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One piece of the puzzle towards 100 Positive Energy Districts (PEDs) across Europe by 2025: An open-source approach to unveil favourable locations of PV-based PEDs from a techno-economic perspective

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ABSTRACT

To reduce CO_2 emissions, the European Commission aims at having 100 Positive Energy Districts (PEDs) planned, developed or established by 2025. A PED annually exports more energy than it imports from the local grid. Because of Europe's diversity, this study aims to indicate where in the EU and under which tariff circumstances an electrified PED will likely thrive most. To do so, the work uses a tailor-made, mixed-integer linear programming model to optimise electrified PED solutions and compare them to the respective status quo for various representative zone-tariff parameter combinations. Results indicate that the optimal potential for PEDs is in southern Europe, with a dynamic electricity tariff and where previously no district heating was used. Under those circumstances, the PED concept could save around 84% of carbon emissions, while being more economical over the project horizon. Pricing of CO_2 emissions of energy services additionally nudges towards PED implementation. By limiting the power exchange of the PED with the grid, some of the negative grid impacts can be reduced. This study provides an essential insight into where in Europe a PED could be a sensible addition compared to where other decarbonisation approaches might be more beneficial.

1. Introduction

Cities are a major contributor to the European Union's (EU) primary energy consumption with around 70%, alongside its CO_2 emissions [1]. While demanding the majority of energy resources, cities do not contribute significantly to the generation of renewable energy [2]. In 2019, the residential sector was responsible for approximately 26% of the final energy consumption across the EU, while more than half was electricity and gas [3]. Fig. 1 clearly shows the end uses of residential energy consumption. Almost 80% of the energy is used for heating (space & domestic hot water (DHW)). Gas is still the primary energy source for heating, while electricity plays a minor role.

To improve the self-supply of renewable energy in urban areas and decrease carbon emissions, the European Commission aims for 100 Positive Energy Districts (PED) to be planned, developed or constructed by 2025 as part of the Strategic Energy Technology (SET) Plan [4]. A PED defines a district that generates more local renewable energy than energy consumed from the outer-district boundaries while keeping a net-zero carbon emission balance. For comparability, this energy exchange is accounted for in primary energy [4,5]. Considering Fig. 1, it is crucial to include heating holistically in PED concepts as space and DHW heating represent the most significant contributions to the final energy consumption of the residential sector before electricity and cooling. Furthermore, heating is still primarily fossil-based, specifically in certain parts of the EU. Therefore, various studies regard electrification of heating as a crucial contribution to the decarbonisation of residential heating demand [6–10], as biomass usage is controversial [11], and its local emissions would persist in any case [12]. Moreover, PEDs require renewable energy generation on a local level. In urban areas, the primary option is electricity generation with solar PV panels on rooftops because, for anything else, space is too scarce or resources are not available.

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Nomenclature

Decision Variables

$c_{y,ts}^{x_c,z_c}$	Cooling flow from technology x_c to z_c
C_y	Total cost per year
cap_{tec}	Capacity of technology
$Cfix_y$	Fix costs
$Cvar_y$	Variable costs
$h_{y,ts}^{x_h,z_h}$	Heat flow from technology x_h to z_h
I_0	Initial investment cost
$p_{y,ts}^{x_e,z_e}$	Power flow from technology x_e to z_e
R_y	Revenue per year

Sets

TEC	Set of technologies
TS	Vector of timesteps per year
V	Vector of optimisation variables
$X_{e/h/c}$	Technologies that can output e, h or c
Y	Years of project
$Z_{e/h/c}$	Technologies that can demand e, h or c

Paramter

η_{bat}	Battery roundtrip efficiency
η_{eb}	Electric boiler efficiency
η_{pv}	PV panel efficiency
$bhp_{y,ts}$	Binary heat pump variable
$cfix_{tec}$	Specific fix costs [€/kWa]
$COP_{c,ts}$	Cooling COP of heat pump
$COP_{h,ts}$	Heating COP of heat pump
$cspec_{tec}$	Specific cost of technology [€/kW(h)]
$cvar_{tec}$	Specific variable costs [€/kWh]
dt	Time resolution [min]
i	Interest rate
M	Large constant
$PEF_{im/ex}$	Primary Energy Factor import or export
$t_{y,ts}$	Tariff each timestep, each year
$tf_{y,ts}$	Feed-in tariff each timestep, each year

Acronyms

AC	Air Conditioner
c	cooling
CCHP	Combined Cooling, Heating and Power
CHP	Combined Heat and Power
CAPEX	Capital Expenditure
CO2	Carbon Dioxide
COP	Coefficient Of Performance
DHW	Domestic Hot Water
e	electricity
ECI	European Cooling Index
EHI	European Heating Index
EU	European Union
FIT	Feed-in tariff
GCR	Ground Cloverage Ratio
h	heating
KG	Köppen-Geiger
MAE	Mean Average Error
MFB	Multi-Family Building
MILP	Mixed-Integer Linear Programming
NPV	Net Present Value
OPEX	Operational Expenditure
PED	Positive Energy District
PR	Performance Ratio
PV	Photovoltaic
RFR	Random Forest Regressor
RMSE	Root Mean Squared Error
SET	Strategic Energy Technology
SOC	State of charge
t	Tonne
ToU	Time-of-Use
ts	time step
US	United States
Z1-5	Zone one to five

One major challenge regarding the European goal of 100 PEDs is that the EU is large and diverse in many crucial characteristics, such as climate and energy cost. Thus, the core objective of this work is to determine the optimal geographical zone and electricity tariff characteristics for electrified[1] multi-energy PEDs across Europe while accounting for grid stability implications. Therefore, a novel 3-step approach consisting of spatial zoning, heating and cooling demand generation, and mixed-inter linear programming optimisation is applied.

2. State-of-the-art

The state-of-the-art academic literature relevant to this work includes the following topics: The concept of Positive Energy Districts, current work on techno-economic modelling of PEDs and their energy balance, and modelling approaches towards energy communities. Finally, this study's contribution to the current state-of-the-art is presented.

2.1. The concept of Positive Energy Districts

The PED concept emerged from related ideas such as (Net/Nearly/Positive) Zero Energy Buildings or Energy Positive Neighbourhoods as part of the evolution from building to multi-building concepts to speed up urban decarbonisation [13,14]. It was initially defined by the European Commission in the SET-Plan Action 3.2 "Smart Cities and Communities" in 2018 [4]. The SET-Plan defines a PED as an urban district that strives towards an excess of local, renewable energy generation as well as net-zero energy imports and carbon emissions. Beyond the energy and emission balance requirements, a PED shall deploy high levels of energy efficiency, provide energy flexibility and security and increase the citizens' quality of life [4]. This results in the three functions of PEDs: Energy efficiency in buildings, local and regional supply of renewable energy and flexibility of the energy consumption. Further institutions, such as the Joint Programming Initiative Urban Europe, extended this definition towards inclusiveness, human-centricity and resilience to the distribution grid [5]. PEDs can be divided into autonomous, dynamic and virtual PEDs. Autonomous and dynamic PEDs have strict spatial boundaries. However, while dynamic PEDs can freely interact with the surrounding energy system, autonomous PEDs are not allowed to import any energy and are therefore self-

[1] PED based on PV, batteries, air-sourced heat pumps and electric boilers.

