# ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF RENEWABLE ENERGY AND ENERGY STORAGE INTEGRATION IN STANDALONE POLYGENERATION SYSTEMS FOR RESIDENTIAL BUILDINGS

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**Abstract**

Energy consumption and $CO_2$ emissions in residential sector plays an important role to face the climate change. Technologies and strategies which allow the reduction of fuel consumption and $CO_2$ emissions in energy supply systems for residential buildings are required. This work analyses the integration of different renewable energy and energy storage technologies for a residential building located in Zaragoza, Spain. It is selected a standalone energy system in order to study in a systematic way how different technologies interact and affect the optimal design, from conventional to polygeneration systems. A Mixed Integer Linear Programming (MILP) model was developed to optimize the system from the economic point of view whereas $CO_2$ emissions are calculated simultaneously. Results show that photovoltaic technology provides a remarkable reduction of costs and along with cogeneration allow a significant $CO_2$ emissions reduction as well. In addition, it was determined the synergies of different technologies, e.g. batteries capacity is reduced when cogeneration and thermal energy storage are considered. Furthermore, a sensitivity analysis of the number of cycles of the Ion Lithium batteries was carried out to show its competitiveness with respect to lead acid batteries.

*Keywords: Polygeneration, MILP, Energy storage, Renewable Energy, Energy systems integration.*

## 1. Introduction

Residential sector plays an important role in the policies to face the climate change since this sector represents about 27% of world energy consumption and about 17% of world $CO_2$ emissions (Nejat et al., 2015). Several studies have demonstrated the advantages of integrating energy systems in order to obtain a more efficient use of natural resources as well as a significant reduction of $CO_2$ emissions in residential buildings applications (Mancarella, 2014; Serra et al., 2009). To achieve it, the design of energy systems must be addressed taking into account the synthesis of the system (installed technologies and capacities, etc.) and the operational planning (strategy concerning the operational state of the equipment, energy flow rates, etc.); however, finding the optimal configuration is a complex task, given the wide variety of technologies option available and great diurnal and annual fluctuations in energy demands, among others (Tapia-Ahumada et al., 2013). Other factors that increase even more the complexity are: i) the incorporation of renewable energy technologies which are characterized by intermittent behaviour and non-simultaneity between consumption and production, and ii) the integration of energy storage, either electrical and/or thermal, which allow to decouple production from consumption.

The aim of this work is to carry out a systematic economic and environmental evaluation of the impact of the integration of different energy and energy storage technologies in the energy supply system of residential buildings located in Zaragoza, Spain. The approach is based on standalone energy systems in order to identify clearer the interactions of different technologies, e.g. batteries, allowing a deeper understanding of their effect on the optimal design of the energy system, from conventional to polygeneration systems. To do this, a MILP (Mixed Integer Linear Programming) model has been developed to obtain the optimal design of energy systems based on different conditions and restrictions.


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## 2. Methodology

MILP model is used to design the energy system for a residential building located in Zaragoza, composed of 40 dwellings with 102.4 m$^2$ of surface area and an average occupancy of 3 people per dwelling. To do this, energy demands and natural resources must be defined beforehand. Ideally, whole year data should be used to evaluate the energy systems; however, this can be intractable computationally, therefore, representative days are used. Superstructure which considers candidate technologies is defined and finally MILP model is developed.

### 2.1 Energy demands and renewable energy production

Space heating and Cooling demands are estimated from annual data (IDAE, 2009). Daily data are obtained by using degree days method and hourly data by applying hourly profiles (Ramos, 2012). To apply the degree days method, base temperature for space heating and cooling is set in 15ºC and 21ºC respectively. Domestic Hot Water (DHW) is calculated considering the reference temperature 60ºC and the mean monthly temperature of the net water (AENOR, 2005). Monthly distribution is carried out by applying a monthly consumption factor (Viti, 1996). It is assumed that every day of each month have the same consumption. An hourly profile (Ramos, 2012) is applied to obtain the hourly demand. In the case of electricity demand, annual electricity demand for appliances according to IDAE (2011a) is monthly distributed by applying a distribution factor, which is divided by the days of the month and distributed by an hourly distribution function (Marín-Giménez, 2004), that considers different hourly consumption for each season. Procedures briefly described above provide the hourly demand data series of heating $Q_d$, cooling $R_d$ and electricity $E_d$, where heating demand consists of space heating and DHW.

Hourly photovoltaic energy production per square meter, $E_{PV}$, is calculated following the procedure described by (Duffie and Beckman, 2013) as a function of the solar radiation over a tilted surface 36º and azimuth angle 0º (Meteotest, 2017).

Hourly solar thermal energy production per square meter, $E_{ST}$, is calculated as a function of the solar radiation over a tilted surface 36º and azimuth angle 0º as well, the mean difference temperature between the collector temperature 60ºC and ambient temperature, and the collector parameters (Salvador Escoda S.A, 2017).

