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Abstract

This paper deals with the optimal design of a hybrid energy plant. The considered hybrid energy plant is composed of a solar thermal collector, a photovoltaic panel, a combined heat and power system, an absorption chiller, an air source heat pump, a ground source heat pump and a thermal energy storage. The optimization goal is to minimize the primary energy demanded throughout the manufacturing and operation phase of the hybrid energy plant. The demanded energy during the manufacturing phase is considered by means of the cumulative energy demand and is calculated by carrying out a cradle-to-gate life cycle assessment, while the demanded energy during the operation phase is evaluated by simulating the system throughout one year. The challenge of non-linear life cycle inventory scaling of energy systems is also addressed. A tower located in northern Italy is selected as a case study and two different approaches are evaluated. The first approach consists of solving the sizing optimization by minimizing primary energy consumption only during the operation phase, while in the second approach primary energy consumption is minimized throughout the life cycle of the plant by integrating the life cycle assessment into the optimization process. The results show that, if life cycle assessment is integrated, the optimal hybrid energy plant configuration is different and the primary energy saving throughout the life cycle is higher (approximately 12 %). Moreover, building energy demands are mostly met by using heat-driven technologies instead of electricity-driven technologies.

Keywords: Hybrid energy plant; Genetic algorithm optimization; Life cycle assessment; Primary energy saving

Nomenclature

A	*area*
a	correction factor
E	energy
EER	energy efficiency ratio
El	electricity
fval	fitness function value
G	input or output flow of the life cycle inventory
i	time point
N	lifetime
P	decision variable or nominal power
PE	primary energy consumption
R	solar radiation
T	temperature
V	volume
η	efficiency

Acronyms

ABS	absorption chiller
AC	auxiliary chiller
ASHP	air source heat pump
CED	cumulative energy demand
CHP	combined heat and power
GA	genetic algorithm
GSHP	ground source heat pump
HEP	hybrid energy plant
AB	auxiliary boiler
ISO	international organization for standardization
LCA	life cycle assessment
LCI	life cycle inventory
LHV	lower heating value
PV	photovoltaic panel
STC	solar thermal collector
SOP	switch-on priority

The short version of the paper was presented at ICAE2018, Aug 22–25, Hong Kong (paper ID 715). This paper is a substantial extension of the short version of the conference paper.

<u>*Subscripts and superscripts*</u>

ABS	absorption chiller
ASHP	air source heat pump
av	average
CHP	combined heat and power
BoS	balance of system
cool	cooling
el	electric
eq	equivalent
fuel	fuel
grid	grid
GSHP	ground source heat pump
k	life cycle assessment scaling exponent
o	optical
op	operation
PV	photovoltaic panel
ref	reference
s	generic energy system
STC	solar thermal collector
sent	sent to the grid
taken	taken from the grid
th	thermal

1. Introduction

Increasing the sustainability of the residential sector may be achieved by reducing primary energy consumption. The integration of technologies powered by renewable energy sources in a Hybrid Energy Plant (HEP) may lead to improved conversion efficiency and a significant reduction in primary energy consumption. Consequently, the environmental impacts associated with producing the thermal, cooling and electrical energy demands of a building are also reduced. Generally, a HEP consists of a combination of two or more energy conversion systems which use different energy sources, which, when integrated, overcome the limitations that may be inherent in either [1]. HEPs have greater potential to provide higher quality and better reliability of energy supply compared to a system based on a single source of energy [1].

The promising energy and environmental benefits of HEPs may be achieved by properly sizing the technologies employed to fulfill the energy demands of the building. However, in order to achieve an optimal design of the energy plant, it is not sufficient to only minimize on-site primary energy consumption because off-site primary energy consumption could outmatch the advantages of on-site optimized systems, thus reducing the overall sustainability performance. This is particularly true for renewable energy technologies. In fact, energy production from renewable energy systems, such as photovoltaic systems and solar thermal collectors, are often seen as carbon-neutral, at least. However, a considerable amount of energy is used in the manufacturing, transporting and decommissioning of the different energy systems comprising the HEP [2]. In other words, the energy and environmental benefits associated with the use of HEPs should be compared with the impacts produced during the manufacturing, transporting and end-of-life phases by following a life cycle approach.

One of the most effective methodologies for the quantification of the off-site primary energy consumption is Life Cycle Assessment (LCA) [3]. LCA is a method for the evaluation of energy and environmental loads associated with the development of a product throughout its life cycle [4]. Several studies were conducted in order to evaluate the environmental performance of energy systems via LCA [5]. For instance, Moore et al. [6] investigated the global warming potential and primary energy demand associated with the life cycle of an electric storage hot water system, a solar electric system, a gas storage, a gas instantaneous and a solar gas instantaneous system installed in Australia. Onshore wind power systems were investigated and analyzed in [7]. The aim of the study was to quantify the environmental loads for producing 1 kWh of electricity compared to other traditional power plants, i.e. coal and natural gas. Colclough et al. [8] used the cumulative energy and cumulative carbon consumption approaches to highlight the importance of adding solar and seasonal energy storage to achieve nearly zero energy heating in passive house buildings. A cradle-to-grave analysis of a photovoltaic plant was carried out by Desideri et al. [9] with the aim of estimating the released environmental impacts. Moreover, Kelly et al. [10] investigated the application of an industrial CHP system via an energy and carbon LCA. However, typically the studies analyze the impact of specific energy technologies with respect to a given functional unit, implicitly ignoring that relevant energy technologies could vary in size and could thus experience scale effects. For the sizing optimization of HEPs which can be composed of renewable and non-renewable energy systems, the Life Cycle Inventory (LCI) of the considered technologies has to be available in a range of sizes, to calculate the off-site primary energy. However, the lack of data is one of the main obstacles facing designers and LCA analysts in conducting the optimization study. In [11], a series of interviews with designers, product development managers and environmental managers was carried out to understand what the main obstacle is for conducting design optimization studies, and it was found that the scarcity of environmental information is a major barrier to design improvement. This problem is often overcome by applying linear scaling for the estimation of the LCI data or the final impacts of a product with its capacity or by using literature data that are not necessarily consistent since they are collected from different sources. With this approach, it is not possible to evaluate the effects of design changes, technology size and future installation. Therefore, the integration of LCA into the system design to target the environmental impacts becomes an obstacle for decision makers.

Keoleian [12] addresses the problem of applying LCA to product design and development. In his study, he presented practical issues to apply LCA in a product design context. Gasafi et al. [13] presented an approach for the application of LCA in the system design and decision making process. Their approach is based on a dominance analysis which can be performed to identify the subsystems in the process chains that contribute most to the overall environmental impacts of a system. The proposed procedure allows an environmental profile of the entire system to be obtained. Then, the obtained profile is analyzed by designers who identify the critical processes of the supply chain and make changes to the product design that could reduce the environmental impacts. However, the method is hierarchical and the implementation of the proposed approach in a computer-aided optimization tool may be complicated. Lu et al. [14] developed an approach to life cycle design and evaluation with the aim of optimizing the functional, environmental and economic performance of a product. The proposed design process model was applied to a simple case study consisting of a "Z" section of a piping structure system. In order to evaluate the impacts associated with the life cycle of the system, an evaluation table was constructed for each stage of the life cycle. However, the suggested model is based on qualitative analysis techniques and requires inventory data adaptions each time a change is made to the product design. In addition, the application of the proposed approach to design complex products such as energy systems is time consuming. Therefore, it could not be suitable for energy system optimization. Stefanis et al. [15] presented a methodology to integrate LCA into the design of chemical process systems, considering a global environmental impact vector, and integrated these environmental criteria into the minimization of objective functions. However, for the implementation of their methodology, inventory data should be available for each process design option and operating condition.

