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A novel methodology and a tool for supporting the transition of districts and communities in Positive Energy Districts

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ABSTRACT

Positive Energy Districts are expected to play a major role in the energy transition of cities. Hence, this paper aims at introducing a novel methodology useful for district energy and environmental analysis and intended to support the accomplishment of the targets of Positive Energy Districts at the district or community level. The proposed approach relies on the basic concepts underpinning the "Baseline Emission Inventory" but encompasses the ambitious and challenging objectives characterizing Positive Energy Districts. For making the proposed evaluation framework accessible to as many user categories as possible (researchers, local institutions, urban planners, etc.), the calculation steps have been transposed in a user-friendly, ready-to-use tool called "En-to-EnD. Energy and Environmental analysis of Districts". The applicability and replicability of the outputs of this work have been proven through the energy and environmental assessment of a reference case study. In particular, the district being analysed is in the South of Italy and is equipped with photovoltaic plants and a wind turbine. The results obtained show that the proposed approach may serve not only to prove the achievement of the Positive Energy District status, but also to guide the design of more sustainable district-based energy systems, thus supporting the decarbonization of cities.

1. Introduction

Urban areas are large contributors to energy consumption and greenhouse gas (GHG) emissions, having a major impact on climate change thereby [1]. In 2020, buildings accounted for 40 % of European final energy consumption and 36 % of GHG emissions [2]. Along with the transport sector, the building sector is recognized to be one of the key responsible for cities' carbon dioxide (CO_2) emissions, which account for 75 % of total CO_2 emissions at a global level [3]. Hence, the sustainability of cities is called for being enhanced to tackle climate change and achieve carbon neutrality by 2050 [4–6].

1.1. Covenant of Mayors for Climate and energy

The European Commission launched the European Union (EU) Strategy on adaptation to climate change in April 2013 [7], which was then updated in 2021 [8]. The main goal is to support the development of mitigation and adaption measures at the regional or local level for gradually increasing the resilience to climate change of all Europe. Cities are especially encouraged to sign up the Covenant of Mayors for Climate and Energy. The Covenant of Mayors initiative was originally launched in 2008 and aimed at engaging local governments to act for achieving the EU 2020 targets about climate and energy [9]. In 2015, the EU 2030 targets were encompassed, and the Covenant of Mayors for Climate and Energy took a key role in the Global Covenant of Mayors initiative in 2016 [10]. The vision of signatory authorities is to promote the decarbonization of cities and to increase their resilience, providing sustainable, affordable, and secure energy to citizens. Among others, their main commitments are:

- use of the Baseline Emission Inventory (BEI) as a common methodological approach for measuring GHG emissions in the baseline year;
- development of the Sustainable Energy and Climate Action Plan (SECAP) to define the comprehensive set of measures to be undertaken to achieve the goals set by 2030 [11].

Indeed, groups of buildings offer interesting opportunities for speeding the decarbonization of urban areas [12].

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Nomenclature

Acronyms

BEI	Baseline Emission Inventory
CP	Cooling Energy Production Plant
DCN	District Cooling Network
DHN	District Heating Network
EF	Emission Factor
EP	Electric Energy Production Plant
EU	European Union
FF	Fossil Fuel
GHG	Green House Gas
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
PED	Positive Energy District
PG	Power Grid
PV	Photovoltaic
RES	Renewable Energy Source
SC#1	Scenario #1
SC#2	Scenario #2
SECAP	Sustainable Energy and Climate Action Plan
T&D	Transmission and Distribution
TP	Thermal Energy Production Plant

Greek letters

α	Emission factor for electric energy [$kgCO_2/kWh_{el}$], [$kgCO_{2eq}/kWh_{el}$]
β	Emission factor for primary energy [$kgCO_2/kWh_p$], [$kgCO_{2eq}/kWh_p$]
η	Electric efficiency [-]

Symbols

CH_4	Methane
CO_2	Carbon Dioxide
CO_{2eq}	Equivalent Carbon Dioxide [$kgCO_{2eq}/y$, tCO_{2eq}/y]
COP	Coefficient of Performance [-]
E	Energy [kWh/y, MWh/y]
EER	Energy Efficiency Ratio [-]
GWP	Global Warming Potential [$kgCO_2/kg$]
m_{CO_2}	Carbon Dioxide Emissions [$kgCO_2/y$, tCO_2/y]
N_2O	Nitrous Oxide
NCP	Total Number of Cooling Energy Production Plants
NEP	Total Number of Electric Energy Production Plants
NTP	Total Number of Thermal Energy Production Plants
PER	Primary Energy Ratio [-]

Subscripts

Cen	Centralized
co	Cooling energy
Dec	Decentralized
el	Electric energy
exp	Energy export
FF	Plant fuelled with fossil fuels
gross	Gross energy
i	*i-th* plant
imp	Energy import
loss	Energy losses within DHNs or DCNs
net	Net energy
p	Primary energy
PG	Related to the power grid
RES	Plant supplied by a renewable energy source
sc	Self-consumed energy
T&D	Transmission and distribution losses
th	Thermal energy

Superscripts

CP	Referred to cooling energy production plants
CP_{el}	Electric-driven cooling energy production plant
Dis	Referred to the district
DCN	Supplied by the district cooling network
DHN	Supplied by the district heating network
E_{co}^{PED}	Referred to the cooling energy balance of the PED
E_{el}^{PED}	Referred to the electric energy balance of the PED
E_{th}^{PED}	Referred to the thermal energy balance of the PED
Ext	Plant located outside the boundaries of the PED (External)
Int	Plant located inside the boundaries of the PED (Internal)
TP	Referred to thermal energy production plants
TP_{el}	Electric-driven thermal energy production plant
Us	Delivered to the users

1.2. Positive energy districts

District and community-oriented approaches have been promoted in the European regulatory framework for achieving the “zero-energy” or even the more challenging “positive energy” target [13,14]. Positive Energy Districts (PEDs) have been defined as: “*mixed-use energy-efficient districts that have net zero CO_2 emissions and actively manage an annual local surplus production of renewable energy. They require interaction and integration between buildings, the users and the regional energy, mobility and ICT system, while ensuring social, economic and environmental sustainability for current and future generations*” [15]. To integrate this definition, the distinction between autonomous, dynamic, virtual and candidate PEDs must be recalled [16].

The deployment of PEDs is expected to significantly improve the sustainability of urban energy systems [17]. In 2018, the European “Positive Energy Districts and Neighbourhoods for Sustainable Urban Development” program was started as a part of the Strategic Energy Technology Plan Action 3.2 “Smart Cities and Communities” [18]. In addition, PEDs have been supported by Horizon 2020 Lighthouse Projects [19], the Urban Europe Joint Programming Initiative [20] and the Annex 83 of the International Energy Agency, Energy in Buildings and Communities [21].

1.3. State of the art about the environmental performance assessment of districts and communities

Since the scope of scientific research is broadening from the building towards a wider scale, new methods and metrics are required [22]. The framework available strives to encompass all key pillars of sustainability through the evaluation of multiple key performance indicators [23]. Available tools mainly focus on strategies for renovating the existing building stock and mapping existing initiatives, especially at the European level [24,25]. A methodology was proposed by Gabaldon Moreno et al. [26] to calculate the energy balance at the district level and evaluate the energy performance of districts striving to achieve the Positive Energy District status. This work was about the evaluation of net carbon dioxide equivalent (CO_{2eq}) emissions as the difference between total CO_{2eq} emissions due to imported primary energy and total CO_{2eq} avoided thanks to the export of renewable energy. At the city level many methods exist for developing GHG inventories [27]. Furthermore, several community-scale protocols evolved from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National GHG Inventories [28], such as the International Standard for Greenhouse Gas for Cities [29], the Global Protocol for Community Scale GHG Emissions [30] and the already mentioned Baseline Emission Inventory [31].

Nevertheless, a globally shared approach is still lacking, especially since the methods adopted for building-oriented analysis are frequently transposed at the district level [32,33]. Table 1 lists some of the main factors which distinguish the approaches adopted in the scientific literature addressing the environmental analysis of districts and communities. The latter is usually intended to determine CO_2 or CO_{2eq} emissions avoided following the installation of renewable-based plants [34]. Most papers focus on the buildings sector, although the transport sector is considered too [35,36]. Ascione et al. applied an integrated approach for the retrofit of buildings in a neighbourhood in Naples by calculating CO_{2eq} due to electricity demand and natural gas combustion [37]. Kim et al. investigated the environmental performance of a net-zero energy community equipped with heat pumps, a district heating network (DHN), solar thermal systems and seasonal thermal energy storages [38]. The proposed configuration allowed to avoid up to 61 % CO_{2eq} emissions compared to the baseline case. Volpe et al. analysed a small neighbourhood of twenty buildings in the South of Italy designed and operated as a PED [39]. The latter was equipped with photovoltaic (PV) panels and a biomass-based DHN. The electricity supplied by the PV panels was considered emission-free, whereas an emission factor equal to 0.133 $kgCO_{2eq}/kWh$ was assigned to biomass combustion. Sameti and Highighat optimized a new district under different scenarios by using a mixed-integer linear programming technique [40]. The CO_{2eq} emissions balance accounted for combustion-based emissions, as well as indirect emissions related to the purchase of electricity from the power grid (PG). Orehounig et al. also considered the emissions released by renewable-based electric energy production in a Swiss village [41]. An 86 % reduction of CO_2 emissions was achieved by means of a DHN activated by biomass, PV panels and small hydropower. Famiglietti et al. adopted the net-balance approach for evaluating the carbon footprint of a district in Milan including 14 buildings and aiming at becoming the first Italian social housing project characterized by net-zero emissions [42]. The results obtained showed that 56 % of GHG emissions pertain to the operational stage.

