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Cradle-to-gate life cycle assessment of energy systems for residential applications by accounting for scaling effects

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HIGHLIGHTS

- Cradle-to-gate LCA of energy systems for residential applications is conducted.
- Factors for impact scaling are provided.
- The scaling procedure is validated vs. published data.
- A comparison of energy alternatives of different sizes is presented.

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ABSTRACT

This paper addresses the life cycle assessment of renewable and non-renewable energy systems which can be employed for residential applications and provides impact curves which can be used for optimization purposes. A cradle-to-gate life cycle assessment is carried out for the following technologies: solar thermal collector, photovoltaic panel, combined heat and power system, absorption chiller, air source heat pump, ground source heat pump, pellet boiler and hot water storage. For each technology, the inputs and outputs flows of the cradle-to-gate life cycle inventory are extrapolated in a range of sizes relevant for residential users. The employed impact indicator is the cumulative energy demand. The novelty of this study consists of a scaling procedure that allows the estimation of the impact of various technologies in a range of sizes and the integration of life cycle assessment for the optimization of complex hybrid energy plants. As an application of the scaling procedure, this paper reports a comparison among some different energy system configurations suitable to residential users. The comparison reveals that the cumulative energy demand of the photovoltaic tends to be noticeably higher than the combined heat and power system for electric installed power larger than 10 kW_e.

1. Introduction

Environmental sustainability and energy conservation are some of the most challenging tasks faced by humanity. Different indicators can be used to evaluate the environmental impact of renewable and non-renewable energy systems. Such indicators can cover a part or the entire life cycle of the systems and can also be applied to compare them from an environmental perspective. They can be used as a decision support to select the products which are more environmentally friendly and support decision makers for design and optimization purposes.

For the optimization of hybrid energy plants, i.e., plants which compose different energy systems, only the on-site energy demand is usually considered [1], whereas, in order to avoid burden shifting, the primary energy consumption associated with the upstream life cycle should be also accounted for [2].

One of the most effective methodologies for the quantification of the environmental impact of energy systems is Life Cycle Assessment (LCA) [3]. LCA is a methodology which allows the evaluation of energy and environmental loads associated with the development of a product throughout its life cycle (cradle-to-grave) including extraction and processing of raw materials, manufacture, transport, use and finally disposal [3].

Many studies are focused on primary energy consumption as an indicator to analyze goods and services [4]. One of the indicators which are currently used to estimate the primary energy consumption for the entire life cycle of a product is the Cumulative Energy Demand (CED) [5,6]. The CED accounts for the total primary energy (direct and indirect) which is used during the complete life cycle of a product or

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Nomenclature

A	area
b	balance vector
C	capital cost
CED	cumulative energy demand
d	final demand vector
e	environmental flows vector
E	energy
EM	environmental matrix
G	life cycle inventory flow
h	environmental impacts vector
k	cost exponent
L	life cycle assessment scaling exponent
P	power
Q	characterization matrix
S	size parameter
TM	technology matrix
V	storage volume
ρ	density

Acronyms

ABS	absorption chiller
ASHP	air source heat pump
CHP	combined heat and power
GSHP	ground source heat pump
ISO	international organization for standardization
LCA	life cycle assessment
LCI	life cycle inventory
PB	pellet boiler
PV	photovoltaic panel
STC	solar thermal collector

Subscripts and superscripts

ABS	absorption chiller
ASHP	air source heat pump
bio	biomass
c	cooling
CHP	combined heat and power
cool	cooling
el	electric
eq	equivalent
f	fossil
GSHP	ground source heat pump
n	nuclear
PB	pellet boiler
PV	photovoltaic panel
ref	reference
so	solar
STC	solar thermal collector
T	total
th	thermal
wa	water
w	wind

service [7,8].

The CED indicator is a potentially convenient option when no enough information is available in the inventory analysis, i.e., its calculation does not require emission estimates and impact factors. In fact, the CED indicator can be transformed into the cumulative CO_2 which is an indicator widely used for environmental analysis [9]. Furthermore, different studies show a strong link between CED and some environmental impact categories like global warming potential and abiotic resource depletion [9,10].

LCA studies of energy systems are usually performed by considering a specific size and by using data which are available in literature, e.g., from databases or measurements [11–13]. The most relevant studies dealing with the energy technologies considered in this paper are reviewed in the following.

Combined heat and power systems are popular and widespread because of their benefit of producing thermal and electric energy simultaneously. Several studies were conducted in order to evaluate their environmental performance via LCA [14]. For instance, Chevalier et al. [15] investigated the environmental impact of a biogas cogeneration system as a function of the fraction of thermal and cooling energy and the distance for crops collection from farm to the plant. Moreover, Kelly et al. [16] evaluated the application of an industrial combined heat and power system via an energy and carbon LCA. They concluded that the employment of industrial heat to generate electricity could lead to a significant reduction of carbon emissions and an improvement of the energy efficiency. A micro-combined heat and power system based on alkaline fuel cell was investigated via LCA by Staffel et al. [17]. The study evaluated the environmental impacts produced from the manufacturing and disposal stages of an alkaline fuel cell and compared the results to other LCA studies about fuel cell technologies concluding that an alkaline fuel cell has lower environmental impacts than the oxide or phosphoric acid fuel cells.

In the context of cooling cycles, refrigeration and air conditioning applications cover almost 20% of the whole worldwide energy consumption [18] and consequently they are responsible for many environmental issues. Aprea et al. [18] conducted an experimental study on a domestic refrigerator and evaluated the energy and environmental performance of the system by proposing the use of more environmental friendly refrigerants. Results revealed that the refrigerant based on HFOs reduces the global warming potential, compared to mixtures based on HFC134a. Boyaghchi et al. [19] proposed and analyzed two refrigeration systems from thermodynamic, economic and environmental point of view. The authors found that the inclusion of an ejector at the entrance of the phase separator of the system allows to reduce the environmental impacts of the refrigeration system. Furthermore, Aasadnia et al. [20] evaluated the environmental performance of absorption chillers used in a hydrogen liquefaction plant.

Water source and air source heat pumps are another type of energy systems which have proven to be environmentally convenient [21,22]. Koroneos and Nanaki [23] investigated a ground source heat pump system and quantified the environmental impacts as the acidification effect, greenhouse effect and eutrophication over a life cycle of 25 years. Huang et al. [24] found that the principal impacts associated with the life cycle of a ground source heat pump are the global warming, acidification and eutrophication.

Solar thermal collectors and photovoltaic systems are one of the most common renewable energy systems as they are always considered as environmental friendly energy systems considering that there are no environmental loads associated with the operation of these technologies. However, some studies investigated the environmental impacts related to the manufacturing and disposal phase showing the importance of examining these life cycle phases [25]. The LCA of two types of solar systems (glazed and unglazed) were studied by Comodi et al. [26]. The outcome was that the energy and CO2 payback times of both systems are very low compared to their life service. In addition, the impact of the disposal phase was lower than 2% for both cases. Longo et al. [27] investigated a small size solar space heating and cooling system by using LCA methodology. A more recent analysis about a solar based tri-generation system, which includes a flat-plate collector, is presented by Montazerinejad et al. in [28] and analyzed from energy, economic and environmental point of view.

The number of studies about photovoltaic systems is rising as a result of the increasing deployment of this technology in the energy sector. Problems about climate change and environmental impacts have led to the analysis of these systems as an efficient eco-friendly alternative compared to other existing non-renewable technologies. Several authors have conducted LCA studies about photovoltaic technologies. Most works attempt to evaluate parameters such as CED, energy payback time, global warming potential and eutrophication [29–31]. In particular, a cradle-to-grave analysis of a photovoltaic plant was carried out by Desideri et al. in [32] aiming at discovering the released environmental impacts. The results showed that the plant has an energy payback time of 4.2 years and an energy return on energy invested of 4.8. The main phase responsible for the environmental impacts was the installation phase, while the disposal and maintenance phases were less harmful. Furthermore, Irshad et al. [33] evaluated the effect of the integration of a building integrated photovoltaic system on the economic and energy consumption of a thermoelectric air cooling duct system. The results showed that, compared to other cooling systems, the integration of a photovoltaic system reduces energy consumption and carbon emissions and increases the economic benefits. Recently, Hosseini-Fashami et al. [34] evaluated the effect of solar energy technologies, such as photovoltaic and photovoltaic/thermal systems, on the greenhouse strawberry production by conducting an energy-environmental LCA. As an indicator, they used the cumulative exergy demand which quantifies the total content of exergy required for a service or product.

