economic data (NPV)			Environmental data	
		CapEx [€]	MCR [€]	O&M [€]	$CO2_{fix}$ [kgCO_{2eq}/yr]	$CO2_{ope}$ [kgCO_{2eq}/yr]
Electric grid	189_{1-6} kW	-	-	**2646955**	-	**159338**
Natural gas	-	-	-	**1186632**	-	**187012**
Biomass	-	-	-	**279649**	-	**15422**
PV	335 kW	367262	0	64129	8425	-
Inv	335 kW	35662	18778	18682	6397	-
BB	295 kWt	104319	0	54647	148	-
GB	867 kWt	0	0	34113	0	-
Mch	637 kWt	0	0	166042	0	-
CM	100 kW	241144	157240	126322	647	-
ACH	30 kWt	38802	0	20326	246	-
BAT 2nd life	68 kWh	6272	11511	33285	1896	-
InvC	25 kW	9698	5107	5080	468	-
	Total	**803160**	**192636**	**4605862**	**18228**	**361771**
	$\|NPV\|$	***5601658***			**TEC**	***380000***
	$\%\Delta\|NPV\|_{Reference}$	***-11%***			$\%\Delta TEC_{Reference}$	***-13%***

Regarding the economic benefits for investing in a polygeneration system, the Fig. 13a shows the operational expenditures in form of cash flows along the project lifetime for the reference system and the polygeneration system. The arrows show the accumulated savings for investing in the polygeneration system. On the other hand, the Fig. 13b shows the payback period, consisting in the time to recover the investment (*CapEx*) from the savings in the *OpEx*. The payback period for this configuration is around 8 years approximately. Note that there is a significant inflexion in the year 10 due to the replacement of the cogeneration module, however, at this point, the investment has already been recovered.

In regard to the operation of the polygeneration system, the Fig. 14 shows the optimal operation on a day of winter and summer. Concerning the electricity demand E_d in winter (Fig. 14a), this is covered only by the electric grid E_{p_e} from 1-6 h that corresponds to the lower electricity price. Taking advantage of this lower price, part of the electricity is stored in the batteries $E_{b_{in}}$. From 7–8 and 18–24, the electricity demand is covered by both the electricity grid E_{p_e} and cogeneration module W_{c_e}. From 9 to 17 it is covered by electricity grid E_{p_e}, cogeneration module W_{c_e} and PV panels W_{pv}, however, in hours 10–11 is also covered by the batteries $E_{b_{out}}$. On the other hand, the heating demand Q_d in winter (Fig. 14b) is covered by the cogeneration module Q_{cq_q}, gas boiler Q_{b_q} and biomass Q_{bb_q} boiler along the day except in hours 13–14 when is covered only by the cogeneration module and biomass boiler. In summer, the electricity demand encompasses electricity for lighting and appliances E_d and for driving the mechanical chiller E_{Mch} (Fig. 14c). It is covered by the electric grid from 1 to 6, and taking advantage of the low electricity price, part of the electricity is stored in the batteries. Likewise, part of the PV production in hours 7–8 is stored in batteries. From 7–8 and 17–19 is covered by the electric grid, cogeneration module and PV panels. Part of the energy stored by the batteries is used in hours 19–20. From 9 to 16, the electricity demand is covered by the cogeneration module and PV panels and from 21 to 24 is covered only by the cogeneration module. In turn, the cooling demand (Fig. 14d) is covered by both the mechanical chiller R_{Mch} and the absorption chiller R_{ach}, this latter driven by the cogeneration module.



(a) (b)

Fig. 13. a) Cash flows along the project lifetime b) Payback period representation for the polygeneration system C.