1.4. Research aim

According to the findings of the literature review, some of the main gaps challenging district-level environmental analysis are:

- the lack of a standardised method encompassing all energy carriers used [43];
- the choice for the macro-sectors to be investigated (buildings, transport, etc.) [36];
- the right balance between accuracy and easy implementation, which may also encourage citizens to be eager to alternative energy systems characterised by high pervasiveness of renewable-based technologies [44].

Table 1
Main factors differentiating current scientific works dealing with the environmental analysis of districts and communities.

Reference	Sectors considered	Emissions accounted	Emissions of renewable-based plants
Ceglia et al. [34]	Industrial and tertiary	CO_2	Not included
Marotta et al. [35]	Commercial and tertiary	CO_{2eq}	Included
Castillo-Calzadilla et al. [36]	Buildings and transport	CO_{2eq}	Included
Ascione et al. [37]	Residential, tertiary, and commercial	CO_{2eq}	Not included
Kim et al. [38]	Commercial	CO_{2eq}	Not included
Volpe et al. [39]	Residential and commercial	CO_2	Not included
Sameti and Highighat [40]	Residential and tertiary	CO_2	Not included
Orehounig et al. [41]	Buildings and industrial	CO_2	Included
Famiglietti et al. [42]	Residential	CO_{2eq}	Included

On these premises, this work aims at introducing a novel approach for the environmental analysis of communities and districts powered by a ready-to-use and user-friendly tool useful to promote and ease its implementation. The proposed methodology is based on a detailed mathematical model that proposes to accurately determine energy and environmental balances related to every kind of user aggregation (i.e., Renewable Energy Communities, PEDs, etc.). Compared to existing methods and supported by the proposed tool, it strives to move beyond a purely mathematical approach and also to verify the achievement of the goals of Positive Energy Districts. In addition, it aims at filling the research gaps emerging from the literature review. First, it seeks to encompass all energy vectors adopted in districts. Besides, it is intended to include the energy demand of residential, tertiary, commercial buildings, in addition to industrial facilities and other activity sectors relevant to the energy demand of the district or community being analysed. As shown in Fig. 1, the proposed approach focuses on thermal, cooling, and electric energy demand and supply during the operation phase of the district. The implementation of energy efficiency measures addressed to reduce the energy demand of the district under investigation, such as the energy renovation of buildings envelope, is left out of the proposed framework. Energy and emission balances are determined on an annual basis, according to the definition of PEDs [15]. In the case of existent districts, actual data referred to thermal, cooling, and electric energy demand collected from bills, surveys, smart meters, etc., can be used. In the case of new districts, estimated data should be adopted. Similar considerations apply to the producibility of plants. Since yearly balances are evaluated, annual data regarding energy demand and supply should be provided in input to the tool. Aggregated data can be regarded as the sum of data available on a shorter timestep. In this way, significant factors affecting the energy balance of the district (e.g., the simultaneity of energy demand and supply from renewable-based plants) may be considered for more accurately determining the share of energy self-consumption, surplus, and deficit production. The proposed methodology also allows to encompass the life-cycle perspective if life-cycle based emission factors are adopted.

The methodology developed in this work is built on the Baseline Emission Inventory and therefore refers to comprehensive guidelines developed by EU institutions [45]. The main characteristics of the BEI are detailed in Section 2, whereas the novel methods proposed are introduced and discussed in Section 3. In Section 4, the tool is described along with a case study used for validating the methodology and showing a reference example for its adoption. Lastly, in Section 5, the conclusions are drawn.

2. The baseline emission Inventory

As defined by Bertoldi et al., the BEI: *"quantifies the amount of CO_2 emitted in the key sectors and other activity sectors in the territory of the Covenant signatory for the baseline year"* [31]. Its main purpose is to identify the most relevant anthropogenic sources of GHGs for prioritizing the reduction measures defined within the SECAP accordingly [45].

2.1. Sectors and scopes

The BEI accounts for the GHG emissions due to energy consumption in four key macro-sectors: building, transport, non-energy related and energy supply [46]. Emission sources covered by the EU Emissions Trading System are not considered [47]. The activity sectors considered

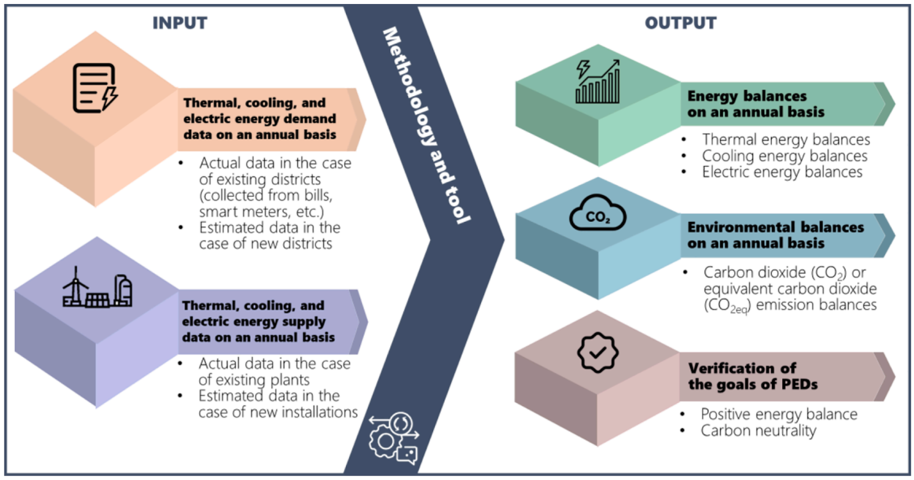


Fig. 1. Overview about the proposed methodology and tool.

in each macro-sector are listed in Fig. 2. Beyond those listed, the agriculture, forestry, and fisheries sectors may be encompassed whenever proper mitigation measures in the SECAP have been defined. The same applies to non-energy related activities concerning waste disposal and wastewater management when not intended for energy supply. In the latter case, their emissions should be accounted with those pertaining to energy supply. Within the energy supply macro-sector, all GHG emissions due to local thermal, cooling, and electric energy supply are quantified. Both fossil and renewable-based generation units, inside or outside the boundaries of the local authority, are considered. In the case of renewable-based electric energy production plants, the total electric energy supply must be reduced by the amount of energy which meets the criteria for guarantee of origin [48] and is sold outside the boundaries of the local authority as certified green energy.

2.2. Emission factors

In the frame of the BEI, both direct and indirect GHG emissions can be determined using the emission factor associated with the energy carrier adopted [46]. The BEI suggests the monitoring of three main GHGs, namely CO_2, methane (CH_4), and nitrous oxide (N_2O). The approach chosen can be activity or life cycle-based. On the one hand, activity-based emission factors (EFs) quantify direct emissions due to the combustion of fuels. On the other, they account for indirect emissions due to electric, thermal, and cooling energy supply through the PG, DHNs, and district cooling networks (DCNs), respectively. The activity-based approach is in line with the IPCC, and it is therefore adopted in national GHG inventories included in the framework of the United Nations Framework Convention on Climate Change and Kyoto Protocol [49]. Moreover, it fits the European regulatory framework on climate and energy [50]. Conversely, EFs based on life-cycle analysis (LCA) quantify the emissions released during the whole life of energy carriers. Emissions are usually reported using the universal unit of measurement accounting for the global warming potential (GWP) of various gases, known as CO_{2eq}, which is not the same as in the case of CO_2 as shown in Table 2.

The default activity and life cycle-based EFs adopted within the Covenant of Mayors for fossil fuels, municipal wastes and some renewables are listed in Appendix A, Table A.1 [54]. Such EFs can be used when country-specific or local data are not available. In addition, Table A.2 and Table A.3 list the default EFs adopted for local electric energy supply from renewable-based plants and national EFs for electricity production referred to 2020, respectively [51].

3. District-level emission inventories

The calculation methodology proposed for assessing the achievement of the targets of PEDs, that is, a positive energy balance and carbon neutrality on an annual basis, is introduced in this section.

3.1. Overview about energy flows in districts

The conditions defined in the BEI still apply in the proposed methodology. Indeed, the emissions of other activity sectors than buildings, such as industries, agriculture, forestry, and fisheries, may be encompassed whenever relevant to the energy consumption of the district

Table 2
100-year time horizon GWP of selected GHGs relative to CO_2 according to the IPCC Third Assessment Report [51], Fourth Assessment Report [52] and Fifth Assessment Report [53].

GHG	IPCC Third Assessment Report [$kgCO_2/kg$]	IPCC Fourth Assessment Report [$kgCO_2/kg$]	IPCC Fifth Assessment Report [$kgCO_2/kg$]
CO_2	1	1	1
CH_4	23	25	28
N_2O	296	298	265

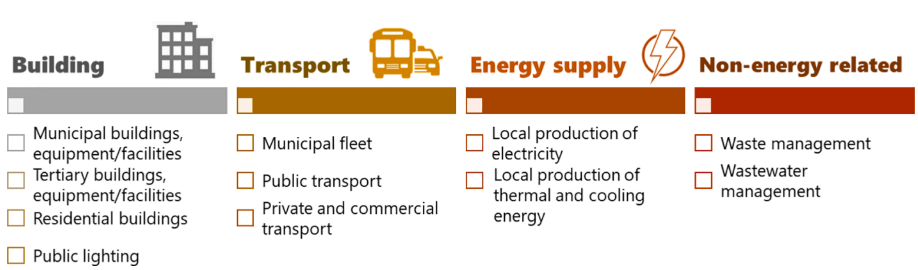


Fig. 2. Macro-sectors and corresponding activity sectors analysed in the BEI.

being analysed. As regards the evaluation of the emissions of the transport sector, the use of average data regarding fuel consumption at national level has already been proven to be affected by spatial bias. The latter could be reduced by using local data, as suggested by the guidelines referring to the development of the BEI [36]. For the purposes of BEI, the bottom-up territorial approach was suggested to be adopted. Yet, local data sources, municipal transport departments or even national authorities for road management might seldom provide information about the traffic flows in district street networks. The use of the top-down fuel sale method, instead, was discouraged even in the frame of the BEI. Indeed, the information related to the sale of fuels is deemed to be very basic at local level. Similar considerations apply to the resident activity method, that is, the second bottom-up approach proposed for the BEI. The latter considers all trips of people living within the borders of the territory being analysed, which could turn out to deliver misleading results if used for focusing on little neighbourhoods. Hence, since the allocation of GHG emissions related to the transport sector is very difficult to realize within the limited boundaries of districts, it has been neglected in this first methodology proposal.