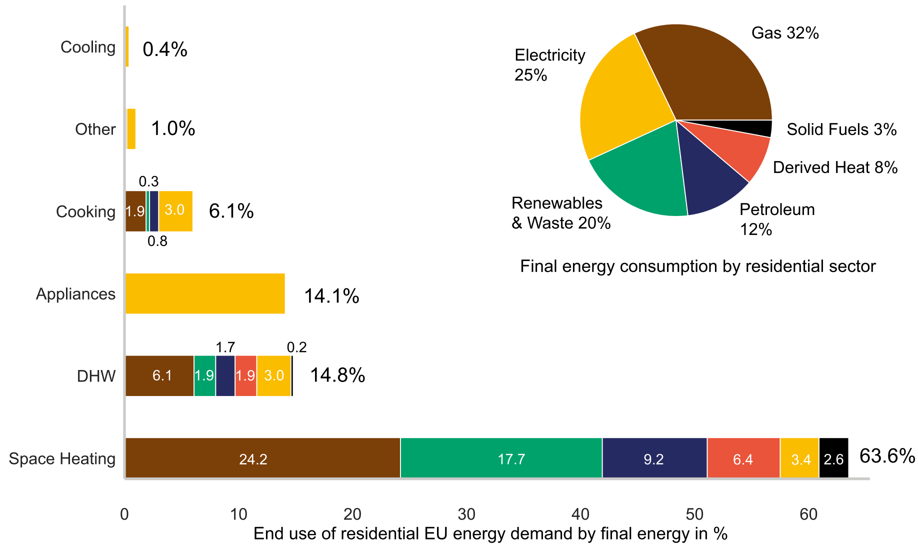

Fig. 1. End use of residential energy demand in the EU and composition of the final energy consumption feeding in each end use in 2019; Data from [3].

sufficient. The virtual PED opens the spatial boundaries of the districts to allow off-site renewable generation [14,15]. Initiatives such as the PED specific subgroup Annex 83 of the International Energy Agency [16] and the PED-EU research network [17], as well as EU-funded projects such as "MAKING CITY" [18], "ATELIER" [19], "+CityxChange" [20], "POCITYF" [21], "SPARCS" [22] or "Smart-BEEjS" [23] spark a strong research interest around PEDs. The Annex 83 works on PED stakeholder involvement, definition refinement, identification of technical solutions and modelling tool creation, as well as sustainability impact assessment of PEDs [16]. Also, academic literature approaches the PED concept from many diverse disciplines beyond the technical one. Ref. [24] for example, presents a framework towards justice and inclusion, and the authors in Ref. [25] analyse potential justice problems in PED development. Authors in Ref. [26] investigate PEDs as forms of sustainable business models to answer the question of how various stakeholders add value to the community. Complementary to the ongoing social research on PEDs, this work focuses on the techno-economic planning and feasibility of dynamic PEDs.

2.2. Techno-economic analysis of PEDs and related concepts

Despite the relative novelty of the concept, techno-economic analyses of PEDs are being actively discussed in the scientific literature. In Ref. [27], the authors assess obstacles of using existing energy modelling software for PED research and development. They conclude that, among others, input data and its customisation, grid impact, the complexity of multi-energy interaction and information on district infrastructure are the key challenges that make existing modelling software not applicable to PEDs. Therefore, most existing literature is based on self-developed PED assessment approaches such as the one proposed by Ref. [28]. The authors describe a multi-energy calculation approach to evaluate PEDs techno-economically. The primary energy factor is used as a metric of comparison. The authors do not apply the proposed methodology to a test case. Authors in Refs. [29,30] assess specific neighbourhoods of Vienna regarding their economic multi-energy PED viability, without optimising the energy technology portfolio or dispatch. The main result shows that the viability of PEDs is strongly related to the floor space index of the neighbourhood, determining the available space for PV power generation compared to the amount of energy demanded. In Ref. [31], the authors elaborate on two optimisation approaches for Energy Positive Neighbourhoods, which are highly similar to PEDs from a technical perspective. While one approach assumes a centrally managed district, the other includes a hierarchical two-level optimisation. Both approaches are applied to an Irish case study, including electricity and heating. Ref. [32] presents a linear programming model for PEDs introducing a dynamic primary energy balance. It is applied to a rural and urban, electricity-only case study on the Spanish island La Palma and accounts for grid impacts. The dynamic balancing approach increases the flexibility of the grid and the PED but requires high-resolution energy generation data of the larger environment. Finally, Ref. [33] defines the loads and technologies, the spatial boundaries, the temporal resolution and the objective function as key factors of modelling that are specifically important for PEDs. The authors highlight that evaluating the modelling goal and target audience is the initial step that shapes the four aspects.

2.3. Energy district/community modelling

A positive energy district can be seen as a spatially-restricted energy community with the requirement to fulfil an annual positive export-import balance as they go beyond the singular ownership model of one prosumer [25]. The district/neighbourhood/community-wide modelling evaluation can be grouped into two approaches: the "collective" district with aggregated demand and supply and the "multi-node" neighbourhood, where each community participant is modelled specifically. The collective district approach does not consider the single participant and is thus mainly used for aggregated technology potential, collective energy dispatch and interaction with the surrounding environment [34]. Authors of [35] use mixed-integer linear programming (MILP) to assess the optimal usage of renewable energy by an urban neighbourhood in the case of Vienna. The analysis includes electricity, heating and cooling supply on an aggregated level. Ref. [36] uses a simulation approach to evaluate the applicability of a biomass-based combined heat and power (CHP) plant, ground sourced heat pumps and PV installations to decarbonise a district in northern Italy. Authors of [37] present a multi-energy hub approach based on MILP to optimise the combined energy generation, storage and conversion portfolio of districts. This collective method of energy community assessment is an adequate approach towards early-stage planning of combined cost and required technology portfolio or early feasibility analysis over a large time horizon. Understanding the interaction between the actors of the energy community and their individual benefits or including spatial limitations requires a disaggregated approach. Common ways to do so include the use of multi-node MILP models [38] to include more spatial detail, bi-level optimisation [39] to account for the objectives of two parties, or the inclusion of game theory [40,41] to integrate multi-agent behaviour. This, however, can raise the complexity of the modelling approach, and it becomes more computationally expensive to, e.g. calculate large time horizons. Thus, there is a trade-off between time-horizon, temporal and spatial resolution, sectoral coverage and technical detail [34]. Therefore, each approach to community modelling serves a specific aim that needs to align with the research questions and shifts priorities to different aspects of modelling.