Regarding the optimization challenges of HEPs in a life cycle perspective, several research papers were presented in the literature. The sizing optimization problem of an HEP composed of a photovoltaic system, a wind turbine, a diesel generator and a battery used for residential building applications is presented in [16]. The optimization of the system is achieved by using a genetic algorithm and considering only the operation phase of the system. The optimal design of a stand-alone PV-wind-diesel engine system with battery storage is investigated by the authors in [17]. In their study, the optimization is conducted by using an evolutionary algorithm which minimizes the levelized cost of energy and life cycle emissions over the lifetime of the HEP. They found that the final configuration of the optimized HEP may be affected by considering the emissions associated with the manufacturing and decommissioning phases in the optimization process. Jing et al. [18] optimized the size of a building energy system with the purpose of maximizing its life cycle energy saving and pollutant emission reduction. Wang et al. [19] presented a methodology for the optimization of a hybrid combined cooling heating and power system assisted with solar energy and natural gas. The aim of the study is to investigate the optimal configuration of the plant by minimizing the life cycle environmental impact of the plant. Energy consumption, pollutant emissions and material inputs during the manufacturing phase were calculated as a function of the capacity of the different systems comprising the studied energy plant. Allouhi et al. [20] proposed an optimization procedure of a centralized solar heating system for the production of hot water with different temperature levels. The configuration optimization of the different systems comprising the plant was carried out with the aim of minimizing the life cycle cost. Investment, installation and maintenance costs were considered linear with the size of the different systems. The results indicated that the use of the proposed system may allow life cycle savings of about 179 kUSD, when considering a life span of 20 years. Kang and Wang [21] investigated the optimization of distributed energy systems with the aim of achieving a cost-effective design option that ensures a high performance operation condition of the system throughout its life cycle. The optimization was conducted by implementing a probabilistic method and carrying out the Monte Carlo simulation. In their study, only the useful-life of the system was considered, while the phases before and after the operation phase were omitted. They found that the proposed optimization method can help to prevent problems of undersizing or oversizing in distributed energy system design. Huang et al. [22] proposed a sizing optimization strategy for heating, ventilating, and air-conditioning systems from a life cycle perspective. The proposed strategy accounted for the uncertainties of the load and cooling supply. In [23], a combined cooling, heating and power system is optimized from a life cycle energy, economic and environmental perspective. The aim of their study is to optimize the capacity of the prime mover, the type of biomass feedstock and the operation strategy. Constructive materials and energy consumption were estimated as a function of system capacity by assuming a linear relationship.

The works mentioned above performed the optimization study of the energy plant by applying linear scaling for the estimation of the impacts of each technology involved in the plant. However, it is well known that the relationship between the LCI flows and the product size follows a power law [24], similarly to produce cost scaling known as economies of scale [25]. Gerber et al. [26] made a comparison between the conventional LCA approach which uses linear extrapolation to evaluate the impact at different sizes and the approach based on the analogy with cost scaling. They observed that the use of a power law for the scaling and the use of cost exponents is more accurate than using the linear scaling approach which assumes a specific constant impact with system size. Furthermore, Caduff et al. [27] investigated whether the size of wind turbines affects the environmental profile of the generated electricity. In order to derive scaling factors and to evaluate the effect of the size on the environment, they considered the LCIs of 12 different onshore wind turbines and quantified the environmental impact of each system. The results show that the larger the turbine, the greener the produced electricity, concluding that scaling size affects the environmental profile.

Based on the literature survey presented above, this paper contributes to the scientific literature by:

- proposing a procedure for optimizing the size of a complex HEP by integrating LCA and considering the non-linear LCI scaling of energy systems;
- evaluating the influence of LCA integration into the optimization process on HEP sizing and primary energy saving;
- assessing the influence of LCA integration on the operation strategy of the different energy technologies comprising the HEP.

The HEP is composed of renewable and non-renewable energy systems and the optimization is conducted with the aim of minimizing the primary energy demanded during the manufacturing, transportation and operation phases. Finally, a case study is considered to demonstrate the effectiveness of the proposed procedure. Two approaches are taken into consideration: in the first approach, LCA is not integrated into the optimization process, while in the second approach the primary energy consumption is minimized throughout the life cycle of the plant by integrating LCA.

The rest of this paper is organized as follows: Section 2 illustrates the HEP considered in this study, presents the mathematical models of the HEP components and describes the control logic used for the allocation of the energy demands among the different technologies. Section 2 also describes the adopted LCA model, discusses the problem of LCA scaling and highlights the optimization procedure. The case study is outlined in Section 3. Finally, sections 4 and 5 discuss the results and conclude the paper, respectively.

2. Model development

The optimal design of the HEP is made by considering an energy-based criterion, i.e. the primary energy demanded throughout the manufacturing and operation phases is minimized. However, a different objective function, such as pollutant emission production or total cost, may be implemented in the model developed in this paper. Sizing optimization is conducted by using a Genetic Algorithm (GA) because of its ability to deal with discrete spaces and solve nonlinear problems [28]. In fact, this kind of evolutionary algorithm does not require limiting assumptions about the underlying objective function. The optimization is conducted by simulating the HEP throughout one year and the analysis is carried out on an hourly basis. For the simulation of the HEP, a model is developed in Matlab®.

2.1. Hybrid energy plant

Figure 1 shows a scheme of the HEP considered in this paper. It is composed of different technologies which use renewable and non-renewable energy sources. In particular, Solar Thermal Collector (STC), Photovoltaic Panel (PV), Combined Heat and Power system (CHP), Absorption Chiller (ABS), Air Source Heat Pump (ASHP), Ground Source Heat Pump (GSHP) and thermal energy storage are considered.

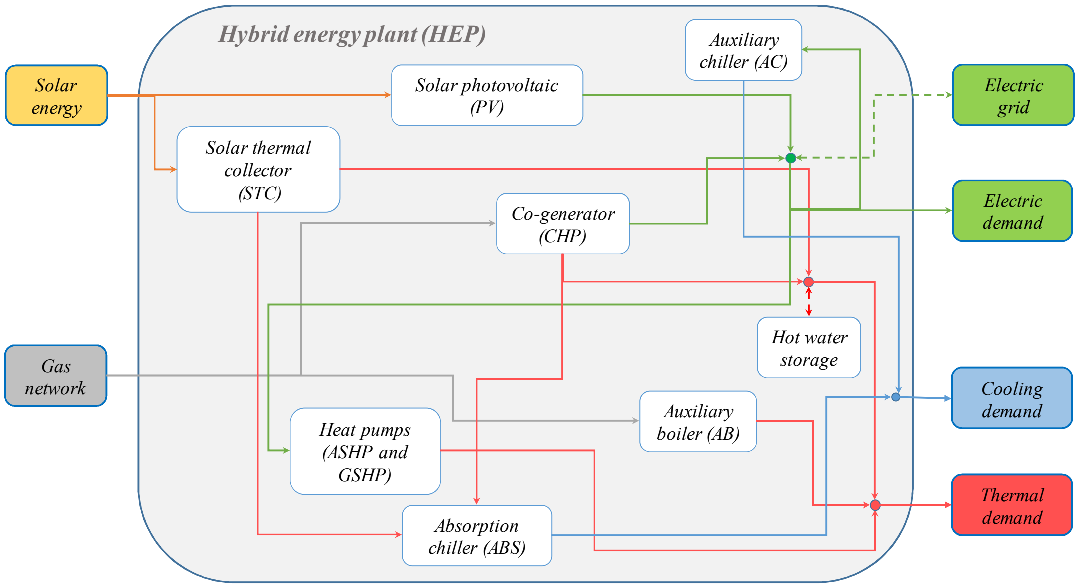


Fig. 1. Schematic diagram of the hybrid energy plant.

In addition, a condensing Boiler (AB) and a Chiller (AC) are also considered as auxiliary systems in order to meet thermal and cooling demands in case that they are not fulfilled by the abovementioned systems. Heat pumps are assumed reversible, i.e. they can produce thermal energy in winter and cooling energy in summer.

