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Developing a new data-driven LCA tool at the urban scale: The case of the energy performance of the building sector

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ABSTRACT

Given the ambitious greenhouse gas emissions reduction targets set by the European Union and the importance of cities in achieving these goals, there is an increasing need to analyze their environmental footprint with a life cycle approach. The life cycle assessment is considered the leading methodology for environmental metrics, permitting a holistic environmental perspective of cities. Developing a complete life cycle assessment can be difficult and time-consuming, particularly discouraging to non-experts. Life cycle assessment software applications are aimed at single product evaluation, making urban scale data management and environmental assessment complicated or impractical. The novelty of this work is a new tool, utilizing a data-driven approach, that allows an extensive environmental evaluation of buildings (of the operational phase). The tool expands the application of the life cycle assessment method at the urban scale where the existing software applications are not specifically designed to be implemented and fail mainly due to the massive data processing. The tool was applied to analyze the city of Milan. Approximately 81,000 building units and 161,935 energy systems were investigated and compared using ecoinvent 3.7 as a secondary database and the Environmental Footprint 3.0 method. The results show that the space heating service is the main contributor to the climate change impact category, followed by domestic hot water and space cooling (41.70, 6.50, and 5.92 $kgCO_2eq$ / m^2 year, respectively). Of practical relevance, no scientific research has ever been carried out on a plurality of buildings and energy systems at an urban scale. Thus, the article's novelty can also be traced to the innovative outcomes obtained by testing the tool on the city of Milan. Additionally, the tool can be used to establish reliable environmental benchmarks to implement policies for buildings and assess the environmental footprint of energy requalification initiatives.

1. Introduction

According to demographic predictions, 70% of the world's population will be living in the cities by 2050 [1]. The importance of their environmental assessment will be strategic because of: i) the growing world populations and urbanization trends, alongside the expansion of the built environment to respond to the escalating need for urban housing in the future, and ii) the significant contribution of cities to the environmental burdens and their role in achieving sustainable development targets [2–4]. Cities are recognized as the principal cause of environmental impacts; as evidence, it is estimated that they account for 70–75% of Greenhouse Gas (GHG) emissions and 60–80% of energy consumption [5,6]. As a fundamental element, the building sector is responsible for 30–40% of energy consumption and CO_2eq emissions at the global level. Therefore, buildings are the key components which needs to be as environmentally efficient as possible to lower the environmental impacts of cities. Thus, improving their energy and environmental efficiency is an indispensable driver for achieving the sustainability targets [7]. The effects of supplying heating, cooling, and domestic hot water on the overall environmental profile of buildings are significant. They, therefore, need to be assessed and studied in greater depth [7], considering both thermo-physical performance of the envelope and the energy production systems. For instance, regarding the operational phase, heating systems account for a substantial share of the building environmental emissions in Europe, approximately equal to 80% of the energy used in households [8–10]. Thus, reducing energy consumption and environmental emissions is of paramount importance.

Given the ambitious GHG reduction targets by the European Union (EU) that demand a decrease in emissions of 55% by 2030 (compared with 1990) and the achievement of carbon-neutrality by 2050, the effective research-based solutions to mitigate the cities' climate

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Nomenclature

Subscripts

el	electric
nren	non-renewable
th	thermal

Abbreviations

A	Acidification
BIPV	Building Integrated Photovoltaic panels
CC	Climate Change
CED	Cumulative Energy Demand
CHP	Combined Heat and Power plant
DH	District Heating
DHW	Domestic Hot Water
EF	Eutrophication Freshwater
EFW	Ecotoxicity Freshwater
EM	Eutrophication Marine
EPBD	Energy Performance of Buildings Directive
ET	Eutrophication Terrestrial
EU	European Union
HHV	Higher Heating Value
HTC	Human Toxicity, Carcinogenic
HTNC	Human Toxicity, Non-Carcinogenic
IR	Ionizing Radiation
JRC	Joint Research Center
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LHV	Lower Heating Value
LPG	Liquified Petroleum Gas
LU	Land Use
OD	Ozone Depletion
PM	Particulate Matter formation
POF	Photochemical Ozone Formation
PV	Photovoltaic
ER-nren	Energy Resources: non-renewable
MRM	Material Resources: Metals/minerals
SC	Space Cooling
SCOP	Seasonal Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
SGUE	Seasonal Gas Utilization Efficiency
SH	Space Heating
WGS84	World Geodetic System 1984
WU	Water Use

footprint become of inevitable urgency. The EU should implement the path towards these targets, avoiding significant harm to other environmental objectives (i.e., climate change adaptation, sustainable use and protection of water resources, transition to a circular economy, pollution prevention and control, preservation and restoration of biodiversity and ecosystems) [11]. Buildings and cities should be evaluated more thoroughly and with a comprehensive life cycle approach [12]. As a quantitative method to assess environmental impacts, the Life Cycle Assessment (LCA) of buildings is now widely accepted and applied in research projects and policy development programs [13,14]. LCA is considered the most reliable analytical method to evaluate complex systems' environmental impact [15].

Several studies have been published regarding the environmental footprint assessment of buildings during the operational phase, focusing the analysis on energy systems to evaluate the environmental impacts of the combination of renewable and non-renewable energy sources. For instance, Luo et al. [16] compared the pros and cons of renewable multi-energy systems with other conventional systems with an LCA approach in 5 cities. They showed the extent to which renewable multi-energy systems' primary energy consumption and CO_2eq emissions could be lower than those of the conventional separate systems. Beccali et al. [17] discussed the LCA performance of solar thermal heating and cooling systems and traditional systems supported by the grid and photovoltaic panels in Italy and Switzerland. Famiglietti et al. [18] compared a condensing boiler with an air-source gas-absorption heat pump as a refurbishing measure of the energy system for old buildings in 3 European climatic zones (cold, average, and warm). Ristimaki et al. [1] combined LCA and the Life Cycle Cost Analysis (LCCA) method to compare different energy systems at an urban scale and provided insightful information for urban energy planning. They assessed district heating, district heating coupled with Building Integrated Photovoltaic (BIPV) panels, ground source heat pumps, and ground source heat pumps coupled with BIPV. Ristimaki et al. concluded that ground source heat pumps connected with BIPV perform the best from an LCA viewpoint. However, higher initial investments are needed for this system, but the total life cycle costs were estimated to be lower than the others due to lower operational energy costs. In the literature, energy systems are commonly assessed in relation to Climate Change (CC) [15,19]. At the same time, only a few papers have included multiple environmental impact categories, which is a research gap and a limitation in the field, as discussed in recent review studies [2].

Although LCA is a globally accepted method to evaluate the environmental profile of buildings at different levels, the complexities of the assessment, massive data collecting, data processing and, the lack of streamlined tools hinder the full LCA's intersectoral and large-scale implementation worldwide. The challenges mentioned above become problematic in implementing LCA at the urban level with higher uncertainty of input data and require considerable computational time and processing. This is highlighted by the high number of specific tools at the single building scale to support decision-makers using the LCA method [20–26] and the lack of devices that allow for a more extensive assessment. To the best of the authors' knowledge, only V.I.C.T.O.R.I.A. [27] gives environmental indications concerning the operational stage of a plurality of buildings. However, the evaluation is limited to the carbon dioxide equivalent (CO_2eq) and particulate matter impact categories; besides, the approach adopted is not "life cycle" and does not comply with ISO 14040-44 [28,29]. To summarize, it can be stated that life cycle assessment software applications (aligned with ISO 14040-44) are aimed at single product evaluation, making multi-product (i.e., district/urban scale, etc.) data management and environmental assessment complicated or impractical.

The authors in this article present a new tool developed in Python to extensively evaluate the environmental profile of buildings during the operational phase. The tool expands the application of the LCA method at the urban scale where the existing tools are not specifically designed to be implemented and fail mainly due to the massive data processing and computational time required. Moreover, no LCA scientific research has ever been carried out on a plurality of buildings and energy systems at an urban scale. Thus, the article's novelty can also be traced to the innovative outcomes obtained. Additionally, the tool can be used as an environmental decision support system: i) to establish reliable environmental benchmarks to implement policies for buildings, ii) to assess the environmental footprint of energy requalification initiatives, and iii) to develop maps of the city using Geographical Information Systems (GIS) to set planning strategies.