In spite of these achievements for some specific technologies and conditions, the lack of data remains a common problem which designers and LCA analysts face in conducting their study about new or already existing energy technologies. Indeed, according to the study carried out by Keoleian et al. in [35], which is based on a series of interviews with designers and environmental analysts, the main obstacle for design optimization is the scarcity of environmental data. This problem is often overcome by applying linear scaling for the estimation of the Life Cycle Inventory (LCI) data. However, the relationship between the flow properties (e.g., mass, heat, electricity) for manufacturing a product and its output capacity is non-linear (i.e., power law relationship [36]). Thus, more reliable approaches are needed. Scaling relationships are also used in economics where the capital cost of a good or a service is estimated as a function of the output capacity by means of a power law relationship; this is known as economies of scale [37] and some example of such relationships may be found in [38].

To the authors' knowledge, very few studies investigated the LCA scaling of energy systems. For instance, Gerber et al. [39] conducted an LCA study for a shell heat exchanger, tube heat exchanger and compressor to evaluate the impact at different sizes. In their study, they made a comparison between the results obtained by applying a linear scaling approach and non-linear scaling approach. They observed that the use of the non-linear approach always provides more accurate results than linear scaling which tends to heavily under- or over-estimate the final results. Furthermore, the effect of the size of onshore wind turbines on the environmental profile of the delivered electricity was investigated by Caduff et al. [40]. The study considered several wind turbines with different sizes. It was concluded that scaling size affects the environmental profile and large turbines allow to produce "greener" electricity than small turbines. Moreover, the scaling effect of biomass boilers and heat pumps on environmental impacts was also addressed by Caduff et al. in [41]. It was found that the scaling factors for these technologies fall in the range from 0.5 to 0.8. Likewise, Whiting et al. [14] extrapolated the LCA results of a combined heat and power system by using a scaling exponent of 0.6.

As can be noted from the works mentioned above, there is no comprehensive research dealing with the LCA scaling of all the energy technologies considered in this study. Therefore, this paper addresses the challenge of deriving impact curves for the energy systems used for meeting heating, cooling and electric energy demands in the residential sector. As an impact indicator, the cradle-to-gate CED of technologies such as 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), pellet boiler (PB) and hot water storage is considered since it is quite straightforward compared to full LCA studies. However, the presented work can be reproduced for estimating other impact indicators, such as global warming potential and resource depletion. The considered technologies are widely used in the residential sector as single systems and also as an aggregate in a hybrid energy system. They can also be found with different sizes and configurations.

This paper contributes to the scientific literature by proposing a general scaling procedure for the quantification of LCI flows of energy technologies in a range of sizes; this helps

- to overcome the obstacles of integrating the LCA into energy systems design and optimization;
- to evaluate the CED as a function of the size for different technologies;
- to compare energy alternatives of different sizes from the point of view of energy depletion.

Moreover, the proposed scaling procedure and the impact curves provided in this paper may be very helpful for the optimization of complex hybrid energy plants by considering the LCA. This is clearly demonstrated by a recent study [2] conducted by the same authors about the optimization of hybrid energy plants and the influence of the integration of LCA into the optimization process.

The paper is organized as follows. Section 2 presents the LCA methodology, which includes the calculation method and the scaling procedure. Section 3 elaborates the goal and scope of the study in more depth, presents the energy systems assessed in this study and describes the assumptions made for quantifying the resources and energy use. The proposed scaling procedure is validated by means of literature studies in Section 4. Section 5 presents and discusses the results. Finally, Section 6 reports some conclusions and practical indications for carrying out LCA studies, also for the optimal design of energy systems.

2. Methodology

The LCA methodology allows the quantification of environmental impacts caused by products, processes or services. This procedure is used to evaluate and compare the environmental effects of different products or systems and helps to identify the "hot spots" throughout their life cycle and improve products from the environmental perspective. The maturity of the methodology is demonstrated by the International Organization for Standardization (ISO) which published related technical standards, i.e., ISO 14040 [42] and ISO 14044 [43].

2.1. Calculation method

In order to solve the inventory problem of the different energy systems, the matrix-based LCA method, which was developed by Heijungs et al. [44], is used in this paper. This method is based on some matrix algebra operations and uses a system of linear equations to solve the inventory problem and to calculate the cumulative environmental loads. In the following, the main steps of the matrix-based LCA method are reported. More details can be found in [44].

Once the data for all the unit processes, which are required to produce a certain product or deliver a certain service, are collected, these are arranged in a technology or economic matrix (*TM*) and environmental or intervention matrix (*EM*). In particular, the technology matrix contains all the economic input and output flows of all the unit processes within the boundary of the system.

$$TM \cdot b = d \quad (1)$$

In Eq. (1), the vector d, called the final demand vector, represents the reference flow that fulfills the chosen functional unit. Generally, in the literature, the vector b is called a scaling vector. However, in order to differentiate it from the scaling exponent (L) defined in Section 3, the vector b is defined as a balance vector in this paper. The vector b multiplies the unit processes of the technology matrix to produce the reference flows of the final demand vector. Each column of TM represents a process vector for a particular unit process. The economic flows (tm_{ij}) of TM correspond to the flows of material, energy, services and waste exchanged between the unit processes of the technology system (or the technosphere). In accordance with the notation in Cartesian geometry and common practice, input flows have a negative sign, while output flows have a positive sign.

It should be mentioned that the inverse of the matrix TM only exists if the matrix is square and non-singular. However, these two conditions are normally fulfilled when dealing with real systems [45].

By using the same formulation adopted in Eq. (1), the system of equations for the environmental part can be expressed as follows:

$$EM \cdot b = e \quad (2)$$

The environmental flows (em_{ij}) of EM correspond to the flows of raw materials, space use, and emissions directly exchanged with the environment (or the biosphere, e.g., air, water and soil), while the vector e represents the cumulative environmental flows exchanged with the environment. By combining Eqs. (1) and (2), the following expression is obtained:

$$e = EM \cdot TM^{-1} \cdot d \quad (3)$$

In order to aggregate the environmental flows in environmental impacts (h), the following equation is used:

$$h = Q \cdot e = Q \cdot EM \cdot TM^{-1} \cdot d \quad (4)$$

where Q is a characterization matrix. This matrix contains factors of characterization that allows the aggregation of the environmental flows participating in an impact category in a single impact indicator (e.g., CED expressed in MJ_{eq}, GWP expressed in kg CO_{2eq}, etc.).

Generally, the matrix-based LCA method is used to calculate the environmental impacts associated with the life cycle of a certain product with a predefined size [44]. Currently, this method is broadly used to solve LCA problems and is implemented in many software tools (e.g., Simapro® and OpenLCA®). An overview of the variables involved in the matrix-based LCA method used to solve the LCA problem, as well as the respective dimensions, is reported in Table 1.

2.2. Scaling procedure

In literature, the LCI flows or environmental impacts of a scaled system are usually calculated by assuming a linear relationship between the LCI flows/impacts and the equipment size. However, it is well known that this relationship is non-linear and tends to assume a similar behavior of the conventional cost scaling [39]. The cost scaling method is known as economy of scale and relates the capital cost of an equipment to its capacity as follows:

$$C = C_{ref} \cdot \left(\frac{S}{S_{ref}} \right)^{k} \quad (5)$$

where C represents the scaled capital cost, C_{ref} the reference capital cost, S the size parameter, S_{ref} the reference size and k the cost exponent. In this study, in order to calculate the impacts of an energy system in a predefined range of sizes, it is assumed that the LCI scaling is also made by assuming the economy of scale [37], i.e., it is described by a power law relationship as reported in Eq. (6):

$$G = G_{ref} \cdot \left(\frac{S}{S_{ref}} \right)^{L} \quad (6)$$

with G representing a key property of the scaled LCI dataset such as mass, energy or emissions associated with the production of the considered equipment, G_{ref} the LCI data used as reference, L the scaling exponent and S and S_{ref} the size parameter and the reference size, respectively. In this paper, G_{ref} represents the materials of construction and energy used for the production of the different energy systems (see Appendix A).

Fig. 1 shows the procedure for the scaling of the LCI flows in a range of sizes. The first step of the methodology consists of defining the parameter S which represents the size of the assessed energy technology. If the LCI data are available for, at least, two different sizes, the scaling exponent L can be directly estimated by assuming the scaling behavior described by Eq. (6). For instance, the scaling exponent can be estimated from the relationships between the total weight or final impact of the equipment and its size.

However, if only one LCI dataset is available at one particular size, LCI data for different sizes may be estimated by using the scaling law described by Eq. (6). As reported by the third step of the procedure, the scaling exponent L can be derived from relationships between the total weight of the equipment and its size considering that the mass follows a similar law to cost scaling [39]; such exponents can be found in the literature for some applications [36,40,41,47]. Otherwise, the scaling exponent can be derived from economy of scale as an approximation by assuming a similarity between cost and LCI scaling. A scaling factor L of 0.6, which is known as the “six-tenths rule” [37], is also recommended when there is no information about the scaling behavior of the system [37,38]. This exponent is commonly used to estimate equipment capital cost as a function of the system size. Once the scaling exponent is found, LCI data can be estimated for different sizes and LCA studies can be performed in a range of sizes.