The electrical production of a wind turbine, is calculated based on the production curve of the turbine with nominal capacity of 30 kW (Aeolos, 2006) and the wind speed (Meteotest, 2017), following the procedure described by (Manwell et al., 2009).

**Tab. 1. Annual and peak values for energy demands and renewable energy production**

| Attribute | Annual Value | | Peak Value | |
|---|---|---|---|---|
| Heating demand ($Q_d$) | 69985 | kWht | 65.6 | kWt |
| Cooling demand ($R_d$) | 14008 | kWht | 70.3 | kWt |
| Electricity demand ($E_d$) | 35268 | kWh | 7.2 | kW |
| Photovoltaic production ($E_{PV}$) | 285 | kWh/m$^2$ | 0.16 | kW/m$^2$ |
| Wind energy ($E_W$) | 6397 | kWh/ud | 3.42 | kW/ud |
| Solar Thermal Production ($E_{ST}$) | 995 | kWht/m$^2$ | 0.79 | kWt/m$^2$ |

### 2.2. Representative days

The optimization of polygeneration systems should be carried out by using whole year data but this can become intractable computationally, mainly when integer variables are involved. Therefore, representative days are selected to tackle this issue. In this case, it was applied a method based on the combination of *k*-medoids (Dominguez-Muñoz et al., 2011) and OPT (Poncelet et al., 2017) methods to obtain the set of 12 representative days with their respective weights $\omega$ presented in Tab. 2. Two additional days corresponding to peak energy demands are considered in the optimization process with $\omega=0$. Therefore, the number of days $N_{rep}$ used in the optimization process is 14.

**Tab. 2. Set of representative days used for the optimization of the energy system**

| Month | *d* | *ω* | Month | *d* | *ω* | Month | *d* | *ω* |
|---|---|---|---|---|---|---|---|---|
| January | 21 | 6 | May | 147 | 51 | August | 240 | 15 |
| February | 37 | 47 | June | 158 | 62 | October | 300 | 41 |
| April | 116 | 21 | June | 166 | 15 | November | 339 | 48 |
| May | 136 | 16 | June | 175 | 34 | December | 352 | 9 |

2.3 Superstructure, technical, economic and environmental data

The superstructure, depicted in the Fig. 1, considers the candidate technologies and the feasible connections between them in the energy system. It is made up for an electrical and thermal part. The electrical part considers a generator GE to produce electricity from gasoil; photovoltaic modules PV; wind turbines WT; inverter Inv, which converts the direct current to alternating current; Lead acid *LA* or Ion Lithium *Ion* Batteries Bat, which can store electric energy; and inverter-charger Inv-Ch, which converts alternating current to direct current and conversely. The thermal part considers conventional boiler GB that consumes gasoil to produce heat; solar thermal collectors ST; a single-effect absorption chiller ACH that uses heat and a small quantity of electricity to produce cooling; and finally thermal energy storage for heating TSQ and cooling TSR, which can charge/discharge thermal energy. Other components such as cogeneration module CM, converting gasoil into electricity and heat, and reversible heat pumps HP, converting the electrical energy into thermal energy either heating or cooling, allow the integration of electric and thermal parts. When HP only produces cooling, it is considered as a mechanical chiller.