2.4. Contribution

This work contributes to the literature two-fold. Firstly, the electrified PED concept is assessed according to all four energy demands/services[2] in different European climate areas to represent the concept's potential across the EU. This is a significant contribution beyond the state of the art of PED modelling as previous work focuses on specific case studies as discussed in Section 2.2. However, due to the highly variant climatic conditions of the EU [42] and different electricity tariffs [43], a single case study is not representative. Thus, this paper contributes to the literature by evaluating the potential of the electrified PED concept across Europe, indicating where it would be most applicable. This is also recognised by the PED specific subgroup Annex 83 of the International Energy Agency, which dedicates a whole task towards PED modelling and optimisation [16]. Secondly, this paper presents an approach to energy system analysis for large areas, such as continents. While most studies on the over-regional potential of energy systems focus on the climate [44–51], this work includes the tariffs as an additional layer of diversification to unveil the optimal conditions under which a fully electrified PED concept thrives. This approach, including its open-source optimisation, is not confined to the concept of PEDs but can be applied to concepts that do not require a positive energy balance. Generally speaking, the sheer amount of EU funded projects on PEDs presented in Section 2.1 shows the significance of the PED concept and therefore the importance of related academic studies. Against the above-mentioned contributions, this paper aims to answer the following specific questions:

- How does the fully electrified PED concept compare to the status quo?
- How does the PED concept compare across Europe?
- Under which electricity cost parameters would a PED concept thrive most?
- How does limiting the grid impact affect the technology portfolio and cost of the PED?

3. Methodology

This section includes an overview of the methodology, followed by an in-depth elaboration of each specific methodological step. As shown in Fig. 2, there are three major parts of the methodology to create a PED potential map across Europe. Step one explains the zoning of Europe in representative areas (Section 3.1). The second step elaborates a random-forest based machine learning algorithm to generate the space heating and cooling demand to overcome data shortage (Section 3.2). Together with the electric load and the DHW demand that are assumed to be equal for each zone, the induced space heating and cooling loads are then fed into the mixed-integer linear programming (MILP) model as the third step of the methodology (Section 3.3). The MILP modelling approach, as the core of the methodology, evaluates the optimal multi-energy portfolio and energy flows for the district. Finally, Section 3.4 introduces the initial scenarios that the work analyses. Section 3.5 describes the parameters that are changed and tested on their influence on the PED potential of a zone.

Sensible multi-energy demand data is a challenging topic in any energy modelling study, in particular when the respective area is as large as Europe. Here, synthetic hourly multi-energy demand profiles are provided by the Fraunhofer Institute using their in-house developed software SynPro[3] [52]. SynPro is a load generator for the German market. To overcome the data gap for the entire Europe, the machine learning demand generator is used, which is taught on profiles from the city of Munich to create loads for the remaining areas. The loads represent a non-renovated multi-family building (MFBold) with six apartments and standard inhabitant behaviour. 20 MFBold assemble a district in this work. Furthermore, the MILP PED model uses ERA5 data from the Copernicus project as meteorological data for the defined zones [53].

3.1. EU zones

The climate is the leading indicator for zoning as it highly affects two types of energy uses, namely space heating and cooling [54]. A widely accepted classification system for climate zones is the Köpper-Geiger (KG) approach [42]. With the KG classification system in mind, combined with European Heating and Cooling Indicies (EHI/ECI), the PVSites[4] consortium established five zones for nearly zero-energy buildings, as shown in Table 1. Nearly zero-energy buildings require almost covering the annual energy demand by local renewable generation and are therefore similar to PEDs. Thus, the presented methodology in this work re-uses the five zones created by the PVSites consortium. Also, Refs. [50,51] apply this method designed by Ref. [54] to determine the impact of climate change on residential buildings across Europe and to investigate the potential of residential multi-energy generation systems across Europe, respectively. Similarly, climate-based approaches have been used for studies of other large countries. Refs. [47,48] study energy systems across the United States by zoning according to the KG zones and heating and cooling degree days, respectively. Finally, Refs. [44,46] investigate energy system potentials across China using five typical Chinese climate zones. Typically, a representative city per climate zone is chosen.

The most prominent KG zones in Europe's mainland are Csa (warm Mediterranean climate), Csb (temperate Mediterranean climate), Cfb (cool oceanic climate), Dfb (temperate continental climate/humid continental climate) and Dfc (cool continental climate/subarctic climate). Thus, this paper compares Seville, Madrid, Munich, Brussels and Stockholm to create a modest

[2] Electric energy, space & DHW heating and space cooling.

[3] SynPro demand profiles encompass electric, DHW, space heating and space cooling demand.

[4] PVSites consortium: EU Horizon 2020 research project about building-integrated PV.

