Economic optimization of the design and operation of polygeneration energy systems by genetic algorithms

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Abstract: Renewable energies currently represent a significant portion of the sources of heat and electricity all over the world. However, their intermittent nature results in a major challenge for the design and management of the systems which exploit these energy sources. Indeed, the residential and industrial energy demand has to be fulfilled without any interruption. To face the aforementioned problem, this paper suggests to adopt polygeneration energy systems. These systems are distinguished by several sources of electrical and heating power, both renewable and traditional one, which interact to fulfill the thermal and electricity hourly demand considering the geographical location where the system is located. Indeed, the atmospheric condition evolution during the day and over the months significantly affect the energy availability from renewable sources. Considering the presented framework, this paper proposes a genetic algorithm for the economic optimization of the design and operation of polygeneration energy systems. The considered system fulfills the electric load through photovoltaic modules integrated with battery energy storage, whereas a natural gas boiler supplies the required thermal power. Furthermore, a cogenerative engine contributes to the demand of both energy types. An original genetic algorithm is developed to determine the optimal size of each polygeneration system module to minimize the levelized cost of energy, determined by the expenditures of both the system installation and operation phases. The energy flows between the polygeneration modules and the demand load are defined considering the hourly evolution of the external environment, as the atmospheric conditions and the electricity price. Finally, the developed genetic algorithm is tested and validated with a real case study represented by the thermal and electricity loads of an Italian manufacturing plant. The design and operation configuration proposed by the algorithm for the installed polygeneration energy system enables to save 9.2% of the costs of traditional energy source exploitation.

Keywords: Genetic algorithm, battery energy storage, heat and power cogeneration, levelized cost of energy, energy flow balance.

1. Introduction and literature review

An adequate design and operation management of the energy systems (ESs) fuelled by renewable energy sources (RESs) is of paramount importance to maximize their technical and economic performances (Bortolini et al., 2015a). Several literature contributions tackle this problem from different perspectives. Ren et al. (2010) developed an optimization model to optimize the operation management of a distributed ES made of several modules. The proposed model considers the module size as fixed and determined to define the optimal energy flows between the modules which maximize the ES economic performances. Fazlollahi et al. (2012) improve this research developing a mixed integer linear programming model to simultaneously manage the ES operation and define the ES module sizes. Unfortunately, the computational complexity of these optimization model exponentially increases with the number of modules and energy flows.

Meta-heuristic algorithms are of strong help to define feasible solutions for highly complex problems in the energy production field of research. Considering the design of such ESs, Askarzadeh (2013) proposed a simulated annealing algorithm to design a RES based ES distinguished by multiple modules, e.g. solar photovoltaic (PV) and wind turbines. Gomez-Lorente et al. (2012) developed a genetic algorithm (GA) for a similar target, but focusing on the design of a grid-connected PV equipped with a battery energy storage system (BES). Rager et al. (2015) and Camargo et al. (2014) focus on the operation management of RES based ESs presenting evolutionary algorithms which define the optimal hourly energy flows of the system considering several technical parameters. Augustin and Dufo-Lopez (2008) as well as Dufo-Lopez and Augustin (2009) developed a relevant contribution to this field of research proposing a GA to simultaneously determine the design of a hybrid ES and to manage the electricity flows between the ES modules. The considered hybrid ES exploits several REN sources to fulfil the electricity demand of a specific user. The developed GA aims at the minimization of the ES total cost, e.g. modules purchase and installation as well as operation during the entire ES lifetime.

The presented literature contributions focused on the ESs aimed at the production of one energy type, e.g. electricity, from multiple modules (Bortolini et al. 2014). However, the simultaneous production of different energy types could represent a major improvement for these ESs (Menon et al., 2013). Polygeneration energy systems (PESs) enables the interaction of several modules able to produce different energy type, e.g. electricity or heating (Lorestani and Ardehali, 2018). Furthermore, at least one of these modules is distinguished by the cogeneration capacity, e.g. the ability to simultaneously produce heating and electricity from a unique fuel or RES (Wang et al., 2010). Finally, energy is typically supplied both from traditional and RES (Collazos et al., 2009; Bortolini et al. ,2015b).