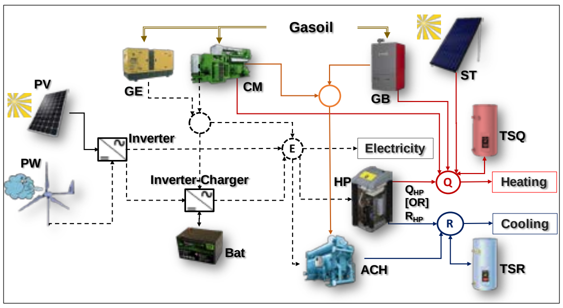



**Fig. 1. Superstructure. Nodes are represented by circles**

*Technical data*

Heat pump operates in heating mode assuming a constant coefficient of performance COP, or in cooling mode assuming 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). In the case of engines GE and CM, they can modulate up to partial load of 15%. For CM, the electrical and thermal productions are proportional to αw and αq factors respectively. Single effect absorption chiller operates with a constant COPACH. The performance ηGB of conventional boiler is assumed constant. Regarding thermal energy storage tanks, the stored energy $S_q$and $S_r$ for heating and cooling respectively, are calculated in each time step taking into account the energy loss by applying a $\lambda$ factor. In the case of batteries, the round trip efficiency $\eta_{rt}$, determines the energy loss during the charging and discharging process in each time step. Further, 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 provoke the failure $N_{c,failure}$, indicated by the manufacturer. This is verified by applying the equivalent full cycle to failure ageing method described by Dufo-López et al. (2014). There are two technologies for batteries proposed for this study, ion lithium and lead acid, but in the optimal configuration, only one of them is selected. Models of capacity $q$, are applied to calculate their dynamic behaviour in the equipment. Ion lithium batteries capacity $q_{ion}$, are modelled according to DiOrio et al.(2015), taking into account both, the maximum charge current Imax,c stablished by manufacturer and the charge ratio $\alpha_c$ in A/Ah described by Homer Energy (2016). For lead acid batteries, the technology used for this study is the OPz batteries applying the KiBaM model (Manwell and McGowan, 1993), which requires three parameters, calculated on the basis of manufacturers' data catalogues: $k$, the rate constant; $c$, the fraction of the capacity that may hold available charge; and the maximum capacity of the battery $q_{max}$, as a function of $k$ and $c$. Taking into account that this study is based on representative days, for both, thermal and electrical storage, the energy stored at the beginning of each representative day must be equal to the energy stored at the end of each representative day. Technical data are shown in Tab. 3.

*Economic data*

The investment cost of every component is calculated from the unit cost $Cu$ and the installed capacity *Cap*. Installation and maintenance costs are considered by applying the factor $F_m$. In order to calculate the fixed annual cost, a Capital Recovery Factor $CRF$=0.082 $yr^{-1}$ is applied based on a lifetime of the installation of 20 years and

an interest rate $= 5\%$ . However, some components have different lifetime $n_r$, hence, a net present value factor $FNPV$ is calculated for every component to consider the total repositions carried out during the lifetime of the installation. The indirect costs are considered by applying a factor $F_{ind}$ of 0.2. For all investments, the Value-Added Tax $VAT$, is applied, whose value for Spain case is 0.21. All economic data are shown in Tab. 3.
Regarding fuel $F$, two types of gasoil have been considered in the energy system: Gasoil A which is used in the GE and CM and gasoil for heating used in the GB. The price of gasoil A and gasoil for heating is 0.1174 €/kWh and 0.0678 €/kWh respectively (IDAE, 2018).

*Environmental data*

In order to evaluate the environmental impact of the polygeneration system, it has been considered the unit $CO_2$eq emissions embodied $CO_2U$ in every component of the superstructure based on the life cycle assessment *LCA* of every component (Tab. 3). The $CO_2$ emissions released due to the fuel combustion (gasoil) are calculated considering a constant value of $CO_2$ emissions associated to gasoil $CO_{2fuel}$ of about 0.294 $kgCO_2$eq/kWh (Carbon footprint, 2016).

**Tab. 3. Technical, economic and environmental data of components**

| **Component $j$** | **Technical data** | **Economic data** | | | **Environmental data** | **References** |
|---|---|---|---|---|---|---|
| | | **Cu [€/*]** | **Fm** | **$n_r$ [Years]** | **$CO_2U$ [$kgCO_2eq$/*]** | |
| PV | $\eta_{PV}$= 15.66% | 113.4 €/m$^2$ | 0.9 | 20 | 161 $kgCO_2$eq/m$^2$ | (Fu et al., 2017)(Atersa, 2017)(Frischknecht et al., 2015) |
| WT | Manufacturer curve | 51230 €/ud | 0.7 | 20 | 21600 $kgCO_2$eq/ud | (Aeolos, 2006)(Orrell and Poehlman, 2017)(Tremeac and Meunier, 2009) |
| ST | $\eta_o = 0.801$<br>$a_1$ =3.188 W/m$^2$K<br>$a_2$ =0.011 W/m$^2$K$^2$ | 254 €/ m$^2$ | 1.5 | 20 | 95 $kgCO_2$eq/m$^2$ | (Guadalfajara, 2016; IDAE, 2011b; Salvador Escoda S.A, 2017) |
| GB | $\eta_b$: 0.96 | 80 €/kWt | 0.5 | 15 | 10 $kgCO_2$eq/kWt | (BAXI, 2017; Pina et al., 2017) |
| HP | COP=3.0, EER= 4.0, β=0.9 | 500 €/kW | 0.5 | 20 | 160 $kgCO_2$eq/kWt | (Beccali et al., 2016; ENERTRES, 2017; Pina et al., 2017) |
| ACH | $COP_{ACH}$= 0.7 | 485 €/kWt | 1.5 | 20 | 165 $kgCO_2$eq/kWt | (Beccali et al., 2016; Pina et al., 2017; U.S. Department of Energy, 2017) |
| GE | $\alpha_w$= 0.28 | 600 €/kW | 0.2 | 10 | 65 $kgCO_2$eq/kWe | (Ayerbe, 2018) |
| CM | $\alpha_w$= 0.28,$\alpha_q$= 0.56 | 1150 €/kWe | 0.7 | 10 | | (Darrow et al., 2017; Pina et al., 2017; Yanmar, 2017) |
| TSQ | λ= 1% | 212 €/kWh | 0.1 | 15 | 31 $kgCO_2$eq/kWht | (ENERTRES, 2017)(Beccali et al., 2016) |
| TSR | λ= 3% | 257 €/kWh | | | 62 $kgCO_2$eq/kWht | |
| Bat LA | $k$=0.11, $c$=0.53<br>$\eta_{rt}$=82%;<br>$DOD$=50%;<br>$N_{c,failure}$ =1500 | 129 €/kWh | 0.25 | 9 | 60 $kgCO_2$eq/kWh | (IRENA, 2017)(Hiremath et al., 2015; McManus, 2012) |
| Bat Ion | $\eta_{rt}$=90%; $\alpha_c$=0.4<br>$DOD$=90%;<br>$N_{c,failure}$ =2000 | 370 €/kWh | 0.25 | 12 | 160 $kgCO_2$eq/kWh | (IRENA, 2017)(Peters et al., 2017) |