It should be mentioned that, in some cases, two components of the same system may have different scaling exponents (e.g., the motor and generator components in a CHP system) as reported in the following. Therefore, the scaling is carried out for the LCI flows of each component of a system using the corresponding scaling exponent. In this way, it is possible to distinguish between components of the system which are size-dependent and others which instead are size-independent, such as cables and electrical parts.

3. Life cycle assessment of energy systems

3.1. Goal and scope

The goal of this study is the evaluation of the environmental impacts and scaling effects by applying a cradle-to-gate life cycle assessment to renewable and non-renewable energy systems, widely used in the residential sector. In particular, the following energy systems are considered:

- Solar thermal collector (STC);

Table 1
Overview of variables of the matrix-based method [46].

Symbol	Name	Dimension (rows × columns)
TM	Technology (or Economic) matrix	Economic flows × processes
EM	Environmental (or Intervention) matrix	Environmental flows × processes
Q	Characterization matrix	Categories × environmental flows
d	Final demand vector	Economic flows × 1
b	Balance vector	Processes × 1
e	Environmental flows vector	Environmental flows × 1
h	Environmental impacts vector	Categories × 1

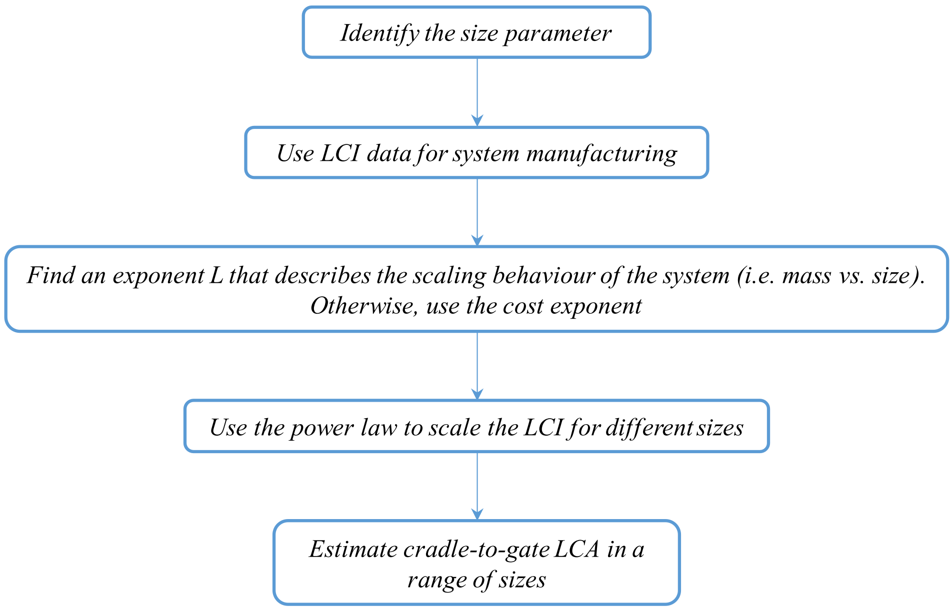

Fig. 1. Scaling procedure.

- Photovoltaic panel (PV);
- Combined heat and power (CHP);
- Ground source heat pump (GSHP);
- Air source heat pump (ASHP);
- Absorption chiller (ABS);
- Pellet boiler (PB);
- Hot water storage.

For a complete cradle-to-grave analysis, data on the product life cycle steps such as manufacturing, transportation, use, and disposal should be available. Since no consolidated information about the disposal phase of the energy systems considered in this paper is available, this phase is not addressed in this paper. A model for the quantification of the on-site impacts is described in another work by the same authors [48].

Thus, the cradle-to-gate analysis carried out in this paper only considers a part of systems life cycle, i.e., in our study from raw materials extraction to the transportation to the market. Fig. 2 shows the approach adopted for the development of the cradle-to-gate analysis. For each of the abovementioned energy systems, the boundaries of the cradle-to-gate analysis include:

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

As hinted before, the aim of this paper is the development of a general approach for LCA scaling. Therefore, for specific stages (e.g., transportation), general assumptions are implemented in the calculations. These assumptions have to be substituted in case of site-specific analyses. For the transportation of raw materials to the manufacturing site, 200 km in freight train and 100 km in a lorry are considered, while a 100 km of distance in a lorry is assumed for the transportation of the manufactured system from the factory site to the market [49].

The calculation was conducted by using the open source software openLCA® 1.6.3 [50]. For each technology, an LCI was constructed and the environmental impacts are analyzed accordingly.

3.2. Energy systems description: Inventory analysis and scaling

The LCI documents the material, water and energy balances for all stages listed above, to quantify the resources in mass units and energy units (electric energy in kWh and thermal energy in MJ). Regarding the LCI of the investigated energy systems, data were obtained from the Ecoinvent® [49] database which contains a large number of production processes with a focus on the European market. Thus, the European energy mix is the reference for the calculation of the demanded energy carriers.

For all systems, the scaling range is fixed from 1 kW to 250 kW and systems with a nominal power of 1 kW, 5 kW, 10 kW, 20 kW, 50 kW, 100 kW, 150 kW, 200 kW and 250 kW are assessed within the scaling interval. These sizes are selected since systems with these capacities are available in the market. Regarding the STC and the PV systems, the area ranges are calculated in such a manner that the production of approximately 250 kW_{th} (STC) or 250 kW_p (PV) is obtained.

In the following, the main assumptions made for modeling and

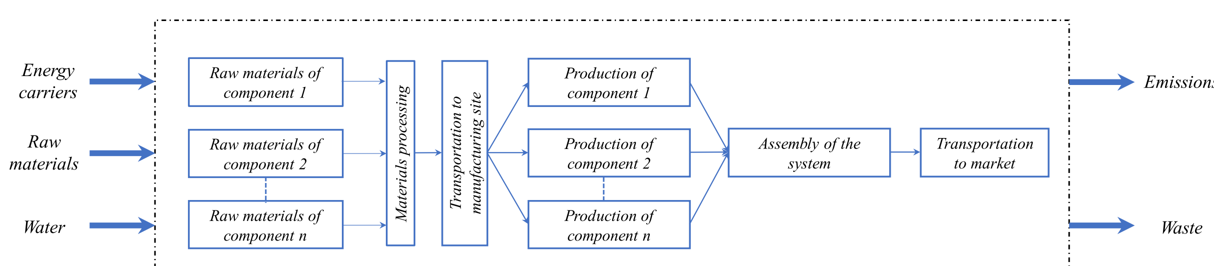

Fig. 2. Energy system boundary.

scaling the LCI of each technology are reported:

- *Solar thermal collector*

The studied STC is a flat plate collector type for multiple dwellings use [51]. As reported in Table A.1, the collector consists of a frame, an absorber with a selective coating, single glazing materials, thermal insulation and a sealing.

For assessing the impacts of the STC as a function of the size, a reference functional parameter of 1 m^2 of solar collector is considered. The chosen functional parameter allows the linear scaling of the LCI as a function of solar thermal collector area. Therefore, the key properties of the scaled LCI are calculated by setting $L = 1$ in Eq. (6).

- *Photovoltaic panel*

In this case, PV panels for grid-connected applications are investigated [52]. As shown in Table A.2, the photovoltaic system is composed of the PV panels and the mounting structure. The PV panels consist of a number of solar cells which are enclosed by glass based laminates and are framed by an aluminum structure. As a type of cells, single crystalline silicon cells are used.

A case study analyzed by the authors in another work [48] considers the use of PV panels for façade applications. Thus, in this paper, it is supposed that the PV panels are mounted for façade building applications. In this type of installations, panels are attached to the façade by an aluminum profile which is fixed to the building structure. A functional parameter of 1 m^2 of PV panels is considered.

Regarding the scaling of the PV system, the LCI for the PV panels and the mounting structure is scaled linearly with the PV area.

- *Combined heat and power system*

As illustrated in Table A.3, the CHP unit considered as a reference is based on internal combustion engine technology and provides 160 kW_{el} and 360 kW_{th}. The CHP system is composed of an engine, a generator, a heat exchanger, a sound insulation system, a control cabinet, electric parts and a catalytic converter [47].

For LCI scaling, the electrical power output $P_{CHP,el}$ is considered as the functional parameter of the CHP system. In this case, the components which depend on the size of the CHP unit such as the motor, generator, heat exchanger, sound insulation, air input/output supply, catalytic converter and the flows needed for motor/generator assembly were distinguished from the parts which are size-independent such as the control cabinet and the electric parts. The LCI flows of the parts which are size-independent are considered constant. Instead, for the size-dependent parts, different scaling exponents are used to extrapolate the LCI in the considered scaling range.