Considering the presented literature framework, this paper proposes a mathematical model to optimize the design and the operation management of a PES equipped with multiple modules fuelled both by traditional and RES. Electricity production is provided by PV modules equipped with BES for energy storage and by the national grid, if needed. A natural gas fuelled boiler produces the required heating power along with a cogeneration unit which provides CHP energy. The complexity determined by the simultaneous production of both electricity and heat by multiple modules is further increased by the intermittent availability of RESs due to the erratic evolution of atmospheric conditions, e.g. temperature and irradiance. Furthermore, the PES has to be properly managed during every daily hour to meet the required heat and electricity user demand with the available production capacity.

As far as the Authors knowledge, this is one of the first contribution which considers all the aforepresented interdependences of such a complex ES. Furthermore, this paper overcomes the traditional approaches which typically focuses either on the design or on the management of PESs limiting the techno-economic performance of such systems. Indeed, this paper proposes a GA for the design and management of a PES fuelled by traditional and RES sources to simultaneously fulfil the heat and electricity demand of a user load. Contrariwise the approaches typically suggested by the literature, the developed algorithm integrate the sizing of the PES modules with the management of the heat and electricity hourly flows within the system considering the evolution of the user demands and the atmospheric conditions over time. Aim of the developed GA is the minimization of the PES total cost determined by the expenditures required to purchase and install its modules and the costs which occur for the system operation evaluated during its entire lifetime.

This manuscript is organized as it follows. Section 2 presents the PES architecture along with a detailed description of its modules. Section 3 proposes a mathematical formulation to represent the PES configuration and the energy flows between the modules and the loads. Section 4 introduces the adopted case study of an Italian manufacturing plant distinguished by the simultaneous requirement of heating and electricity. Furthermore, the atmospheric conditions of the installation location are proposed along with the PES technical and economic parameters. The obtained results are extensively discussed in Section 5 before drawing the paper conclusions together with suggestions for further research in the last Section 6.

2. PES architecture

This Section presents the architecture of the considered PES. Figure 1 shows the polygeneration modules and the energy flows between them and the user load. In the proposed representation, h is the index for hours. The hourly energy demand (EL_h) is met using renewable and traditional sources. The electric load is fulfilled through the integration of several sources, including PV, BES and connection to the national grid. A CHP contributes to the demand of both electricity and heat. Moreover, this module is combined with a boiler to provide the required heating power. The PV module exploits solar energy to produce electric power. Due to the irregular energy supply of PV, the architecture provides the connection to the national electricity grid. In the considered system, both the opportunity to buy and sell electricity are considered.

The electricity supplied by the PV plant (EA_h) depends on the hourly solar irradiation, the module area and the conversion efficiency. In particular, solar irradiation depends on the plant geographical location, whereas the production efficiency linearly decreases with the temperature. The modules are assumed to be installed southwards with an inclination angle of 30°. EA_h can be dispatched to the user (EAL_h), to the BES (EAB_h) or sold to the electric national grid (EAR_h). The battery energy storage is characterised by its state of charge (SOC_h), which ranges between the maximum battery capacity and the minimum battery level, e.g. depth of discharge (DOD). The BES could store energy both from the PV (EAB_h) or from the cogeneration unit (ECB_h) and it supplies energy to the user (EBL_h).