For the estimation of district annual energy and CO_2 (or CO_{2eq}) emissions balances related to thermal, cooling, and electric energy supply and demand, the same procedure as the BEI is adopted. Indeed, EFs are multiplied by activity data, which can be estimated distinguishing between the different energy carriers provided to users. Fig. 3 shows a simplified diagram describing the energy flows involved in common districts characterized by electric (E_{el}), thermal (E_{th}) and cooling (E_{co}) energy requests. Centralized or decentralized plants can be installed to cover users' energy needs. The production plants can convert the primary energy (E_p) supplied by renewables or fossil fuels (FFs), as well as electric energy in the case of plants supplying thermal/cooling energy. According to the definition of virtual PEDs given by Lindholm et al. [55], electric (EP), thermal (TP) and cooling (CP) energy production plants exploiting renewables can be located even outside of the geographical boundaries of the district. Conversely, the energy supplied by centralized and decentralized renewable-based plants located within the boundaries of the district and exceeding the demand of users can be exported outside of the geographical boundaries of the district. In Fig. 3, energy exports are shown by the arrows starting from the blocks representing internal energy production plants as well as DHN/DCNs and crossing the dotted box representing the geographical boundaries of the district. Electricity surplus, for instance, can be injected into the PG. In turn, electricity can be taken from the PG in the case of deficit production from renewable-based plants.

Hereinafter, the superscripts Int_{Cen} and Ext_{Cen} are used to identify all centralized energy production plants serving the district and located inside and outside of its boundaries, respectively. The superscript Int_{Dec} is instead reserved to decentralized energy conversion systems installed in the district and owned by single users. This generalised categorization allows the proposed methodology to involve all kind of TPs, CPs and EPs. Boilers, every type of heat pumps (such as absorption, ground-source, gas engine-driven, electric-driven, etc.) and all other kinds of fossil and renewable-based plants for thermal, cooling and electric energy supply plants can be encompassed, including plants for the combined production of heat and power and polygeneration (combined cooling, heating and power) plants. Short-term or seasonal energy storages may be included too, along with power-to-X technologies.

3.2. Energy and emissions balances related to thermal and cooling energy demand and supply

Fig. 4 shows an example of the thermal and cooling energy flows that can be involved in a generic district. Thermal energy can be supplied by decentralized TPs owned by single users, or instead by centralized TPs activating DHNs. The total thermal energy delivered to the DHN includes thermal energy imports from external TPs supplied by renewable energy sources (RESs). Conversely, it neglects the share of thermal energy supplied by renewable-based TPs and exported outside the district. To evaluate the final amount of thermal energy supplied to the users on an annual basis, the losses within the DHNs may be considered too. The latter also include the losses due to thermal energy storage tanks. For evaluating the CO_2 (or CO_{2eq}) emissions associated with the activation of TPs, a distinction is needed between electric-driven TPs and TPs converting the primary energy supplied by FFs or RESs. In the latter case, emissions can be evaluated by multiplying the primary energy demand of the plant by the EF of the FF used or the RES exploited, such as those reported in Table A.1. On the contrary, in the case of an electric-driven TP, the activity data to consider for evaluating corresponding indirect emissions is the electric energy input to the energy conversion system. Similar considerations apply to cooling energy flows and related energy and emissions balances.

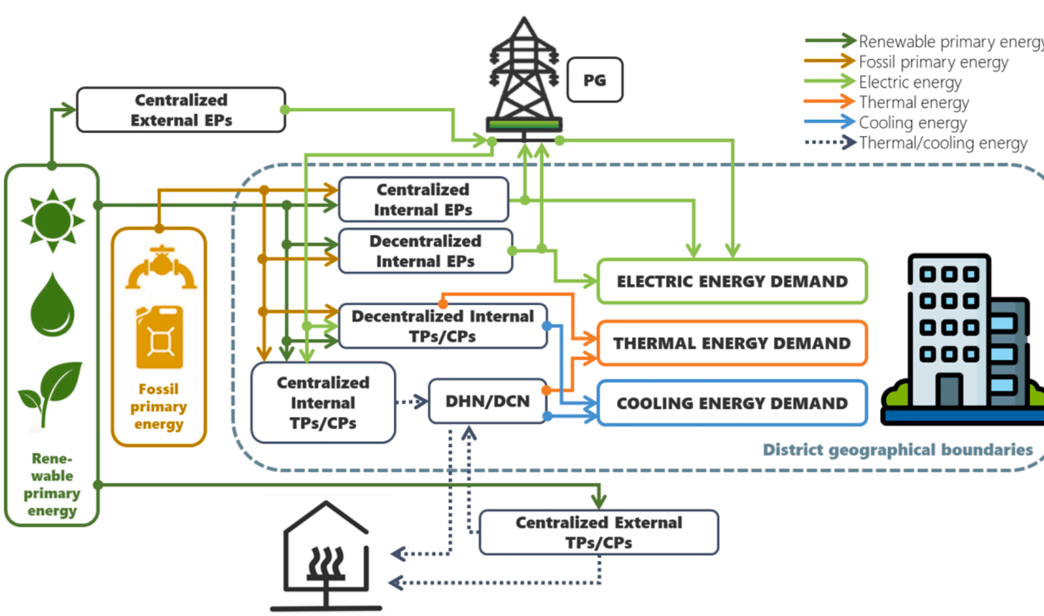


Fig. 3. Example layout of energy flows involved in a generic district.

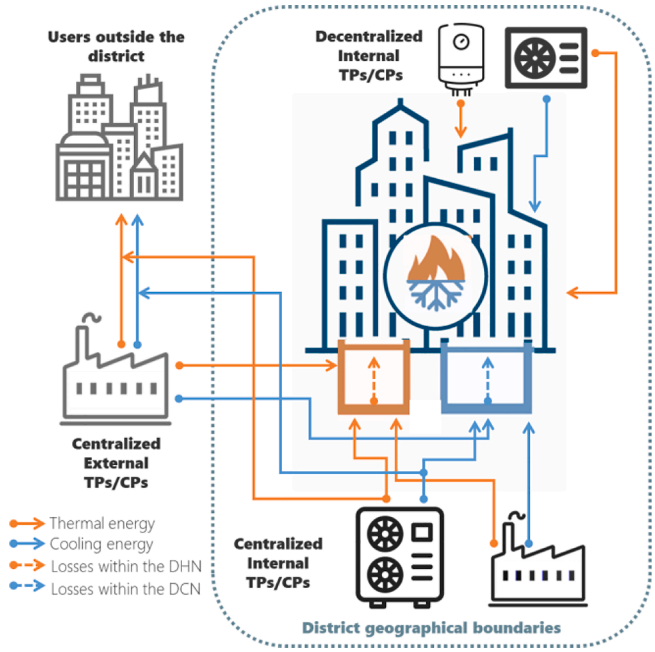


Fig. 4. Example layout of thermal and cooling energy flows involved in a generic district.

The annual thermal energy demand of the users in the district (E_{th}^{Dis}) can be evaluated according to Eq. (1),

$$E_{th}^{Dis} = E_{th}^{DHN^{Us}} + \sum_{i=1}^{NTP^{Int_{Dec}}} E_{th_i}^{TP^{Int_{Dec}}} \tag{1}$$

$E_{th}^{DHN^{Us}}$ is the yearly thermal energy delivered to the users (Us) by the DHN, whereas $E_{th_i}^{TP^{Int_{Dec}}}$ is the yearly thermal energy supplied to the users by decentralized thermal energy production plants (TPs). The sum is calculated from 1 to $NTP^{Int_{Dec}}$, which is the total number of decentralized TPs within the district. Details about the evaluation of E_{th}^{Dis} in terms of energy supply are given in Appendix B, Eqs. (B.1)–(B.4). In particular, E_{th}^{Dis} can be supplied by TPs supplied by fossil energy sources (primary energy) or electric energy, as stated in Eqs. (B.5)–(B.7). The annual primary energy demand related to the supply of thermal energy (E_p^{TP}) is given by Eq. (2). The subtractive term ($E_{p,exp}^{TP_{RES}^{Int_{Cen}}}$) accounts for the primary energy demand due to the yearly thermal energy exports, which should not be attributed to the total primary energy balance of the district. $E_{p,exp}^{TP_{RES}^{Int_{Cen}}}$ can be determined as stated in Appendix B, Eq. (B.8).

$$E_p^{TP} = \sum_{i=1}^{NTP_{FF}^{Int_{Cen}}} E_{p_i}^{TP_{FF}^{Int_{Cen}}} + \sum_{i=1}^{NTP_{RES}^{Int_{Cen}}} \left(E_{p_i}^{TP_{RES}^{Int_{Cen}}} - E_{p,exp_i}^{TP_{RES}^{Int_{Cen}}} \right) + \sum_{i=1}^{NTP_{FF}^{Int_{Dec}}} E_{p_i}^{TP_{FF}^{Int_{Dec}}} + \sum_{i=1}^{NTP_{RES}^{Int_{Dec}}} E_{p_i}^{TP_{RES}^{Int_{Dec}}} + \sum_{i=1}^{NTP_{RES}^{Ext}} E_{p_i}^{TP_{RES}^{Ext}} \tag{2}$$

Lastly, the annual CO_2 (or CO_{2eq}) emissions due to thermal energy demand and supply within the district ($m_{CO_2}^{E_{th}^{Dis}}$) can be determined according to Eq. (3). The latter has been obtained by multiplying all terms of Eq. (2) by the EF of the source exploited in each TP, which is referred to as β and is expressed in $kgCO_2/kWh_p$ (or $kgCO_{2eq}/kWh_p$). It should be noticed that Eq. (2) neglects the emissions of electric-driven TPs, whose contribution is accounted for in the next section.

$$m_{CO_2}^{E_{th}^{Dis}} = \sum_{i=1}^{NTP_{FF}^{Int_{Cen}}} E_{p_i}^{TP_{FF}^{Int_{Cen}}} \bullet \beta_i + \sum_{i=1}^{NTP_{RES}^{Int_{Cen}}} \left(E_{p_i}^{TP_{RES}^{Int_{Cen}}} - E_{p,exp_i}^{TP_{RES}^{Int_{Cen}}} \right) \bullet \beta_i + \sum_{i=1}^{NTP_{FF}^{Int_{Dec}}} E_{p_i}^{TP_{FF}^{Int_{Dec}}} \bullet \beta_i + \sum_{i=1}^{NTP_{RES}^{Int_{Dec}}} E_{p_i}^{TP_{RES}^{Int_{Dec}}} \bullet \beta_i + \sum_{i=1}^{NTP_{RES}^{Ext}} E_{p_i}^{TP_{RES}^{Ext}} \bullet \beta_i \tag{3}$$

The methods discussed in this section may also be used for quantifying CO_2 (or CO_{2eq}) emissions due to the demand and supply of cooling energy ($m_{CO_2}^{E_{co}^{Dis}}$).