As reported in Table 2, the LCI input and output flows of the engine and the generator are related to the capacity of the CHP with scaling exponents of 0.64 and 0.68, respectively. The scaling exponents for the engine and generator are identified in [36] by considering different types of engines/generators and using a regression method to disclose the relationship between the mass [kg] and the power output [kW] of the engine/generator. It should be noted that an assumption was made about the scaling of electricity, heat and water flows. In fact, these were scaled in the same fashion as the raw material flows supposing that the same scaling behavior also applies here.

The LCI flows of the remaining parts (excluding the control cabinet and the electric parts, which were considered constant) were extrapolated by using a scaling exponent L of 0.66. This exponent was calculated from the relationship between the total weight of the CHP unit and the input power [47].

- *Ground and air source heat pumps*

For both heat pumps, GSHP and ASHP, the reference system is characterized by a nominal thermal power of 10.25 kW_{th} [53]. Moreover, it was supposed that the cooling mode of operation does not affect the amount of materials and energy required for the manufacturing of both systems. The LCI for the GSHP is illustrated in Table A.4. In this study, the same list of materials used for the GSHP was supposed for manufacturing the ASHP. In fact, the LCI of the ASHP is calculated by multiplying the LCI of the GSHP by a factor of 1.6 [53], since the ASHP is characterized by a higher weight and refrigerant use compared to the GSHP [53]. The main components of both heat pumps are: the housing, the compressor, the evaporator, the condenser and the control system. Moreover, a borehole heat exchanger which consists of two U-tubes is considered for the GSHP system. The refrigerant R134 is the working fluid considered for both systems.

The functional parameter considered for scaling the LCI of both GSHP and ASHP systems is the thermal power ($P_{GSHP/ASHP,th}$) expressed in [kW_{th}].

The extrapolation of the LCI key properties for the GSHP and ASHP is conducted by using scaling exponents from literature which relate the total mass of the equipment to the system capacity. As can be seen from Table 3, scaling exponents of 0.60 and 0.67 were used to calculate the LCI of the GSHP and ASHP at different sizes, respectively [41]. Materials for electrical cables, i.e., copper and PVC, were considered size-independent for both cases (GSHP and ASHP). Moreover, the amount of refrigerant (in kg) is calculated by using a scaling exponent of 0.62 for the GSHP, while an exponent of 0.91 is used for the amount of refrigerant needed for the ASHP operation [41]. Finally, the borehole heat exchanger was considered size-independent by supposing that the length of the probes does not vary with the GSHP nominal power and the effect of the probes diameter is negligible.

- *Absorption chiller*

The ABS unit inventoried in this study is a single-stage water/ammonia system with a cooling capacity of 100 kW [54]. A hybrid cooler is also included in the ABS boundary. Table A.5 reports the LCI flows for the assessed system.

The functional parameter $P_{ABS,cool}$, i.e., the installed cooling power of the ABS, is used for LCI scaling. A cost exponent L of 0.54 is used to estimate the LCI flows of the ABS at different sizes, by considering the similarity between cost and LCA scaling. The cost exponent equal to 0.54 is obtained from the literature [55] and relates the investment cost of the equipment to its cooling power expressed in [kW_c].

- *Pellet boiler*

The PB unit considered as reference is a 12 kW_{th} unit which consists of steel body with a fully insulated cladding [56]. The system includes a pellet feeding system, a speed controlled vacuum fan for air supply regulation and a stainless steel burner. The LCI data for the considered system are reported in Table A.6.

The functional parameter of the PB is represented by the nominal thermal power $P_{PB,th}$. The default cost exponent ($L = 0.6$) is used to scale the LCI in the range from 1 kW_{th} to 250 kW_{th}, as suggested in [38].

Table 2
Scaling exponents of the different components of the CHP unit (size parameter $S = P_{el}$).

	Scaling exponent L	Reference
Engine	0.64	[36]
Generator	0.68	[36]
Control cabinet	0 (Size-independent)	–
Electric parts	0 (Size-independent)	–
Other parts	0.66	[47]

Table 3
Scaling exponents of the different components of the GSHP and ASHP unit (size parameter S = $P_{GSHP/ASHP,th}$).

	Scaling exponent	Reference
GSHP	0.60	[41]
ASHP	0.67	[41]
Refrigerant/GSHP	0.62	[41]
Refrigerant/ASHP	0.91	[41]
Borehole heat exchanger	0 (Size-independent)	–
Electrical cables	0 (Size-independent)	–

- *Hot water storage*

The reference system is a storage unit with 2000 l of volume of water [51]. As illustrated in Table A.7, the main input materials composing the system are low-alloyed steel and chromium steel. The functional parameter for the storage is the volume expressed in [l].

The scaling interval of the thermal water storage was fixed by calculating the volume of the storage required to store up to 250 kWh of thermal energy as reported in Eq. (7):

$$V_{storage} = \frac{E_{storage}\cdot 3600\cdot 1000}{\rho_{water}\cdot c_{water}\cdot \Delta T} \quad (7)$$

where $V_{storage}$ is the volume of the storage expressed in [l], $E_{storage}$ is the maximum storable energy expressed in [kWh], ρ is the density of water in [kg/m^3], c_{water} is water specific heat in [kJ/(kg·K)] and ΔT is the temperature difference assumed equal to 35 K [57]. Thermal water storage is widely used for residential building applications where it can be coupled with both solar and CHP systems.

For estimating the LCI of storage systems with different volumes a cost exponent of 0.81 is used in this study, according to the cost scaling relationship presented in [55].

3.3. Impact assessment indicator

The presented cradle-to-gate analysis focuses on the widely used impact parameter CED of selected energy systems for residential applications. The CED of a system stands for the direct and indirect energy consumption in units of energy (MJ_{eq}) throughout the life cycle. The total CED consists of the sum of the fossil, nuclear, biomass, water, wind and solar energy demand in the life cycle of the analyzed product [7] as reported in Eq. (8):

$$CED_T = CED_f + CED_n + CED_{bio} + CED_{wa} + CED_w + CED_{so} \quad (8)$$

The fossil CED (CED_f) can be considered as an impact indicator as it represents the depletion of energy resources related to the life cycle of a certain product. It is mainly related to the amount of consumed and burned fossil fuels which in turn has a high impact on the environment.

4. Validation

Although several LCA studies dealing with energy systems suitable to residential applications were carried out, a homogeneous comparison of all the technologies presented in this paper is difficult because of the different functional units, regional variations, inclusion/exclusion of different life cycle stages and different life cycle impact assessment methodologies. Therefore, a comparison to other studies is made in this Section only for the technologies and sizes available in the literature. The comparison of the results obtained by means of the methodology developed in this paper to published data shows a good agreement, thus validating the LCA scaling procedure developed in this paper.

4.1. Validation of the scaling procedure for PBs of different sizes

Since linear scaling, i.e., $L = 1$ according to Eq. (6), is commonly applied in LCA studies, the influence of using a linear approach instead of nonlinear scaling and the relevance of scaling by using power-law relationships is illustrated in this Section. The considered technology is a pellet boiler, since data from different sources and at different sizes were available only for this system. The size parameter S used for scaling the LCI for different sizes is the installed thermal power of the boiler.

In order to validate the proposed methodology, LCI data for the PB should be available, at least, for two different sizes. Thus, detailed LCI data are taken from different sources and for different sizes. In particular, LCI data for manufacturing a 12 kW_{th} PB are taken from Chiesa et al. [56], a second LCI dataset available for a 46 kW_{th} PB is reported by Cellura et al. [58] and finally the LCI of a 25 kW_{th} and a 300 kW_{th} boilers are found in [59].

Fig. 3 compares the total CED per kW_{th} calculated by using literature LCI data available at different sizes of the pellet boiler to the values obtained by using linear scaling (specific CED independent of the size) and the approach proposed in this paper, i.e., LCI scaling with power law relationship.

As previously discussed, since no information about PB scaling is available, the nonlinear scaling with power law relationship is performed by using a costs exponent of 0.6, taken from the literature [38]. Moreover, linear scaling and scaling with power law relationship were both performed by using the 12 kW_{th} pellet boiler as the reference.