## 2.4 Optimization Model

MILP model is developed by using the software LINGO (LINDO Systems Inc, 2013). The objective function is to minimize the total annual cost. At the same time, environmental cost which encompasses $CO_2$ emissions embodied in the equipment $CO2_{fix}$ and release due to the fuel combustion during the operation $CO2_{ope}$ is also calculated.

$MIN = Total\ anual\ cost$ (eq. 1)

$Total\ annual\ cost = CIA + C_g$ (eq. 2)

$CIA = (1 + VAT) \cdot (1 + F_{ind}) \cdot CRF \cdot \sum_{j=component} Cu_j \cdot Cap_j \cdot (1 + FNPV_j)\left(1 + F_{m_j}\right)$ (eq. 3)

$C_g = \sum_{d=1}^{N_{rep}} \omega_d \cdot \left(\sum_{h=1}^{24} cp_{fuel} \cdot F(h)\right)_d \cdot (1 + VAT)$ (eq. 4)

The objective function is subject to the next constraints:

Balance equations:

An energy balance is carried out in each node $m$ (Intersection points of energy fluxes) of the superstructure:

$\sum_m (E_{in}^m - E_{out}^m) = 0$ (eq. 5)

Equipment efficiency:

GB: $\eta_{GB} \cdot F_{GB} - Q_{GB} = 0$ (eq. 6)

HP: $Q_{HP} - E_{HP} \cdot COP = 0$ (eq. 7)

HP: $R_{HP} - E_{HP} \cdot EER = 0$ (eq. 8)

GE: $\alpha_w \cdot F_{GE} - W_{GE} = 0$ (eq. 9)

CM: $\alpha_w \cdot F_{CM} - W_{CM} = 0$ (eq. 10)

CM: $\alpha_q \cdot F_{CM} - Q_c = 0$ (eq. 11)

ACH: $R_{ach} = COP_{ach} \cdot Q_{ach}$ (eq. 12)

For thermal energy storages for heating *q* and cooling *r*:

$S_{q,r}(t) = S_{q,r}(t-1) \cdot \lambda_{q,r} + E_{in_{q,r}} - E_{out_{q,r}}$ (eq. 13)

Equipment's capacities:

For renewable energy production components:

PV: $W_{PV} = E_{PV} \cdot A_{PV}$ (eq. 14)

ST: $Q_{ST} = E_{ST} \cdot A_{ST}$ (eq. 15)

WT: $W_W = E_{PW} \cdot N_{WT}$ (eq. 16)

For each component j, the energy production is equal or lower than its nominal capacity. Thus, for heating $Q$, cooling $R$ or electricity $W$ production:

$Q_j \leq Cap_j$ (eq. 17)

$R_j \leq Cap_j$ (eq. 18)

$W_j \leq Cap_j$ (eq. 19)

Stored energy S is equal or lower to nominal capacity of the energy storage.

$S \leq Cap_{nominal}$ (eq. 20)

$Environmental\ cost = CO2_{fix} + CO2_{ope}$ (eq. 21)

$CO2_{fix} = \sum_j CO_2U(j) \cdot CAP(j) \cdot (1 + Repl_j)/nyr$ (eq. 22)

$CO2_{ope} = \sum_{d=1}^{N_{rep}} \omega_d \cdot \left(\sum_{h=1}^{24}\left(CO_{2_{fuel}} \cdot F(h)\right)\right)_d$ (eq. 23)

## 3. Results

In order to evaluate the economic and environmental impact of different technologies, seven systems were defined, from conventional to polygeneration systems. Tab. 5 shows the 6 different energy systems studied, in which the different technologies are progressively incorporated as candidates. System 0 represents the reference system in which electricity is produced in an electric generator GE supported with a battery Bat either lead acid (*LA)* or ion-lithium (*Ion),* heat is produced in a conventional boiler GB, and cooling is produced in a mechanical chiller. System 1 further includes the option of producing heat in a reversible heat pump HP. System 2 incorporates the possibility of including a cogeneration module CM and a single effect absorption chiller ACH, which combination is well known as combined cooling, heating & power *CCHP*. System 3 considers all previous candidate technologies as well as thermal energy storage, both for heating and cooling. Systems 4, 5 and 6 incorporate progressively the possibility of installing renewable energies as follows: solar thermal ST, in system 4; ST and wind turbine WT, in system 5; and all candidate technologies (Fig. 1), including photovoltaic modules PV in system 6.