3.3. Energy and emission balances related to electric energy demand and supply

Fig. 5 shows an example of electricity flows characterizing a generic district. The electric energy production plants (EPs) serving it may be installed inside or outside its geographical boundaries. In the former case, decentralised and centralised EPs can be distinguished. Users can take electricity from the PG in the case of deficit production from renewable-based EPs. Conversely, electricity can be injected into the PG whenever the supply from renewable-based EPs exceeds users' demand. Indirect emissions are related to the electricity taken from the PG and can be determined using the EF of the PG. A distinction is needed regarding EPs fuelled with FFs or exploiting RESs. In the former case, emissions are usually evaluated by multiplying the primary energy demand of the plant by the EF associated with the combustion of the FF used. The same applies to renewable-based EPs activated by combustion, for example of renewable fuels, biomass, etc. On the other hand, the EF associated with non-combustion-based EPs (such as PV plants, wind turbines, hydroelectric plants, etc.) is referred to the electric energy supplied.

As already mentioned, Eq. (3) neglects the indirect carbon emissions related to electric-driven TPs. In fact, they can be accounted with those referred to the annual electric energy demand of the district (E_{el}^{Dis}). E_{el}^{Dis} can be estimated as stated in Eq. (4), where E_{el}^{Us} is the yearly electricity demand of users and $E_{el}^{TP_{el}^{Int_{Cen}}}$ and $E_{el}^{CP_{el}^{Int_{Cen}}}$ are the requests due to the activation of centralized electric-driven TPs and CPs, respectively, calculated on an annual basis. The methods available for determining each term of Eq. (4) are detailed in Appendix C, Eqs. (C.1)–(C.5).

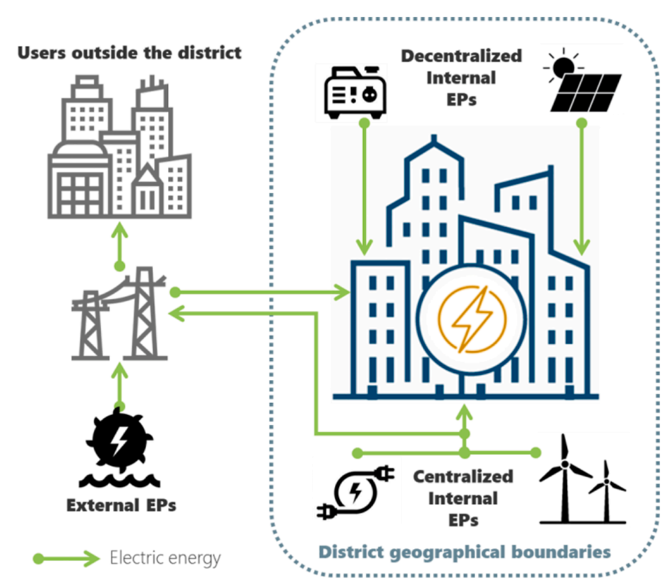


Fig. 5. Example layout of electric energy flows in a generic district.

$$E_{el}^{Dis} = E_{el}^{Us} + E_{el}^{TP_{el}^{Int_{Cen}}} + E_{el}^{CP_{el}^{Int_{Cen}}} \tag{4}$$

Once known E_{el}^{Dis}, the electric energy supplied by centralized fossil-based EPs ($E_{el,net}^{EP_{FF}^{Int_{Cen}}}$), centralized renewable-based EPs ($E_{el,net}^{EP_{RES}^{Int_{Cen}}}$), external renewable-based EPs ($E_{el,net}^{EP_{RES}^{Ext}}$) as well as decentralized EPs ($E_{el,net}^{EP^{Int_{Dec}}}$), the electricity yearly purchased from the PG (E_{el}^{PG}) can be evaluated as stated in Eq. (5).

$$E_{el}^{PG} = E_{el}^{Dis} - E_{el,net}^{EP_{FF}^{Int_{Dec}}} - E_{el,net}^{EP_{RES}^{Int_{Dec}}} - E_{el,net}^{EP_{FF}^{Int_{Cen}}} - E_{el,net}^{EP_{RES}^{Int_{Cen}}} - E_{el,net}^{EP_{RES}^{Ext}} \tag{5}$$

The annual primary energy demand of the district related to electric energy demand and supply (E_p^{EP}) is given by Eq. (6). It includes only the contributions due to the activation of combustion-based EPs, whose calculation methods are introduced in Appendix C, Eqs. (C.6)–(C.7). These terms can be used to estimate corresponding emissions through the emission factor β of the source exploited. The latter is expressed in $kgCO_2/kWh_p$ (or $kgCO_{2eq}/kWh_p$). For obtaining the total primary energy demand, the primary energy demand related to the electricity taken from the PG should be considered too, as well as the primary energy demand of non-combustion based renewable EPs. In particular, the primary energy demand of the PG can be evaluated using the efficiency of the PG [56].

$$E_p^{EP} = \sum_{i=1}^{NEP_{FF}^{Int_{Cen}}} E_{p_i}^{EP_{FF}^{Int_{Cen}}} + \sum_{i=1}^{NEP_{FF}^{Int_{Dec}}} E_{p_i}^{TP_{FF}^{Int_{Dec}}} + \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} E_{p_i}^{TP_{RES}^{Int_{Cen}}} + \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} E_{p_i}^{Int_{Dec}} + \sum_{i=1}^{NEP_{RES}^{Ext}} E_p^{TP_{RES}^{Ext}} \tag{6}$$

Eventually, annual carbon emissions due to electric energy demand and supply ($m_{CO_2}^{E_{el}^{Dis}}$) can be estimated according to Eq. (7). Indirect emissions due to non-combustion-based EPs can be determined by multiplying the emission factor α of the EP by the electric energy supplied. α is usually expressed in terms of $kgCO_2/kWh_{el}$ (or $kgCO_{2eq}/kWh_{el}$). Indirect CO_2 (or CO_{2eq}) related to the electricity taken from the PG can be determined using the EF of the PG, which is referred to as α_{PG}. α_{PG} is multiplied by the difference between E_{el}^{PG} and $\sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} E_{el,exp_i}^{EP_{RES}^{Int_{Cen}}}$ and $\sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} E_{el,exp_i}^{EP_{RES}^{Int_{Dec}}}$. Indeed, the electricity injected into the PG by renewable EPs accounts for an emission credit which lowers total emissions. The adoption of α_{PG} greatly eases the calculation, since it avoids collecting data regarding the national electricity production mix. It should be noted that the emission factor α of non-combustion-based renewable EPs is usually zero, except under the life-cycle approach (Table A.2).

$$\begin{aligned} m_{CO_2}^{E_{el}^{Dis}} = {} & \sum_{i=1}^{NEP_{FF}^{Int_{Cen}}} E_{p_i}^{EP_{FF}^{Int_{Cen}}} \bullet \beta_i + \sum_{i=1}^{NEP_{FF}^{Int_{Dec}}} E_{p_i}^{EP_{FF}^{Int_{Dec}}} \bullet \beta_i + \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} E_{p_i}^{EP_{RES}^{Int_{Cen}}} \bullet \beta_i \\ & + \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} E_{p_i}^{EP_{RES}^{Int_{Dec}}} \bullet \beta_i + \sum_{i=1}^{NEP_{RES}^{Ext}} E_p^{EP_{RES}^{Ext}} \bullet \beta_i + \left(E_{el}^{PG} - \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} E_{el,exp_i}^{EP_{RES}^{Int_{Cen}}} \right. \\ & \left. - \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} E_{el,exp_i}^{EP_{RES}^{Int_{Dec}}} \right) \bullet \alpha_{PG} + \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Cen}}} - E_{el,exp_i}^{EP_{RES}^{Int_{Cen}}} \right) \bullet \alpha_i \\ & + \sum_{i=1}^{NEP_{RES}^{Int_{Dec}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Dec}}} - E_{el,exp_i}^{EP_{RES}^{Int_{Dec}}} \right) \bullet \alpha_i + \sum_{i=1}^{NEP_{RES}^{Ext}} \left(E_{el,gross_i}^{EP_{RES}^{Ext}} - E_{el,exp_i}^{EP_{RES}^{Ext}} \right) \bullet \alpha_i \end{aligned} \tag{7}$$

3.4. Positive energy balance and carbon neutrality check

The district being analysed reaches the positive energy balance target whenever the conditions expressed by Eqs. (8), (9) and (10) are met simultaneously. That is, the thermal, cooling, and electric energy supply of renewable-based plants exceeds the thermal, cooling, and electric energy demand of the district at the same time, respectively.