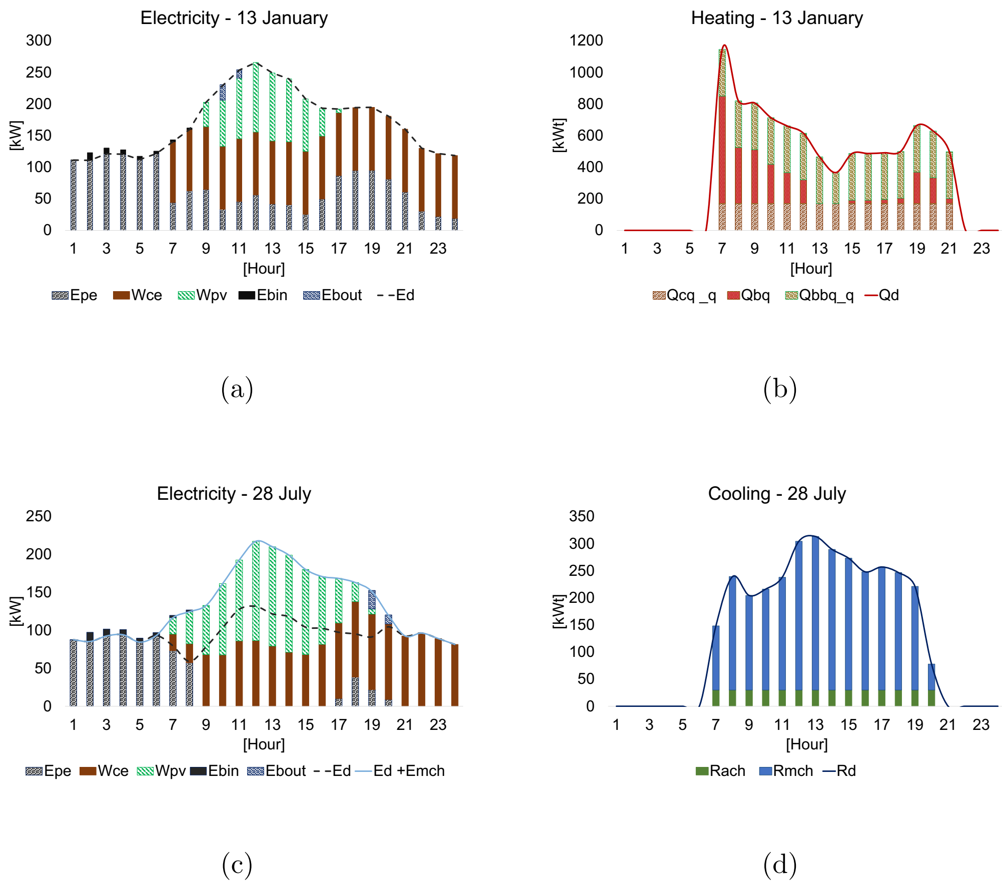


Fig. 14. Optimal operation of the polygeneration system of the trade-off solution C. a) Winter operation to cover electricity demand; b) Winter operation to cover heating demand; c) Summer operation to cover electricity demand; d) Summer operation to cover cooling demand.

3.4. Cost-effective and sustainable polygeneration system avoiding natural gas consumption: Configuration E

The Fig. 15 shows the optimal configuration of the polygeneration system corresponding to the trade-off solution E. This is a cost-effective and sustainable polygeneration system that allows to cut off the natural gas consumption completely. It consists of the electric grid and PV panels to cover the electricity demand. The heating demand is covered by the biomass boiler and heat pump. This latter can also produce cooling along with the mechanical chiller to attend the cooling demands. 2nd life batteries and thermal energy storage for heating are also selected in the optimal configuration. Note that in this case there is no gas boiler, however, since this is already installed, it could be used as a backup, or it could be sold (or a part of its total installed capacity) to obtain some benefits. These are decisions to be considered by the owner.

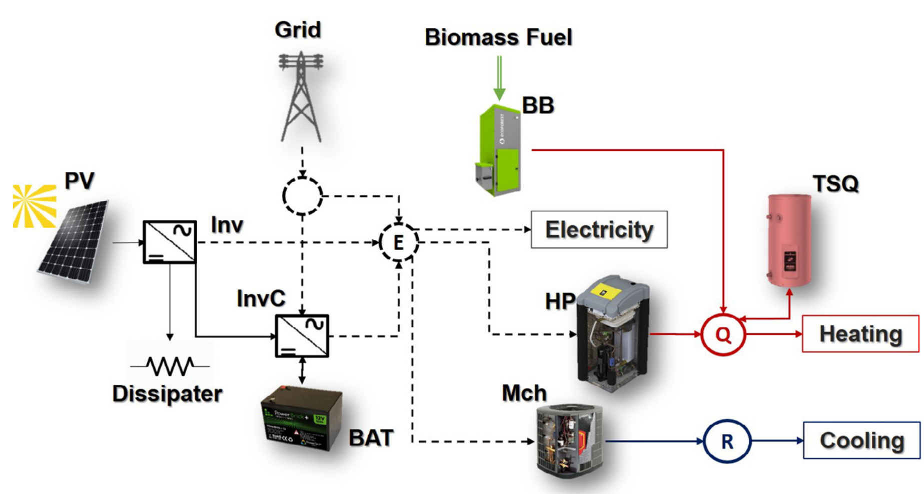


Fig. 15. Optimal configuration of the polyegenration system E.