Equations (1), (2) and (3) express the balance of thermal energy, cooling energy and electric energy demands to be met by the different technologies of the HEP:

$$E_{\mathrm{AB,th}}(i) = E_{\mathrm{th}}(i) - \left(E_{\mathrm{STC,\,th}}(i) + E_{\mathrm{CHP,th}}(i) + E_{\mathrm{GSHP,th}}(i) + E_{\mathrm{ASHP,th}}(i) + E_{\mathrm{storage,th}}(i)\right) \quad (1)$$

$$E_{\mathrm{AC,cool}}(i) = E_{\mathrm{cool}}(i) - \left(E_{\mathrm{ABS,cool}}(i) + E_{\mathrm{GSHP,cool}}(i) + E_{\mathrm{ASHP,cool}}(i)\right) \quad (2)$$

$$E_{\mathrm{el}}(i) + E_{\mathrm{GSHP,el}}(i) + E_{\mathrm{ASHP,el}}(i) + E_{\mathrm{AC,el}}(i) = E_{\mathrm{PV,el}}(i) + E_{\mathrm{CHP,el}}(i) + E_{\mathrm{grid,el,taken}}(i) \quad (3)$$

As can be seen, these equations ensure the fulfilment of the thermal, cooling and electric energy demands at each time step i (equal to one hour) of the entire simulation period of one year. In particular, from Eq. (1), E_{th}, which represents the space heating and hot water demand, can be met by the STC, CHP, GSHP and ASHP systems. The AB ensures the fulfillment of the thermal demand in case it is not met by the other systems. From Eq. (2), E_{cold}, which represents the cooling demand, is fulfilled by the ABS, GSHP and ASHP systems. The AC ensures the fulfillment of the cooling demand if not fulfilled by the other systems. As reported in Eq. (3), the electric energy demand (E_{el}), the electricity required by the heat pumps ($E_{\mathrm{GSHP,el}}$ and $E_{\mathrm{ASHP,el}}$) and the AC ($E_{\mathrm{AC,el}}$) are provided by the PV ($E_{\mathrm{PV,el}}$) and CHP ($E_{\mathrm{CHP,el}}$) systems. If these systems are not able to fulfill the demand of electric energy, the remaining part, which is represented by $E_{\mathrm{grid,el,taken}}$, is imported from the grid. Otherwise, the excess of the produced electric energy from the CHP system and the PV panel is delivered to the grid.

Equation (4) defines the primary energy used during the operation phase. It is defined as the sum of primary energy consumption of the CHP, AB and the primary energy referred to the electricity exchanged with the grid.

$$PE_{\mathrm{op}} = PE_{\mathrm{fuel,CHP}} + PE_{\mathrm{fuel,AB}} + PE_{E_{\mathrm{grid,eltaken}}} - PE_{E_{\mathrm{grid,elsent}}} \quad (4)$$

2.2. Energy systems

The technologies considered in this paper are selected according to two criteria. The first criterion is that the candidate technologies are market available (in quite a wide range of sizes) and suitable for residential users as both single components and aggregate systems. Though ORC systems may be a promising alternative as the prime movers of micro-CHP systems in addition to internal combustion engines, they still present some challenges for real applications, as discussed by Ziviani et al. in [29]. Because of the purpose of the analyses carried out in this paper, the second criterion used to select the technologies is the availability of quantitative LCA data.

The technologies which are considered in this study are modelled by following a gray-box modelling approach. In particular, systems are defined by power and efficiency curves. It should be noted that the efficiency of all the energy technologies, with the exception of STC and PV panels of which performance only depends on ambient conditions, vary with the load. The basic correlations for each technology comprising the HEP are reported in the following.

Photovoltaic panel

Regarding the PV panels, single-crystalline silicon solar cells are considered. The efficiency of the PV system takes into account the efficiency of the inverter and electrical connections considering a Balance of System (η_{BoS}) equal to 0.9 [30, 31]:

$$\eta_{\mathrm{PV}} = \eta_{\mathrm{M}} \cdot \eta_{\mathrm{BoS}} \quad (5)$$

With;

$$\eta_{\mathrm{M}} = \eta_{\mathrm{M,ref}} \cdot \left[1 - \beta \cdot \left(T_{\mathrm{c}} - T_{\mathrm{ref}}\right)\right] \quad (6)$$

where $\eta_{\mathrm{M,ref}}$ is the efficiency of the PV at reference conditions, β a temperature penalty coefficient, T_{c} the operating temperature of the cell and T_{ref} the reference temperature of the cell. The operating temperature (T_{c}) of the cell depends on the external air temperature and solar radiation.

Solar thermal collector

The STC efficiency is estimated by means of the following equation reported in [32]:

$$\eta_{\mathrm{STC}} = \eta_{\mathrm{o}} - a_1 \cdot \left(\frac{T_{\mathrm{av}} - T}{R}\right) - a_2 \cdot \left(\frac{T_{\mathrm{av}} - T}{R}\right)^2 \quad (7)$$

where η_{o} is the optical efficiency, a_1 and a_2 are correction factors, T the hourly external ambient temperature, T_{av} the average temperature and R the solar radiation. The collector efficiency varies during the year because it depends on both the external ambient temperature and the global solar radiation. The average temperature is assumed equal to 80 °C during summer, and 50 °C during winter.

Combined heat and power system

The CHP system considered in this study is based on an internal combustion engine. The size of the CHP system is defined by the nominal electric power. The electric efficiency and the nominal thermal power are calculated as a function of the nominal electric power as reported in [33]:

$$\eta_{\mathrm{CHP,el,nom}} = 0.232 \cdot \left(P_{\mathrm{CHP,el,nom}}\right)^{0.084} \quad (8)$$

$$P_{\mathrm{CHP,th,nom}} = 2.5 \cdot \left(P_{\mathrm{CHP,el,nom}}\right)^{0.91} \quad (9)$$

The performance of the CHP varies with the ambient temperature and load variation which is defined as the ratio between the actual thermal power and nominal power [33]. The minimum load is assumed equal to 10 % of the nominal thermal load [34]. Moreover, CHP system start-up is modelled by adding a penalty equal to the fuel consumption for five minutes at nominal conditions.

Heat pumps

The performance of the GSHP and ASHP systems is calculated by using the technical standard [34]. The nominal cooling power is calculated as a function of the nominal thermal power by following the same approach reported in [33]:

$$P_{\mathrm{GSHP,cool,nom}} = 0.82 \cdot P_{\mathrm{GSHP,th,nom}} \tag{10}$$

$$P_{\mathrm{ASHP,cool,nom}} = 0.88 \cdot P_{\mathrm{ASHP,th,nom}} \tag{11}$$

For both heating and cooling modes, the performance of the heat pumps varies depending on the temperature of the external heat exchanger, internal heat exchanger and the load. The minimum load is assumed equal to 10 % of the nominal load [33, 36].

Absorption chiller

A single-effect H_2O-BrLi ABS is considered. The nominal efficiency of the ABS, represented by the energy efficiency ratio (*EER*), is assumed equal to 0.7 [33]. The capacity of the ABS system is defined by the nominal thermal power. The nominal cooling power is calculated as follows:

$$P_{\mathrm{ABS,cool,nom}} = P_{\mathrm{ABS,th,nom}} \cdot EER_{\mathrm{ABS,nom}} \tag{12}$$

The part load operation can affect the performance of the ABS. The minimum load is fixed equal to 25 % of the nominal load [37].

Auxiliary systems

A condensing boiler powered by natural gas and an electric chiller are considered as auxiliary generation systems. The nominal thermal efficiency (on an LHV basis) of the AB is assumed equal to 1.06, while the *EER* of the AC is assumed equal to 2.7. Both systems are considered as modulating systems. The minimum load of the AC is assumed equal to 10% [38], while the AB can modulate between 0 and 100 %. Moreover, a variation of the performance with load is assumed for both systems.

2.3. The control logic

In an HEP, the control logic of the different technologies defines which systems are switched on/off or regulated. Generally, control logic approaches such as time-led, heat-led, cold-led or electricity-led are implemented for the definition of the starting order of the systems involved [39]. In other cases, some hybrid function may be implemented to enhance the performance of the supply/demand matching.

In this work, the control logic of the different technologies is defined by Switch-On Priority (SOP) mapping, which defines the starting order and allows the minimization of on-site primary energy consumption during the considered period. The SOP mapping procedure is described and discussed in [40]. The mapping is developed by considering the demands for winter and mid-season and the summer season separately, and the SOP control logic is defined by maximizing the efficiency of the system depending on the nominal capacity and the types of systems utilized. Renewable energy systems, such as STC and PV are not considered in the mapping, since they are not controllable and must be activated first. Furthermore, the AB and AC are not considered in the mapping because they are considered as auxiliary systems and their size is set equal to the peak of the thermal and cooling energy demand, respectively. The CHP size ranges between (50 to 500) kW, with a step of 50 kW and the ASHP and GSHP capacities range between (30 to 300) kW with a step of 30 kW. The nominal thermal power of the ABS is defined equal to the CHP thermal nominal power.