Fig. 3 demonstrates that scaling with power law relationship clearly

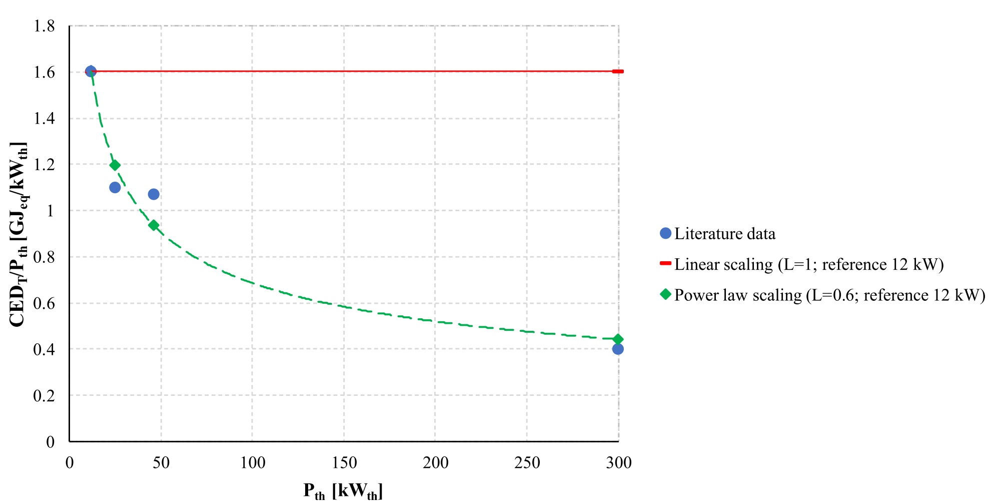

Fig. 3. Specific CED trend for a pellet boiler, using linear scaling and power law scaling and comparison to the CED calculated using LCI literature data.

provides more accurate results compared to the conventional LCI scaling which assume a constant CED per kW_{th}. In fact, considering the 300 kW_{th} system, the total CED calculated by scaling the LCI with power law relationship and with linear scaling is equal to 132.7 and 480.8 GJ_{eq}, respectively, while the total CED calculated by using available LCI data is equal to 119.5 GJ_{eq}. The results show that linear scaling heavily over-estimate (in this case) the calculated impact (with a maximum error equal to 302%), while the proposed approach allows more accurate results with a maximum error of 12%.

4.2. Validation of the scaling exponents to be used for CHP system scaling

Whiting et al. [14] used a similar scaling approach based on power law relationships to scale up the environmental impacts associated with the manufacturing of a CHP system and an aerobic digestion plant. For both systems, environmental impacts were scaled by using an exponent value of 0.6. Likewise, investment costs of a CHP plant were scaled by Lantz [60] following the economy of scale approach and using a costs exponent of 0.66. These two works show the validity of the power law for the LCA scaling and its analogy with the costs scaling. The analogy between LCI scaling and costs scaling was also demonstrated by Gerber et al. [39]. They recommend the use of power law relationship for LCI scaling instead of linear scaling. Moreover, they showed that, when no information about the scaling behavior is available (i.e., relationship between mass and equipment size), the use of costs exponents always allows better results than linear scaling. The same is also confirmed by Caduff et al. [41] that recommend the use of scaling factors in the range from 0.5 to 0.8 for the scaling of energy technologies.

4.3. Validation of the scaling procedure for STC, PV, ASHP and hot water storage

Table 4 shows the CED estimated in this study and CED values reported in the literature for the STC, PV panel, ASHP and hot water storage. As can be seen, the CED of the STC calculated in this study is slightly higher than the one calculated by Ardente et al. [25]. The small difference (about 11.5%) may be due to the different transport distances and energy mix assumed by the authors which used the Italian energy mix to model the production of electricity.

The results for the PV system agree well to the studies carried out by Kabakian et al. [31] and Tiwari et al. [61]. In their studies, the specific CED associated with the manufacturing of a PV system is 4.78 GJ_{eq}/m^2 and 4.96 GJ_{eq}/m^2, respectively. Thus, these results are fully consistent with the CED found in this study.

The CED for the production of a 10 kW ASHP is in agreement with the data published in [62]. Once again, this small difference may be due to the different assumptions made in both studies.

The CED of the hot water storage calculated in this work is compared to two other studies. The first study was carried out by Beccali et al. [63] and considers a 2000 l hot water storage, while the second study was carried out by Gürzenich et al. [64] and considers a 100 l storage. Comparisons show that the CED calculated in this work is fully comparable to the data published by Beccali et al. [63], since both studies assume the European mix. On the other hand, as expected, a slight variation is found compared to the work of Gürzenich et al. [64], since this study reflects the Indian situation. However, both comparisons show that results are fully consistent, by considering that LCA results are subject to different factors [3].

5. Results and discussion

5.1. CED impact curves vs. technology size

Fig. 4 show the total CED and fossil CED calculated for the STC, PV, CHP, GSHP, ASHP, ABS, PB and hot water storage technologies. The full symbols represent the results of the systems considered as a reference, while the empty symbols represent the results of the scaled systems.

As highlighted from Fig. 4, the impact indicators calculated for the STC and PV systems are characterized by a linear trend, which is due to the linear scaling approach adopted for both systems. It should be noted that, though the absolute values of the total CED and fossil CED diverge by increasing STC/PV area, the fraction of fossil energy demand of the total CED, for the manufacturing of the STC/PV system, remains constant independent of system functional parameter.

With regard to the specific impact expressed in [Units of impact/Units of functional parameter], it can be noted that the scaling effect is noticeable for the energy technologies of which a non-linear scaling approach is assumed, i.e., CHP, GSHP, ASHP, ABS, PB and hot water storage. For instance, by comparing the 1 kW_{el} and 250 kW_{el} CHP units, it is found that the specific total CED decreases from 292.8 GJ_{eq}/kW_{el} for a 1 kW_{el} CHP unit to 3.2 GJ_{eq}/kW_{el} for a 250 kW_{el} CHP, the fossil CED decreases from 191.1 GJ_{eq}/kW_{el} to 2.4 GJ_{eq}/kW_{el}. From these results, it can be stated that the higher the size of the CHP, the lower is the impact referred to the produced energy; this proves that linear scaling may under- or over- estimate LCA results (see Section 3). The same applies to the other energy technologies, with the exception of STC and PV systems. Moreover, unlike the non-linear scaling approach used for the abovementioned energy technologies, the linear scaling approach leads to a constant specific impact independent of system size. The impact reported in Fig. 4 represent one of the main achievements of this paper.

5.2. Comparison of different energy system configurations

To highlight the effect of the scaling procedure developed in this study and identify the best option in order to meet a given energy demand, a comparison is made between the different technologies by varying their capacity. In particular, Fig. 5 reports a comparison between the CHP and the PV panels as a function of the installed electric power. It can be seen that the increase of the total CED is noticeable for the PV panels as a function of the installed capacity, while the increase of the total CED of the CHP system is much lower compared to the PV system.

Fig. 6 illustrates a comparison between the STC, GSHP and ASHP units as a function of the installed thermal power. As can be seen, the STC is the system which has the highest impact with the exception of the cases of 1 and 5 kW_{th} power capacity. It can also be noticed that, for sizes lower than 100 kW_{th}, the impact related to the production of the ASHP is lower than the impact of the GSHP, while this impact tends to be higher for sizes greater than 100 kW_{th}. This can be explained by the fact that the borehole heat exchanger impact of the GSHP weighs more for small sizes even if the ASHP requires more materials and energy.

Table 4
CED values reported in the literature and CED values estimated in this paper.

Technology	Functional unit	This paper	Literature
STC	1 m^2	1.53 GJ_{eq}	1.73 GJ_{eq} [25]
PV panel	1 m^2	4.69 GJ_{eq}	4.78 GJ_{eq} [31]; 4.96 GJ_{eq} [61]
ASHP	1 unit (size: 10 kW_{th})	12.0 GJ_{eq}	12.5 GJ_{eq} [62]
Hot water storage	1 unit (size: 2000 l)	14.2 GJ_{eq}	14.8 GJ_{eq} [63]
Hot water storage	1 unit (size: 100 l)	1.27 GJ_{eq}	1.54 GJ_{eq} [64]