$$\sum_{i=1}^{NTP_{RES}^{Int_{Cen}}} E_{th_i}^{TP_{RES}^{Int_{Cen}}} + \sum_{i=1}^{NTP_{RES}^{Int_{Dec}}} E_{th_i}^{TP_{RES}^{Int_{Dec}}} + \sum_{i=1}^{NTP_{RES}^{Ext}} E_{th,imp_i}^{TP_{RES}^{Ext}} > E_{th}^{Dis} \tag{8}$$

$$\sum_{i=1}^{NCP_{RES}^{Int_{Cen}}} E_{co_i}^{CP_{RES}^{Int_{Cen}}} + \sum_{i=1}^{NCP_{RES}^{Int_{Dec}}} E_{co_i}^{CP_{RES}^{Int_{Dec}}} + \sum_{i=1}^{NCP_{RES}^{Ext}} E_{co,imp_i}^{CP_{RES}^{Ext}} > E_{co}^{Dis} \tag{9}$$

$$\begin{aligned} & \sum_{i=1}^{NEP_{RES}^{Int_{Cen}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Cen}}} - E_{el,sc_i}^{EP_{RES}^{Int_{Cen}}}\right) + \sum_{i=1}^{NCP_{RES}^{Int_{Dec}}} \left(E_{el,gross_i}^{EP_{RES}^{Int_{Dec}}} \right. \\ & \quad \left. - E_{el,sc_i}^{EP_{RES}^{Int_{Dec}}}\right) + \sum_{i=1}^{NEP_{RES}^{Ext}} E_{el,imp_i}^{EP_{RES}^{Ext}} \\ & \quad > E_{el}^{Dis} \end{aligned} \tag{10}$$

The net annual CO_2 (or CO_{2eq}) emissions of the district being analysed ($m_{CO_2}^{Dis}$) can be determined as stated in Eq. (11), that is as the sum of emissions due to electric ($m_{CO_2}^{E_{el}^{Dis}}$), thermal ($m_{CO_2}^{E_{th}^{Dis}}$) and cooling energy ($m_{CO_2}^{E_{co}^{Dis}}$) demand and supply. The condition of carbon neutral district is reached whenever the resulting value is null or negative. Indeed, such a result proves that the emissions due to the thermal, cooling, and electric energy supply are counterbalanced by the emissions credit due to the electricity exports to the PG. Surplus thermal and cooling energy exported outside of the district boundaries could be considered for the evaluation of emission credits too. However, choosing the reference EF for evaluating carbon emissions avoided owing to the export of thermal and/or cooling energy surplus could turn out to be not straightforward as in the case of electricity. In the latter case, the EF of the PG can always be adopted. Since an equivalent of the PG for thermal and cooling energy supply is lacking, the EF of the source used outside of the district and substituted by surplus thermal and cooling energy exports, respectively, should be used.

$$m_{CO_2}^{Dis} = m_{CO_2}^{E_{el}^{Dis}} + m_{CO_2}^{E_{th}^{TP}} + m_{CO_2}^{E_{co}^{CP}} \tag{11}$$

Eventually, the district under analysis can be recognized as a PED whenever the conditions stated by Eqs. (8), (9) and (10) are met simultaneously and $m_{CO_2}^{Dis}$ results in a null or negative value at the same time.

4. A tool for the emission inventory of districts: "*En-to-EnD. Energy and Emission analysis of Districts*"

The proposed calculation methodology has been transposed into a user-friendly tool which, once filled with the necessary input data, allows to automatically evaluate the energy and CO_2 (or CO_{2eq}) emissions balances of the district under analysis and to eventually verify the achievement of the PED condition. The spreadsheet is called "*En-to-EnD. Energy and Environmental analysis of Districts*" and is available online [57]. The dataset used for defining default EFs can be modified and updated as needed based on the approach chosen (activity or life cycle-based) and the information held by the user, especially when case-specific data are available. The EFs currently used for fossil and renewable energy sources, as well as the PG, are those listed in Table A.1, A.2 and A.3 [54,58]. Note that the default version of the tool refers to CO_{2eq} emissions estimated under the life-cycle perspective to keep the approach as generalised as possible. However, CO_2 emissions as well as activity-based CO_{2eq} emissions balances can be determined too, by simply updating the EFs provided in the dataset section.

The tool is organised into five sections. The sections about energy and CO_{2eq} emissions balances related to thermal and cooling energy are in turn structured into three subsections: energy demand, energy supply, and preliminary results. The section about electric energy includes an additional subsection for characterizing the efficiency, the transmission and distribution (T&D) losses factor and the EF of the PG. The input data required in each section are listed in Fig. 6. Users' energy demand must be defined at first. Then, each production plant must be characterized in terms of energy input (fossil, renewable or electric), exploited source, efficiency, gross production, and energy self-consumption (in the case of

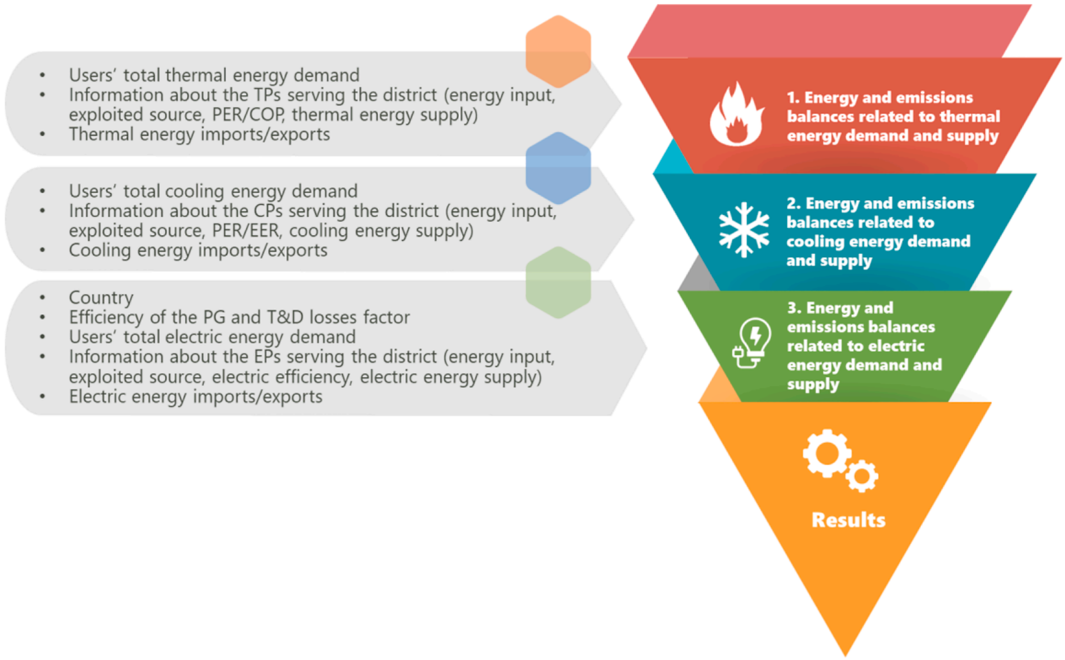


Fig. 6. Input data to all sections of the tool.

EPs). Energy imports and exports must be indicated too. Eventually, based on the data received as input, the tool automatically determines district annual primary energy demand and CO_2 (or CO_{2eq}) emissions in the result section.

4.1. Validation, replicability and upscaling

This section is about the application of the proposed methodology through the *En-to-EnD* tool to real case studies. The reference district investigated in this work is in the industrial area of Benevento, a city in the South of Italy [59]. It includes three users: the industrial wastewater treatment plant, a mixed-use building, and an office building. The selection of a case study in an industrial area shows that the proposed methodology may be applied to various districts, regardless of the sectors involved. Despite the low number of users in the selected district, the loads considered are highly diversified and meaningful within the industrial site. Hence, the case study chosen provides an interesting reference for the validation of the proposed methodology. Users are characterized by electricity needs only. Indeed, the space heating and cooling energy demand of mixed-use and office buildings is met by split air conditioning systems and an electric heat pump. The electric load of all users is known on a quarter-hour basis [60], and is equal to 956 MWh/y. For achieving the PED condition, PV panels and a wind turbine are installed. Two scenarios are considered:

- in the first scenario (SC#1), the district is equipped with PV panels, for a total peak power equal to 466 kW;
- in the second scenario (SC#2), a 250 kW wind turbine is installed in addition to PV panels.

The producibility of renewable plants has been dynamically simulated in HOMER Pro® [61] on a quarter-hour basis. On a yearly basis, the electricity supplied by the PV plants and the wind turbine is equal to 594 and 403 MWh/y, respectively. Renewable electricity exports have been determined by using the data regarding the energy supply of renewable-based plants and users' demand available with a fifteen-minutes timestep. As a result, surplus energy exported outside of the boundaries of the district is equal to 265 and 473 MWh/y in SC#1 and SC#2, respectively. These data are used for filling the *En-to-EnD* template.