As mentioned, the novelty of this work is focused on reducing the computational time and processing, not yet resolved by the other LCA tools. To highlight and support the originality of the proposed model, the developed tool is applied to measure 16 environmental impact categories, using the Environmental Footprint 3.0 method [30], of approximately 81,000 building units in Milan (computational time approx. 1,263.6 s). The energy systems installed are also evaluated. The test application of the tool at a large city-scale vividly supports the novelty of the tools and methods developed in this paper by providing accurate results while avoiding extensive computational time. The test case was performed using information reported into the Energy Performance Certificates (EPCs) as input variables. The results obtained are presented and discussed, giving a holistic view of the state of the art of energy consumption and energy systems used in the city to provide heating (SH), cooling (SC), and Domestic Hot Water (DHW) services.

The research objective of this study is to analyze at urban scale a plurality of buildings and energy systems from an environmental viewpoint. It allows the possibility to evaluate the strengths and weaknesses of the energy systems commonly installed in residential and non-residential buildings (i.e., most affecting impact categories beyond climate change, systems often not correctly sized, etc.). But the tool can also be used, potentially, to plan the decarbonization strategies for achieving Europe's 2050 targets, at least for Italian cities. With this in mind, the environmental profile is surveyed with 16 impact categories, permitting the assessment of the potential shifting burden to impact categories other than climate change during the decarbonization pathway: e.g., shifting problems from climate change to acidification potential, depletion of non-renewable mineral resources, etc. In the following sections, the main features of the tool are described.

2. Material and methods

In this section, the authors explain the general structure of the tool, providing detailed information concerning the engine developed. The system boundaries, multifunctionalities, cut-off rules, Functional Unit (FU), and Life Cycle Impacts Assessment (LCIA) are defined, considering the attributional approach and the process-based method [31].

The outcomes obtained were verified with SimaPro software [32], standard commercial Life Cycle Assessment software. Fixed input parameters were used to implement the test, SimaPro results were compared with each of the Life Cycle Inventories (LCIs) described in section 2.1.2. As mentioned, life cycle assessment software applications are not aimed for district/urban scale evaluations.

2.1. The tool development; description of the engine

The tool developed is an engine written in Python [33] characterized by three interconnected sections, as summarized in Fig. 1.

2.1.1. First section; data preparation

In the first section, the following information is imported from external databases: i) activity data regarding the operational phase of buildings, ii) LCIs with Life Cycle Impacts Assessment (LCIA) characterized scores of all necessary secondary datasets from ecoinvent 3.7 [34], and iii) normalization and weighting factors from the Environmental Footprint (EF) 3.0 method. In particular, the activity data required for the operation of the tool are: i) the intended use and geographical location of the buildings (physical addresses and World Geodetic System 1984 - WGS84 coordinates), ii) primary energy consumption (renewable and non-renewable), and energy needs per service (SH, DHW, and SC), iii) types of energy systems and energy vectors per service and related capacities, iv) seasonal efficiencies (Gas Utilization Efficiencies, Coefficient Of Performances, Energy Efficiency Ratios) and producibility, v) useful heated and cooled surface, vi) amount of electricity from the grid consumed, and vii) amount of electricity or heat produced in site (i.e., from photovoltaic panels, solar thermal water heaters, combined heat and power plant, wind turbine, etc.) auto-consumed and exported.

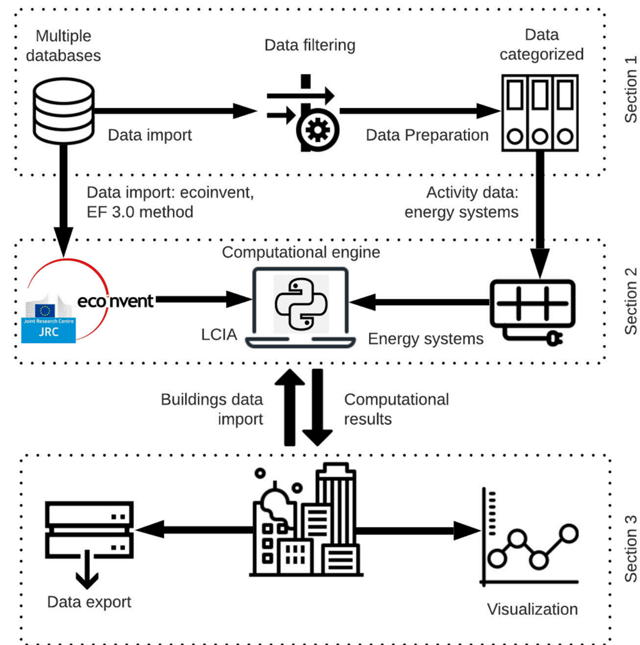

Fig. 1. Engine design.

Once the activity data have been imported and checked, they are prepared for phase two. To do this, the engine linked the activity data concerning each energy system with specific LCI datasets developed.

2.1.2. Second section; environmental profile of the energy systems

In the second section, the LCIs received the information from the first section as input parameters. The environmental profiles of each appliance used by buildings for the three services under analysis (SH, DHW, and SC) are assessed, scaling-up specific LCIs created using the input parameters as variables. The LCIs, containing the life cycle stages listed in section 2.2 of this article, were developed utilizing manufacturers' primary data and the ecoinvent database utilizing its descriptive reports. Consequently, the quantity of materials used for capital equipment and the amount of energy vectors used during the whole life of appliances are scaled up for the evaluations.

The engine covers the following energy systems:

- natural gas, traditional and condensing boilers and water heaters;
- fuel oil boilers;
- Liquified Petroleum Gas (LPG) boilers;
- biomass (pellet) boilers;
- water, air, brine source electric-driven heat pumps;
- joule effect systems;
- Combined Heat and Power plant (CHP) systems (reciprocating internal combustion engine, combined cycles – turbogas plus turbosteam, gas turbines, and Organic Rankine Cycle - ORC);
- gas absorption heat pumps;
- gas engine heat pumps;
- solar thermal array systems;
- district heating systems (as a composition of the previous systems plus the network).

The amounts of material or energy used are provided in percentages (concerning the total mass of the energy system). The total mass is assessed by the engine using the following equations (from 1 to 5), where nominal power (in kW) – mass (in kg) ratios used to scale up the appliances are shown.

- Natural gas boilers, LPG boilers, and gas water heaters masses are obtained using the equation provided by Kemna et al. [35], ranging from 25 to 100 kW - $R^2 = 0.85$:

$$Mass[kg] = 140.860*\ln(P_{nom}) - 415.000 \tag{1}$$

The appliances lower than 25 kW were conservatively evaluated considering a fixed value of 36 kg; the mass was calculated using the equation n. 1 with nominal power equal to 25 kW.