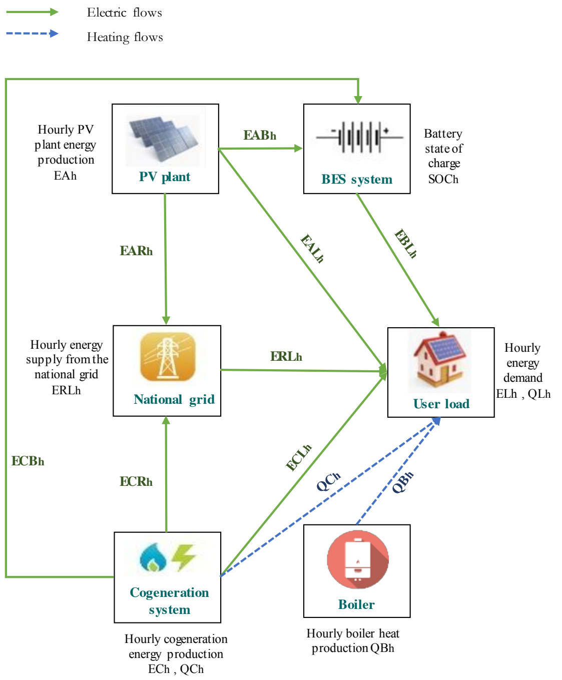
The total energy produced by the cogeneration unit is directly proportional to the burned fuel volume and its lower heating value (LHV). This energy provides both electricity (EC_h) and heat (QC_h). Any surplus electricity produced can be sold to the national grid (ECR_h). A natural gas fuelled boiler (QB_h) aids the CHP unit to meet the user heating demand.

3. Mathematical model

This Section presents the mathematical model of the PES operation and economic performance to compute the total cost of energy. A detailed description for every symbol presented in the following is proposed in the Nomenclature Section.

A detailed analysis of the energy flows between the PES modules allows to identify its configuration and economic. Eq. 1 represents the electricity production of the PV module (EA_h). XPV represents the decision variable of the PV size. The total hourly irradiation (HI_h) is primarily influenced by the geographical installation location. The PV module efficiency linearly decreases with the temperature respect to the reference condition of 25°C as defined by $\eta PV_h(TA_h)$.

$$EA_h = HI_h \cdot \eta PV_h(TA_h) \cdot XPV/(\eta_{module} \cdot HR) \quad (1)$$



Note : Variable notations presented in Nomendature.

Figure 1. PES architecture

The overall PV system efficiency depends on the electrical energy efficiency (η_e), the progressive PV module degradation (η_d) which occurs over its lifetime (j) and the efficiency decrease due to the module temperature (Eq. 2). Thus, the PV module efficiency decreases linearly with the temperature respect to the reference condition $Tref$ of 25°C (Hernández-Moro et al., 2013). Furthermore, β and $NOCT$ depends on the considered PV module type. Such specifications are generally provided by the module manufacturers. Finally, the DC/AC electric conversion is affected by the inverter efficiency (η_{inv}).

$$\eta PV_h = \eta_e \cdot (1 - (j - 1) \cdot \eta_d) \cdot \eta_{inv} \cdot (1 - \beta \cdot ((TA_h + ((NOCT - 20)/800) \cdot HI_h) - Tref)) \quad (2)$$

Focusing on the BES, the hourly state of charge (SOC_h) cannot exceed the maximum capacity (K_B) and it has to be higher than the minimum capacity, defined through the so-called maximum allowable depth of discharge (DOD), Eq. 3. These limits depend on the battery technical restrictions for the charging current, to avoid improper charging process, battery degradation and efficiency decrease. In Eq. 4, SOC_h is related to the flows between the BES, the CHP, the PV module and the user. K_B represents the decision variable of the BES size.

$$(1 - DOD) \cdot K_B \leq SOC_h \leq K_B \quad (3)$$

$$SOC_h = SOC_{h-1} \cdot (1 - \sigma) + EAB_h \cdot \eta_{ch} - EBL_h + ECB_h \cdot \eta_{ch} \cdot \eta_{inv} \quad (4)$$

Eqs. 5-13 represent the constraints of the electric flows dealing with the PES system. For sake of brevity, in the current mathematical model the limitations on the charge and discharge current of the BES is not represented by any related Eq. However, in the model implementation and resolution this relevant BES characteristic is considered to determine the hourly electricity flows.