In order to develop the SOP mapping, for each combination of component sizes, the on-site primary energy consumption is calculated and the best SOP control logic is evaluated. For the considered components, the developed SOP mapping consists of a 3D matrix which contains 1000 size combinations. At each iteration of the optimization process, the developed SOP mapping is used by the optimization algorithm to define the proper SOP which minimizes the on-site primary energy consumption.

2.4. Life cycle assessment model

In order to evaluate the primary energy demanded during the manufacturing phase of the PV, STC, CHP, GSHP, ASHP, ABS and the storage, a cradle-to-gate LCA is carried out. AB and AC are not assessed, since they are considered as auxiliary systems and they are not involved in the optimization process. The disposal phase is not taken into account in this study due to lack of consolidated data. Figure 2 shows the boundary considered for the development of the cradle-to-gate analysis. For each technology comprising the HEP, the boundaries of the cradle-to-gate analysis include:

- Raw material extraction (cradle);
- Raw material processing;
- Transportation of processed materials to the manufacturing site;
- Manufacturing of the final product;
- Transportation to market;
- System at market (gate).

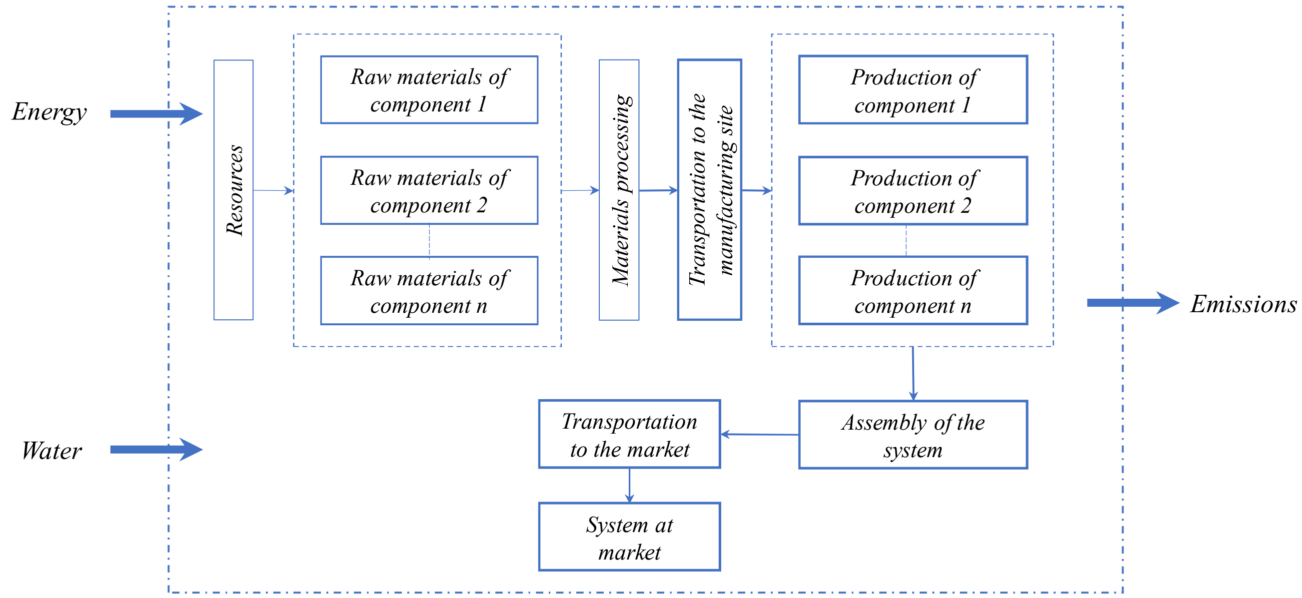


Fig. 2. Boundary of the technologies comprising the HEP.

The LCIs of the investigated systems were obtained from Ecoinvent® [41] by considering the European market. The calculation is conducted by using the software openLCA® [42]. The cumulative energy demand (CED) is considered as the impact indicator. The CED takes into account the primary energy demanded throughout the cradle-to-gate life cycle and represents the depletion of energy resources associated with the life cycle of the system [43].

For sizing optimization purposes, in order to calculate the CED of a system of an arbitrary size, the CED values should be available at different sizes of the considered system. However, LCI databases usually provide inventory data for a certain product at a predefined size. In the literature, this problem is usually overcome by the linear scaling of the LCI flows of equipment with its capacity. Nevertheless, linearization may over- or under- estimate the final results because the relationship between LCI flows (or impacts) and system size is not linear and follows a power law trend, in a fashion similar to the economies of scale [44]. Among others, the analogy between LCI scaling and cost scaling was demonstrated by Gerber et al. [26] who recommend the use of the power law relationship for LCI scaling instead of linear scaling. Moreover, they showed that, when no information about the scaling rule is available (i.e. the relationship between mass and equipment size), the use of cost exponents always allows better results than linear scaling. Furthermore, Whiting et al. [45] used a scaling exponent of 0.6 to scale up LCA results of a CHP system. Likewise, Lantz [46] scaled the investment costs of a CHP plant by using a cost exponent of 0.66. These two works confirm the validity of the analogy between LCA and cost scaling. The use of scaling factors is also recommended by Caduff et al. [44]. In their study, they suggest the use of scaling factors in the range from 0.5 to 0.8 for the scaling of energy technologies. Therefore, to calculate the CED of a system in a range of sizes, the LCI data were scaled as in Eq. (13):

$$G = G_{\text{ref}} \cdot \left(\frac{P}{P_{\text{ref}}} \right)^{k} \tag{13}$$

where G represents the scaled LCI flows (i.e. material, energy, emission, etc.) at the scaled size P, G_{ref} the flows at a reference size P_{ref} and k the scaling exponent which ranges from 0 to 1. The LCI flows (G_{ref}) at the reference size are obtained from the Ecoinvent® database, while the scaling exponent (k) is derived from the literature. It should be mentioned that, nonlinear scaling was only carried out for the CHP, GSHP, ASHP, ABS and hot water storage equipment, while the LCI of the STC and PV systems was scaled linearly (i.e. k=1) as a function of the respective area. Indeed, the choice of 1 m^2 as a functional parameter for the STC/PV allows the linear scaling of the LCI as a function of the STC/PV area. Scaling exponents (k) for the CHP, GSHP, ASHP, ABS and hot water storage were obtained from the literature. The scaling exponents for the abovementioned technologies are reported in Table 1.

Table. 1. Scaling exponents of the CHP, GSHP, ASHP, ABS and storage equipment.

	Scaling exponent (k)	Reference
STC/PV	1	-
CHP	0.66	Heck et al. [47]
GSHP	0.60	Caduff et al. [44]
ASHP	0.67	Caduff et al. [44]
ABS	0.54	Eicker et al. [48]
Storage	0.81	Eicker et al. [48]

Moreover, in order to calculate the primary energy associated with the manufacturing of the grid, the Italian grid was also modelled by using the Ecoinvent® database. The *CED* associated with the cradle-to-gate life cycle of the optimized technologies is calculated as in Eq. (14):

$$CED = CED_{\text{HEP}} + CED_{\text{grid}}(E_{\text{grid,el,taken}}) = \sum_{\text{s}} \frac{CED_{\text{s}}(P_{\text{s}})}{N_{\text{s}}} + CED_{\text{grid}}(E_{\text{grid,el,taken}}) \tag{14}$$

where CED represents the total CED expressed in MJ_{eq} per year, the first term on the right-hand side (CED_{HEP}) is the sum of the primary energy associated with the cradle-to-gate life cycle of the optimized systems and CED_{grid} represents the primary energy associated with the life cycle of the Italian grid and depends on the electricity taken from the grid per year of operation. Finally, for each system, the variables N_{s} and P_{s} represent the useful lifetime and the decision variable (or the size), respectively.

2.5. Optimization model

The methodology for sizing optimization of HEPs is outlined in Fig. 3. The GA is initialized by generating a random population of individuals in the design space and each individual represents a combination of sizes of the technologies comprising the HEP.