- Electric driven heat pumps/chillers (air, brine, or water source) masses are obtained using primary data of 17,666 appliances (range 3 to 40 kW - $R^2 = 0.56$) and primary data of 78 appliances (range from 41 to 1,000 kW - $R^2 = 0.95$), both from Conto Termico [24]:

$$Mass[kg] = 33.771*e^{(0.0758*P_{nom})} \tag{2}$$

$$Mass[kg] = 8.330*P_{nom} + 336.570 \tag{3}$$

- Gas absorption heat pumps/chillers masses are obtained using primary data of 3 appliances from a manufacturer (Robur) and own primary data of 5 machines ranging 7 to 40 kW - $R^2 = 0.93$:

$$Mass[kg] = 8.800*P_{nom} + 16.339 \tag{4}$$

- Gas engine heat pumps/chillers masses are obtained using 32 primary data from 3 manufacturers (Tecnocasa, Panasonic, and Yanmar), range 5 to 90 kW – $R^2 = 0.53$:

$$Mass[kg] = 250.490*P_{nom}{}^{0.330} \tag{5}$$

Fuel oil boilers, solar-powered water heaters, biomass boilers, and CHPs are scaled up using the information reported by the ecoinvent database. In particular, fuel oil boilers are evaluated using linear interpolation assessed by the three datasets provided (10 kW, 100 kW, and 1,000 kW) as a base. Solar-powered water-heaters are evaluated considering an LCI for a collector of 12.3 m^2. For biomass boilers and CHPs, the datasets provided by the ecoinvent are directly used. It delivers:

- 3 datasets for biomass boilers (from 5 to 19 kW, from 20 to 99 kW, and from 100 to 500 kW);
- 4 datasets for reciprocating internal combustion engine CHPs (from 2 to 25 kW_{el}, from 25 to 99 kW_{el}, from 300 to 699 kW_{el}, and from 700 to 1,000 kW_{el});
- 1 dataset for gas turbine (10 MW_{el}), combined cycle (400 MW_{el}), and Organic Rankine Cycle (from 100 to 499 MW_{el}).

If the input power data are out of range (higher), the engine considers two or more technologies within the given range whose relative sum gives the input power value. E.g., 450 kW natural gas boiler:

$$Mass[kg] = \left[140.860*\ln\left(\frac{P_{nom}}{i}\right) - 415.000\right]*i \tag{6}$$

Where (i) is the nominal power value (450 kW) divided for the upper bound of the range (equal to 100 kW, according to Eq. 1) rounded up (in this case, equal to 5).

Joule effect systems are assessed considering a fixed appliance with 163 L of water as storage. The storage volume is calculated as an average of the electric water heaters reported by Conto Termico.

Gas leakages for electric-driven or gas-engine heat pumps/air conditioners were evaluated in compliance with the PEP ecopassport program [36], equal to 2% of the total charge per year. R410a was considered as average gas. The assumption was made by consulting the report of the alternatives to hydrofluorocarbons (HFC) used in Italy for climate conditioning developed by the Italian Institute for Environmental Protection and Research, ISPRA [37]. The tool also allows the management of other gases, i.e., R410a, R22, R32, R290, R404a, R407c, and R515b.

Equation 7 shows the refrigerant charge per kW formula used to assess the amount of gas from the capacity of the appliance (range from 3 to 1,000 kW – $R^2 = 0.62$). The equation was assessed using 16,907 primary data from Conto Termico, as a mix of appliances that uses R134a (n. 22), R410a (n. 10 235), R22 (n. 53), R32 (n. 6517), R290 (n.8), R404a (n. 1), and R407c (n. 74).

$$Mass\ [kg] = 0.322*P_{nom}^{0.932} \tag{7}$$

For gas heat pumps/chillers, the amount of water and ammonia was considered fixed equal to 7 and 4 kg, respectively, as reported by Famiglietti et al. [18].

The equations presented need future improvements to increase the tool's precision, especially for n. 2 and n.7 characterized by low R^2 and high application. Vapor compression heat pumps will be increasingly used in the future in the decarbonization pathway within the building sector [38]. With respect to the equations present in the literature [35,39], the tool utilizing the equations listed provides accurate results, being broadly representative of the Italian context, having been determined by gathering a large sample of primary data from manufacturers active on the market. The authors provide a comprehensive description of LCIs developed in the supplementary reference section.

2.1.3. Third section; building-level assessment and presentation of results

The evaluations carried out in the second section are recomposed, associating to each building the environmental profile assessed for SH, DHW, and SC. Due to the environmental profile of the energy systems and the energy needs for each specific service reported as input parameters, the potential impacts in terms of m^2 year (of useful floor) are calculated. The engine returns a Microsoft Excel file in which the building units are integrated with the environmental results achieved (16 different environmental impact categories, evaluated with a life cycle approach).

2.2. System boundary

The energy systems are evaluated with a cradle to grave approach, considering the following life cycle phases:

- component productions (raw material supply and production);
- assembling (manufacturing with energy and water consumptions, welding, waste, transport of components plus packaging);
- distribution;
- use stage (energy vector consumptions plus maintenance);
- end of life stage (transport, waste processing for reuse, recovery or/and recycling, and disposal).

The installation phase was neglected because of a lack of data [18] for all the energy systems except for the District Heating network (DH). Also, the distribution systems inside buildings (pipes, heat emitters, etc.) and water consumption during domestic hot water service were not considered. Water consumption is attributed to user behavior. For DH, the water inside the pipes was excluded for the same reason [40].

Each appliance was evaluated according to the time boundaries, as shown in Table 1. These assumptions are based on literature data (i.e., Kemna et al., and ecoinvent) and experience (i.e., for the district heating network). The time boundaries of the appliances can be modified if necessary.

Table 1
Lifespan considered for each energy system.

Energy systems	Lifespan	Source
Natural gas boilers	19 years, capacity lower than 70 kW. 21 years, capacity between 70 and 400 kW. 26 years, capacity higher than 400 kW	Kemna et al. (average condensing and non-condensing).
Fuel oil boilers	28 years and 80 years for the chimney and tank, respectively.	Kemna et al. and ecoinvent
LPG boilers	19 years, capacity lower than 70 kW. 21 years, capacity between 70 and 400 kW. 26 years, capacity higher than 400 kW.	Based on natural gas boilers
Biomass boilers	15 years, capacity lower/equal than 100 kW. 20 years, capacity higher than 100 kW.	ecoinvent
Joule effect	21 years.	Kemna et al.
CHPs	4000 operational hours for capacity lower than $25kW_{el}$. 100 000 operational hours for capacity higher/equal than $100kW_{el}$.	ecoinvent
Electric-driven heat pumps/chillers	21 years.	Kemna et al.
Gas-driven heat pumps/chillers	21 years.	
District heating network - steel pipes	50 years.	Primary data
Gas-driven water heaters	21 years.	Kemna et al.
Solar-powered water heaters	21 years for the thermal collector.	Kemna et al.

2.3. Multifunctionalities and cut-off rules

The tool allows the management of the multifunctionality following the ecoinvent cut-off database concerning (i) component production, (ii) assembly, (iii) distribution, and iv) end of life phases. Specifically for the end-of-life phase, the idea behind the allocation rule adopted, called 100:0 or cut-off or recycled content [41], is that the primary production of materials is always allocated to the primary user. If the material is recycled, the primary producer receives no environmental benefit for providing recyclable materials. As a result, recyclable materials are available without charge to the recycling processes, and the impacts associated with the recycling process are attributed entirely to the second life of the material.

In relation to the use phase, the tool permits the management of the multifunctionality of Combined Heat and Power (CHP) plants in three ways: i) system expansion (substitution), ii) allocation applying the separate production reference method [42], iii) allocation based on the exergy method. For Waste To Energy (WTE) plants supplying thermal energy to the district heating network, if the allocation is applied, 50% of the impacts are attributed to the end of life of the incinerated product [43] and the remaining 50% to energy (electricity and heat). Besides, the environmental profile of thermal energy recovered from industries was set equal to zero, in line with EN 15316-4-5 [44]. The exergy method was used for the results shown in this article.

The cut-off rules were set at 1% in terms of environmental impacts. Seals, glues, design stage, and transport of packaging materials to the manufacturing sites were not included in the model.

2.4. Functional units

The tool provides the results according to two Functional Units (FUs), intending to quantify the performances of energy systems and buildings. According to their life span, energy systems are assessed considering 1 kWh of useful energy provided (downstream of the appliance); see Table 1. Indeed, the FU used for buildings is 1 m^2 of useful conditioned surface per year [45].