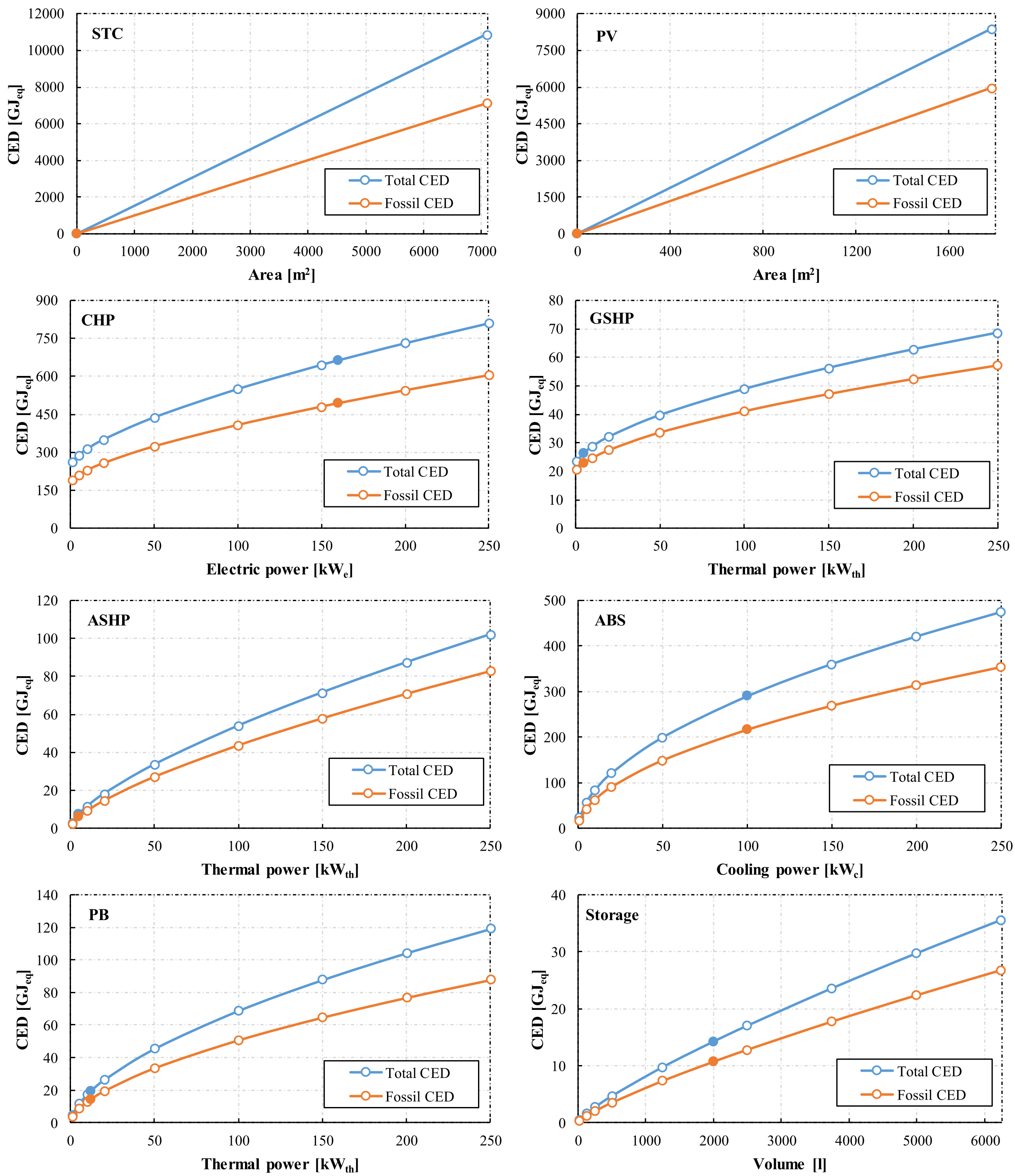

Fig. 4. Total CED and Fossil CED trend vs. technology size.

However, by considering that the borehole was assumed GSHP size-independent, the impact of the ASHP tends to be more predominant.

Whereas above each technology is compared solely, in the following hybrid systems, i.e., system combining electricity and heat generation, will be in the center of interest, comparing them with a CHP. The hybrid systems under investigation are PV for electricity generation with STC, GSHP and ASHP, respectively, for the heat supply.

In order to calculate the thermal power produced from the CHP system as a function of the nominal electric power, a market survey [65] was conducted on CHP based internal combustion engines, by analyzing the engines currently available in the range 1 kW_{el} − 294 kW_{el}. The result of this analysis is expressed by the following relationship:

$$P_{CHP,th} = 2.98 \cdot (P_{CHP,el})^{0.87} \quad (9)$$

The results of the comparison between CHP and hybrid systems are reported in Fig. 7. In order to have a consistent comparison between the combined and separate scenario, it was supposed that the electric power of the CHP can be produced from a PV system with an appropriate area, while the thermal power of the CHP can be produced from the STC, GSHP or ASHP. Fig. 7 demonstrates that, for an installed electric power higher than 10 kW, the CHP based system requires less primary energy than the aggregate systems PV + GSHP and PV + ASHP, while this option tends to require more energy for lower

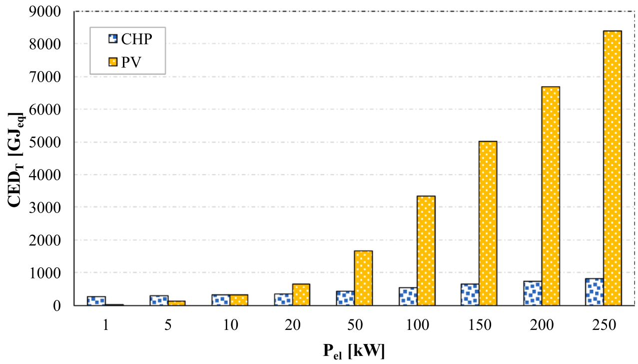

Fig. 5. Comparison of the total CED of the CHP and PV systems.

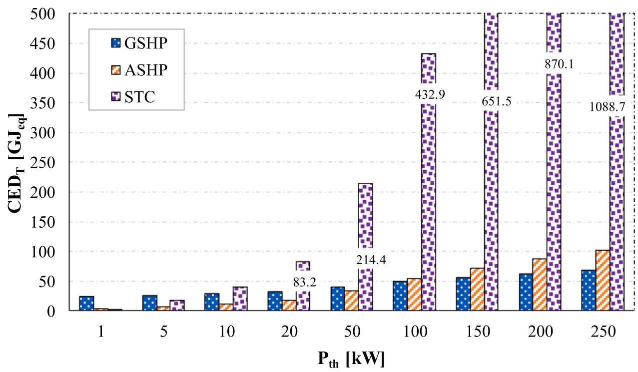

Fig. 6. Comparison of the total CED of the GSHP, ASHP and STC.

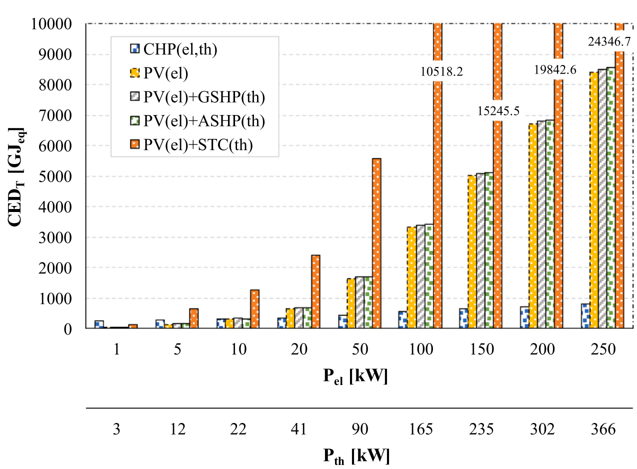

Fig. 7. Total CED of the CHP and the different aggregate systems as a function of the thermal and electrical installed capacity.

capacities. It can also be noticed that for small electric power (approximately 1 kW), compared to the CHP option, the other options are more convenient. At 5 kW a mixed result can be observed. While PV with heat pumps demands less CED than a CHP, PV + STC systems realize higher CED values.

Moreover, the increase of the CED of the CHP system with its size is much smaller than the increase of the CED of the aggregate systems. However, it should be mentioned that this analysis only takes into account the manufacturing phase, while the operation phase is not included; this could influence the ranking of the different technologies.

Whereas the CED for PV + heat pump systems are dominated by the CED of PV systems – the share of CED of PV is higher than 90%, a different picture can be observed for PV + STC systems.

5.3. Dominance analysis

In order to identify the processes and activities of the life cycle which are responsible for the greatest (dominant) environmental impact, a dominance analysis of the fossil CED with regard to the life cycle processes is performed (see Fig. 8). In fact, environmental impacts are closely-related to the use of fossil energy. This type of analysis allows to identify where improvements are most needed. The dominance analysis is performed for all energy technologies by considering the same reference functional parameter used for scaling.