For each individual of the population, the primary energy PE_{op} used during the operation phase is calculated from the simulation model of the HEP as reported in Eq. (4), while the CED associated with the cradle-to-gate life cycle of the considered technologies and the Italian grid is calculated by means of the LCA model according to Eq. (14).

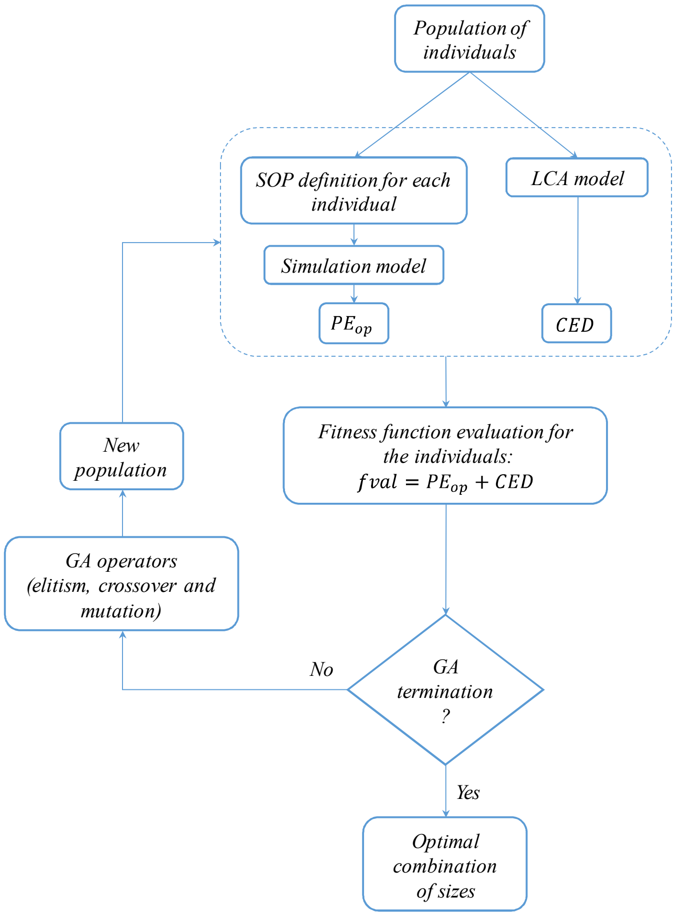


Fig. 3. GA optimization flowchart.

Consequently, the GA evaluates the fitness function of each individual in the current population as follows:

$$fval = f(P) = PE_{op} + CED \tag{15}$$

Then, based on the values of the individuals in the current population, the GA creates a new population by applying three operators (elitism, crossover and mutation). These mechanisms are repeated by the GA until a certain criterion is met and the best individual, which represents the optimal combination of sizes, is selected.

The decision variables P which represent the sizes of the technologies to be optimized are $P_{CHP,el,nom}$, $P_{GSHP,th,nom}$, $P_{ASHP,th,nom}$, $P_{ABS,th,nom}$, A_{STC} and A_{PV}. The volume of the storage $V_{storage}$ is calculated according to [49] as a function of the CHP and STC decision variables. In particular, a ratio equal to 0.04 m^3/m^2 is considered between the storage volume and the STC area, while the storage volume associated to the CHP system is assumed equal to 2 kWh/kW_{th}. Finally, the size of AB and AC are imposed equal to the peak of the thermal and cooling energy demands, respectively.

3. Case study

A tower composed of thirteen floors, located in the northern Italy, is considered as a case study [40]. In the tower, 1189 m^2, corresponding to a volume of 5735 m^3, are used as commercial premises, while 4457 m^2, corresponding to a volume of 20187 m^3, are used as offices.

3.1. Environmental data

The ambient temperature and solar radiation for the considered case study is calculated by using the procedure recommended in the standard [35]. This standard identifies one representative day of each month. Then, the hourly profiles of temperature and total solar radiation are calculated for the Italian climatic zone “A”, where the considered building is situated, according to the standard [50]. The monthly air temperature and total solar radiation values are reported in Fig. 4a and Fig. 4b, respectively.

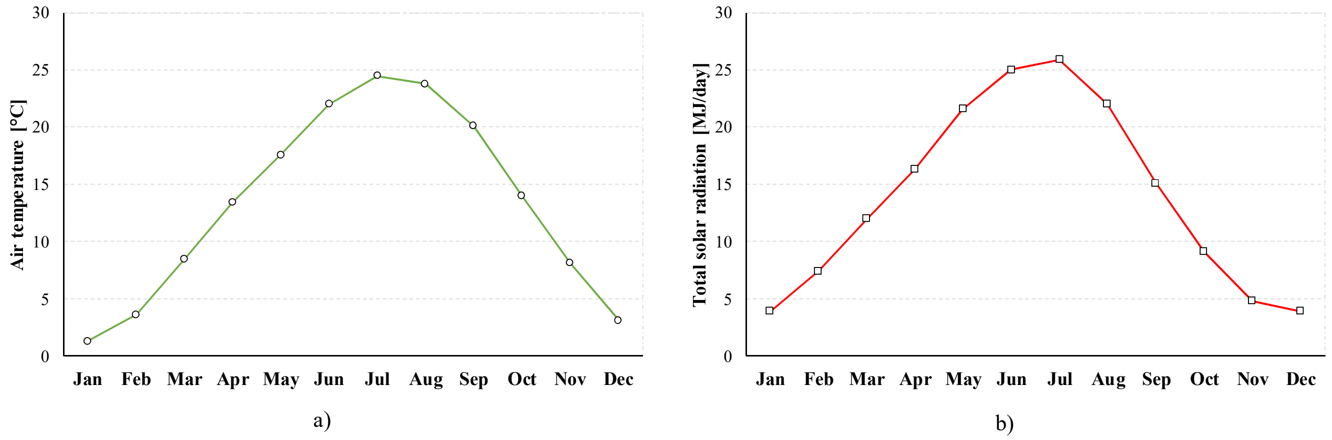


Fig. 4. Average air temperature (a) and daily total solar radiation (b).