2.5. Life cycle assessment impacts

The environmental profile of the buildings is expressed considering 16 impact categories, following the Environmental Footprint (EF) method 3.0 normalization and weighting set – impact assessment method of EF initiative [30]: (1) Climate Change (CC) with a time horizon of 100 years; (2) Ozone Depletion (OD) with a time horizon of 100 years; (3) Ionizing Radiation (IR); (4) Photochemical Ozone Formation (POF); (5) Particulate Matter (PM) formation; (6) Human Toxicity, Non-Carcinogenic (HTNC); (7) Human Toxicity, Carcinogenic (HTC); (8) Acidification (A); (9) Eutrophication Freshwater (EF); (10) Eutrophication Marine (EM); (11) Eutrophication Terrestrial (ET); (12) Ecotoxicity Freshwater (EF); (13) Land Use (LU); (14) Water Use (WU); (15) Energy Resources: non-renewable (ER – nren); (16) Material Resources: Metals/minerals (MRM).

3. A test case, application of the tool in the city of Milan

In this section, the engine developed is described, providing information concerning the test performed on Milan city. The city of Milan was chosen as a test case because it is the second most important city in Italy (after Rome) with its 1.393 million inhabitants [46], the economic capital of the country, and one of the most important cities in Europe. Therefore, the authors considered it a test case with potential replicability in other Italian contexts (or European in perspective) and a source of significant emissions.

3.1. Input data checking

The data from the CENED 2.0 [47] database, from now on, also referred to as "CENED" – an open-source database containing the Energy Performance Certificates (EPCs) of building units (as a part of buildings) from Lombardy region (Northern Italy) – were used as input variables. The CENED database contains the EPCs developed in compliance with the European Energy Performance of Buildings Directive (EPBD) [48], the Energy Efficiency Directive [49], and decree DGR n. 3868 / 2015.

The values were preemptively checked, cutting off approx. 108,300 out of 189,500 EPCs, ensuring consistency in the results by removing data with interpretation difficulties. The checks performed were as follows:

- EPCs out of the city boundaries, controlled through WGS84 coordinates (approx. 9,000);
- EPC duplicates were removed, keeping the most recent (for Milan we found approx. 6,000 duplicates);
- the operating hours of the appliances were verified, setting thresholds (approx. 81,300 EPCs were removed). EPCs, where appliances work less than 100 h equivalent (full capacities) per year during the winter season, were excluded. This limit on equivalent hours was defined considering the 25th percentile energy needs for space heating and heated surface (equal to 74 kWh / m^2 year and 44 m^2, respectively) provided by a boiler with a capacity equal to 34 kW (higher nominal power from Conte Termico). The same limit was also defined for space cooling. The thresholds were judged

sufficiently conservative not to exclude machines not adequately sized; specific sensitivity analyses were implemented in this regard;
- outliers were removed using the box plot method [50], approx. 12,000. For each intended use of unit buildings, the energy need outliers were deleted, defined separately concerning the energy needs for Space Heating (SH), Domestic Hot Water (DHW), and Space Cooling (SC) services. The outliers were determined as differing significantly from the InterQuartile Range (IQR) - extreme values (3.0 * IQR). CENED contains the following intended use of unit buildings, residential, office, hospital and clinic, recreational and leisure activities, commercial, sports club, schools, and industrial, artisan, or similar activities.

Table 2 shows the types and amount of energy systems found in the CENED database after filtering. CENED subdivides the energy systems into two (1 and 2) generators for SH and SC. While for DHW, it provides just one type of generator.

3.2. Input data preparation

The engine assessed the seasonal efficiencies of each appliance using the information provided by CENED concerning the amount of primary energy consumed and the energy needs for a specific service. The seasonal efficiencies were calculated by multiplying the energy needs for the specific primary energy conversion factor provided by CENED and divided for the related primary energy non-renewable. For boilers, gas-driven heat pumps, etc., the primary energy consumptions (at the denominator, see equation n. 8) were subtracted by the amount of electricity consumed by the auxiliary (considered the fixed value provided by Famiglietti et al. and ecoinvent). E.g., for natural gas boilers, the assessment of the Seasonal Gas Utilization Efficiency (SGUE) is the following:

$$SGUE_{i,j}[\%] = \frac{Energy\ \ needs_{i,j}*1.05}{EP_{nren,i,j} - Energy\ \ needs_{i,j}*1.95*0.049} \tag{8}$$

Where:

- the Energy $needs_{i,j}$ is the energy needs for the specific service (i) through the generator (j);
- 1.05 is the primary energy (nren) conversion factor for natural gas according to CENED, in [$kWh_{EP,nren}$ / kWh];
- $EP_{nren,\ i,j}$ is the primary energy (nren) consumption for the service (i) through the generator (j);
- 1.95 is the primary energy (nren) conversion factor for electricity from the national grid, according to CENED, in [$kWh_{EP,nren}$ / kWh];
- 0.049 is the amount of electricity consumed by the boiler auxiliary to provide 1 kWh_{th}.

CENED provides information regarding primary energy and energy needs in an aggregated manner. Thus, to derive the amount of energy provided for a specific service from two different energy systems (e.g., SH #1 from heat pump and SH #2 from natural gas boiler), it was divided between both by their nominal powers. 60% of the energy was allocated to generator n.1 and 40% to generator n. 2, as an average utilizing this approach. CENED reports also in aggregated form (for 773 EPCs) the amount of electricity produced and auto-consumed from photovoltaic panels (PV). The authors, in this case, break down the consumption among services considering the electricity demand, taking into account the energy needs, the seasonal efficiencies, and the electrical demand for controlled mechanical ventilation, artificial lighting, and vertical transport (services reported by CENED but out of scope of this article). In mathematical form, the percentage of electricity consumed from PV for a specific service was obtained through equation n. 9:

$$W_{PV,i,j}[\%] = W_{PV,j}*\frac{W_{i,j}}{W_{TOT,j}} \tag{9}$$

Where:

- $W_{PV,\ i,j}$ is the percentage of electricity consumption from PV compared to the total electricity demand for the service (i) of the building unit (j);
- $W_{PV,\ j}$ is the percentage of electricity supplied from PV compared to the total electricity demand of the building unit (j);
- $W_{i,\ j}$ is the electricity demand for the service (i) of the building unit (j);
- W_{TOT} is the total electricity demand of the building unit (j).

Table 3 shows the arithmetical mean of seasonal efficiencies (i.e., Seasonal Coefficient Of Performances – SCOPs, Seasonal Energy Efficiency Ratios – SEERs, Seasonal Gas Utilization Efficiencies – SGUEs) and producibilities per energy system and service. The SGUEs for gas-driven heat pumps/chillers, natural gas, fuel oil, LPG, biomass boilers, and CHPs were referred to as the Higher Heating Values (HHV). The values for solar-powered water heaters were expressed in kWh_{th} / m^2 year (producibilities).

CENED does not give information about the cold/warm sources for heat pumps/chillers, types of technology for gas-driven heat pumps/chillers, and CHPs. To deal with sources, the intake infrastructure (i.e., piping, boreholes, etc.) was not considered in the case of cold/warm sources from groundwater or geothermal (from the ground). Thus, heat pumps and chillers were evaluated in terms of LCI only, including thermal generation units. The electricity consumption related to potential pumping was considered within the SCOP and SEER. Gas-driven heat pumps/chillers were assessed utilizing data from CURIT [51], the cadastre of thermal plants for the Lombardy region, considering 74% of energy systems as absorption-driven and 26% as engine-driven (vapor compression systems). The CHPs within CENED were evaluated as reciprocating internal combustion engines, apprizing the limited size of the plants (lower than 1 MW_{th}). Combined cycles and gas turbines generally have higher capacities.

Table 2
Numbers of energy systems per service.

Energy systems	SH #1	SH #2	DHW	SC #1	SC #2
Natural gas boilers	52,954	2,395	37,260	0	0
Fuel oil boilers	1,080	40	288	0	0
LPG boilers	151	1	95	0	0
Biomass boilers	43	50	1	0	0
Joule effect	315	136	8,722	0	0
CHPs	6	4	0	0	0
Electric-driven heat pumps/ chillers	4,035	1,675	1,617	39,156	2,043
Gas-driven heat pumps/ chillers	84	56	10	184	5
District heating	1,166	35	291	0	0
Gas-driven water heaters	0	0	7,880	0	0
Solar powered water heaters	0	53	104	0	0

Table 3
Average values of seasonal efficiencies (SCOPs, SEERs, GUEs) and producibilities.