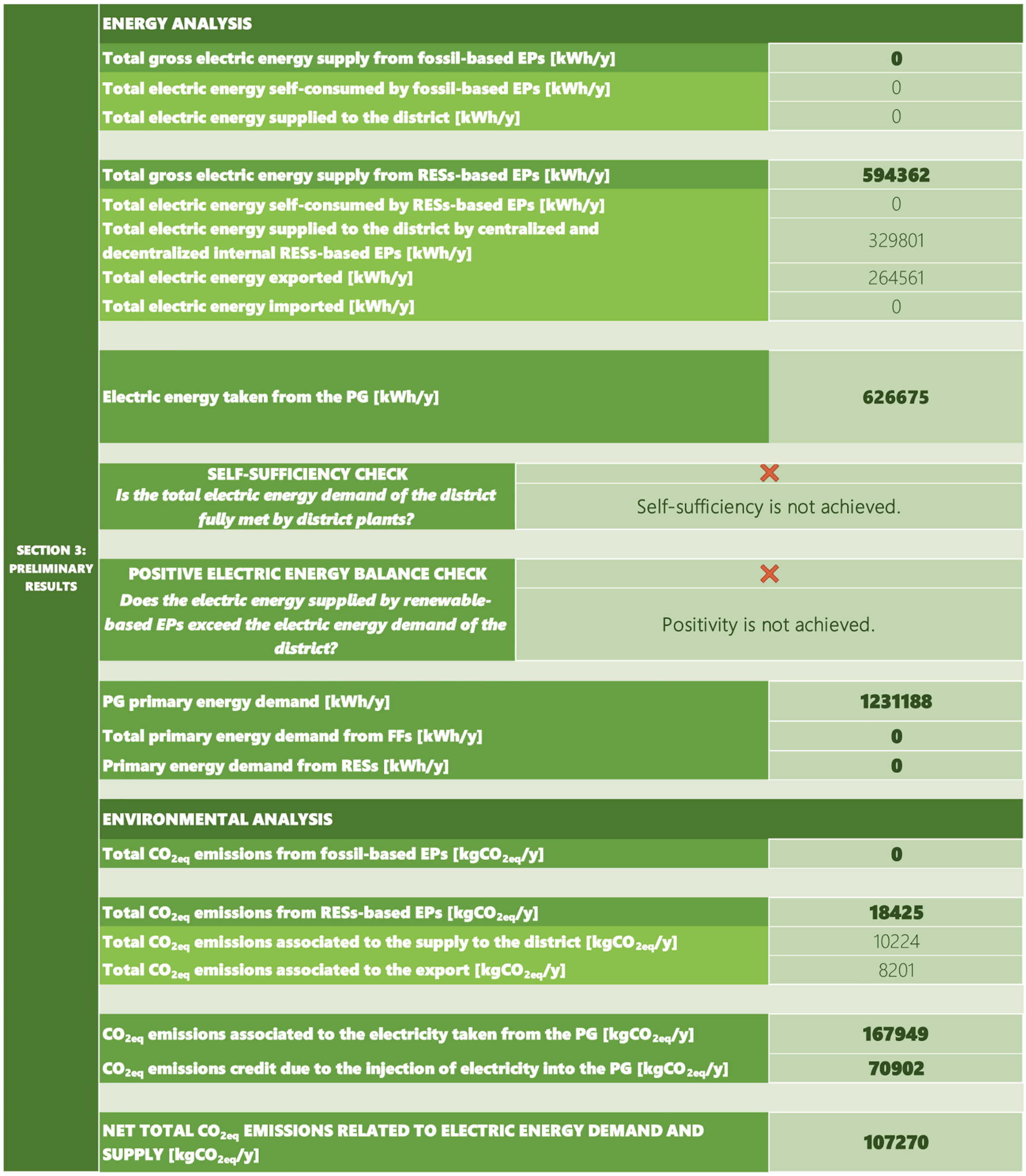
Since the district has electricity requests only, the section to be completed using the data available is the one referred to electric energy demand and supply. Focusing on SC#1 first, Fig. 7 shows the preliminary results obtained from the tool. Users take from the PG 627 MWh/y. Being the EF of the Italian PG equal to 0.268 $kgCO_{2eq}/kWh_{el}$ under the life-cycle approach (Table A.3), corresponding CO_{2eq} emissions are equal to 168 tCO_{2eq}/y. The emission credit due to electric energy export is equal to 71 tCO_{2eq}/y. Hence, net CO_{2eq} emissions are equal to 107 tCO_{2eq}/y by including 10 tCO_{2eq}/y due to self-consumption of electricity from PV panels. As it is emphasized by the tool, in the current scenario the district is not energy self-sufficient, and the energy balance is not positive. It should be noted that only the primary energy demand of the PG has been determined, assuming the efficiency of the PG equal to 0.509 [59].

Fig. 8 shows the preliminary results obtained in SC#2. After the installation of the 250 kW wind turbine, the gross electricity supply from RESs-based plants increases to 998 MWh/y and exceeds users' annual electric load thereby. Although the positive energy target has been achieved, the district is still not self-sufficient. As a matter of fact, users still take electricity from the PG, for a total of 432 MWh/y. Resulting net CO_{2eq} emissions are equal to 3 tCO_{2eq}/y, even if more than a half of users' electric load is covered by renewable plants.

Fig. 9 shows the result section of the tool in SC#2. It gives a summary about district total emissions, which are equal to 130 tCO_{2eq}/y accounting for the sum of 116 tCO_{2eq}/y due to the electricity taken from the PG and 14 tCO_{2eq}/y due to the self-consumption of electricity supplied by renewable-based plants. The emission credit related to the export of surplus electricity is instead equal to 127 tCO_{2eq}/y.

The tool also provides as output various charts which support the understating of the results obtained, as in Fig. 10. Fig. 10(a) shows that in SC#2 the PG supplies about 30 % of users' total electric load. Based on the approach chosen, only the primary energy demand of the PG has been determined (Fig. 10(b)). CO_{2eq} missions due to the PG are about 89 % of the total (Fig. 10(c)).

According to the results obtained, the renewable-based plants proposed for installation in the district do not allow to achieve carbon neutrality, although SC#2 is characterised by a positive energy balance. This outcome mainly reflects the mismatch between renewable



SECTION 3: PRELIMINARY RESULTS		
	ENERGY ANALYSIS	
	Total gross electric energy supply from fossil-based EPs [kWh/y]	**0**
	Total electric energy self-consumed by fossil-based EPs [kWh/y]	0
	Total electric energy supplied to the district [kWh/y]	0
	Total gross electric energy supply from RESs-based EPs [kWh/y]	**594362**
	Total electric energy self-consumed by RESs-based EPs [kWh/y]	0
	Total electric energy supplied to the district by centralized and decentralized internal RESs-based EPs [kWh/y]	329801
	Total electric energy exported [kWh/y]	264561
	Total electric energy imported [kWh/y]	0
	Electric energy taken from the PG [kWh/y]	**626675**
	SELF-SUFFICIENCY CHECK *Is the total electric energy demand of the district fully met by district plants?*	✗ Self-sufficiency is not achieved.
	POSITIVE ELECTRIC ENERGY BALANCE CHECK *Does the electric energy supplied by renewable-based EPs exceed the electric energy demand of the district?*	✗ Positivity is not achieved.
	PG primary energy demand [kWh/y]	**1231188**
	Total primary energy demand from FFs [kWh/y]	**0**
	Primary energy demand from RESs [kWh/y]	**0**
	ENVIRONMENTAL ANALYSIS	
	Total CO_{2eq} emissions from fossil-based EPs [kgCO_{2eq}/y]	**0**
	Total CO_{2eq} emissions from RESs-based EPs [kgCO_{2eq}/y]	**18425**
	Total CO_{2eq} emissions associated to the supply to the district [kgCO_{2eq}/y]	10224
	Total CO_{2eq} emissions associated to the export [kgCO_{2eq}/y]	8201
	CO_{2eq} emissions associated to the electricity taken from the PG [kgCO_{2eq}/y]	**167949**
	CO_{2eq} emissions credit due to the injection of electricity into the PG [kgCO_{2eq}/y]	**70902**
	NET TOTAL CO_{2eq} EMISSIONS RELATED TO ELECTRIC ENERGY DEMAND AND SUPPLY [kgCO_{2eq}/y]	**107270**

Fig. 7. Preliminary results obtained in SC#1.

electricity supply and users' electric energy demand. Hence, the analysis of this case study highlights the usefulness of the results provided by the proposed methodology and tool. Indeed, they may guide the design of alternative configurations aimed at increasing users' energy self-sufficiency, with consequent positive effects on the environmental impact of the district. As such, this novel evaluation framework is not limited to characterize the district being analysed from the energy and environmental perspective for ultimately verifying the accomplishment of positive energy balance and carbon neutrality goals on an annual basis. Rather, it aims at assessing energy and emission balances for drawing current and future scenarios intended to foster the achievement of climate and energy goals. The availability of the tool is intended to make the methodology accessible to all users, including researchers, municipalities, and local stakeholders willing to be engaged in actions targeted to sustainability. In this way, the findings of this work may support the energy transition of cities, by encompassing into the energy and environmental goals set at community or district level those more ambitious and challenging characterizing PEDs.

5. Conclusions

In the scientific literature a globally shared approach for supporting the energy transition of cities, which represent the core of the energy transition claimed for achieving carbon neutrality by 2050, is still lacking. This paper proposes a novel methodology for the energy and environmental analysis of districts and communities aimed at verifying the accomplishment of the goals of Positive Energy Districts. The proposed approach relies on the basic concepts underpinning the "Baseline Emission Inventory", introduced in the European Union under the "Covenant of Mayors for Climate and Energy". As such, it brings together the successful methodological principles adopted within the European policy framework and the ambitious and challenging objectives characterizing Positive Energy Districts. The detailed mathematical model developed in this work has been transposed in a user-friendly, ready-to-use tool called *"En-to-EnD. Energy and Environmental analysis of Districts"* which is already available online. Once received all necessary input data, the tool automatically returns the desired energy and carbon emission balances, thus confirming or not the achievement of the