**Tab. 4 Different energy system from conventional to polygeneration systems with their respective candidate technologies. ✓: Candidate technology. ×: Technology not considered as a candidate in energy system.**

| System | Different technologies | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Conventional system | | | | | | CCHP | | Thermal Energy storage | Renewable energy | | |
| | GE | Bat | | GB | Heat Pump | | | | | | | |
| | | LA | Ion | | Cooling | Heating | CM | ACH | TS | ST | WT | PV |
| **System 0** | ✓ | ✓ | ✓ | ✓ | ✓ | × | × | × | × | × | × | × |
| **System 1** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × | × | × | × | × |
| **System 2** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × | × | × |
| **System 3** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × | × |
| **System 4** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| **System 5** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × |
| **System 6** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

## 3.1 Optimization of energy systems: Impact on system design

Tab. 5 presents the capacity of every component considered in the optimal configuration of energy systems. It can be observed the influence of each technology in the sizing of the energy system. From reference system to system 1, GB capacity is reduced to the half when reversible HP is taken into account. System 2 considers CCHP technology as a candidate; however, it is not selected in the optimal configuration which is equal to the previous one. System 3 considers TS, in this case the optimal configuration changes by selecting CCHP and TSR whereas Bat is not selected. Reversible HP and GB capacities reduce in about 70% and 17% respectively. The optimal configuration does not change when ST is considered in the system 4, so it is equal to the previous one. In system 5, the optimal configuration selects CCHP, HP, GB, TSR, WT and LA Bat. CM capacity reduces in about 6%, HP capacity increases about 56% whereas ACH and TSR capacity reduce about 24%. In system 6, optimal configuration is composed of CM, HP, GB, PV, WT, TSR and LA Bat. CM capacity reduces in about 47%, HP and GB capacities increase in about 43% and 66% respectively. TSR and LA Bat capacities increase in about 40% and 403% respectively. WT capacity reduces in about 81% due to selection of PV technology.

According to the results, LA Bat technology is required in the optimal configuration from system 0 to 2 as auxiliary component due to the partial load of the prime mover and it is avoided when CCHP and TSR are selected in the optimal configuration. On the other hand, batteries start to play an important role, beyond the auxiliary component when renewable energy technologies such as PV and WT are considered in the optimal configuration. It performs as storage management to take advantage the renewable energy production.

The cost of the CM is approximately the double of GE cost, therefore, CM starts to be feasible as a prime mover in the optimal configuration when its installed capacity is approximately the half of the GE in previous system, as can be observed in system 3. Moreover, the presence of PV and/or WT reduces the prime mover capacity even more.

Due to the presence of PV and/or WT, HP capacity increases whereas ACH capacity decreases up to be not considered in the optimal configuration of system 6. On the other hand, TSR allows to reduce the capacity of cooling production components as well as battery capacity, besides, it increases the flexibility of the system to manage the electricity from PV and/or WT. Note that in systems 3 and 4 the availability of relatively cheap thermal energy combined with TS allows to remove the batteries, e.g. electric energy storage. This fact shows a close and deep integration between thermal and electrical energy, showing its strong interaction when energy conversion systems, such as reversible HP, converting electrical energy into thermal energy are available.

**Tab. 5. Results of installed capacity in the design of energy systems**

| Technologies | System 0 | System 1-2 | System 3-4 | System 5 | System 6 |
|---|---|---|---|---|---|
| **GE [kWe]** | 67 | 67 | 0 | 0 | 0 |
| **CM [kWe]** | 0 | 0 | 33 | 31 | 16 |
| **Mechanical Chiller [kWt]** | 260 | 0 | 0 | 0 | 0 |
| **Rev HP [kWt]** | 0 | 260 | 78 | 122 | 174 |
| **GB [kWt]** | 219 | 102 | 85 | 85 | 141 |
| **ACH [kWt]** | 0 | 0 | 91 | 69 | 0 |
| **TSQ [kWht]** | 0 | 0 | 0 | 0 | 3 |

| | | | | | |
|---|---|---|---|---|---|
| **TSR [kWht]** | 0 | 0 | 152 | 116 | 162 |
| **Bat LA [kWh]** | 19 | 18 | 0 | 13 | 66 |
| **Bat Ion [kWh]** | 0 | 0 | 0 | 0 | 0 |
| **ST [$m^2$]** | 0 | 0 | 0 | 0 | 0 |
| **WT [kWe]** | 0 | 0 | 0 | 21 | 4 |
| **PV [kWe]** | 0 | 0 | 0 | 0 | 52 |

The investment and operational cost of each system are presented in Tab. 6. From system 0 to system 2, the total annual cost reduction is due to the reduction in GB investment cost, on the other hand, from system 2 to system 6, the total annual cost is reduced because of the significant operational cost savings, despite the total investment cost increases, for instance, comparing system 6 with respect reference system, it is possible to reduce the total annual cost up to 22% with an increasing in the investment cost of about 41%.