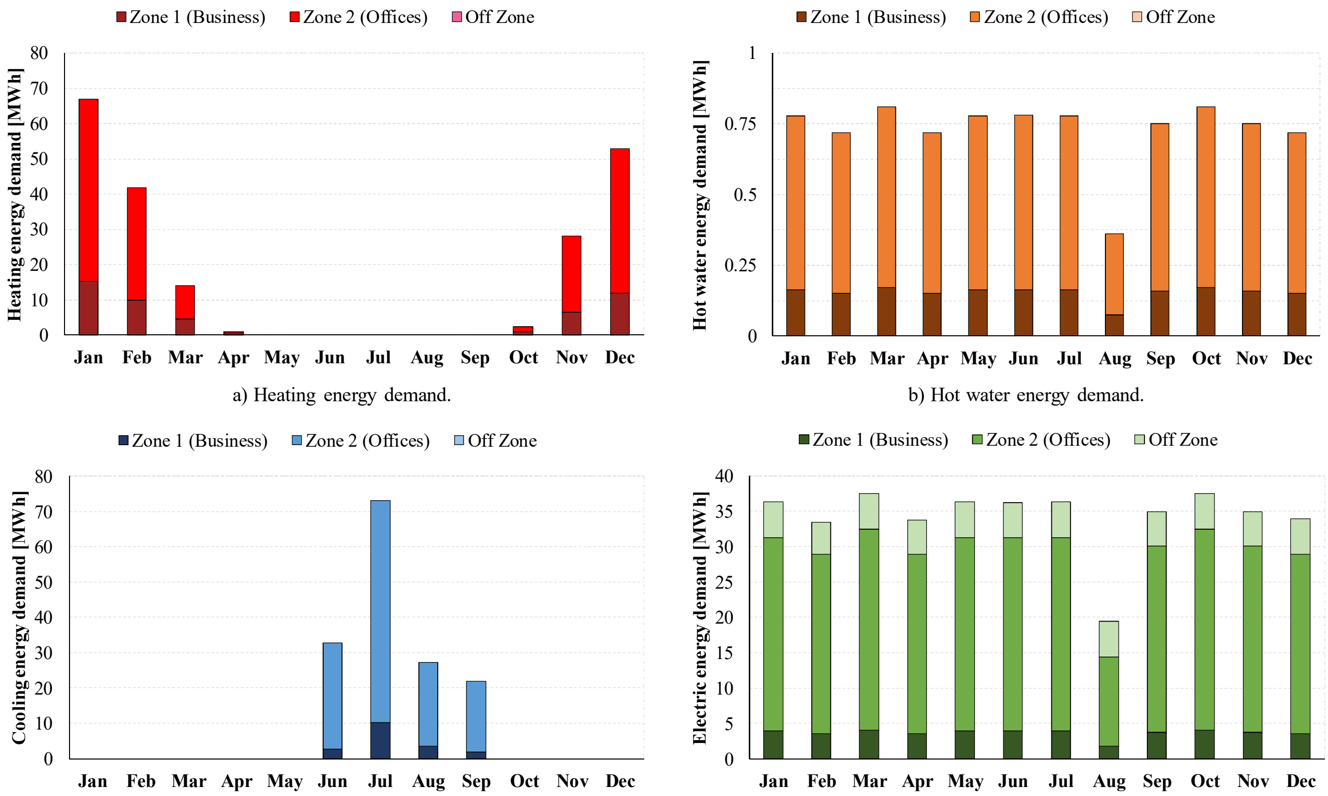
3.2. Energy demands

Figures 5a through 5d report the monthly energy demand for space heating, hot water, space cooling and electricity, respectively. The monthly energy demands were characterized for three different zones and calculated by using the EdilClimaEC700® software [40]. Zone 1 is for business use, Zone 2 is for offices and the Off Zone comprises elevators, lighting, parking lots, and the outdoor lighting basement. The energy demand is estimated equal to 207.17 MWh/year for space heating (Fig. 5a), 8.75 MWh/year for domestic hot water (Fig. 5b), 154.83 MWh/year for space cooling (Fig. 5c), and 410.92 MWh/year for electricity (Fig. 5d). The hourly demand presents a power peak of 234 kW for space heating and hot water, 294 kW for space cooling and 103 kW for electricity.

The energy demands were evaluated by considering 292 days of occupancy. The heating period for the climatic zone in which the building is located begins on 15th October and ends on 15th April, while the cooling period goes from 15th June to 15th September. Energy demands for domestic hot water and electricity are present throughout the whole year. In order to obtain hourly profiles of the energy demands, monthly energy demands are converted into hourly energy demands by using non-dimensional profiles which consider the types of users [51].

3.3. System variables and optimization algorithm set-up

The sizing optimization problem of the HEP is carried out based on the efficient matching between building energy demands and the energy supplied by the considered technologies, with the aim of minimizing the objective function represented by Eq. (15). The optimization aims at optimizing the STC and PV area (A_{STC} and A_{PV}) which can cover the available total area (328 m^2), the CHP nominal electric power ($P_{CHP,el,nom}$), which is an integer in the range (0 to 500) kW_e, the GSHP and ASHP nominal thermal power ($P_{GSHP,th,nom}$ and $P_{ASHP,th,nom}$) in the range (0 to 300) kW_{th} and the ABS nominal thermal power ($P_{ABS,th,nom}$) in the range (0 to 400) kW_{th}. Regarding the GA set-up, 100 generations with a population of 300 individuals for each generation are evaluated and the elite count (i.e. the number of individuals with the best fitness values that survive to the next generation) is set equal to 10.



a) Heating energy demand.

b) Hot water energy demand.

c) Cooling energy demand.

d) Electricity energy demand.

Fig. 5. Energy demands of the considered case study [40].

4. Results

Table 2 shows the optimization results of the two approaches considered in this study. In the first approach (LCA not integrated), LCA is not integrated into the optimization process, i.e. only the primary energy used during the operation phase is taken into account, while the second approach (LCA integrated) optimizes the sizes of the technologies considering the primary energy demanded throughout the cradle-to-gate life cycle and the operation phase of these systems.

As can be seen, the integration of LCA may lead to a different combination of sizes. In fact, by adding the off-site primary energy consumption evaluated by the LCA method, the area of the PV system increases in favor of the STC of about 37 m^2, the size of the CHP is increased from 93 kW_e to 114 kW_e, the size of the GSHP is decreased from 298 kW_{th} to 120 kW_{th}, the size of the ASHP decreases from 121 to 32 kW_{th} and the ABS nominal power increases from 153 to 235 kW_{th}. It should be noted that a sensitivity analysis was carried out (but the results are not reported in this paper for the sake of brevity) by increasing the available total area which can be covered by STC and PV panels (increased up to three times). The analysis revealed that, in the optimal solution, almost the entire available area is covered by PV panels.

Table 2. Optimal sizes of the technologies

Optimization decision variables (*P*)	A_{STC} [m^2]	A_{PV} [m^2]	$P_{CHP,el,nom}$ [kW$_e$]	$P_{GSHP,th,nom}$ [kW$_{th}$]	$P_{ASHP,th,nom}$ [kW$_{th}$]	$P_{ABS,th,nom}$ [kW$_{th}$]	$V_{storage}$ [l]
LCA not integrated	40.3	287.5	93	298	121	153	892.6
LCA integrated	2.7	324.7	114	120	32	235	935.5

Figure 6 reports the annual CEDs associated with the cradle-to-gate life cycle of the two combinations of technology sizes (see Table 2) per one-year lifetime obtained by applying the two approaches. With reference to the CED of the GSHP, it can be noted that, even if the size of the GSHP is more than halved by passing from the "LCA not integrated" approach to the "LCA integrated" approach, the value of the CED does not decrease proportionally. This is due to the nonlinear scaling approach adopted in this paper. Indeed, this justifies that linear scaling may under- or over- estimate LCA results and affect the optimization results.

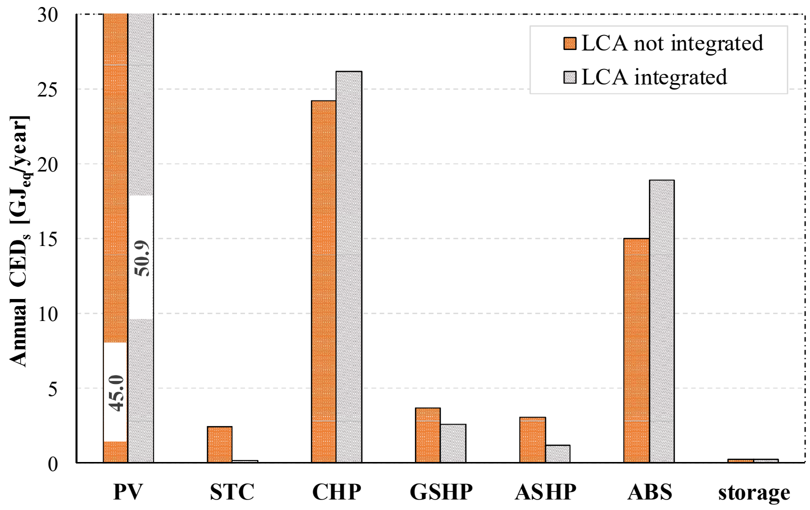


Fig. 6. Annual CED of the different technologies.

Figure 7 shows the primary energy associated with the grid (CED_{grid}), the cradle-to-gate life cycle of the whole plant (CED_{HEP}), the operation phase (PE_{op}) and the total primary energy consumption (*fval*). It can be seen that CED_{grid} most heavily affects the optimization results.

It should be mentioned that CED_{grid} can be evaluated only by considering both LCA and the operation. This is due to the fact that CED_{grid} is related to the electricity taken from the grid which depends on the operation policy of the different technologies. Furthermore, by integrating LCA into sizing optimization, the GA algorithm tends to increase the PV area in favor of the STC and also increases the size of the CHP, in order to minimize the amount of electricity taken from the grid. Moreover, the integration of LCA leads to a primary energy saving of about 12.5 %.