Eqs. 5-6 limit the flow from the PV module to the different PES unit.

$$EA_h = EAB_h + EAL_h + EAR_h \quad (5)$$

$$EAB_h \leq \frac{K_B - SOC_h}{\eta_{ch}} \quad (6)$$

The electricity flow between the BES and the user is constrained by Eqs. 7-8.

$$EBL_h \leq \frac{EL_h - EAL_h \cdot \eta_{inv}}{\eta_{ch} \cdot \eta_{inv}} \quad (7)$$

$$EBL_h \leq SOC_h - (1 - DOD) \cdot K_B + EAB_h \cdot \eta_{ch} \quad (8)$$

Eqs. 9-10 limit the electricity flow from the CHP unit to the BES.

$$ECB_h \leq EC_h - ECL_h - ECR_h \quad (9)$$

$$ECB_h \leq \frac{K_B - SOC_h - EAB_h \cdot \eta_{ch} + EBL_h}{\eta_{ch} \cdot \eta_{inv}} \quad (10)$$

The variables determined by Eqs. 9-10 depends from the aforepresented variables. The electricity surplus produced by the PV and by the CHP units sold to the national grid are defined in Eqs. 11-12. Furthermore, the electricity bought from the grid to meet the user demand is evaluated in Eq.13.

$$EAR_h \leq EA_h - EAL_h - EAB_h \quad (11)$$

$$ECR_h \leq EC_h - ECL_h - ECB_h \quad (12)$$

$$ERL_h \leq EL_h - EAL_h \cdot \eta_{inv} - EBL_h \cdot \eta_{ch} \cdot \eta_{inv} - ECL_h \quad (13)$$

Focusing on the CHP unit, Eqs. 13-14 represent the heat and the electricity obtained burning a VC_h quantity of fuel characterized by LHV lower heating value at the CHP system. The produced heat and electricity depends on CHP production efficiently, η_{th} and η_{el} respectively.

$$QC_h \leq \frac{VC_h \cdot \text{LHV}}{\eta_{comb}} \cdot \eta_{th} \quad (14)$$

$$EC_h \leq \frac{VC_h \cdot \text{LHV}}{\eta_{comb}} \cdot \eta_{el} \quad (15)$$

Similarly, Eq. 16 assess the heat obtained burning VB_h quantity of fuel at the boiler distinguished by η_{bo} heating efficiency.

$$QB_h \leq \frac{VB_h \cdot \text{LHV}}{\eta_{comb}} \cdot \eta_{bo} \quad (16)$$

Eqs. 17-18 limit the variation range of variables QB_h and QC_h. MAX_{QB} represents the decision variable of the boiler size, whereas MAX_{QC} represents the decision variable of the CHP size. IB_h is equal to 1 if the boiler operates in hour *h*, 0 otherwise. IC_h is similarly defined.

$$\text{MIN}_{QB} \cdot \text{IB}_h \leq QB_\text{h} \leq \text{MAX}_{QB} \cdot \text{IB}_h \quad (17)$$

$$\text{MIN}_{QC} \cdot \text{IC}_h \leq QC_\text{h} \leq \text{MAX}_{QC} \cdot \text{IC}_h \quad (18)$$

The heating load (QL_h) and electricity load (EL_h) fulfilment is ensured by Eqs. 19-20.

$$QL_\text{h} = QB_\text{h} + QC_\text{h} \quad (19)$$

$$EL_h = EAL_h + EBL_h + ERL_h + ECL_h \quad (20)$$

The considered objective function aims to minimize the total cost of energy, including purchase, installation, operative and maintenance costs evaluated considering the entire system lifetime. The purchase and installation cost is evaluated by Eq. 21 and it considers the PES different modules, namely PV, BES, boiler and CHP. PV purchase cost (C_{PV}) exponentially decreases with the installed rated power (XPV) accordingly to updated market prices (*a,b*) as shown in Eq. 22. BES purchase is proportional to the battery capacity (K_B) (Eq. 23), whereas the installation cost of the boiler and the CHP unit depends on their sizes, e.g. Eqs. 24-25.