**Tab. 6. Investment and operational annual cost [€/yr]**

| | **Technology** | **System 0** | **System 1-2** | **System 3-4** | **System 5** | **System 6** |
|---|---|---|---|---|---|---|
| **Investment cost [€/yr]** | **GE** | 9038 | 9061 | 0 | 0 | 0 |
| | **CM** | 0 | 0 | 11955 | 11276 | 5983 |
| | **Mechanical Chiller** | 18197 | 0 | 0 | 0 | 0 |
| | **HP** | 0 | 18197 | 5448 | 8515 | 12181 |
| | **GB** | 4531 | 2122 | 1768 | 1760 | 2918 |
| | **ACH** | 0 | 0 | 12899 | 9797 | 0 |
| | **TSQ** | 0 | 0 | 0 | 0 | 131 |
| | **TSR** | 0 | 0 | 7439 | 5648 | 7912 |
| | **Bat LA** | 744 | 713 | 0 | 507 | 2552 |
| | **Inv-Ch** | 1118 | 1081 | 0 | 592 | 1626 |
| | **ST** | 0 | 0 | 0 | 0 | 0 |
| | **WT** | 0 | 0 | 0 | 7044 | 1305 |
| | **PV** | 0 | 0 | 0 | 0 | 8341 |
| | **Inv** | 0 | 0 | 0 | 1725 | 4613 |
| | **Total cost** | ***33628*** | ***31175*** | ***39509*** | ***46865*** | ***47560*** |
| **Operational annual cost [€/yr]** | | 71143 | 71380 | 59284 | 48527 | 34044 |
| **Total annual cost [€/yr]** | | **104771** | **102555** | **98793** | **95392** | **81604** |

The investment cost breakdown of each system is shown in the Fig. 2. The weight of the mechanical chiller and reversible heat pump on the total investment cost is above 50% in the reference system and system 1-2. The weight of HP decrease drastically in subsequent systems. In systems 3-4 the *CCHP* technology investment cost is above 60% on the total investment cost. However, in the systems 5 and 6, none of the technologies exceed the 50% of the total investment cost, in fact, in system 6 the highest investment cost is 26% corresponding to HP technology. From the point of view of reliability, this shows an advantage of the use of polygeneration systems, which avoid a high dependency on a specific device to produce one product, and reduce the operational and economic impact on the system when a replacement of a component must be carried out.