Figures 8a through 8c show the production of thermal energy, cooling energy and electric energy from the different technologies, respectively. As can be noted from Fig. 8a, the system which fulfills most of the thermal energy demand is the CHP followed by the GSHP while ASHP and AB are not used for the production of thermal energy. By considering the case of "LCA integrated", the CHP produces about twice the thermal energy fulfilled by the same technology when LCA is not integrated into the optimization process. Indeed, about 40 % of the energy produced from the CHP (in the "LCA integrated" approach) is used to operate the ABS which is used to produce cooling energy. So, the integration of LCA makes the thermal energy to be met higher because, in addition to building thermal energy demand, the thermal energy required by the ABS also has to be fulfilled. But, even if the thermal energy demand is increased, the reversible GSHP is not used for the fulfillment of the thermal energy demand, while the thermal energy produced by the STC is lower because it is characterized by a smaller size.

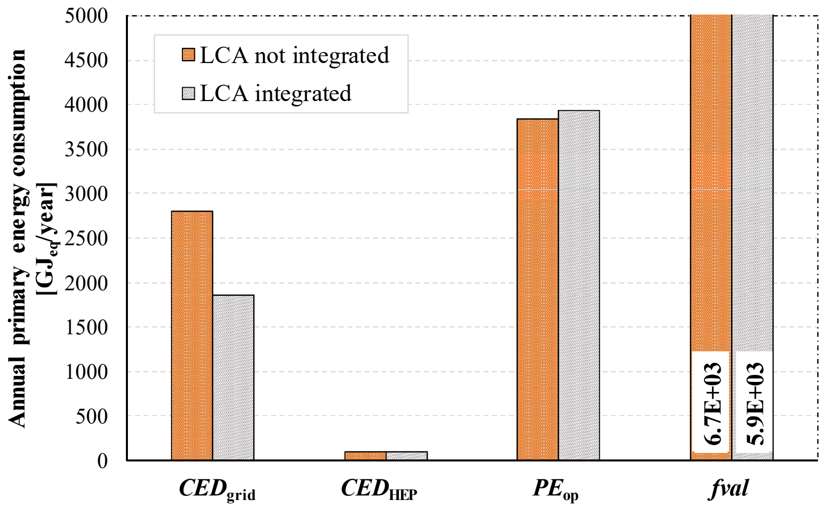
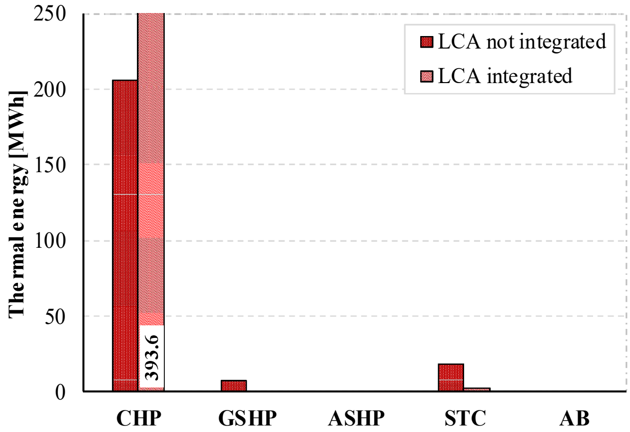
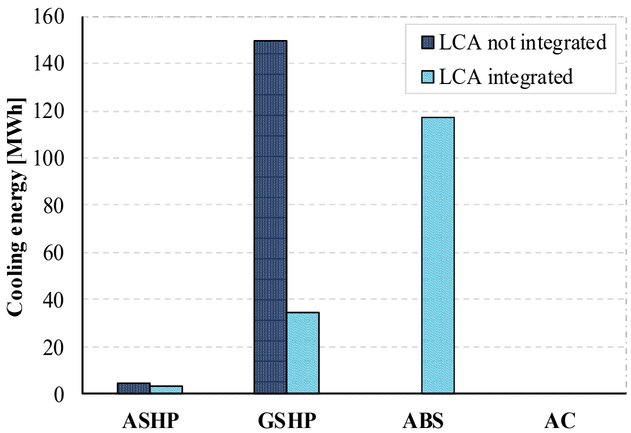


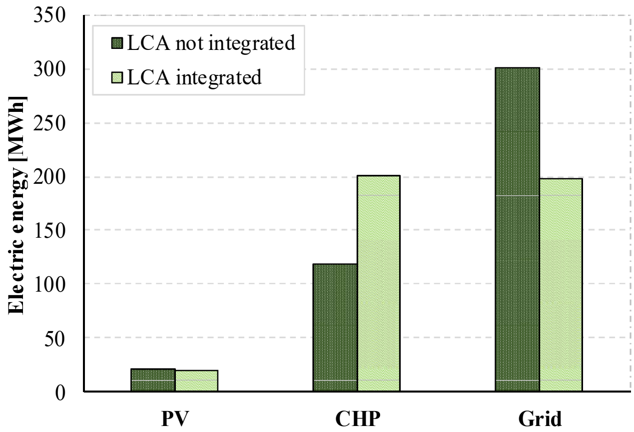
Fig. 7. Contribution of the grid, HEP and operation phase to primary energy consumption.



a) Thermal energy produced from the different HEP components.



b) Cooling energy produced from the different HEP components.



c) Electric energy produced from the different HEP components.

Fig. 8. Energy production from the different HEP components.

By analyzing the cooling energy production of the different systems, Fig. 8b shows that, if LCA is not integrated, the cooling energy demand is mostly fulfilled by the GSHP (about 90 %) followed by the ASHP (about 10 %), while the ABS is not used. However, by integrating LCA, most of the cooling energy demand is fulfilled by the ABS (about 68 %) followed by the GSHP unit which produces about 25 % of the energy produced by the same machine when LCA is not accounted for (Fig. 8b). As reported before when analyzing the thermal energy production of the "LCA integrated" approach, a certain amount of thermal energy produced by the CHP is used by the ABS which in turn fulfills a large portion of the cooling energy demand.

Figure 8c shows the electric energy produced by the PV, CHP system and the electricity taken from the grid for both approaches. The produced electricity is used to fulfill building electric demand and to operate the heat pumps. It can be seen that, by considering LCA into optimization, the solution identified by the GA tends to produce more electricity (and consequently more thermal energy) from the CHP system and tends to decrease the amount of electricity taken from the grid. This result is explained by the fact that the life cycle of the grid has a higher weight on the primary energy demanded throughout the life cycle (see Fig. 7). Moreover, by integrating LCA, the solution found by the algorithm tries to fulfill the cooling energy demand by using more heat driven technologies, such as the ABS, and to limit the production of energy (both thermal and cooling energy) from the electricity driven technologies.

Figures 9 and 10 highlight how the HEP components are managed during a typical winter and summer day in order to meet the thermal and cooling energy demand. In Fig. 9, "Storage In" represents the energy produced by the CHP system and STC and stored in the storage, "Storage Out" stands for the stored energy used to meet the thermal energy demand, while "Storage State of Charge" is the thermal energy available in the storage. As can be noted from Figs. 9a and 9b, the integration of LCA affects the operational results of the different technologies comprising the HEP. In particular, when LCA is not integrated (Fig. 9a), the thermal energy demand is met by the STC, CHP system, GSHP and hot water storage. In particular, in each hour, the storage is the first system that contributes to meeting the thermal energy demand.