Energy systems	SH #1	SH #2	DHW	SC #1	SC #2
Natural gas boilers	77%	80%	76%	–	–
Fuel oil boilers	75%	79%	75%	–	–
LPG boilers	79%	78%	79%	–	–
Biomass boilers	71%	76%	68%	–	–
Joule effect	94%	90%	86%	–	–
CHPs	55%	–	–	–	–
Electric-driven heat pumps	3.5	3.0	3.3	2.9	2.7
Gas-driven heat pumps	1.4	1.4	1.2	1.4	1.0
Gas-driven water heaters	–	–	85%	–	–
Solar-powered water heaters	–	200	95	–	–

Table 4
District heating scenario.

Energy systems	#	Total power [MW_{th}]	DH [GWh_{th}/y]	DH [%]
Natural gas boilers	59	518	343.2	28.0%
Fuel oil boiler	1	50	6.6	0.5%
CHP – Reciprocating internal combustion engine	12	77	113.6	9.3%
CHP – Combined cycle	2	91	169.1	13.8%
CHP – Turbogas	2	16	13.6	1.1%
Waste to Energies	2	153	528.7	43.1%
Heat pumps – Groundwater source	2	30	34.6	2.8%
Industrial heat recovery	1	3.0	22.7	1.9%
Total	–	–	1,225.6	100.0%

The District Heating (DH) network was assessed by consulting reports of the Italian Association of Urban Heating [52] and primary data provided by A2A S.p.A. (the principle operator of Milan DH networks and the sole concessionaire for the distribution of district heating service on the city's public land). The construction materials used for the networks were taken consulting Fröling et al. [53], considering an average nominal diameter of 260 mm. The LCI of each appliance supplying the network (equal to 240.8 km) was evaluated as described in the previous sections. Table 4 shows the scenario used for the model; the column "DH" reports the amount of energy produced by each energy system that supplies the network. The heat losses were set equal to 12%. The energy demand for pumping the water within the network was apprized equal to 0.5% of the energy provided to the final consumer [54]. The end of life stage was modelled by considering leaving the pipes in place and filled with concrete [40].

4. Results and discussion

In this section, the results obtained for the city of Milan by transforming the LCIs explained previously in potential environmental terms are shown and discussed. Analyzing in detail the environmental profile of the energy systems reported in the CENED database, a holistic environmental perspective of the city of Milan is provided concerning the emissions related to the operational phase of building units.

Table 5 presents the characterization results, according to the ISO 14040-44, utilizing the EF 3.0 method for the three services considered for this study, Space Heating (SH), Domestic Hot Water (DHW), and Space Cooling (SC). The outcomes are presented using m^2 year as FU, as described in section 2.4 of this article, and showed the SH as the primary contributor (highest impact for 15 out 16 indicators), followed by SC (highest impact for 1 and mid for 12 out 16 indicators), and DHW. The results were in line with the mean values of energy needs assessed, 132 kWh /m^2 year (for SH), 18 kWh /m^2 year (for DHW), 25 kWh /m^2 year (for SC).

The only exception obtained relates to the impact on "water use", where the most significant contributor appears to be the SC (18% higher than SH – assessed as a difference between SC and SH divided for SH value). Chillers supplied this service with a higher electricity consumption ratio compared to SH energy systems used (main natural gas boilers, as shown in Table 2) for useful thermal energy provided. It causes a worsening of the environmental profile due to electricity produced by hydropower plants (11% of the share for the Italian electricity mix, consulting ecoinvent 3.7). In line with energy needs, SC compared with DHW was confirmed as the main contributor for 13 out of 16 impact categories. The only exceptions were concerning "climate change" and "energy resources, non-renewable" due to the benefits for chillers, thanks to the renewable energy used for producing thermal energy (as an average equal to 66% for electric-driven and 27% for gas-driven chillers). Also, for Ozone Depletion (OD), DHW had a higher impact compared to SC (8% higher) even though the OD indicator is highly sensitive to refrigerant gas emissions due to losses during the operational phase of the vapor compression cycle machines. However, in this case, the high fuel consumption (mainly natural gas) of the appliances serving domestic hot water, caused by low seasonal efficiency, was decisive.

It should also be noted that the results obtained mainly reflect the residential building units. In fact, of the total number of EPCs analyzed (equal to 81,164), the breakdown is as follows: residential (n. 68,145), offices (n. 6,593), hospitals and clinics (n. 80), recreational and leisure activities (n. 652), commercial (n. 4,209), sports clubs (n. 73), schools (n. 85), and industrial, artisan or similar activities (n. 1,327).

Table 6 shows the "climate change" results for thermal energy delivered by the energy systems used to provide SH service. The table reports the number of EPCs evaluated for each energy system, the mean and median values, the Standard Deviation (SD), the Standard Error of the Mean (SEM), the 25th and 75th percentile.

Table 5
Environmental profile of building units in Milan (per m^2 year).

Potential impacts	Units	SH	DHW	SC
Climate change (CC)	kg CO_2 eq	4.17E+01	6.50E+00	5.92E+00
Ozone depletion (OD)	kg CFC11 eq	6.27E−06	1.01E−06	9.33E−07
Ionizing radiation (IR)	kBq U-235 eq	5.42E−01	2.12E−01	5.31E−01
Photochemical ozone formation (POF)	kg NMVOC eq	4.53E−02	8.62E−03	1.10E−02
Particulate matter formation (PM)	disease inc	2.04E−07	5.05E−08	8.98E−08
Human toxicity, non-carcinogenic (HTNC)	CTUh	1.41E−07	2.61E−08	5.53E−08
Human toxicity: carcinogenic (HTC)	CTUh	8.26E−09	2.31E−09	2.48E−09
Acidification (A)	mol H+eq	4.97E−02	1.20E−02	2.10E−02
Eutrophication freshwater (EF)	kg P eq	1.61E−03	5.59E−04	1.44E−03
Eutrophication marine (EM)	kg N eq	1.17E−02	2.41E−03	3.41E−03
Eutrophication terrestrial (ET)	mol N eq	1.28E−01	2.65E−02	3.81E−02
Ecotoxicity freshwater (EFW)	CTUe	1.36E+02	3.63E+01	8.57E+01
Land use (LU)	Pt	3.30E+01	9.86E+00	2.23E+01
Water use (WU)	m^3 depriv.	1.97E+00	9.28E−01	2.32E+00
Energy resources, non-renewable (ER-nren)	MJ	6.07E+02	9.45E+01	6.67E+01
Material resources, metals/minerals (MRM)	kg Sb eq	2.04E−04	4.98E−05	1.45E−04

Table 6
Environmental profile for space heating (*) [gCO_2eq / kWh_{th}]

Energy system	#	Mean	Median	SD	SEM	25th perc.	75^{th}perc.
Natural gas boilers	53,226	339	328	46	0.2	310	360
Fuel oil boilers	1,098	413	408	36	1.1	387	434
LPG boilers	152	344	336	44	3.6	318	357
Biomass boilers	84	81	47	151	16.5	34	69
Joule effect	436	505	467	190	9.1	455	485
CHPs	6	142	142	2	0.7	142	143
Electric-driven heat pumps	5,196	205	168	123	1.7	129	246
Gas-driven heat pumps	96	243	228	51	5.2	218	276
District heating	1,199	161	161	0	0.0	161	161
Solar powered water heaters	35	44	32	28	4.7	21	60

(*) Indoor temperature and indoor relative humidity.