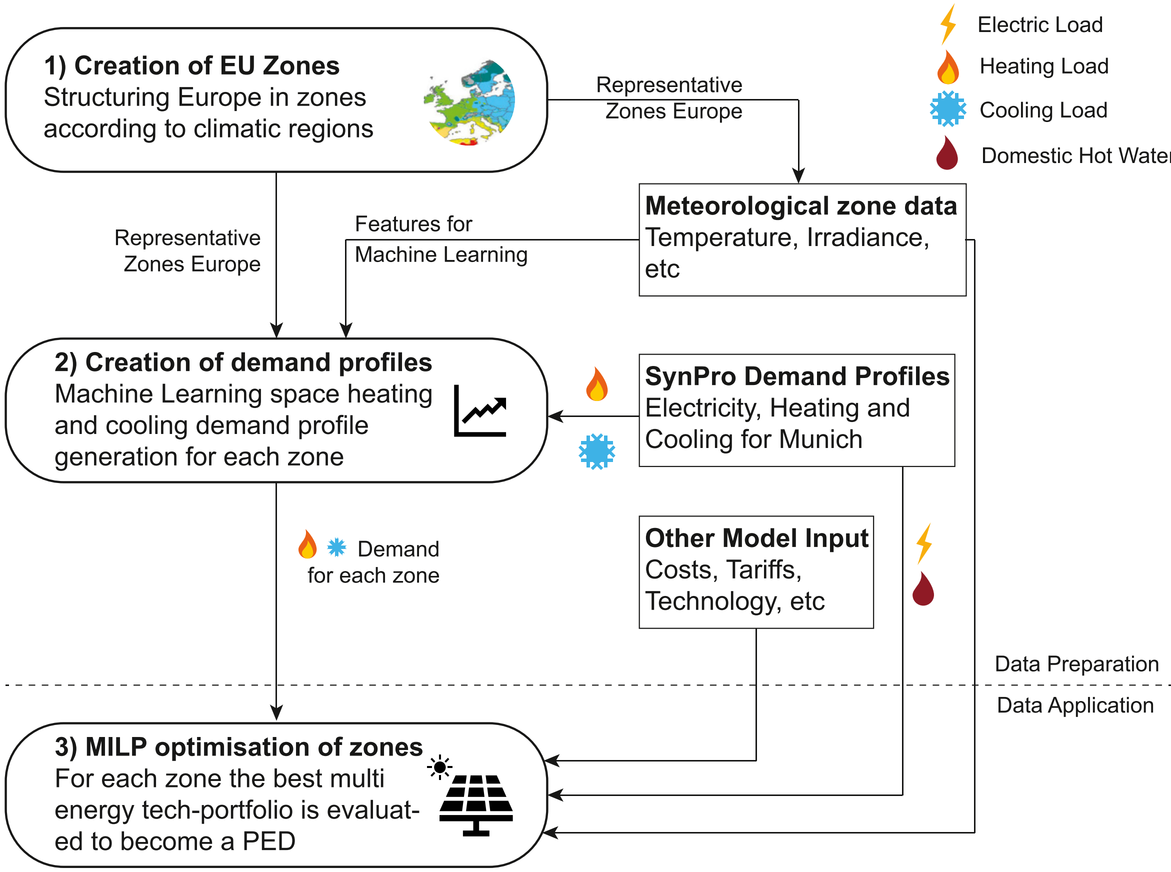

Fig. 2. Overview of the methodology (climate map from [54]).

Table 1
Zones for comparison according to Ref. [54]; highlighted cities are used in this work; colours represent zones in Fig. 3.

Zone	Example Cities	KG
1	**Seville**, Athens, Larnaca, Luga, Catania	Csa
2	**Madrid**, Lisbon, Marseille, Rome	Csa, Csb
3	**Munich**, Bratislava, Budapest, Ljubljana, Milan	Dfb
4	**Brussels**, Amsterdam, Copenhagen, Dublin, London, Paris	Cfb/Dfb
5	**Stockholm**, Helsinki,Riga, Gdansk, Tovarene	Dfc

representation of the EU's climatic conditions. It is assumed that neither the demand for electricity nor domestic hot water changes across the specified zones. Fig. 3 shows the aforementioned zones on the map of the EU. The map mixes the KG approach with the EHI and ECI [54]. The EHI and ECI are normalised indices with 100 being the European average. Strassbourg is a typical average space heating and cooling city, where EHI and ECI 100 intersect. Colours refer to the colours of the zones in Table 1.

3.2. Machine learning demand profile generation

As the multi-energy demand profiles for the district are only available for Munich, further profiles have to be derived for each zone. A random forest [55] algorithm is applied in this work to generate those missing profiles according to specific input data, called features. Features optimally have a strong correlation or significance to the parameter to be determined (heating/cooling demand at each time step). In this study, features and the hyperparameter “number of trees” in the random forest algorithm are manually selected according to trial and error. Hyperparameters are values that set up a specific machine learning algorithm and have to be chosen beforehand, compared to model parameters optimised throughout the learning process [56]. Fig. 4 explains the applied machine learning training process to create a functioning random forest model capable of building heating and cooling demand profiles for further areas.

80% of the 365 days of time-series data is used for training, while the remaining 20% is taken for evaluation [57]. This allows maximal usage of the scarce data for model creation, while still having a smaller share to validate the correctness. The training and test set is split to have non-zero data in both sets. This is specifically important for the cooling data, as cooling is barely needed in Munich. The random forest regressor from the python-based, open-source machine learning toolbox scikit-learn is used [58]. A model is created for the heating and cooling demand label, each with the same input features. The used features are shown in Table 2. The values predicted for the two time steps before are highly important to consider the inertia of space heating and cooling. This study uses the mean absolute error (MAE) and the root mean squared error (RMSE) as typical indicators for evaluation, which are

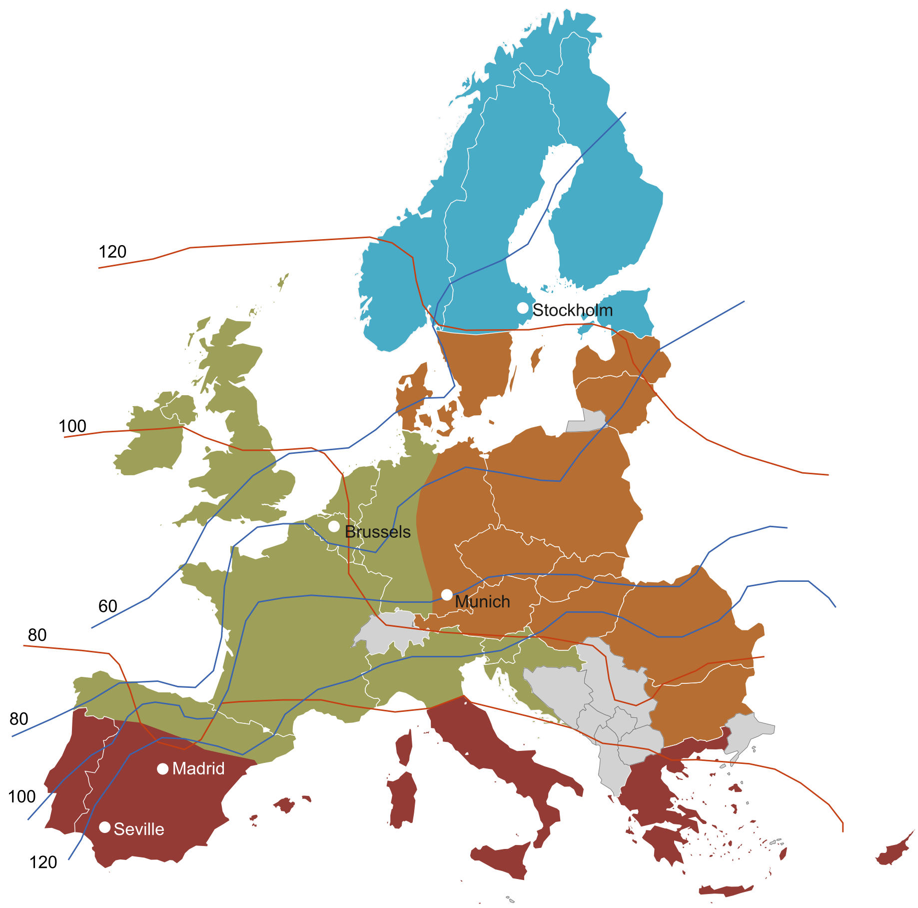

Fig. 3. EU zones map according to Ref. [54] with European Heating Index (EHI) & European Cooling Index (ECI) on red and blue lines, respectively; 100 marks the "standard" heating/cooling line; each other line has a heating/cooling demand of X % compared to locations on the "standard" line, with X being the number on the line.