The Table 13 presents the technical, economic and environmental data of this configuration. In this case, the contracted power is reduced about 12% with respect to the reference system which means a more dependency on the electric grid regarding the configuration C. As there is no gas boiler, the biomass boiler capacity increases about 183% and the thermal energy storage for heating, in this case, is selected regarding the previous configuration C. Besides, the heat pump, that can produce either heat or cooling, is also selected. In this case, the polygeneration system offers a reduction of about 6% in the *NPV* and about 36% in the environmental impact concerning the reference energy system. Although this is a cost-effective and sustainable solution to cut off the natural gas consumption, this is thanks to a high biomass consumption which should be evaluated in a large scale demand.

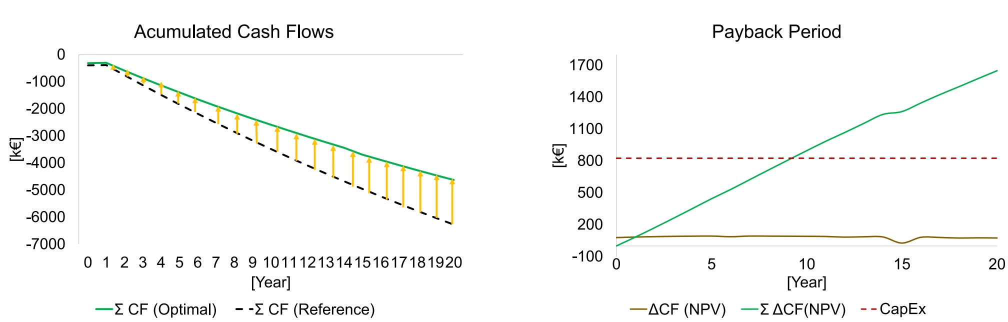
At this point, regarding the share of CO_{2eq} emissions in the polygeneration systems, it is worthy to remark that the share of CO_{2eq} emissions embodied in the equipment is only about 5% and 7% of the total CO_{2eq} emissions *TEC* in configurations C and E respectively. Therefore, up to a certain point, the CO_{2eq} emissions embodied in the equipment could be disregarded in this type of analysis, in locations like Spain.

Concerning the economic benefits for investing in a polygeneration system, the Fig. 16a shows the operational expenditures in form of cash flows along the project lifetime for the reference system and the polygeneration system. Aforementioned, the arrows show the accumulated savings for investing in the polygeneration system. On the other hand, the Fig. 16b shows the payback period, consisting in the time to recover the investment (*CapEx*) from the savings in the *OpEx* due to the investment in the polygeneration system. In this case, the payback period is in around 10 years approximately.

Regarding the operation of the polygeneration system, the Fig. 17 shows the optimal operation on a day of winter and summer. Concerning the electricity demand in winter (Fig. 17a), in this case representing both electricity for lighting and appliances E_d and for driving the heat pump E_{hp}, this is covered only by the electric grid E_{p_e} from 1-8 h, that corresponds to the lower electricity price, and from 18 to 24 h. Taking advantage of the lower electricity price of the first hours, part of this is stored in the batteries $E_{b_{in}}$. From 9 to 17, it is also covered by the PV panels production W_{pv}, however, in hours 10–11 is covered by the batteries $E_{b_{out}}$ as well. On the other hand, as mentioned before, in winter (Fig. 17b) part

Table 13
Technical, Economic and Environmental results of Cost-effective and sustainable polygeneration system: Configuration E.