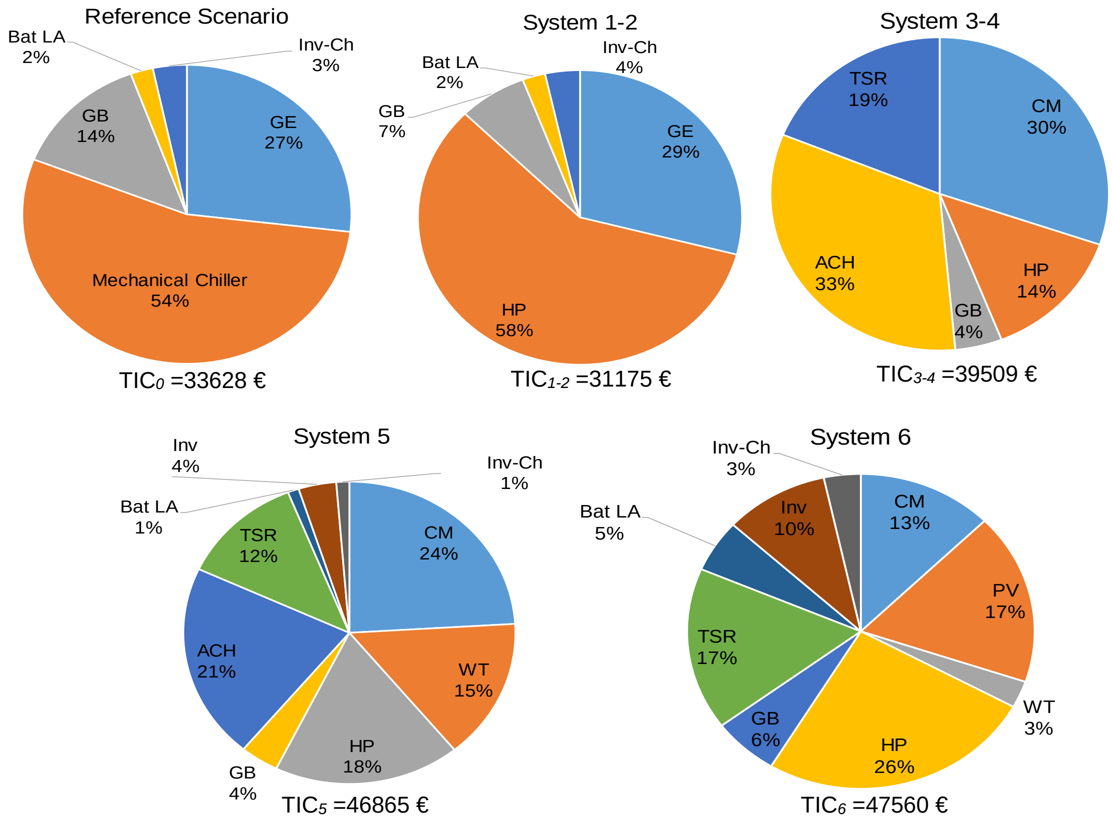



**Fig. 2. Investment cost breakdown of each energy system evaluated. TIC$_i$: Total annual Investment Cost of the system *i*.**

## 3.2 Economic and environmental impact of energy system integration

The integration of energy systems allows to obtain economic savings or $CO_2$ emissions reductions, or both of them. Fig. 3 shows the economic and environmental impact of energy systems integration respectively. From system 0 to 2, there is a reduction in total annual cost of about 2% only when considering a reversible heat pump for cooling and heating instead of a mechanical chiller, whereas any change in $CO_2$ emissions can be neglected. From system 2 to 4, there is a total annual cost reduction of about 4% as well as a remarkable $CO_2$ emissions reduction of about 22% due to the selection of *CCHP* and TSR technologies in the optimal configuration. From system 4 to 5, there is a total annual cost reduction of about 3% and $CO_2$ emissions reduction of about 14% because WT technology is selected. Finally, from system 5 to 6, both total annual cost and $CO_2$ emissions have a remarkable reduction of about 14% and 22% respectively, when PV technology is selected in the optimal configuration.

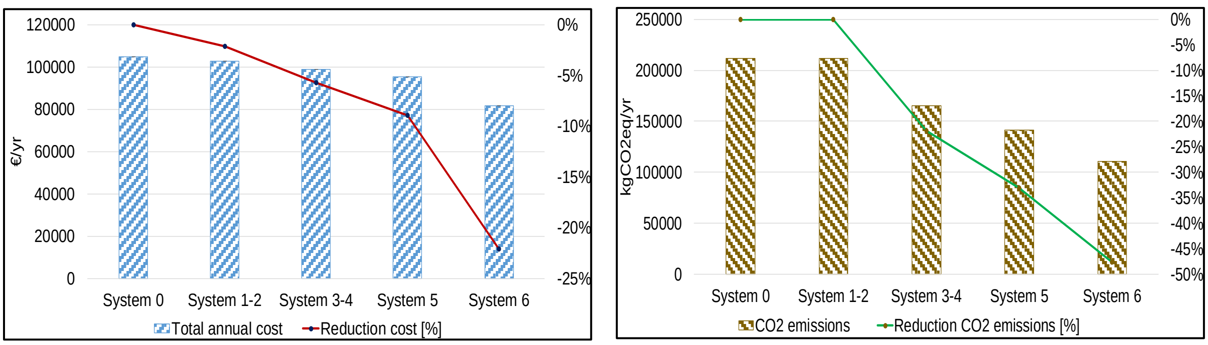
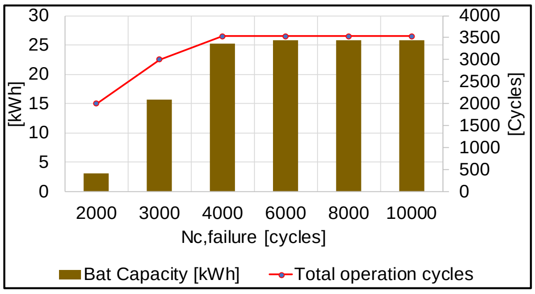