$$C_{IN} = C_{PV} + C_{BES} + C_B + C_C \quad (21)$$

$$C_{PV} = a \cdot XPV^b \quad (22)$$

$$C_{BES} = c \cdot K_B \quad (23)$$

$$C_B = funB(\text{MAX}_{QB}) \quad (24)$$

$$C_C = funC(\text{MAX}_{QC}) \quad (25)$$

Eqs. 26 assess the operating and maintenance annual costs (year *j*). For each PES module, except for the BES unit and the inverter, their maintenance costs are considered in this model as a percentage of their purchase and installation costs. BES and inverter are assumed to be substituted in years ISUB_j during the PES lifetime and the inverter cost is considered a portion (ξ) of the PV purchase expenditure. Furthermore, fuel consumption and electricity purchase from grid are considered as further costs, whereas revenues for surplus energy sale to the grid have a positive impact on the expenditure.

$$C_{OP,j} = p \cdot C_{IN} + \text{ISUB}_j \cdot (C_{BES} + \xi \cdot C_{PV}) + \sum_{h=1}^{8760} ERL_h \cdot ppurch_h - \sum_{h=1}^{8760} (EAR_h \cdot \eta_{inv} + ECR_h) \cdot psale_h + \sum_{h=1}^{8760} (VC_h + VB_h) \cdot cf \quad (26)$$

The objective function of the proposed model is to minimize the net present value of the total cost of energy (CoE) over the entire system lifetime considering the discounted cash flows given by Eq. 27.

$$\text{CoE} = \text{C}_{IN} + \sum_{j=1}^{n} \frac{C_{OP,j} \cdot (1+g)^{j-1}}{(1+OCC)^j} \quad (27)$$

4. Case study

The mathematical model proposed in Section 3 is tested and validated to design and manage the hourly energy flows of a PES located in Bologna (Italy) to provide electricity and heating to an Italian manufacturing plant. The irradiation and temperature hourly profiles of the installation site are presented in the following Figure 2, whereas Figure 3 shows the hourly energy demand of the user, both electricity and heating.

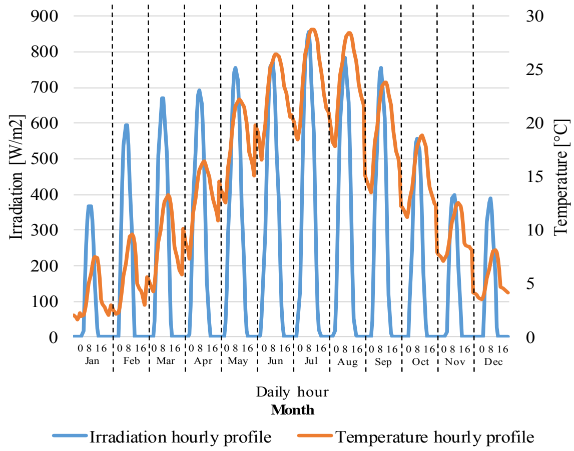


Figure 2. Irradiation and temperature hourly profiles of the installation site, for every month.

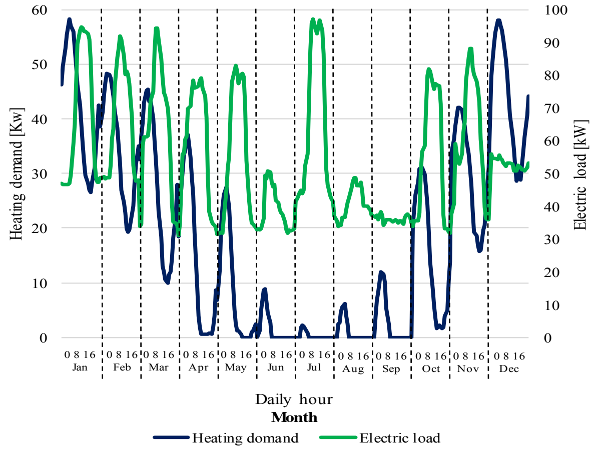


Figure 3. Hourly heating demand and electrical load of the user, for every month.