The analysis reveals that transports are of minor importance for all the assessed technologies. Fig. 8a shows that aluminum and chromium are the most dominant production processes causing the greatest energy consumption for the manufacturing of the STC. From Fig. 8b, it can be seen that the largest energy consumption for the manufacturing of PV panels is due to wafers production. The production of silicon products, such as silicon wafers for photovoltaics and electronic grade silicon, requires large amounts of electricity, so the electricity use is the most important factors. Thus, the production of silicon products usually takes place in countries with low prices and a secure supply. As highlighted in Fig. 8c, the major contributor process to the fossil CED of the CHP system is the control cabinet, which is mainly due to the use of fossil energy sources, such as hard coal (7.4%) and natural gas (9.7%). Since the control cabinet is considered a size-independent component, the contribution of the latter to the total fossil CED is expected to decrease by considering a larger size compared to the reference (160 kW_{el}). Indeed, by considering the CHP unit with 250 kW_{el}, the share of the control cabinet decreases to 20.6%, which is still important. However, this demonstrates how scaling and distinction between size-dependent and size-independent components may affect the final results and consequently the action of decision makers. Regarding the GSHP (Fig. 8d), the 75.5% of the overall fossil CED is caused by the borehole heat exchanger process, which in turn is coming out from the production of polyethylene and ethylene glycol with about 51.3% and 19.6% of the total fossil CED, respectively. Thus, opportunities to reduce the demanded energy throughout the life cycle of GSHP systems lie in enhancing the energy efficiency of industrial sectors such as polymerization where high temperatures are required for the cracking of naphtha, which is the most important raw material for polymer production. From Fig. 8e through h, it is possible to observe that the major contributors to the fossil CED are metals and this reflects the functional unit composition of the ASHP, ABS, PB and hot water storage which are mainly made of steel. The relatively high consumption of fossil fuels is mainly due to processes which require high temperatures, such as blast furnace process for the production of hot metal and blast oxygen furnace converter process which is used for steel making.

6. Conclusions

At present, technologies such as solar thermal collector (STC), photovoltaic panel (PV), combined heat and power system (CHP), ground source heat pump (GSHP) air source heat pump (ASHP), absorption chiller (ABS), pellet boiler (PB) and hot water storage are widely used in residential applications. However, comprehensive life cycle assessment (LCA) studies are not widespread and a general methodology for LCA scaling of these energy systems is not established.

Therefore, this study applied an LCA methodology to evaluate the cumulative energy demand (CED) of the considered systems by taking into account scaling effects by means of a power law. The relevance of the proposed scaling approach is illustrated by the case of a pellet boiler and results show that power law scaling is by far more accurate than linear scaling, thus validating the assumption of power law scaling and its analogy with costs scaling. Further validation of the scaling procedure proposed in this paper was also conducted on other technologies and sizes available in the literature.

The analyses carried out in this work allow the following

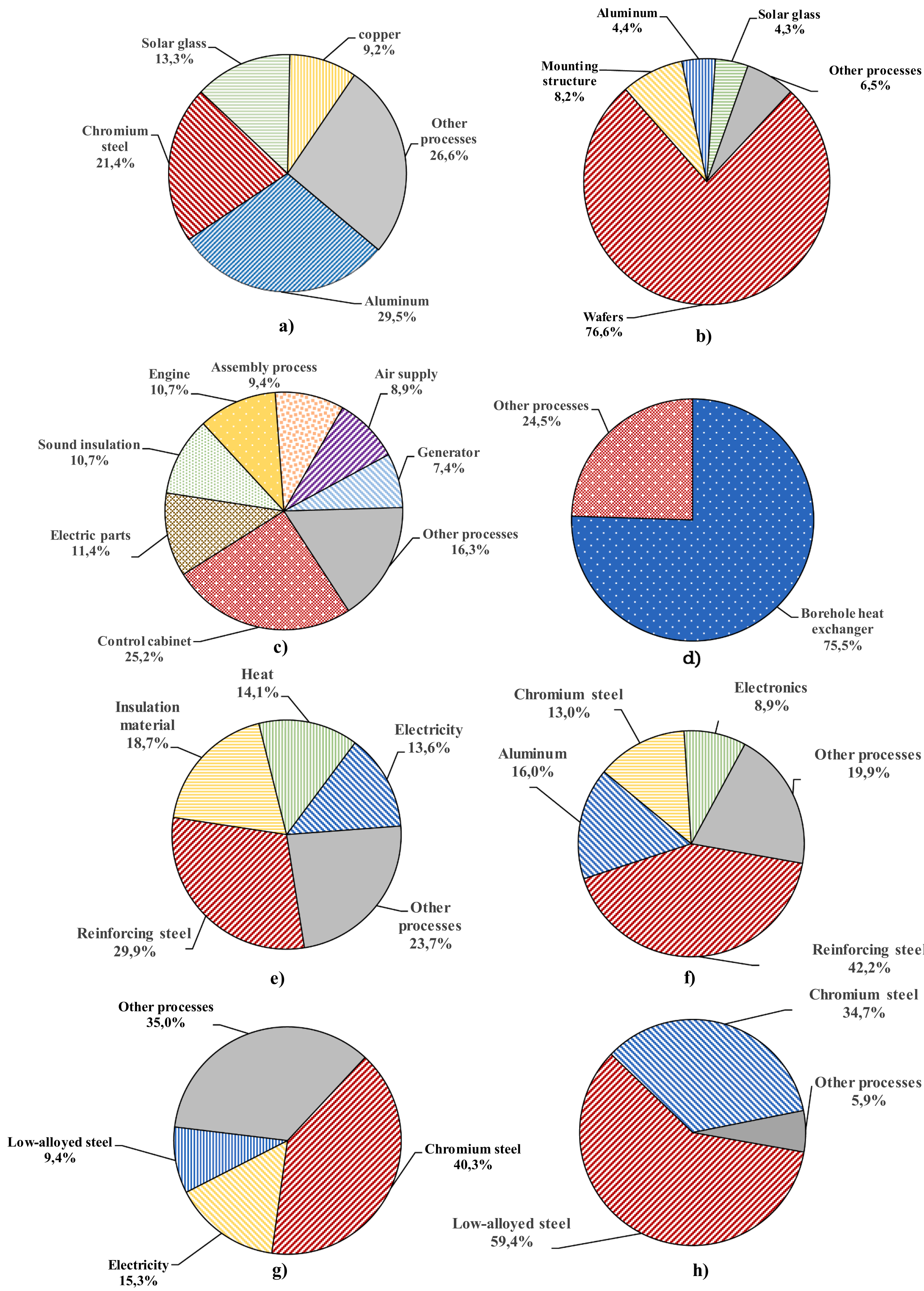

Fig. 8. Dominance analysis of the fossil CED of the STC (a), PV (b), CHP (c), GSHP (d), ASHP (e), ABS (f), PB (g) and hot water storage (h).

conclusions:

- The specific impact decreases when the size increases, i.e., the higher the size, the lower is the impact per unit of installed nominal power. This clearly demonstrates that linearization could dramatically over- or under- estimate the environmental impacts;
- The fact that components can be size-dependent or size-independent leads to a change of the contribution of the components to the total impact; this has relevant consequences on the reliability of LCA studies;
- By comparing the CHP system and PV with the same installed electric power, the total CED related to the production of the CHP is

higher than the CED of the PV up to electric power of 10 kW, while the impact of the PV tends to be noticeably higher than the CHP for higher installed power;
- From the comparison between the CHP and the aggregate system composed of STC + PV, GSHP + PV and ASHP + PV, the option of producing electric and thermal energy by using a CHP unit is more convenient than the other options for sizes greater than 10 kW electric;
- For a given installed thermal power of the STC, GSHP and ASHP, the highest impact is related to the STC (with the exception of the cases of 1 and 5 kW_{th} power capacity). By comparing the GSHP and ASHP units, the results showed that GSHP systems are more environmentally friendly than ASHP systems for sizes larger than 100 kW_{th}.

The main achievements of this paper are represented by:

- a scaling procedure, which can be adapted to other technologies and environmental impacts;
- impact curves of different technologies covering the range of power output suitable to residential users.

The scaling procedure and impact curves, which are novel in the literature, can be used for optimization purposes, to overcome the problem of lacking data and compare technologies of different capacities from a comprehensive point of view.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Appendix A. Life cycle inventory data of the studied technologies

See Tables A1–A7.

Table A1
LCI data for the manufacturing of 1 m^2 of STC [51].

	Amount	Unit
Materials and energy requirements		
Aluminum	3.93	[kg]
Copper	2.82	[kg]
Chromium steel 18/8, hot rolled	4.14	[kg]
Solar glass, low-iron	9.12	[kg]
Brazing solder, cadmium free	0.00368	[kg]
Propylene glycol, liquid	1.01	[kg]
Silicone product	0.0588	[kg]
Soft solder, Sn97Cu3	0.0588	[kg]
Stone wool, packed	2.43	[kg]
Synthetic rubber	0.732	[kg]
Corrugated board box	3.68	[kg]
Electricity, medium voltage	1.16	[kWh]
Water, completely softened	1.38	[kg]
Tap water	9.4	[kg]
Materials processes		
Sheet rolling, copper	2.82	[kg]
Selective coating of copper sheet, black chrome	1	[m2]
Anti-reflex-coating, solar glass	1	[m2]

Table A2
LCI data for the manufacturing of 1 m^2 of PV panel [52].