Technology	Cap [*]	Economic data (NPV)			Environmental data	
		CapEx [€]	MCR [€]	O&M [€]	$CO2_{fix}$ [kgCO_{2eq}/yr]	$CO2_{ope}$ [kgCO_{2eq}/yr]
Electric grid	285_{1-6} kW	-	-	**3924709**	-	**226738**
Biomass	-	-	-	**601383**	-	**33164**
PV	335 kW	367262	0	64129	8425	-
Inv	335 kW	35662	18778	18682	6397	-
BB	835 kWt	295157	0	154616	418	-
Mch	593 kWt	0	0	154522	0	-
HP	82 kWt	48801	0	25564	658	-
TSQ	415 kWht	59293	31220	31060	1287	-
BAT 2nd life	85 kWh	7846	14401	4110	2372	-
InvC	28 kW	11178	5886	5856	540	-
	Total	**825200**	**70284**	**4984632**	**20097**	**259903**
	$\|NPV\|$	***5880116***			**TEC**	***280000***
	$\%\Delta\|NPV\|_{Reference}$	***-6%***			$\%\Delta TEC_{Reference}$	***-36%***



(a) (b)

Fig. 16. a) Cash flows along the project lifetime b) Payback period representation for the polygeneration system E.

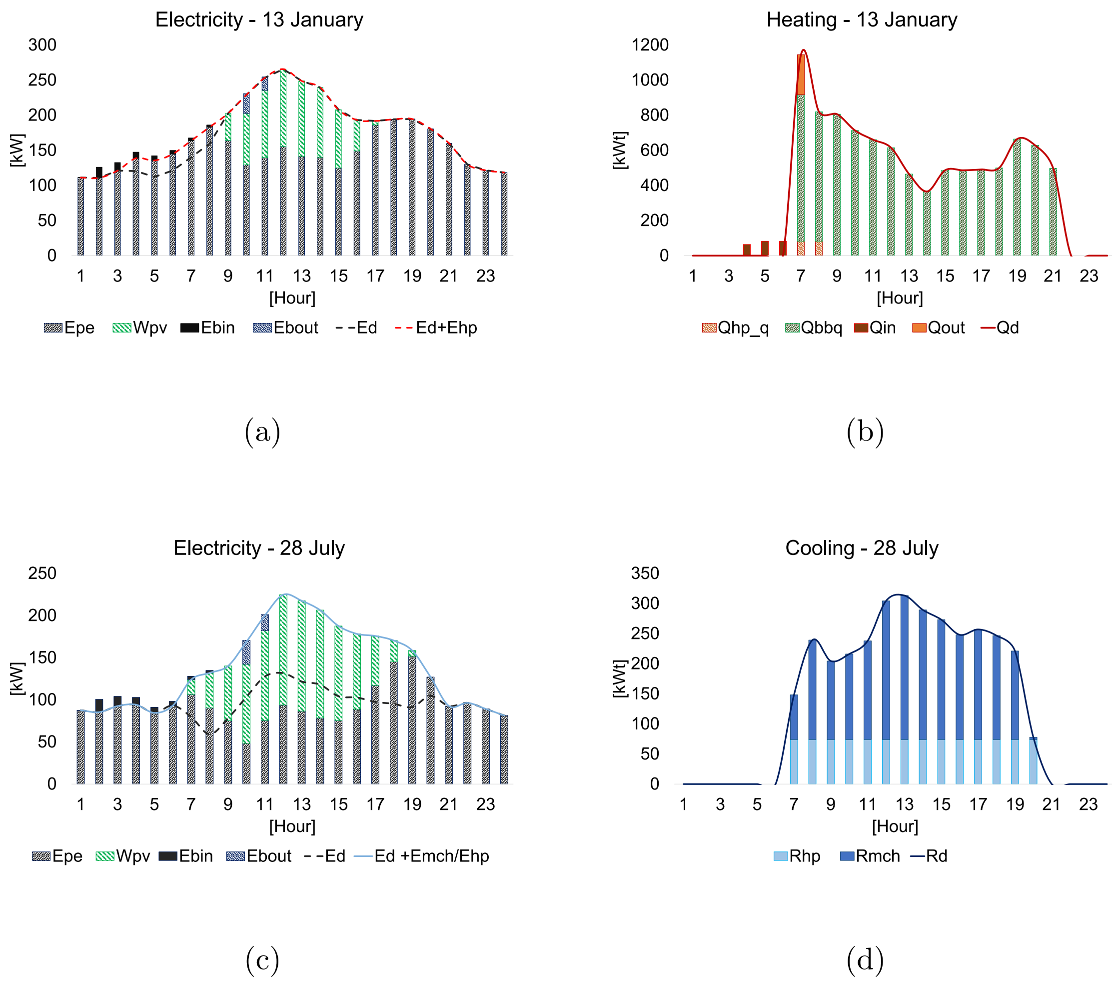


Fig. 17. Optimal operation of the polygeneration system of the trade-off solution E. a) Winter operation to cover electricity demand; b) Winter operation to cover heating demand; c) Summer operation to cover electricity demand; d) Summer operation to cover cooling demand.