SECTION 3: PRELIMINARY RESULTS		
	ENERGY ANALYSIS	
	Total gross electric energy supply from fossil-based EPs [kWh/y]	**0**
	Total electric energy self-consumed by fossil-based EPs [kWh/y]	0
	Total electric energy supplied to the district [kWh/y]	0
	Total gross electric energy supply from RESs-based EPs [kWh/y]	**997813**
	Total electric energy self-consumed by RESs-based EPs [kWh/y]	0
	Total electric energy supplied to the district by centralized and decentralized internal RESs-based EPs [kWh/y]	524475
	Total electric energy exported [kWh/y]	473337
	Total electric energy imported [kWh/y]	0
	Electric energy taken from the PG [kWh/y]	**432001**
	SELF-SUFFICIENCY CHECK *Is the total electric energy demand of the district fully met by district plants?*	✗ Self-sufficiency is not achieved.
	POSITIVE ELECTRIC ENERGY BALANCE CHECK *Does the electric energy supplied by renewable-based EPs exceed the electric energy demand of the district?*	✓ Positivity is achieved.
	PG primary energy demand [kWh/y]	**848724**
	Total primary energy demand from FFs [kWh/y]	**0**
	Primary energy demand from RESs [kWh/y]	**0**
	ENVIRONMENTAL ANALYSIS	
	Total CO_{2eq} emissions from fossil-based EPs [$kgCO_{2eq}$/y]	**0**
	Total CO_{2eq} emissions from RESs-based EPs [$kgCO_{2eq}$/y]	**26091**
	Total CO_{2eq} emissions associated to the supply to the district [$kgCO_{2eq}$/y]	13923
	Total CO_{2eq} emissions associated to the export [$kgCO_{2eq}$/y]	12168
	CO_{2eq} emissions associated to the electricity taken from the PG [$kgCO_{2eq}$/y]	**115776**
	CO_{2eq} emissions credit due to the injection of electricity into the PG [$kgCO_{2eq}$/y]	**126854**
	NET TOTAL CO_{2eq} EMISSIONS RELATED TO ELECTRIC ENERGY DEMAND AND SUPPLY [$kgCO_{2eq}$/y]	**2844**

Fig. 8. Preliminary results obtained in SC#2.

TOTAL EMISSION BALANCES	TOTAL CO_{2eq} EMISSIONS [$kgCO_{2eq}$/y]	129699
	TOTAL CO_{2eq} EMISSIONS FROM FOSSIL-BASED PLANTS [$kgCO_{2eq}$/y]	0
	TOTAL CO_{2eq} EMISSIONS FROM RENAWABLE-BASED PLANTS [$kgCO_{2eq}$/y]	13923
DISTRICT EMISSION BALANCES	TOTAL CO_{2eq} EMISSIONS RELATED TO RENEWABLE ENERGY SUPPLY [$kgCO_{2eq}$/y]	13923
	TOTAL CO_{2eq} EMISSIONS RELATED TO RENEWABLE ENERGY EXPORT [$kgCO_{2eq}$/y]	12168
	TOTAL CO_{2eq} EMISSIONS FROM THE POWER GRID [$kgCO_{2eq}$/y]	115776
	CO_{2eq} EMISSIONS CREDIT DUE TO THE INJECTION OF ELECTRICITY INTO THE POWER GRID [$kgCO_{2eq}$/y]	126854
	NET TOTAL CO_{2eq} EMISSIONS [$kgCO_{2eq}$/y]	2844
DISTRICT POSITIVITE ENERGY BALANCE CHECK	Are thermal, cooling and electric energy supply from renewable-based plants simultaneuosly higher than users' thermal, cooling and electric energy demand, respectively?	✓ Yes. Hence, the positive energy target has been achieved
DISTRICT CARBON NEUTRALITY CHECK	Are net total CO_{2eq} emissions null (or negative)?	✗

Fig. 9. Results section in SC#2.

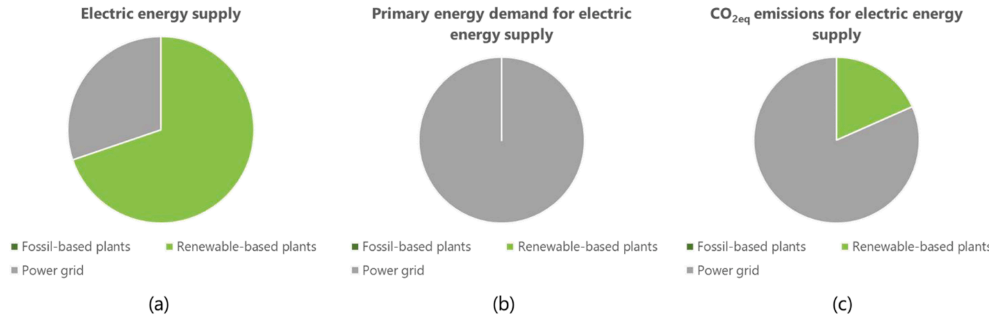


Fig. 10. En-to-EnD output charts in SC#2.

Positive Energy District status. The results obtained may support the development of measures targeted to the improvement of the sustainability of cities, owing to an approach accessible to every kind of users, including researchers, municipalities, and stakeholders. For demonstrating the applicability of the methods proposed, a reference case study in Benevento, a city in the South of Italy, has been analysed in two scenarios. The district under investigation does not achieve carbon neutrality, although in the second scenario the electric energy balance turns out to be positive thanks to the installation of photovoltaic panels (466 kW) and a wind turbine (250 kW). Hence, the results obtained turn out to be useful for the design of alternative configurations aimed at ensuring higher energy self-sufficiency and better environmental performance.

CRediT authorship contribution statement

E. Marrasso: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **C. Martone:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **G. Pallotta:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **C. Roselli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **M. Sasso:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendices.

Appendix A. Appendix to Section 2.2: Emission factors

Table A1
Default activity and life-cycle based EFs adopted within the Covenant of Mayors.

Energy carriers (IPCC denomination)		Activity-based EFs		LCA-based EFs	
		[tCO_2/MWh]	[tCO_{2eq}/MWh]	[tCO_2/MWh]	[tCO_{2eq}/MWh]
Natural gas		0.202	0.202	0.226	0.242
Liquefied Petroleum Gases		0.227	0.227	0.276	0.287
Natural Gas Liquids		0.231	0.232	–	–
Diesel		0.267	0.268	0.296	0.308
Motor gasoline		0.249	0.250	0.301	0.314
Lignite		0.364	0.365	0.370	0.377
Anthracite		0.354	0.356	0.371	0.395
Other Bituminous Coal		0.341	0.342	0.357	0.382
Sub-Bituminous Coal		0.346	0.348	0.363	0.387
Peat		0.382	0.383	0.388	0.391
Municipal Wastes (non-biomass fraction)		0.330	0.337	0.429	0.437
Other liquid biofuels	Carbon neutral	0	0.001	0.029	0.043
	Non carbon neutral	0.287	0.287	0.316	0.330
Bio-gasoline	Carbon neutral	0	0.001	0.124	0.177
	Non carbon neutral	0.255	0.256	0.379	0.432
Biodiesel	Carbon neutral	0	0.001	0.068	0.105

(continued on next page)

Table A1 (*continued*)

Energy carriers (IPCC denomination)		Activity-based EFs		LCA-based EFs	
		[tCO_2/MWh]	[tCO_{2eq}/MWh]	[tCO_2/MWh]	[tCO_{2eq}/MWh]
	Non carbon neutral	0.255	0.256	0.323	0.360
Wood/Wood Waste	Carbon neutral	0	0.007	0.047	0.056
	Non carbon neutral	0.403	0.410	0.450	0.460
Municipal wastes (biom. fraction)	Carbon neutral	0	0.007	0.053	0.061
	Non carbon neutral	0.360	0.367	0.413	0.421
Other primary solid biomass	Carbon neutral	0	0.007	0.008	0.019
	Non carbon neutral	0.360	0.367	0.368	0.379
Biogas	Carbon neutral	0	0.0002	0.026	0.047
	Non carbon neutral	0.197	0.197	0.222	0.244
Solar thermal		0	0	0.036	0.036
Geothermal		0	0	0.090	0.090

Table A2
Default activity and life-cycle based EFs for electric energy supply from RESs adopted within the Covenant of Mayors.

Renewable-based electric energy production plants	Activity-based EFs		LCA-based EFs	
	[tCO_2/MWh_{el}]	[tCO_{2eq}/MWh_{el}]	[tCO_2/MWh_{el}]	[tCO_{2eq}/MWh_{el}]
PV	0	0	0.030	0.031
Wind turbine	0	0	0.019	0.019
Hydroelectric	0	0	0.101	0.106

Table A3
Default activity and life-cycle based national EFs for electricity production proposed within the Covenant of Mayors and referred to 2020.

Country	Activity-based [tCO_2/MWh_{el}]	LCA-based [tCO_{2eq}/MWh_{el}]
Austria	0.130	0.132
Belgium	0.181	0.183
Bulgaria	0.528	0.530
Croatia	0.145	0.146
Cyprus	0.684	0.686
Czech Republic	0.594	0.596
Denmark	0.058	0.061
Estonia	0.414	0.419
Finland	0.065	0.067
France	0.066	0.067
Germany	0.375	0.376
Greece	0.377	0.378
Hungary	0.186	0.187
Ireland	0.296	0.297
Italy	0.267	0.268
Latvia	0.074	0.076
Lithuania	0.059	0.060
Luxembourg	0.015	0.016
Malta	0.349	0.349
Netherlands	0.337	0.339
Poland	0.722	0.725
Portugal	0.212	0.214
Romania	0.332	0.333
Slovak Republic	0.187	0.188
Slovenia	0.297	0.299
Spain	0.185	0.186
Sweden	0.013	0.014

Appendix B. Appendix to Section 3.2: Energy and emissions balances related to thermal and cooling energy demand and supply

$E_{th}^{DHN^{Us}}$ results from Eq. (B.1), where $E_{th,net}^{DHN}$ represents the total net thermal energy available from the DHN on a yearly basis and $E_{th,exp}^{DHN}$ the annual thermal energy exported outside of the district. In turn, $E_{th,net}^{DHN}$ equals the difference between the gross thermal energy delivered to the DHN ($E_{th,gross}^{DHN}$) and the losses occurring within the DHN ($E_{th,loss}^{DHN}$), as stated in Eq. (B.2). The latter account for all types of losses, including those related to thermal energy storage tanks.