	Amount	Unit
Single-Si solar panel		
Materials and energy requirements		
Aluminum alloy, AlMg3	2.63	[kg]
Copper	0.113	[kg]
Solar glass, low iron	10.1	[kg]
Photovoltaic cell, single-Si wafer	0.932	[m2]
Glass fiber reinforced plastic, injection molded	0.188	[kg]
1-propanol	0.00814	[kg]
Acetone, liquid	0.013	[kg]
Brazing solder, cadmium free	0.00876	[kg]
Corrugated board box	1.1	[kg]
Ethyl vinyl acetate, foil	1	[kg]
Lubricating oil	0.00161	[kg]

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Table A2 (*continued*)

	Amount	Unit
Methanol	0.00216	[Kg]
Nickel, 99.5%	0.00016	[kg]
Polyvinyl fluoride, film	0.11	[kg]
Silicone product	0.122	[kg]
Vinyl acetate	0.00164	[kg]
Polyethylene terephthalate, granulate, amorphous	0.373	[kg]
Electricity, medium voltage	4.71	[kWh]
Heat	5.41	[MJ]
Tap water	21.3	[kg]
Materials processes		
Wire drawing, copper	0.113	[kg]
Tempering, flat glass	10.1	[kg]
Mounting structure		
Materials and energy requirements		
Steel, low-alloyed	1.8	[kg]
Aluminum	2.64	[kg]
Corrugated board box	0.04	[kg]
Polyethylene, high density, granulate	0.00073	[kg]
Polystyrene, high impact	0.00360	[kg]
Materials processes		
Sheet rolling, steel	0.11	[kg]
Hot rolling, steel	1.8	[kg]
Section bar rolling, steel	1.69	[kg]
Section bar extrusion, aluminum	2.64	[kg]

Table A3
LCI data for the manufacturing of 160 kW_{el} CHP unit [47].

	Amount	Unit
Internal combustion engine		
Materials and energy requirements		
Cast iron	1250	[kg]
Reinforcing steel	125	[kg]
Chromium steel 18/8	125	[kg]
Steel, low-alloyed	250	[kg]
Electricity, medium voltage	201.25	[kWh]
Heat	19,700	[MJ]
Water	2.625	[m3]
Materials processes		
Hot rolling, low-alloyed steel	250	[kg]
Hot rolling, chromium steel	125	[kg]
Generator		
Materials and energy requirements		
Cast iron	743.75	[kg]
Copper	318.75	[kg]
Electricity, medium voltage	231.25	[kWh]
Heat	22,700	[MJ]
Water	1.6	[m3]
Assembly motor/generator		
Materials and energy requirements		
Reinforcing steel	560	[kg]
Electricity, medium voltage	64.2	[kWh]
Heat	6300	[MJ]
Water	0.84	[m3]
Heat exchanger		
Materials and energy requirements		
Reinforcing steel	737.5	[kg]
Steel, low-alloyed	737.5	[kg]
Water	2.2125	[m3]

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Table A3 (*continued*)

	Amount	Unit
Materials processes		
Hot rolling, low-alloyed steel	737.5	[kg]
Sound insulation		
Materials and energy requirements		
Reinforcing steel	1920	[kg]
Stone wool	480	[kg]
Water	2.88	[m3]
Control cabinet		
Materials and energy requirements		
Aluminum	0.15	[kg]
Copper	10.8	[kg]
Lead	0.76	[kg]
Nickel	0.34	[kg]
Platinum	0.00210	[kg]
Polyethylene, low density, granulate	78.5	[kg]
Polyvinylchloride, emulsion polymerized	0.95754	[kg]
Polyvinylchloride, suspension polymerized	6.54255	[kg]
Reinforcing steel	276	[kg]
Tin	1.62	[kg]
Zinc	0.25	[kg]
Electricity, medium voltage	1690	[kWh]
Heat	16.54	[MJ]
Water	0.434	[m3]
Air input/output supply		
Materials and energy requirements		
Reinforcing steel	288	[kg]
Electricity, low voltage	2830	[kWh]
Electricity, medium voltage	33.3	[kWh]
Heat	33,345	[MJ]
Water	0.432	[m3]
Electric parts		
Materials and energy requirements		
Aluminum	0.1	[kg]
Copper	6.5	[kg]
Lead	0.47	[kg]
Nickel	0.21	[kg]
Platinum	0.0013	[kg]
Polyethylene, low density, granulate	47.4	[kg]
Polyvinylchloride, suspension polymerized	0.5	[kg]
Reinforcing steel	52.7	[kg]
Tin	0.997	[kg]
Zinc	0.154	[kg]
Electricity, medium voltage	5670	[kWh]
Heat	29,355	[MJ]
Water	0.0914	[m3]
Catalytic three way converter		
Materials and energy requirements		
Corrugated board	2.75	[kg]
Palladium	0.041	[kg]
Platinum	0.2045	[kg]
Rhodium	0.041	[kg]
Chromium steel	330	[kg]
Zeolite powder	19	[kg]
Electricity, medium voltage	955	[kWh]
Water	0.495	[m3]
Materials processes		
Hot rolling, chromium steel	330	[kg]
Assembly of CHP components		
Materials and energy requirements		
Electricity, low voltage	4940	[kWh]
Heat	27,000	[MJ]

Table A4
LCI data for the manufacturing of 10 kW_{th} GSHP pump and borehole heat exchanger [53].

	Amount	Unit
GSHP		
Materials and energy requirements		
Copper	22	[kg]
Reinforcing steel	75	[kg]
Steel low-alloyed, hot rolled	20	[kg]
Refrigerant R134a	3.09	[kg]
polyvinylchloride, bulk polymerized	1	[kg]
Lubricating oil	1.7	[kg]
Tube insulation, elastomere	10	[kg]
Electricity, medium voltage	140	[kWh]
Heat	1400	[MJ]
Water	0.708	[m3]
Borehole heat exchanger		
Materials and energy requirements		
Reinforcing steel	33	[kg]
Polyethylene low density granulate	180	[kg]
Ethylene glycol	102	[kg]
Cement	33	[kg]
Activated bentonite	8	[kg]
Water	10.2	[m3]

Table A5
LCI data for the manufacturing of 100 kW_c ABS unit [54].

	Amount	Unit
Materials and energy requirements		
Aluminum	420	[kg]
Copper	480	[kg]
Chromium steel 18/8, hot rolled	480	[kg]
Reinforcing steel	3220	[kg]
Polyethylene, high density, granulate	40	[kg]
Ammonia liquid	72	[kg]
Electronics, for control units	60	[kg]
Ethylene glycol	150	[kg]
Stone wool	70	[kg]
Tube insulation, elastomer	90	[kg]
Electricity, medium voltage	133	[kWh]
Heat	950	[MJ]
Water	5.98	[m3]
Materials processes		
Sheet rolling, aluminum	420	[kg]
Wire drawing, copper	480	[kg]
Sheet rolling, chromium steel	480	[kg]
Sheet rolling, reinforcing steel	3220	[kg]
Zinc coating, coils	68	[m2]
Injection molding, polyethylene	40	[kg]

Table A6
LCI data for the manufacturing of 12 kW_{th} PB unit [56].

	Amount	Unit
Materials and energy requirements		
Brass	0.659	[kg]
Copper	0.010	[kg]
Iron burner	29.51	[kg]
Steel pipes	1.974	[kg]
Galvanized steel	22.639	[kg]
Lead	0.280	[kg]
Chromium steel 18/8	117.761	[kg]
Low-alloyed steel	55.417	[kg]
Unalloyed steel	41.096	[kg]
Expanded vermiculite	2.560	[kg]
Glass fiber	0.517	[kg]
Rock wool	0.810	[kg]
Nylon 6–6	0.880	[kg]

(continued on next page)

Table A6 (*continued*)

	Amount	Unit
Polyethylene low density granulate	0.030	[kg]
Silicone product	0.605	[kg]
Synthetic rubber	0.291	[kg]
Expanded vermiculite	2.560	[kg]
Glass fiber	0.517	[kg]
Rock wool	0.810	[kg]
Electronics for control units	1.880	[kg]
Packaging film low density LDPE	1.044	[kg]
Heat	647.136	[MJ]
Electricity, medium voltage	1375.164	[MJ]

Table A7
LCI data for the manufacturing of 2000 l hot water storage [51].

	Amount	Unit
Materials and energy requirements		
Steel low-alloyed, hot rolled	305	[kg]
Welding gas steel	10	[m]
Chromium steel 18/8, hot rolled	35	[kg]
Alkyd paint, white, in 60% solution state	1.7	[kg]
Glass wool mat	25	[kg]
Sawnwood, softwood, dried (u = 20%)	0.06670	[m3]
Electricity, medium voltage	45	[kWh]
Electricity, low voltage	45	[kWh]
Heat	344	[MJ]

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.applthermaleng.2020.115062.

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