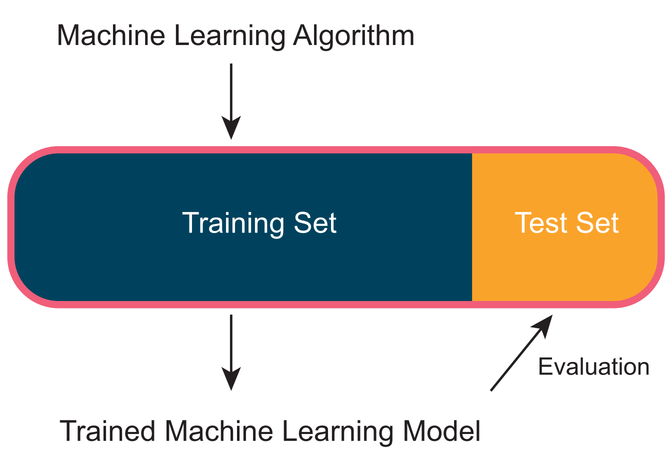

Fig. 4. Machine learning training and evaluation process.

Table 2
Features used in random forest regressor.

Features
Predicted value of ts-1
Predicted value of ts-2
Hour of the day
Ambient temperature
Direct Irradiance
Diffuse Irradiance

mathematically described in Equations (1) and (2).

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - y_i'| \tag{1}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - y_i')^2} \tag{2}$$

Here, N represents the number of samples, y_i the real value of the test set and y_i' the predicted value.

3.3. Mixed integer linear programming PED model

The mixed-integer linear programming model is a tailor-made technology portfolio and energy dispatch optimisation model for PEDs. It extends the in Ref. [32] presented linear programming model to a MILP model in terms of electricity-based heating and cooling to cover the district's energy demand entirely. The model is developed in Python using the well-known Pyomo optimisation extension [59,60] and is publicly available at [61] under an open-source licence. While the model offers user-defined time resolution, this study works with an hourly resolution over a 20 years time horizon. Therefore, the following section describes essential constraints from Ref. [32] and additionally the air-sourced heat pump and the electric boiler mathematically. For further information regarding technology modelling such as PV or battery, we refer to Ref. [32]. Fig. 5 shows an overview of the specifically developed PED MILP model. The model takes several input data regarding technology, time series, emissions, and the case location. The primary constraint requires the annual energy positivity of the final result. The model maximises the district's net present value (NPV).

The objective function is the maximisation of the NPV (shown in Equation (3)). It is composed of the initial investment cost I_0 (Equation (4)), the annual revenues R_y shown in Equation (5) and the annual total cost. The annual total cost is a product of the yearly fixed and variable cost, described in Equations (6) and (7), respectively.

$$\max_{v\in V} NPV = \max_{v\in V}\left(-I_0+\sum\nolimits_{y=1}^{Y}(R_y-C_y)*\left(\frac{1}{(1+i)^y}\right)\right) \tag{3}$$

$$I_0=\sum_{tec}^{TEC} cap_{tec}*cspec_{tec} \tag{4}$$

$$R_y=\sum\nolimits_{ts}^{TS}\sum\nolimits_{x_e}^{X_e} p_{y,ts}^{x_e,grid}*\frac{dt}{60}*tf_{y,ts} \tag{5}$$

$$Cfix_y=\sum_{tec}^{TEC} cap_{tec}*cfix_{tec} \tag{6}$$

$$Cvar_y=\sum_{tec}^{TEC}\sum\nolimits_{ts}^{TS}\sum_{z}^{Z}\left(p_{y,ts}^{tec,z}*\frac{dt}{60}*cvar_{tec}\right)+\sum\nolimits_{ts}^{TS}\times\sum_{z}^{Z}\left(p_{y,ts}^{grid,z}*\frac{dt}{60}*t_{y,ts}\right) \tag{7}$$

Equation (8) sets the primary constraint of the model, which forces it to reach an annual positive energy balance. As this work focuses on electrification, no other form of energy beyond electricity is included in the equation. The primary energy factor of the imported electricity is assumed to be that of the grid generation mix. Since the locally generated electricity needs to be renewable by the PED definition, the primary energy factor for export is set to be the same as the PEF_{im}, because exported electricity would substitute less sustainable and more expensive generation on the marginal cost curve of the grid.

$$\sum\nolimits_{ts}^{TS}\sum\nolimits_{x_e}^{X_e} p_{y,ts}^{x_e,grid}*\frac{dt}{60}*PEF_{ex}>\sum\nolimits_{ts}^{TS}\sum\nolimits_{z_e}^{Z_e} p_{y,ts}^{grid,z_e}*\frac{dt}{60}*PEF_{im} \tag{8}$$

Equation (9) describes the electricity consumption of the heat pump. At each time step, the heat pump requires electricity to generate the delivered heating or cooling, considering the respective coefficient of performance. The COP_h in heating mode is dependent on the outdoor temperature as the heat source and modelled according to Ref. [62]. The COP_c for the heat pump's cooling mode depends on the indoor temperature as the heat source. Here, this work assumes a room temperature of 27 °C that initiates the heat pump to cool.

$$\sum\nolimits_{x_e}^{X_e} p_{y,ts}^{x_e,hp}=\sum\nolimits_{z_h}^{Z_h}\frac{h_{y,ts}^{hp,z_h}}{COP_{h,ts}}+\sum\nolimits_{z_c}^{Z_c}\frac{c_{y,ts}^{hp,z_c}}{COP_{c,ts}} \tag{9}$$

Equations (10) and (11) assure that the heat pump can only function in heating or cooling mode at a specific time step. The binary variable $bhp_{y,ts}$ is one in heating mode and zero in cooling mode. M is a sufficiently large constant that needs to be bigger than the highest possible value of the heat pump capacity. Equation (12) restricts the heating output of the heat pump to its maximal capacity, and Equation (13) the cooling output to a share of the maximal heating capacity. The term $COP_{c,ts}+1$ is the COP of heating the outdoor environment as the heat sink when using the indoor environment as the heat source during cooling mode.