Table 7
Environmental profile for domestic hot water [gCO_2eq / kWh_{th}]

Energy system	#	Mean	Median	SD	SEM	25th perc.	75th perc.
Natural gas boilers	37,232	341	329	45	0.2	312	362
Fuel oil boilers	288	409	409	32	1.9	388	417
LPG boilers	95	345	334	51	5.2	317	359
Biomass boilers	1	26	26	–	–	26	26
Joule effect	8,690	541	529	82	0.9	507	549
CHPs	–	–	–	–	–	–	–
Electric-driven heat pumps	1,617	219	173	161	4.0	149	244
Gas-driven heat pumps	10	267	273	43	13.5	235	294
District heating	291	161	161	–	–	161	161
Gas-driven water heaters	7,757	330	326	22	0.2	320	333
Solar powered water heaters	45	177	245	108	16.1	42	255

Table 8
Environmental profile for space cooling (*) [gCO_2eq / kWh_{th}]

Energy system	#	Mean	Median	SD	SEM	25th perc.	75th perc.
Electric-driven chillers	39,362	246	228	92	0.5	181	296
Gas-driven air chillers	185	282	293	90	6.6	237	322

(*) Indoor temperature and indoor relative humidity.

Table 7 shows the "climate change" results for thermal energy delivered by the energy systems used to provide DHW service.

Table 8 shows the "climate change" results for thermal energy delivered by the energy systems used to provide SC service. Concerning space cooling plants, a worse environmental profile is noted if the chillers (electric and gas-driven) are compared with the heat pumps. It was due to lower efficiency (as shown in Table 3) and a higher power per useful floor ratio.

The results obtained for each energy system evaluated were consistent with what was found by previous studies. For the heat pumps (both electric and gas-driven) and natural gas boilers, the order of magnitude was in line with Famiglietti et al. [18], Giuntoli et al. [55], and Lin et al. [56]. LPG boilers, biomass boilers, and solar-powered water heaters aligned with Casasso et al. [57], Paletto et al. [58], and Ardente et al. [59]. Summarizing the scientific articles report the following values range: i) from 198 to 219 [gCO_2eq / kWh_{th}] for gas-driven heat pumps, ii) from 235 to 286 [gCO_2eq / kWh_{th}] for condensing boilers, iii) from 150 to 205 [gCO_2eq / kWh_{th}] for hybrid heat pumps (electric heat pump plus condensing boiler), iv) 273 [gCO_2eq / kWh_{th}] for LPG boilers, v) from 24 to 165 [gCO_2eq / kWh_{th}] for a biomass boilers, vi) 25 [gCO_2eq / kWh_{th}] for solar-powered water heaters. The higher value of solar-powered water heaters related to DHW service was due to the low producibility, equal to 95 [kWh_{th} consumed / m^2 year], as shown in Table 3. For all energy systems, the average values obtained were slightly higher than the literature data. On the other hand, the literature data were close to the 25th percentile values shown in the tables, underscoring how much proper sizing affects appliance performance.

In Fig. 2, the Cumulative Energy Demand (CED), primary energy - not renewable based on HHV [60] in "kWh_{PE} / m^2 year" is plotted against Climate Change (CC in $kgCO_2eq$ / m^2 year), Acidification (A in mol H + eq / m^2 year), and weighting results (mPt / m^2 year), for (a) sum of SH and DHW, and (b) SC. The weighting results were obtained firstly normalizing the impact categories values, thus dividing by selected reference, and then converting by using numerical factors based on value-choices. The engine was programmed, as already stated, with the EF 3.0 method that utilizes (i) the global annual released mass of each impact category per person (considering a world population equal to 6,895,889,018) to calculate the normalization factors and (ii) a panel-based method for weighting. The EF 3.0 method gives a higher factor to climate change and a lower factor to human toxicity non-cancer [61].

The figure also reports the breakdown of the environmental profile between residential and non-residential building units, graphically showing the mean, median, and percentile values (25th and 75th). As expected, the primary energy (nren) consumption and associated potential environmental impacts were higher for non-residential building units, caused by more significant energy needs than residentials.

The impact of acidification was chosen from the remaining 15 indicators as a significant impact from the normalization results [18]. In addition, compared to the climate change impact category, acidification reports a lower correlation with non-renewable primary energy consumption assessed using a life cycle approach (called Cumulative Energy Demand - CED). It can be seen physically looking at the figure, comparing the subplot n.1 vs. subplot n.3 and confirmed by Pederson's linear correlation coefficient [62]. The coefficient (denoted with letter r) was equal to 0.99 (high correlation) for climate change and 0.56 for acidification between non-renewable primary energy consumption. This

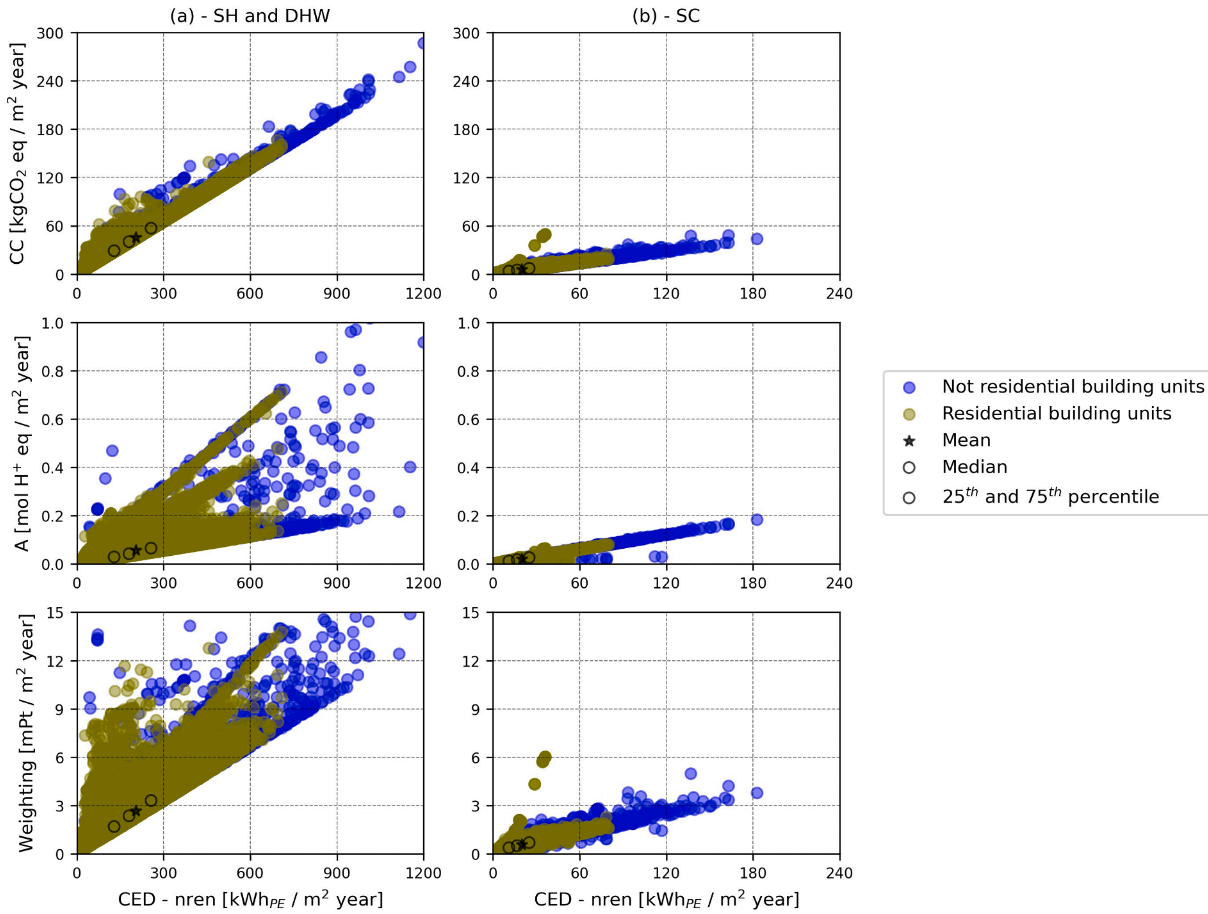

Fig. 2. (a) Sum of space heating and domestic hot water and (b) space cooling for residential and not residential building units.

finding needs to be confirmed by analyzing the energy systems with multifunctionality in detail. The approach used for dealing with multifunctionality could vary the results, especially for district heating networks supplied by a higher share of heat from WTE plants; WTEs are characterized by three functions (end-of-life management of goods, electricity, and heat production). Other impact categories not reported in Fig. 2 showed a low correlation ($r < 0.50$) as in the case between acidification and non-renewable primary energy consumption. i.e., ionizing radiation, particulate matter formation, human toxicity non-carcinogenic and carcinogenic, eutrophication freshwater, ecotoxicity freshwater, land use, water use, and resource use minerals and metals.