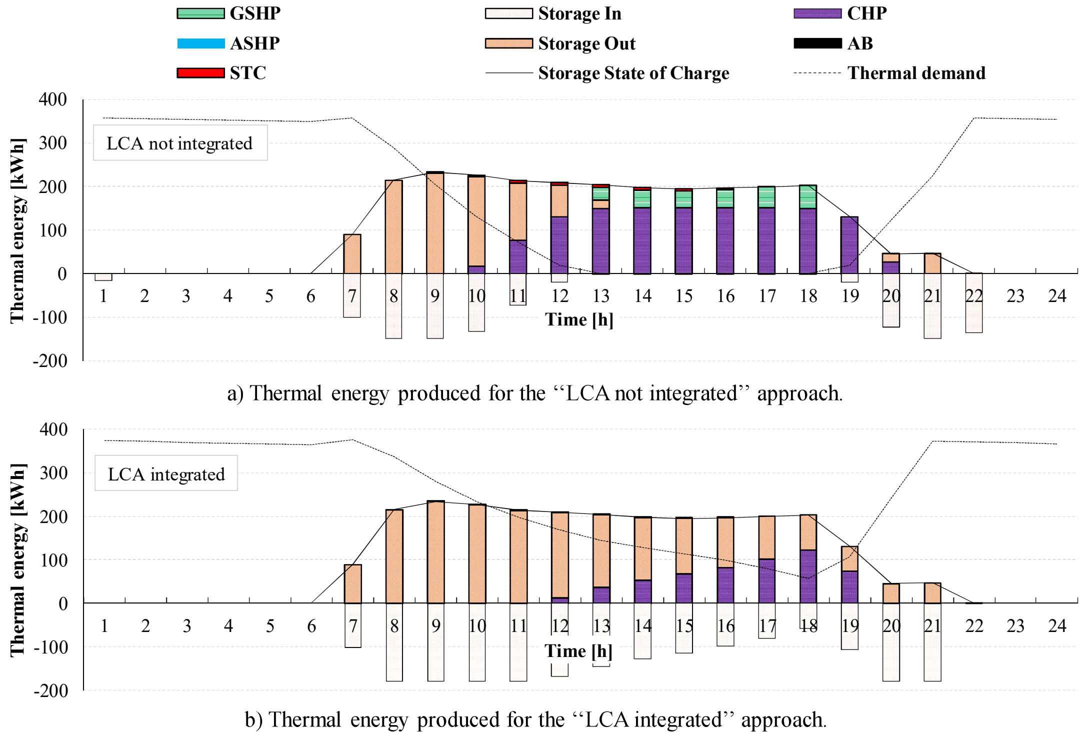
The CHP system is directly used to meet the demand, if the stored energy is not sufficient, and the excess thermal energy is stored. The GSHP is activated during peak hours when the stored energy and the CHP system are not able to meet the energy demand.

With regard to the "LCA integrated" approach (Fig. 9b), the same also applies here, i.e. the thermal energy demand is first met by the storage, supported by the CHP system and the STC. Instead, the GSHP is no longer used and the activation of electric driven technologies is avoided. In fact, the integration of LCA suggests increasing the size of both the CHP system and hot water storage. Consequently, the demand is fully met by these two technologies. For both approaches, the thermal demand met by the STC is negligible. However, when LCA is not integrated, the demand met by the STC is slightly higher, since the area of the STC is larger than in the case of the "LCA integrated" approach.

Figure 10 shows the contribution of each component to meet the cooling energy demand for the "LCA not integrated" approach (Fig. 10a) and "LCA integrated" approach (Fig.10b). When LCA is not integrated, the system which mostly contributes is the GSHP followed by the ASHP, while the ABS and AC are not used. This is mainly due to the fact that the GSHP requires lower energy consumption than ASHP and ABS. However, by integrating LCA (Fig. 10b), the rank of the different energy technologies is changed and the cooling demand is mostly met by the ABS. Furthermore, the GSHP and ASHP systems are used during peak loads or when cooling demand is lower than the minimum load of the ABS. This outcome confirms that, when LCA is integrated, it is advisable to first meet the cooling energy demand by using the CHP system coupled with the ABS.

5. Conclusions

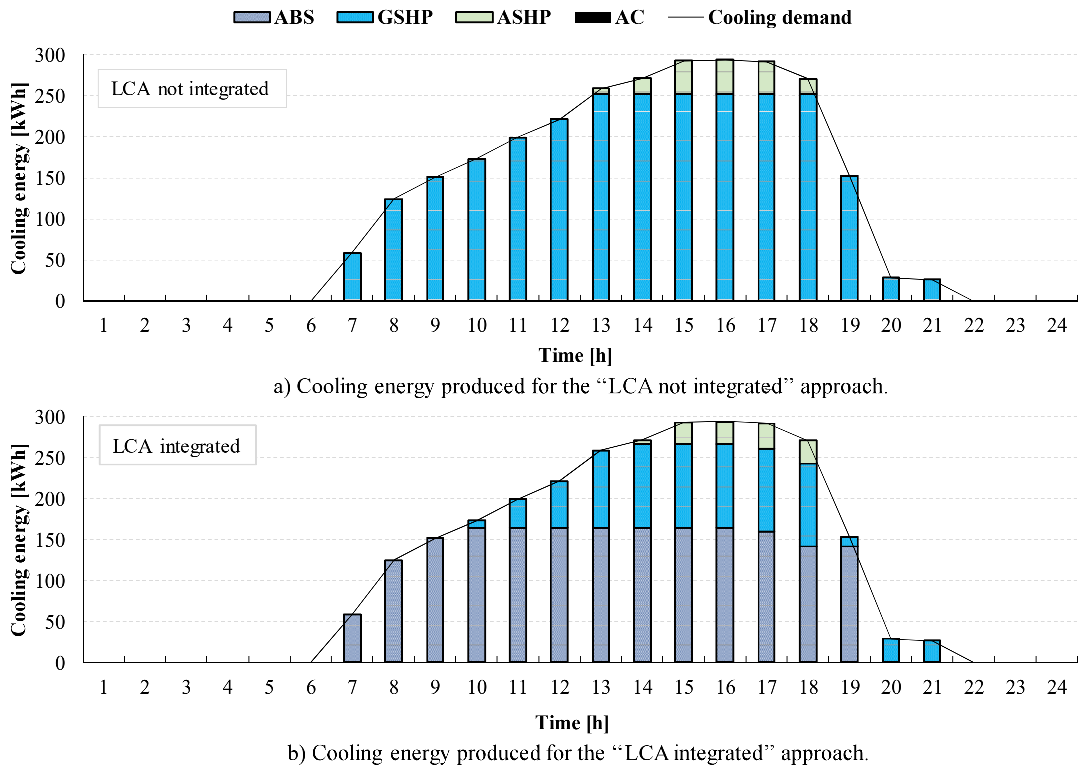
This paper addresses the problem of integrating up-stream energy demands of energy technologies into design optimization and investigates the effect of considering the up-stream impacts on the optimal size of a hybrid energy plant. The work covered the evaluation of off-site primary energy consumption by using the life cycle assessment (LCA) methodology, the challenge of life cycle assessment scaling of renewable and non-renewable energy technologies and the problem of integration of life cycle assessment in system design and optimization.



a) Thermal energy produced for the ‘‘LCA not integrated’’ approach.

b) Thermal energy produced for the ‘‘LCA integrated’’ approach.

Fig. 9. Contribution to thermal energy demand of the CHP system, GSHP, ASHP, STC, AB and storage during a winter day.



a) Cooling energy produced for the ‘‘LCA not integrated’’ approach.

b) Cooling energy produced for the ‘‘LCA integrated’’ approach.

Fig. 10. Contribution to cooling energy demand of ABS, GSHP, ASHP and AC during a summer day.

A methodology based on a genetic algorithm is used for the optimization of hybrid energy plants and two approaches were conducted in order to evaluate the influence of the integration of life cycle assessment on the optimal size and plant configuration. For both approaches (“LCA not integrated” and “LCA integrated”), the system which fulfills most of the thermal energy demand (more than 90 %) is the CHP system. If the life cycle assessment is not integrated, the cooling energy demand is mostly fulfilled by the ground source heat pump (about 90 %) followed by the air source heat pump (about 10 %), while the absorption chiller is not used. However, by integrating life cycle assessment, the thermal energy produced by the CHP system is almost doubled and about 40 % of the thermal energy produced by the CHP system is used to operate the absorption chiller which fulfills most of the cooling energy demand (about 68 %).

The life cycle of the grid has a major weight on the primary energy demanded throughout the life cycle, when considering life cycle assessment into optimization, the amount of electricity taken from the grid is decreased and more electricity is produced from the CHP. Moreover, by integrating the life cycle assessment, the cooling energy demand is fulfilled by using more heat driven technologies, such as the absorption chiller, and the production of cooling energy from the electric driven technologies, such as the ground source heat pump and air source heat pump, is limited. Finally, when considering off-site primary energy consumption may lead to a different configuration of the hybrid energy plant and to higher primary energy saving (about 12 %); this in turn results in a lower depletion of energy resources and lower environmental impact.

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