$$\sum\nolimits_{z_h}^{Z_h} h_{y,ts}^{hp,z_h}\le M*bhp_{y,ts} \tag{10}$$

$$\sum\nolimits_{z_c}^{Z_c} c_{y,ts}^{hp,z_c}\le M*(1-bhp_{y,ts}) \tag{11}$$

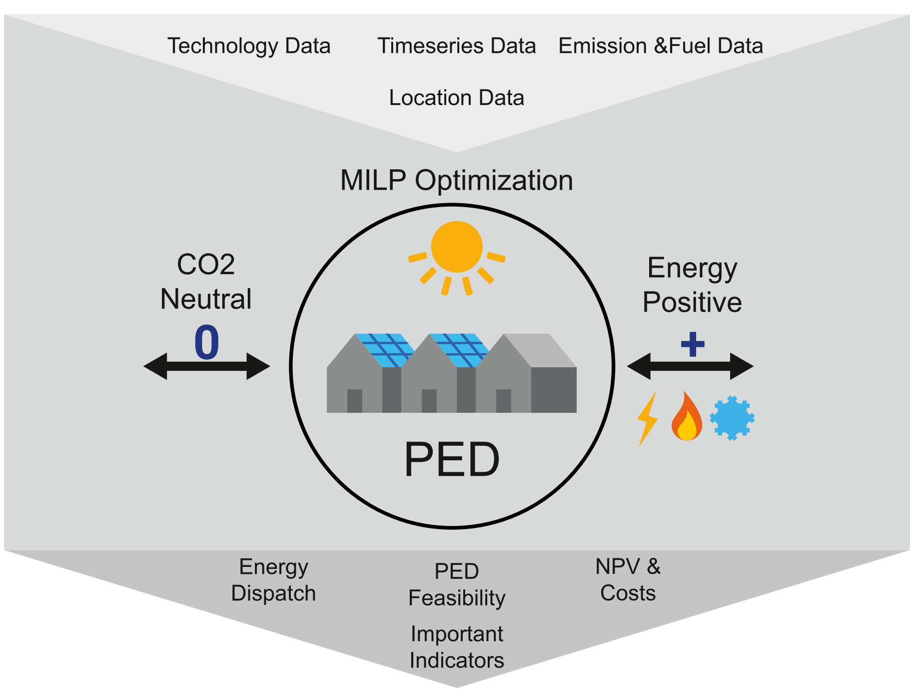

Fig. 5. Overview of the MILP PED model.

$$\sum\nolimits_{Z_h}^{Z_h} h_{y,ts}^{hp,z_h} \leq cap_{hp} \tag{12}$$

$$\sum\nolimits_{Z_c}^{Z_c} c_{y,ts}^{hp,z_c} \leq cap_{hp}*\frac{COP_{c,ts}}{COP_{c,ts}+1} \tag{13}$$

Equation (14) describes the heating behaviour of the electric boiler, and Equation (15) the restriction of its heating output to the maximal capacity.

$$\sum\nolimits_{Z_h}^{Z_h} h_{y,ts}^{eb,z_h} = \sum\nolimits_{X_e}^{X_e} p_{y,ts}^{x_e,eb}*\eta_{eb} \tag{14}$$

$$\sum\nolimits_{Z_h}^{Z_h} h_{y,ts}^{eb,z_h} \leq cap_{eb} \tag{15}$$

3.4. Scenarios

Initially, this work considers three main scenarios for each zone:

1. Status quo
2. Full electrification without PED requirement
3. Full electrification with PED requirement

Firstly, the status quo scenario assumes electricity supply by the grid only, heating by the zones typical technology (gas or district heating) and cooling by standard air conditioning units (AC). Secondly, heating and cooling must be fully electrified and thirdly also fulfil the PED criteria of an annual positive energy balance. This means that each district needs to generate more energy by renewable sources as they demand from the grid annually. A district of 20 multi-family houses is assumed in all cases.

3.4.1. PV generation space available

Each house is assumed to have 250 m^2 m of free north and south-facing roof area available. In addition, each house has 50 m^2 m of unused flat garage or carport roof space available. It is assumed that no PV installations are yet installed. The roof space is estimated according to a map analysis of some buildings in Munich's suburbs.

3.4.2. Energy tariffs

The same static electricity tariff is applied to all zones in the three initial scenarios. The average cost of electricity per kWh in the EU was 0.2134 EUR/kWh in 2020 [63]. A feed-in tariff (FIT) of 0.05 EUR/kWh is assumed for any electricity sold to the grid. The gas tariff of 0.07 EUR/kWh is taken as the average cost for residential customers in the EU [43]. District heating is assumed to cost approximately 0.05 EUR/kWh of heat delivered [35]. Electricity, gas and DH tariffs are assumed to grow 2% each year.

3.4.3. Carbon intensity of energy

For the carbon intensity of the electricity grid, the average EU value of 2019 is taken for the base scenarios, amounting to 275 gCO_2/kWh [64]. Additionally, for the status quo scenario, the CO_2 factor of natural gas is 198 gCO_2/kWh_{gas} [65]. Ref. [35] assumes 100 gCO_2/kWh of heat delivered in Vienna's DH. Accounting for some stronger influence of coal in countries such as Poland and Germany, this paper works with 200 gCO_2/kWh of heat delivered as an EU average. In order to comply with the European Green Deal, energy generation is required to be carbon-free by 2050. This work assumes a linear reduction of CO_2 intensity of the electricity grid and the district heat generation to reach carbon neutrality by 2050 [66].

Table 3
Technology available and its connection with energy types (Electricity – e, Heat – h and Cooling – c); Z stands for input of energy and X for output of energy.

Technology	Z_e	X_e	Z_h	X_h	Z_c	X_c
Photovoltaic		+				
Battery	+	+				
Heat Pump	+			+		+
Electric Boiler	+			+		

3.4.4. Technology available

Table 3 shows the technology selection available for the model to cover the energy demands. The heat pump is assumed to be an air to water heat pump to cover space heating/cooling and domestic hot water demand. Required tubing is assumed to be already available by the preexisting technology (gas/DH). Fig. 6 illustrates the four technologies in an exemplary building of the PED. Derived from Refs. [67,68], this work assumes district heating for Zone 3 and 5 and natural gas for the remaining zones in the respective status quo scenarios.[5]

For further assumptions regarding technology costs and paramters refer to Appendix A.