of the electricity is used to drive the heat pump to produce heat. This heat is stored from 4 to 6 h taking advantage of the low electricity price to be used in the peak hour 7 along with the biomass boiler Q_{bb_q} and the heat pump Q_{hp_q}. In hour 8 the heating demand Q_d is covered by the heat pump Q_{hp_q} and the biomass boiler Q_{bb_q}. For the rest of the hours, the heating demand Q_d is covered only by the biomass boiler Q_{bb_q}. In summer, the electricity demand includes the electricity for lighting and appliances E_d and the electricity for driving the mechanical chiller E_{Mch} and the heat pump E_{hp} (Fig. 17c). It is covered only by the electric grid from 1 to 6 and 20 to 24 h. Taking advantage of the low electricity price from 2 to 6 h, part of the electricity from the grid is stored in the batteries. Likewise, part of the PV production is stored in the batteries in hours 7 and 8 h. From 7–19 is covered by the electric grid and PV panels. The energy stored by the batteries is used in the hours 10–11. In turn, the cooling demand (Fig. 17d) is covered by both the mechanical chiller R_{Mch} and the heat pump R_{hp} along the day.

4. Conclusions

This study has carried out a thorough analysis of the feasibility of polygeneration systems for the energy system retrofit of the TR5 building located in Terrassa-Spain. The effect of the inflation and hence, the potential change of energy prices has been considered to optimize from the economic viewpoint a polygeneration system to cover the different energy demands. Different technologies have been considered in the superstructure remarking the alternative of using 2nd life Li-Ion batteries for self-consumption to enhance the circular economy of this technology. It was carried out the economic optimization of the polygeneration system for the TR5 building by using a tailored MILP model. Although the result was cost-effective, the environmental impact was higher regarding the reference system. This shows the importance of including in the project's model not only economic indicators but also the environmental ones, in order to be sure of achieving both cost-effective and sustainable results. Likewise, a sensitivity analysis was carried out to visualize the impact of the electricity price on the making-decisions on different technologies. Thus, the results remark the feasibility of the PV technology and 2nd life Li-Ion batteries from about 40% of the 2021 tariff. Taking into consideration that the polygeneration system in the economic optimum had a higher environmental impact than the reference energy system, a multi-objective optimization was carried for the purpose of obtaining different trade-off solutions. It was highlighted the most cost-effective and sustainable solutions concerning the current installed energy system in the TR5 building that has been taken as a reference system. In particular, two configurations were selected to fulfil a thorough analysis. The first, configuration (C), included the electric grid, PV panels, cogeneration module, absorption chiller, natural gas and biomass boilers, mechanical chiller and 2nd life Li-Ion batteries. This polygeneration system reduces the CO_{2eq}

emissions about 13% with respect to the reference system, and the investment cost can be recovered in around 8 years. On the other hand, the second configuration (E) allows cutting off the natural gas consumption. This latter plays an important role, thinking about the current geopolitical tensions. This polygeneration system is made up of the electric grid, PV panels, biomass boiler, mechanical chiller, heat pump, thermal energy storage for heating and 2^{nd} life Li-Ion batteries. In this case, the polygeneration system reduces the CO_{2eq} emissions about 36% regarding the reference system and the investment cost can be recovered in around 10 years. Although it has been demonstrated that it is feasible to cut off the natural gas consumption through a cost-effective and sustainable solution, this is done by high consumption of biomass which must be analysed thoroughly when is considered for a large scale solution, for instance, for a city or country. On the other hand, it is worthy to remark the presence of 2^{nd} life Li-Ion batteries in several optimal configurations, among them, in the economic optimum to foster this business model. In general, the results of this paper pretend to help the stakeholders for making decisions as well as the policymakers to take suitable decisions in accordance with international agreements.

5. Future directions

There is a clear limitation to reduce further the energy consumption and CO_{2eq} emissions because this work has focused only in the energy system retrofit. Therefore, future works should include the building envelope retrofit in the optimization process to enhance the results obtained.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Edwin S. Pinto reports financial support was provided by Europe Union-NextGenerationEU and the Ministry of Universities of Spain..

Acknowledgements

The authors thank to the Margarita Salas grant funded by the Europe Union-NextGenerationEU and the Ministry of Universities of Spain.

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