Considering the different PES modules, the PV module is distinguished by high quality multi-crystalline components manufactured in the European area. The PV module installation cost includes the PV purchase, engineering, installation and labour costs. The BES module adopts batteries based on the valve regulated lead acid technology, which is a mature and cheap option suitable for these applications. Concerning the PES heating power, a commercial reverse-flame steam boiler is adopted in this case study, along with a back-pressure steam cogeneration plant for the simultaneous production of electricity and heating. Both these PES modules are fuelled by natural gas.

A precautionary approach is adopted to select the case study economic parameter. Aim of this procedure is to strengthen the economic assessment to not underestimate the PES total cost of energy. The future cost cash flow uncertainty is mitigated with the following approaches. First, the OCC value is limited to 3% to reduce the impact of the future negative cash flows. The future cash flow will be equal or higher than the forecasted one resulting in a cautelative approach. Furthermore, the natural gas price is expected to increase in the near future, as well as the electricity purchase price in the country where the PES is located (IEA, 2017). This cautelative approach significantly strengths the reliability of the economic results. Considering the aforepresented scenario, the PES economic performances forecasted by the GA could only improve during the system real operation over the years.

The design and operation management of the presented case study PES are determined by the adoption of a GA to solve the mathematical model proposed in Section 3. The aforementioned GA defines the best size of each PES module along with the hourly energy flows between the modules and the load considering the interdependences between the electric and heating power determined by the CHP module. The GA is accurately tuned to define the most appropriate GA parameters for the considered case study. The GA initial population is set to 120 members. The adopted crossover approach suggests to select the best half of parents distinguished by the lowest objective function value. Finally, the GA iteration is terminated after 120 iterations obtaining the objective function asymptote, e.g. no further improvement achievable with additional iterations.

5. Results and discussion

The solution provided by the GA suggests to exploit all the PES modules. Table 1a proposes the module optimal sizes. PV is distinguished by a remarkable electricity supply capacity, twice as high as the maximum required by the load over the entire year. On the contrary, the BES are able to store enough electricity to fulfil the load just for 67 minutes, on average. Neither the boiler, nor the CHP are able alone to fulfil the peaks of the heating demand during the year, whereas their cooperation guarantees the supply of this energy source, whatever the considered hour is.

This PES design is distinguished by a remarkable economic performance (Table 1b). The net present value of the total cost to supply the energy required by the user over the system lifetime is 1.914 M€ (approximately 76.5 k€ per year), of which 87% is determined by the electrical load and 13% by the thermal one. The traditional solution for the energy supply of such manufacturing plants is to exploit uniquely the grid for the electricity demand and natural gas boilers for heating requirement. Compared to this scenario, the developed PES distinguished by the aforementioned modules is able to save up to 9.2% of the total cost of energy.

Table 1a. Proposed PES design.

PES module	Module size
PV	218 kW
BES	57 kWh
Boiler	40 kW
CHP	20 kW heating 8.5 kW electricity

Table 1b. PES economic performances.

Objective function component	Net present cost over the entire PES lifetime [M€]
Total cost of electricity	1.665
Total cost of heating	0.248
Total cost of energy	1.914

A detailed analysis of the electricity supplied to the load provides an interesting insight on how the different modules are exploited (Table 2). PV plays a major role in this scenario. 45% of the yearly electricity demand of the load is supplied by this module. The BES contribution is not negligible, since it acts as a buffer to store the excess of electricity produced by the PV during the central hours of summer days and it supplies the load when the sun has set (10% of the yearly electricity demand). Finally, the contribution of the CHP is marginal (6%) whereas the grid still represents an indispensable source of electricity (39% of the electricity demand) to mitigate the intermittence of RESs.