3.5. Sensitivity parameters

In order to determine what set of electricity cost parameters supports the diffusion of the PED concept, this work conducts a sensitivity analysis. Parameters subject to change in this study are the electricity tariff cost, its structure and a CO_2 cost. The initial scenario uses the average electricity cost of the EU. Therefore, the sensitivity analysis studies the two extreme cases of Germany and Bulgaria with 0.3 EUR/kWh and 0.1 EUR/kWh, respectively [63]. Secondly, the tariff structure is an important criterion that becomes more dynamic in many countries to incentivise customers to a more favourable consumption from the grid and generation perspective. A first step away from static tariffs are time-of-use (ToU) tariffs that induce demand-side flexibility. The most simple form of ToU pricing is static, in which a certain price is dedicated to a time window throughout the day. On the other hand, dynamic or real-time pricing is based on the wholesale electricity price and is more fluctuant [69]. This paper investigates the effects of a static ToU tariff as real-time pricing is not practical in a study spanning multiple countries with particular wholesale markets. The exact tariff structure can be seen in Appendix B. Additionally, this work investigates the effects of a CO_2 price that directly affects the electricity tariff according to the grid's CO_2 intensity. Therefore, a CO_2 price of 351 EUR/tCO_2 is taken for 2040 according to the "Techno-Friendly"[6] pathway to reach the 1.5 °C goal by the end of the century [70]. Taking a current CO_2 price of 60 EUR/tCO_2, our analysis assumes an annual growth of the carbon price of 9.75% [71]. Finally, electrification of heating and large solar PV installations can adversely affect the grid [72]. Therefore, this work investigates the effects of a bidirectional grid power limit of twice the initial maximal power consumption of 152 kW when heating was not electrified. Table 4 gives an overview of the sensitivity analysis cases. In the sensitivity analysis, only the PED cases and their respective status quo scenarios are investigated.

[5] This is a fairly conservative assumption as many households still use oil or biomass for heating.

[6] The "Techno-Friendly" pathway is one of the four storylines to decarbonisation developed by the openENTRANCE project and relies on technology novelty and a smart society [70].

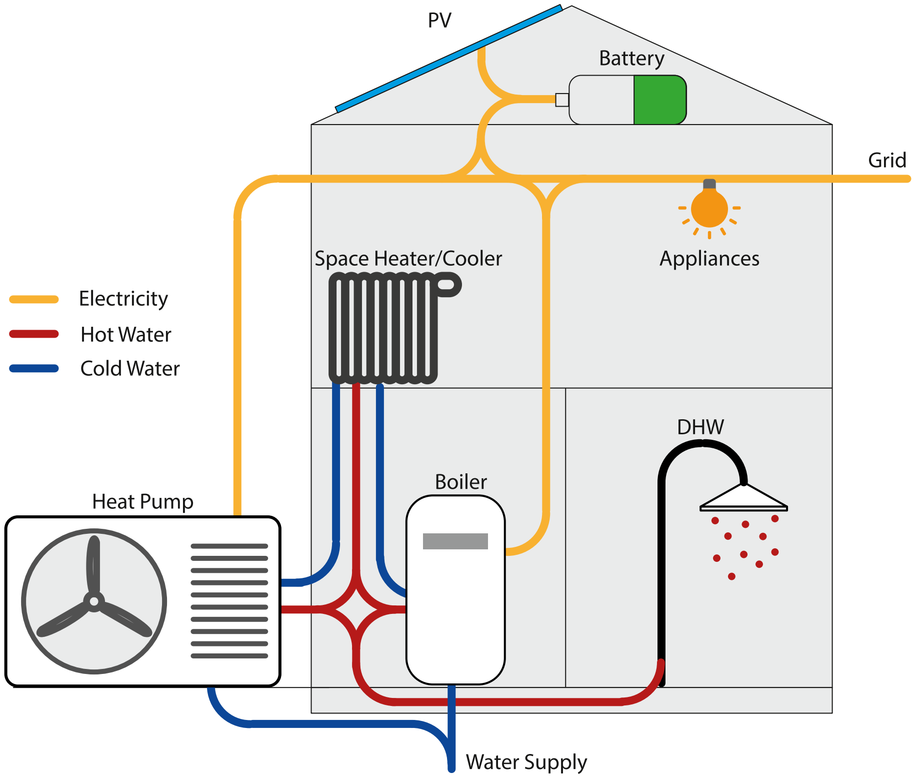

Fig. 6. Simplified sketch of available technology for the district buildings.

Table 4
Sensitivity parameters.

Case	Description
Electricity cost	10 ct/kWh and 30 ct/kWh
Tariff structure	Time of use tariff (Appendix B)
CO_2 cost	Rising CO_2 cost additional to electricity tariff
Power exchange limit	Export and import of electricity limited to 304 kW

Table 5
MAE and RSME in [W] of heating and cooling demand creation by the RFR for the old multi-family building.

Building Type	$MAE_{heating}$	$RSME_{heating}$	$MAE_{cooling}$	$RSME_{cooling}$
MFB_{old}	625	832	91	441

4. Results and discussion

This section presents the results of the previously elaborated study and discusses them. Firstly, in Section 4.1, the machine learning-based space heating and cooling demand generator results are shown. Section 4.2 shows and discusses the results of the PED potential under the initial scenario assumptions, and Section 4.3 integrates further variables such as variation of electricity cost and structure, CO_2 cost and grid limitation.

4.1. Space heating and cooling demand generation

The following section presents the results obtained by the Random Forest Regressor (RFR) for demand generation. Table 5 shows the MAE and RSME for the machine learning created heating and cooling load for the MFBold. It can be seen that the MAE is a lot higher for the heating demand than for the cooling demand because of two reasons. Firstly, on average, the heating demand is significantly higher with 14.6 kW compared to 3.6 kW of cooling demand, not considering zero values. Thus, the MAE is 4.3% and 2.6% for heating and cooling demand, respectively, relative to the mean values. Secondly, cooling is hardly used compared to heating. While cooling is used during 199 h of the year, heating is not zero during 6335 h. Therefore, there are significantly more zero-values to predict by the cooling demand model, which is comparably easy and reduces the mean average error. The RSME lies above the MAE in both cases. However, for the heating demand creation, the RSME is only 33% higher, while for the cooling demand creation, the RSME increased 385% over the MAE. The RSME is highly sensible to significant errors due to squaring the actual and predicted value difference. Therefore, it also shows that while the MAE is similar relative to the average heating and cooling demand, respectively, the cooling demand prediction creates significantly more large errors. This is primarily due to the small data set for learning since cooling is only applied for 199 h of the entire year.

Fig. 7 compares the space heating and cooling demand of one multi-family building from the two most extreme zones one and five, represented by Seville and Stockholm, respectively. The building in Seville requires less energy for heating, both in terms of absolute days and relatively if heating is switched on. However, heating is still necessary to keep the living environment at the defined conditions by the synPro simulation. On the other hand, the building in Stockholm barely needs cooling energy to keep the room temperature down. In contrast, Seville's high summer outdoor temperatures make cooling necessary between May and October. In general, the heating and cooling demand generator supplies sensible results, as shown in Fig. 7, even though the cooling demand is less accurate.