$$E_{th}^{DHN^{Us}} = E_{th,net}^{DHN} - E_{th,exp}^{DHN} \tag{B1}$$

$$E_{th,net}^{DHN} = E_{th,gross}^{DHN} - E_{th,loss}^{DHN} \tag{B2}$$

$E_{th,gross}^{DHN}$ accounts for the sum of the yearly thermal energy supplied by external RES-based TPs and imported in the district ($E_{th,imp}^{DHN}$) and the annual thermal energy supplied by the centralized internal TPs ($E_{th}^{TP^{IntCen}}$), whose total number is referred to as $NTP^{Int_{Cen}}$ in Eq. (B.3). To sum up, Eq. (1) can be rewritten in the extended form given by Eq. (B.4).

$$E_{th,gross}^{DHN} = E_{th,imp}^{DHN} + \sum_{i=1}^{NTP^{IntCen}} E_{th_i}^{TP^{IntCen}} \tag{B3}$$

$$E_{th}^{Dis} = E_{th,imp}^{DHN} + \sum_{i=1}^{NTP^{IntCen}} E_{th_i}^{TP^{IntCen}} - E_{th,loss}^{DHN} - E_{th,exp}^{DHN} + \sum_{i=1}^{NTP^{IntDec}} E_{th_i}^{TP^{IntDec}} \tag{B4}$$

For evaluating the annual primary energy demand of thermal energy production plants supplied by primary energy (E_p^{TP}), their primary energy ratio (*PER*) must be considered. In addition, the distinction between FFs and RESs-based plants must be made. The yearly primary energy demand of the *i-th* TP fuelled with a FF ($E_{p_i}^{TP_{FF}}$) is given by Eq. (B.5). Accordingly, the yearly primary energy demand of the *i-th* TP exploiting a RES ($E_{p_i}^{TP_{RES}}$) is given by Eq. (B.6). Conversely, the annual electric energy request of the *i-th* electric-driven TP ($E_{el_i}^{TP_{el}}$) can be determined using Eq. (B.7), where COP_i represents the coefficient of performance of the *i-th* TP.

$$E_{p_i}^{TP_{FF}} = \frac{E_{th_i}^{TP_{FF}}}{PER_i} \tag{B5}$$

$$E_{p_i}^{TP_{RES}} = \frac{E_{th_i}^{TP_{RES}}}{PER_i} \tag{B6}$$

$$E_{el_i}^{TP_{el}} = \frac{E_{th_i}^{TP_{el}}}{COP_i} \tag{B7}$$

Substituting $E_{th_i}^{TP_{FF}}$ and $E_{th_i}^{TP_{RES}}$ with $E_{th_i}^{TP^{IntDec}}$ in Eq. (B.5) or (B.6), the primary energy demand due to the activation of decentralized FFs ($E_p^{TP_{FF}^{IntDec}}$) or RESs-based ($E_p^{TP_{RES}^{IntDec}}$) TPs, respectively, can be estimated. Eq. (B.6) can be used for determining the primary energy demand of RESs-based TPs installed outside the boundaries of the PED ($E_p^{TP_{RES}^{Ext}}$) too. In this regard, two alternatives exist:

- if the district is provided with all the thermal energy supply of the plant, then its gross annual thermal energy production ($E_{th_i}^{TP_{RES}^{Ext}}$) should be used in the numerator;
- if only a part of the thermal energy supplied by the TP is provided to the district, then the numerator should be equal to the yearly thermal energy import of the district increased by the losses occurring within the DHN connecting the TP with the district itself ($E_{th,imp}^{DHN}$).

The primary energy demand due to the yearly thermal energy exports ($E_{p,exp}^{TP_{RES}^{IntCen}}$) results from the ratio of E_{th,exp_i}^{DHN} to the *PER* of the *i-th* renewable-based TP supplying the thermal energy exported according to Eq. (B.8).

$$E_{p,exp}^{TP_{RES}^{IntCen}} = \frac{E_{p,exp}^{TP_{RES}^{IntCen}}}{PER_i} \tag{B8}$$

Appendix C. Appendix to section 3.3: Energy and emission balances related to electric energy demand and supply

For evaluating E_{el}^{Dis} using Eq. (4), $E_{el}^{TP_{el}^{IntCen}}$ can be determined as stated in Eq. (C.1). In particular, the term $E_{el_i}^{TP_{el}^{IntCen}}$ results from Eq. (B.7). Similar considerations apply to $E_{el}^{CP_{el}^{IntCen}}$. In fact, $E_{el_i}^{CP_{el}^{IntCen}}$ can be evaluated using Eq. (B.7) by substituting $E_{th_i}^{TP_{el}}$ with $E_{co_i}^{CP_{el}}$ and COP_i with the energy efficiency ratio of the *i-th* CP (EER_i).

$$E_{el}^{TP_{el}^{IntCen}} = \sum_{i=1}^{NTP_{el}^{IntCen}} E_{el_i}^{TP_{el}^{IntCen}} \tag{C1}$$

The annual net electric energy provided by the centralized internal EPs fuelled with FFs ($E_{el,net}^{EP_{FF}^{IntCen}}$) is given by Eq. (C.2). It equals the sum of each plant's electric energy gross production ($E_{el,gross_i}^{EP_{FF}^{IntCen}}$) decreased by electricity self-consumption ($E_{el,sc_i}^{EP_{FF}^{IntCen}}$) on an annual basis. Eq. (C.3) can be instead used to determine the yearly electric energy supplied by centralized EPs exploiting RESs ($E_{el,net}^{EP_{RES}^{IntCen}}$). This value must be reduced by the electricity exports ($E_{el,exp_i}^{EP_{RES}^{IntCen}}$) too. The sums in Eqs. (C.2) and (C.3) are evaluated over the total number of electric generation plants inside the district fuelled with FFs (NEP_{FF}^{IntCen}) and exploiting RESs (NEP_{RES}^{IntCen}), respectively. Eq. (C.3) can apply also to decentralized EPs.

$$E_{el,net}^{EP_{FF}^{IntCen}} = \sum_{i=1}^{NEP_{FF}^{IntCen}} E_{el,gross_i}^{EP_{FF}^{IntCen}} - E_{el,sc_i}^{EP_{FF}^{IntCen}} \quad (C2)$$

$$E_{el,net}^{EP_{RES}^{IntCen}} = \sum_{i=1}^{NEP_{RES}^{IntCen}} E_{el,gross_i}^{EP_{RES}^{IntCen}} - E_{el,sc_i}^{EP_{RES}^{IntCen}} - E_{el,exp_i}^{EP_{RES}^{IntCen}} \quad (C3)$$

Yearly net electric energy supplied by external RESs-based EPs ($E_{el,net}^{EP_{RES}^{Ext}}$), whose total number is given by NEP_{RES}^{Ext}, can be estimated using Eq. (C.4). In addition to the each plant's self-consumption ($E_{el,sc_i}^{EP_{RES}^{Ext}}$), also the transmission and distribution (T&D) losses ($E_{el,T\&D}^{EP_{RES}^{Ext}}$) due to the transit of electricity on the PG must be counted as a subtractive term. The latter can be determined using a specific factor, which is typically provided by the national Transmission System Operator [56]. Furthermore, the annual gross electricity supply of each external EP ($E_{el,gross_i}^{EP_{RES}^{Ext}}$) must be reduced by the share of electricity exported ($E_{el,exp_i}^{EP_{RES}^{Ext}}$). Lastly, Eq. (C.5) can be adopted to estimate the net electric energy supplied to the users by decentralized EPs ($E_{el,net}^{EP^{IntDec}}$) on an annual basis and activated either by FFs or RESs. In the latter case, also electricity exports ($E_{el,exp_i}^{EP_{RES}^{IntDec}}$) must be considered.

$$E_{el,net}^{EP_{RES}^{Ext}} = \sum_{i=1}^{NEP_{RES}^{Ext}} \left(E_{el,gross_i}^{EP_{RES}^{Ext}} - E_{el,sc_i}^{EP_{RES}^{Ext}} - E_{el,exp_i}^{EP_{RES}^{Ext}} \right) - E_{el,T\&D}^{EP_{RES}^{Ext}} \quad (C4)$$

$$E_{el,net}^{EP_{FF/RES}^{IntDec}} = \sum_{i=1}^{NEP^{IntDec}} E_{el,gross_i}^{EP_{FF/RES}^{IntDec}} - E_{el,sc_i}^{EP_{FF/RES}^{IntDec}} - E_{el,exp_i}^{EP_{RES}^{IntDec}} \quad (C5)$$

Eq. (C.6) allows to determine the annual primary energy demand of the *i-th* EPs fuelled with FFs ($E_{p_i}^{EP_{FF}^{IntCen/Dec}}$), being it centralized or not. η_i is the electric efficiency of the *i-th* EP. Likewise, the primary energy demand of decentralized or centralized renewable EPs ($E_{p_i}^{EP_{RES}^{IntCen/Dec}}$) can be determined as stated in Eq. (C.7). Indeed, the primary energy demand due to electricity exports must not be taken into account in the total emission balance of the district. As regards the primary energy demand of external EPs ($E_{p_i}^{EP_{RES}^{Ext}}$), two alternatives exist. On the one hand, if the external EP supplies electric energy to the district only, then its gross electric energy supply ($E_{el,gross_i}^{EP_{RES}^{Ext}}$) should be considered. Conversely, the electric energy imports increased by the T&D losses which occur within the PG should be taken into account.

$$E_{p_i}^{EP_{FF}^{IntCen/Dec}} = \frac{E_{el,gross_i}^{EP_{FF}^{IntCen/Dec}}}{\eta_i} \quad (C6)$$

$$E_{p_i}^{EP_{RES}^{IntCen/Dec}} = \frac{E_{el,gross_i}^{EP_{RES}^{IntCen/Dec}} - E_{el,exp_i}^{EP_{RES}^{IntCen/Dec}}}{\eta_i} \quad (C7)$$

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