Fig. 3 highlights the type of energy system utilized for the specific service. Within the hybrid category, the authors report all combinations of energy plants belonging to EPCs that do not have the same technology for SH #1, SH #2, and DHW or SC #1 and SC #2 as indicated in Table 2. For this reason, systems strictly related to domestic hot water production, such as solar-powered and electric or gas water heaters, were not included in the legend because they were categorized under hybrid systems.

The figure shows that non-hybrid plants exhibit well-defined trends, with different angular coefficients for the acidification impact category. The lowest angular coefficient for both sides (a) and (b) relates to natural gas-driven, the highest for electric-driven systems. The high impact of electric-driven on potential acidification is mainly due to plants that use coal for electricity generation (equal to 10% for the Italian national grid).

The trends shown for acidification were also confirmed in the weighting results, except for heat pumps, predominantly electric-driven. This finding was due to Material Resources, Metals/minerals (MRM) category impact. The MRM for heat pumps was very significant, being complex from a thermodynamic viewpoint, having a higher weight-to-power ratio than other technologies, as also demonstrated by Kemna et al., approx. 24 [kg/kW] vs. 3 [kg/kW]. Furthermore, the electric heat pumps (HPs) analyzed in CENED seem to be not properly sized, with high variability of power per air-conditioned useful surface compared to other plants.

As a final comment related to Fig. 3, the authors note that EPCs with low primary energy consumption but high weighting results were building units supplied by biomass boilers, predominantly under the hybrids category (yellow dots in the figure). This result was due to the high particulate matter emissions causing significant impact to Particulate Matter formation (PM) impacts and toxicity categories as Ecotoxicity freshwater (EFW).

Fig. 4 shows the six most commonly used energy systems in Milan (see Table 2). Namely, joule effect systems, natural gas boilers, fuel oil boilers, electric-driven heat pumps, LPG boilers for SH and DHW (Fig. 4, a-e), and the electric-driven heat chillers for SC (Fig. 4, f). The figure reports the best correlation between the energy needs and climate change obtained for each energy system, which allows finding the climate change impact according to the energy need in each building unit. These outcomes help to realize the potential effects of climate change and provide insightful information on the benefits of transitioning from one system to another.

The results show an almost linear correlation between energy need and climate change for natural gas boilers, joule effect, fuel oil boilers, and LPG boilers. The 95% confidence bounds are also illustrated in Fig. 4, which indicates that the best-fitted line can be found between the bounds. The 95 % confidence bounds were larger than others for the fuel oil boilers and LPG boilers. It can be attributed to the lower number of building units with these energy systems in the CENED database;

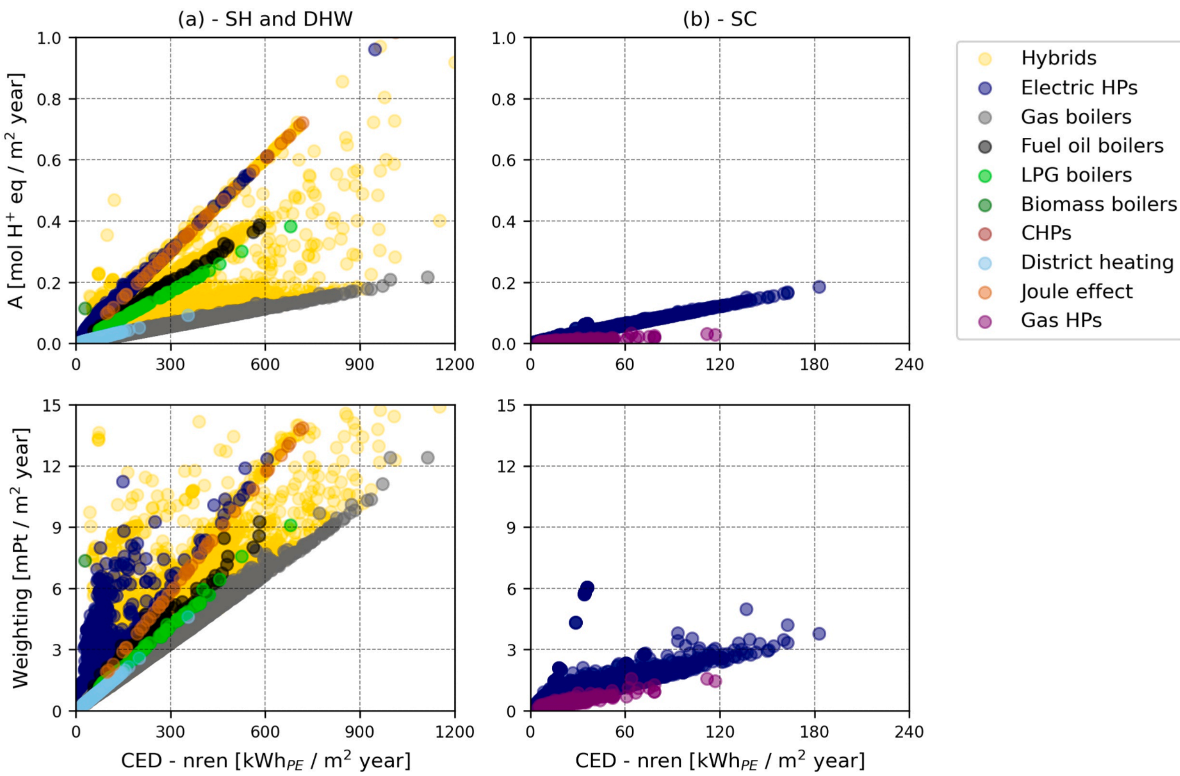

Fig. 3. (a) Sum of space heating and domestic hot water and (b) space cooling for different energy systems.

however, the fitted line's accuracy for these systems is high enough ($R^2 > 0.944$) to predict climate change impact by energy needs.

The best-fitted curve for electric-driven chillers (f) shows a lower accuracy than the other energy systems. As discussed in Fig. 3, the emissions linked with the consumption of the energy carrier during the operational phase were less significant than the other systems analyzed, so more sensitive to proper sizing by the designer (e.g., the impact of refrigerant gas leaks and capital equipment). Therefore, a weaker correlation was found between the energy need and the climate change impact. However, the best curve was defined to be as accurate as possible, respecting all observed building units, particularly those with lower energy demand. Future buildings will tend to have lower energy needs, and the curves can provide helpful information for future studies.

5. Conclusions

In this article, the authors explain the general structure of the LCA tool developed. The engine was written in Python and permits Life Cycle Assessment evaluations (from the cradle to the grave) during the operational phase of buildings (for space heating, domestic hot water, and space cooling). 16 potential impact categories are highlighted using ecoinvent 3.7 as a background database and Environmental Footprint 3.0 as characterization, normalization, and weighting set method. The engine requires to operate the following input information:

- the intended use and geographical location of the buildings;
- primary energy consumption (renewable and non-renewable) and energy needs per service;
- types of energy systems and energy vectors per service and related capacities;
- seasonal efficiencies;
- useful heated and cooled surface;
- amount of electricity from the grid consumed;
- amount of electricity or heat produced in site, auto-consumed and exported.