Table 2. Yearly electricity demand supplied by the different PES sources.

Electricity source	Contribution to supply the yearly electricity demand
PV	45%
BES	10%
National Grid	39%
CHP (electricity)	6%

Focusing on the electricity side of the PES, the following Figure 4 proposes the destination of the electricity produced by the PV during an average day of July. During the daytime, from 8 to 16, half of this electricity is used to fulfil almost in full the load demand. The exceeding portion is mostly sold to the grid to benefit of the substantial selling price, whereas a limited but constant portion contributes to load the BES to supply the user demand during the night with cheap and clean electricity.

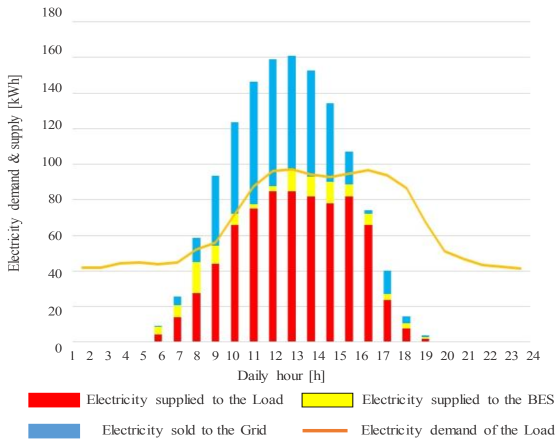


Figure 4. Dispatching of the electricity produced by the PV during an average day of July to the other PES modules.

Figure 5 proposes the supply of the load heating demand by the boiler and the CHP during an average day of March. During those hours (14-22) in which the heating demand is lower than the boiler minimum production capacity, the only option is to exploit the CHP module which can produce limited heating power. On the contrary, for the heating demand peaks (hours from 2 to 10) the boiler is exploited at its minimum power to benefit also from the

CHP usage and its simultaneous production of electricity and heating.

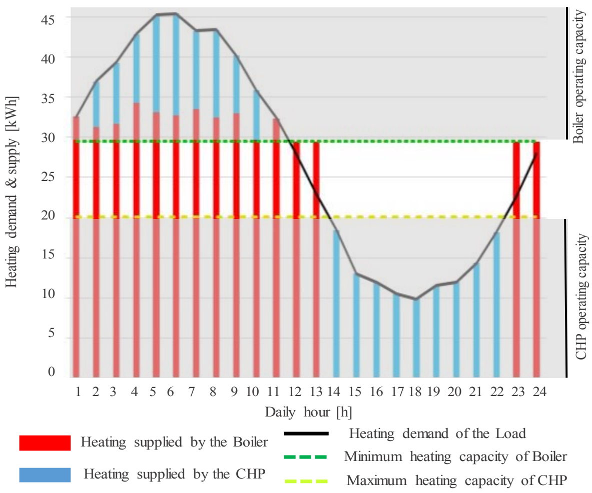


Figure 5. Supply of the load heating demand by the boiler and the CHP during an average day of March.

6. Conclusions

This paper aims to define the optimal design and operation management of a PES. The targeted PES is connected to the national grid and it is equipped with PV modules which can exploit a BES for electricity storage. A natural gas fuelled boiler provides the required heating power along with a cogeneration unit which generates CHP energy. A proper mathematical model simultaneously defines the size of each PES module along with the electricity and heating hourly flows between them and the load. The model considers for every hour of the year the load energy requirements along with the most relevant atmospheric conditions, e.g. irradiance and temperature. The computational complexity of the mathematical model suggested to develop a GA to solve the proposed mathematical model. Aim of the developed GA is the minimization of the PES total cost determined by the expenditures required to purchase and install its modules and the costs which occurs for the system operation evaluated during its entire lifetime. The mathematical model is tested and validated for a case study PES located in Bologna (Italy) aimed at providing the electricity and heating to an Italian manufacturing plant. The irradiation and temperature hourly profiles of the installation site are known, as well as the hourly energy demand of the user, both electricity and heating. The PES design and operation management proposed by the GA suggests to provide the PV with a remarkable electricity supply capacity, whereas the proposed BES is able to store enough electricity to fulfil the load just for one hour. The cooperation between the boiler and the CHP guarantees to fulfil the peaks of the heating demand, whatever the considered hour is. The total cost to supply the entire energy required by the PES over its lifetime is approximately 76.5 k€ per year. Compared to the traditional configuration of the energy supply of such manufacturing plants distinguished uniquely by the grid for the electricity demand and the natural gas boilers for heating requirement, the developed PES is able to save up to 9.2% of the total cost of energy.