**Fig. 3. Economic (left) and environmental (right) impact of energy system integration**

### 3.3 Lead Acid Vs Ion Lithium batteries technology

According to the result, when batteries appear in the optimal configuration, Lead acid technology is the most suitable from the economic point of view. However, this is a mature technology which is hardly to improve its performance or reduce its cost. On the contrary, Ion-Lithium technology has a high potential of performance improvement and reduction cost. Actually, the performance and unit cost used in this work were based only on the NMC (Nickel Manganese Cobalt) technology; however, there is a wide range of Ion-Lithium technologies which improve its performance. In addition, although their cost is higher than Lead acid batteries nowadays, they have a perspective of reduction in a near future (IRENA, 2017). Based on these facts, a sensitivity analysis has been carried out varying the number of cycles to failure $N_{c,failure}$ for ion lithium batteries from 2000 to 10000, which is the current available range in the market, in order to obtain the optimal configuration of the system 6. The considered lifetime for the batteries is 12 years. Fig. 4 shows the battery capacity, the total number of executed cycles during the operation and total annual cost as a function of the number of cycles to failure. It is observed that above 4000 cycles there is no change in the total annual cost, which means that the optimal configuration remains beyond this value. The maximum number of operation cycles is about 3500, therefore, when $N_{c,failure}$ increases beyond this value, lifetime should be increase as well, and the total annual cost must decrease.



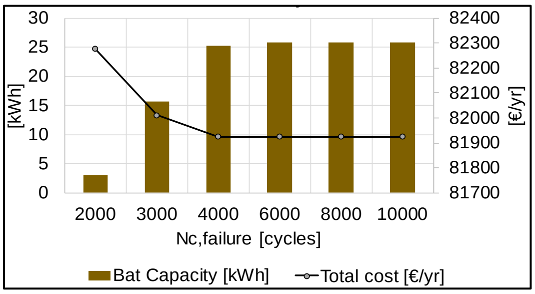




**Fig. 4. Ion- Lithium battery capacity as a function of $N_{c,failure}$. Total number of executed cycles during the operation as a function of $N_{c,failure}$ (left) and total annual cost of the system as a function of as a function of $N_{c,failure}$ (right).**

This is an iterative process which is depicted in the Fig. 5. By applying this procedure, it was found that, at current cost, Ion-Lithium technology could be feasible when $N_{c,failure}$ is about 6000 cycles which allows to increase the lifetime battery up to 20 years approximately in this case of study. It is worthy to say that the total number of cycles executed is below 6000, which means that increase the $N_{c,failure}$ does not implies improve the objective function. Therefore, this could be considered the optimal design of the Ion-Lithium battery for this application.

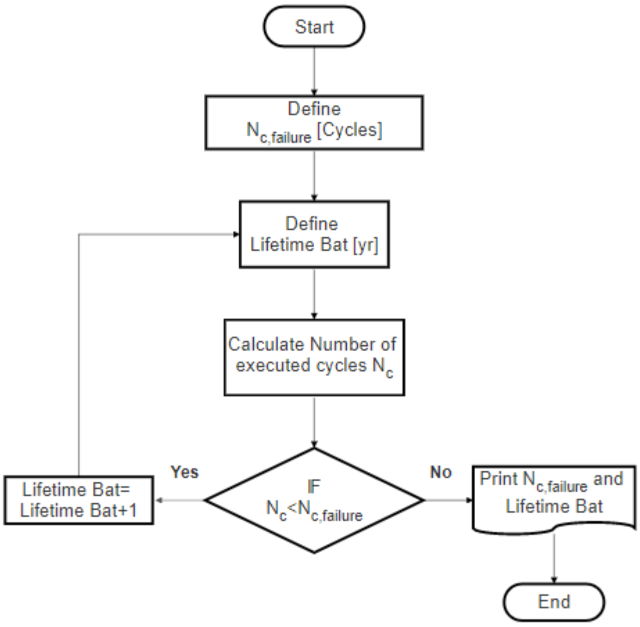



**Fig. 5. Iterative process to calculate the lifetime battery as function of $N_{c,failure}$**

## 4. Conclusions

By using MILP it was possible to evaluate the economic and environmental impact of the integration of energy systems for a residential building in Zaragoza. A systematic integration of different technologies was carried out from conventional to polygeneration systems. Results show that reversible HP allows to reduce the GB capacity as well as to take advantage the electricity production from renewable energy technologies, leading to high $CO_2$ emissions reduction. Energy storage permits to decouple the energy production and energy demand. In this sense, both thermal and electric energy storage allows to manage the renewable energy production. In particular, by using TSR it is possible to reduce the capacity of cooling production components such as HP, leading to reduce the investment cost as well. Batteries can be used as an auxiliary component to support the partial load operation of the prime mover, but they are not required in system 3, being displaced by CCHP and TSR technologies. Nonetheless, batteries become necessary when renewable energy technologies such as PV or WT are considered. It was demonstrated the saving costs and $CO_2$ emissions reduction achieved by integrating different technologies, being remarkable in the maximum level of integration when PV technology is selected.

As regard batteries technology, it was carried out a sensitivity analysis in which different number of cycles of Ion-lithium battery were evaluated in order to show their competitiveness with respect to Lead acid technology. Results have shown that, for the studied case, at current cost, Ion-lithium batteries could be competitive when the maximum number of cycles to failure is about 6000 cycles.

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