The authors tested the tool using data from the CENED 2.0 database for the city of Milan. Open-source database of the Lombardy Region (Northern Italy), where Milan is located, contains energy performance certificates for building units in compliance with the European energy performance of buildings directive, the energy efficiency directive, and decree DGR n. 3868 / 2015. The evaluation implemented covered approx. 81,000 properties. It corresponds to about 11% of the total floor area of the city, equal to 81 km^2 (value provided by Agenzia Mobilità Ambiente Territorio of the Municipality of Milan). To verify the outcomes, the authors implemented two checks:

- each Life Cycle Inventory described in section 2.1.2 was tested with SimaPro software (standard Life Cycle Assessment software);
- the results shown in section 3 were compared with what was found by previous scientific studies.

The engine allows the evaluation across a plurality of buildings, focusing on the climate change impact category and providing insight into other impact categories (as mentioned previously, 16 in total). Thus, allowing for a holistic view of the energy consumptions and the associated emissions at neighborhood or city scale and, therefore, be utilized as a planning tool for achieving Europe's 2050 targets. The tool also permits the assessment of the potential shifting burden to impact categories other than climate change during the decarbonization pathway, e.g., shifting problems from climate change to acidification potential, depletion of non-renewable mineral resources, etc.

The main advantage of the developed tool over those preceding it, lies in its capability to implement accurate life cycle assessments of the building sector in large-scale cities. However, the existing tools provide accurate results, but they are not efficient in measuring the environmental profile of cities containing big data. In contrast, the model

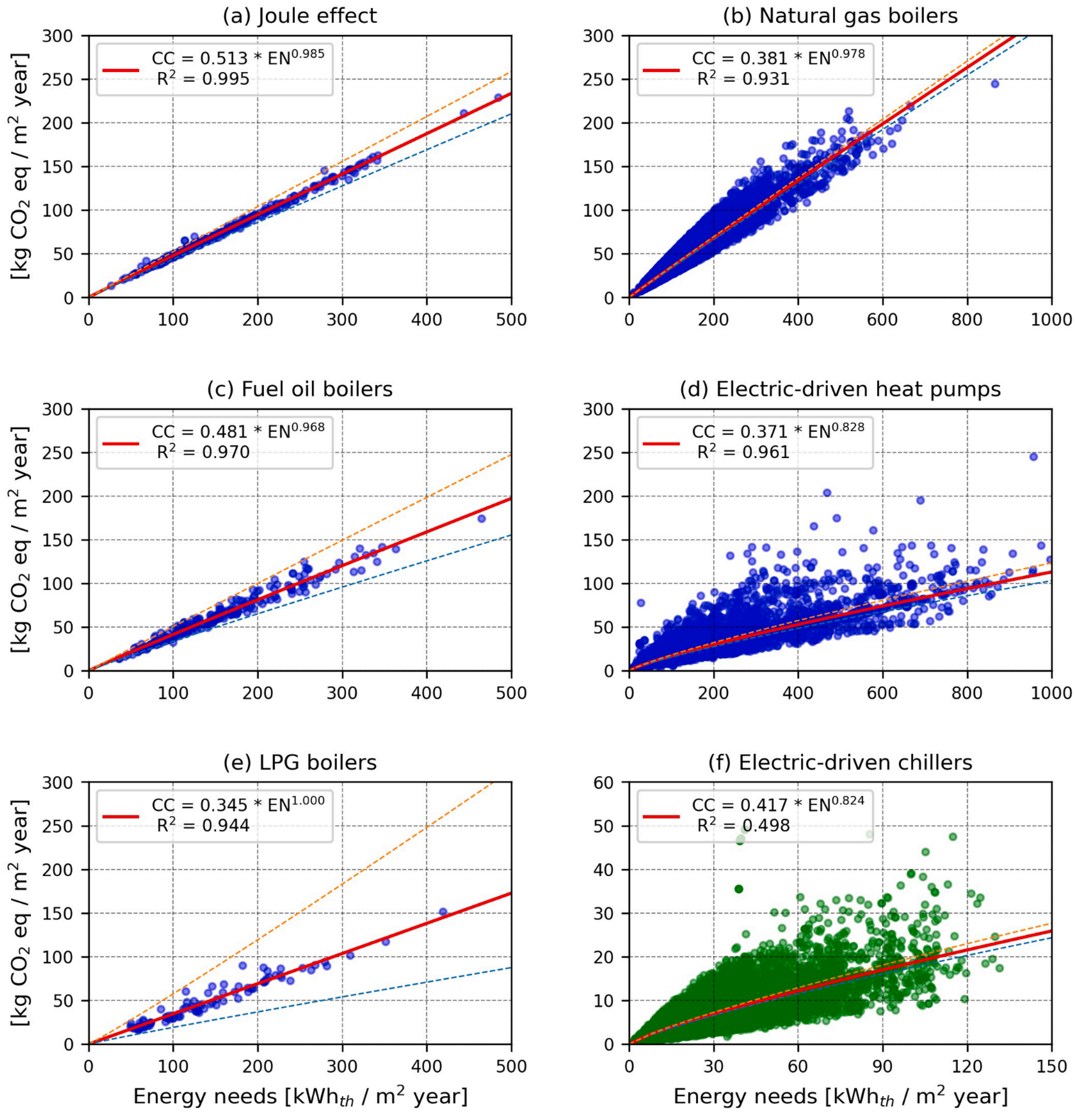

Fig. 4. The correlation between the energy needs and climate change impact (kg CO_2eq/m^2year) for SH and DHW in joule effect system (a), natural gas boilers (b), fuel oil boilers (c), electric-driven heat pumps (d), LPG boilers (e), and for SC by electric-driven chillers (f).

described in this article maintains the accuracy and transparency of the results while providing the added value of implementing complex LCA studies at the urban scale through a data-driven approach. As practical relevance, the findings obtained (Table 7, Table 8, and Fig. 3) underscore how proper sizing affects appliance performance. Heat pumps and solar thermal water heaters are energy systems where the environmental relevance of the capital equipment (like the generator) is more significant. The results also highlight how climate change is more affected by primary non-renewable energy consumption, regardless of the energy system, than other impact categories (i.e., acidification, water-use, etc.), assessed by Pederson's linear correlation coefficient (Fig. 3). Besides, Fig. 3 shows how electric heat pumps currently create a shifting burden. They have a lower climate footprint than the other energy systems but a high environmental profile (weighting results). The decarbonization of the Italian electric grid, in the near future, will have to be done, taking into account not only the climate change category to avoid this shifting.

In addition, the use of energy performance certificates for building units (from CENED 2.0) potentially allows the engine to be directly utilized in all the cities of the Lombardy region (Northern Italy). The authors also tested the tool for Brescia (see supplementary reference section), selected as the second biggest city of the Lombardy region (approx. 200,000 inhabitants), to show the broad applicability of the model. Moreover, the life cycle inventory data developed (focused on the Italian market – Conto Termico) allows the application of the tool in other Italian cities. The application in European cities is possible with due revision of the life cycle inventory.

The starting point for future improvements is to refine the life cycle inventory of the energy systems and extend the assessment on more building units to cover a higher percentage of the surface heated and cooled. It allows testing different decarbonization strategies at an urban scale and guiding stakeholders in being more environmentally responsible. Additionally, the tool gives the opportunity:

- to establish reliable environmental benchmarks to implement policies for buildings (new constructions or refurbished);
- to allow simulations of energy requalification (e.g., an extension of IV or V Generation district heating networks, conversion from natural gas to hydrogen, use of refrigerant gas with lower global warming potential);
- to develop maps of the city using Geographical Information Systems (GIS) to set planning strategies;
- to associate cost and socio-economic indicators with the environmental profile to identify priority areas of intervention and obtain a Life Cycle Sustainability Assessment (LCSA).

CRediT authorship contribution statement

Jacopo Famiglietti: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Investigation, Software. **Hashem Amini Toosi:** Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Alice Dénarié:** Writing – review & editing, Investigation. **Mario Motta:** Supervision, Project administration, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2022.115389.

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