Future research should compare the proposed GA with traditional procedures for the design and operation management of PESs. Indeed, the economic performance of traditional design approaches does not only depend on the design variables but also on the adopted methods to dispatch the hourly energy flows between the PES modules and the user load. The GA proposed in this paper should be compared with multiple traditional scenarios. From the design perspective the PV could be sized to meet the minimum, maximum or average electricity demand, whereas the CHP could be designed to fulfil the electricity or the heating demand. Finally, the optimal management of hourly energy flows proposed by the GA has to be compared with different greedy or heuristic rules, e.g. the electricity produced by the PV primarily fulfils the load, then the BES and ultimately is sold to the grid, or different criteria.

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Nomenclature

$C_{OP,j}$	Operating cost for year j, €/year
C_{PV}	PV module installation and purchase cost, €/kW
CoE	Total cost of energy, €
DOD	BES system depth of discharge, %
EA_h	Energy supplied by PV system for hour h, kWh
EAB_h	Energy supplied by PV system to the BES for hour h, kWh
EAL_h	Energy supplied by PV system to the load for hour h, kWh
EAR_h	Energy supplied by PV system to the national grid for hour h, kWh
EBL_h	Energy supplied by BES system to the load for hour h, kWh
EC_h	Electricity supplied by CPH system for hour h, kWh
ECB_h	Electricity supplied by the CHP system to the BES system for hour h, kWh
ECL_h	Electricity supplied by CHP system to the load for hour h, kWh
ECR_h	Electricity supplied by CHP system to the national grid for hour h, kWh
EL_h	Electricity load for hour h, kWh
ERL_h	Electricity supplied by national grid to the load for hour h, kWh
HI_h	Total in-plane irradiation for hour h, kWh/m^2
HR	Yearly module reference in-plane irradiation, kWh/m^2
IB_h	Boiler state for hour *h*, 1 operating; 0 otherwise
IC_h	CHP system state for hour *h*, 1 operating; 0 otherwise
ISUB_j	Battery and inverter replacement during year *j*, 1 yes; 0 otherwise.
K_B	BES nominal capacity, kWh
LHV	Lower heating value, KWh/m^3
MAX_{QB}	Boiler size, kW
MAX_{QC}	CHP system size, kW
MIN_{QB}	Minimum heating power produced by the boiler, kW
MIN_{QC}	Minimum heating power produced by the CHP system, kW
$NOCT$	Normal operating cell temperature, °C
OCC	Opportunity cost of capital
$ppurch_h$	purchase price of electricity, €/kWh
$psale_h$	Selling price of electricity, €/kWh
QB_h	Heat supplied by boiler for hour h, kWh
QC_h	Heat supplied by CPH system for hour h, kWh
QL_h	Heating load for hour h, kWh
SOC_h	BES system state of charge for hour h, kWh
TA_h	Ambient temperature for hour h, °C
$Tref$	PV cell reference temperature, °C
VB_h	Volumetric flow rate of the fuel into the boiler system for hour *h*, m^3/h
VC_h	Volumetric flow rate of the fuel into the CPH system for hour *h*, m^3/h
XPV	PV system nominal power rate, kWp
ηPV_h	PV system overall efficiency for hour h, %
η_{bo}	Boiler system efficiency, %
η_{ch}	BES system charging/discharging efficiency, %