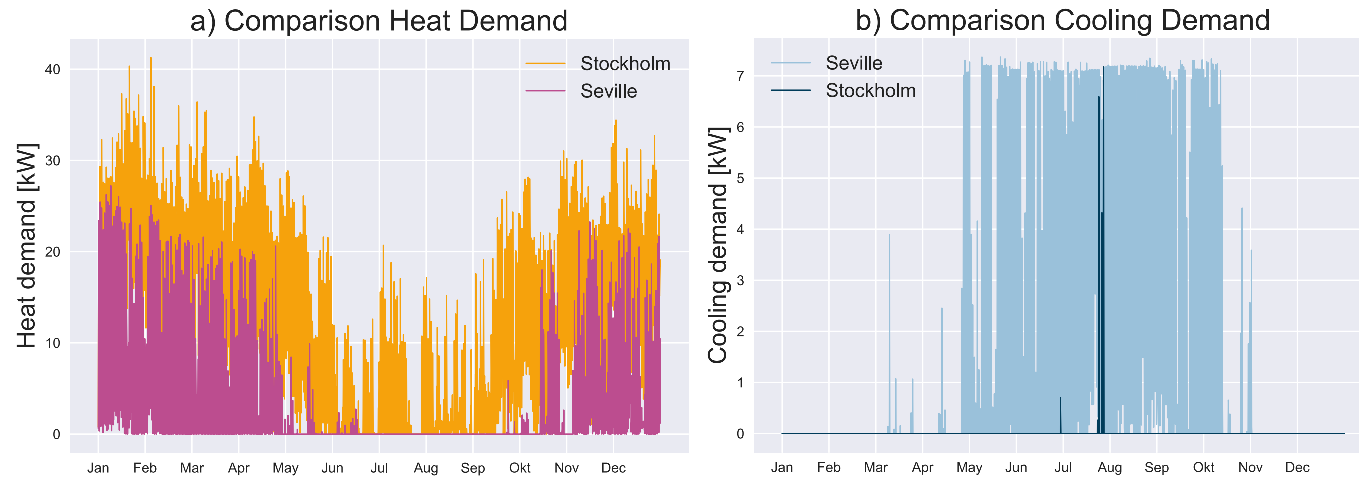

Fig. 7. Comparison of space heating and cooling demand of the two most extreme zones.

Table 6
Net Present Value and CO_2 emissions of status quo scenario for each zone.

Zone	NPV [EUR]	CO_2 [t]
1 (Seville)	- 1,966,958	6,234
2 (Madrid)	- 2,412,457	9,391
3 (Munich)	- 2,412,784	6,213
4 (Brussels)	- 2,762,349	12,384
5 (Stockholm)	- 2,681,952	7,251

4.2. PED potential across the EU

Table 6 shows the net present value of the status quo scenario for each zone over 20 years. Compared to the other zones, the NPV and associated CO_2 emissions of zone three and five are low. Representing north and north-east Europe, these zones are likely to have district heating supply for (sub-) urban districts that is cheaper and assumed to become less carbon-intensive in the future than gas usage for heating.

Table 7 shows the NPV, the technology portfolio, the electricity export-import balance and the PED-related CO_2 emissions for each zone. Every zone evaluates those parameters for a full electrification scenario without and with the PED requirement of an annual positive energy balance. For zones 1 and 2, the PED balance is fulfilled in any case without enforcing it as the economically optimal solution. For the remaining zones, the PED status needs to be imposed. The results suggest a strong north-south trend of increasing PED potential. The export-import ratios of the districts without PED enforcement decrease with increasing latitude. Therefore, the economic viability of PEDs drops the further north the district is located. While PV and battery capacity are larger in southern zones due to the better resource availability and favourable demand pattern, electric boiler and heat pump capacities rise with the latitude because of increased heating demand. In zones 3, 4 and 5, the PED balance is only slightly larger than one, as the PED would not be the optimal solution due to lower solar irradiance and increasing heating demands. Carbon emissions associated with the imported electricity rise with the latitude too. One exception is zone 3 and 4, represented by Munich and Brussels, respectively. Even though Munich is south of Brussels, the aforementioned south-north relation is reversed for these zones. An explanation could be the great difference in altitude and in the proximity to the sea, resulting in more extreme temperatures for Munich.

In the solar-poor northern zone 5, batteries are not feasible, and instead, high PV capacity installations are used to reach PED status. Zones 3 and 4 use small battery capacities in the PED cases. Fig. 8 illustrates the NPV composition of each zone's PED. It is very well visible that southern PEDs have the highest initial investment due to large PV and battery capacities. However, they can offset the investment by reducing the electricity consumption of the grid and, therefore, the variable costs in addition to revenues from grid exports. Northern PEDs have higher variable costs. This suggests that they cannot cover large parts of their electricity consumption by PV power generation and therefore need to import more electricity from the grid.

Comparing Figs. 9 and 10 that draw the energy flows of the zone 1 and 5 PED, as the two extremes, supports this assumption. The Sankey diagram of zone 1 shows that most of the direct electricity

Table 7
NPV, technology portfolio, export-import ratio and CO_2 emissions for each zone for the PED and non-PED electrification scenario; Bat: Battery, B: Electric Boiler, HP: Heat Pump and Ex/Im: Export-Import ratio; Zone 1 is located most south represented by Sevilla; Zone 5 is the most northern zone represented by Stockholm.

Zone	NPV [EUR]	PV_f [kW_p]	PV_t [kW_p]	Bat [kWh]	B [kW_p]	HP [kW_p]	Ex/In [$-$]	CO_2 [t]
1	- 1,634,188	152	950	608	279	355	7.35	677
1 PED	- 1,634,188	152	950	608	279	355	7.35	677
2	- 2,262,904	152	950	591	298	458	4.80	1,183
2 PED	- 2,262,904	152	950	591	298	458	4.80	1,183
3	- 3,349,720	0	780	7	279	519	0.79	2,673
3 PED	- 3,353,438	0	923	81	278	520	1.00	2,544
4	- 3,051,714	0	590	0	244	478	0.55	2,461
4 PED	- 3,075,490	0	888	37	242	480	1.00	2,311
5	- 4,098,844	0	607	0	320	554	0.35	3,475
5 PED	- 4,309,430	152	1240	0	304	571	1.00	3,203

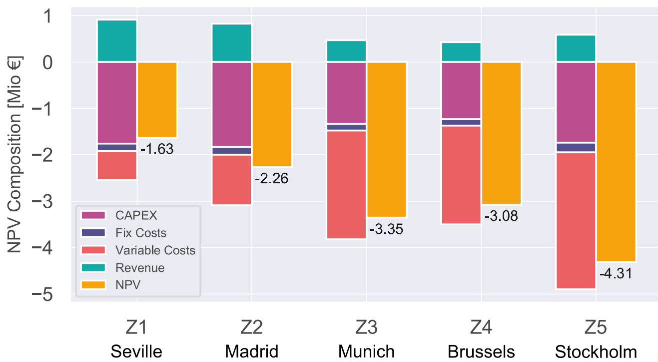

Fig. 8. Net present value composition of the PED for each zone.

demand and large parts of the heat pump and boiler consumption are covered by the PV plant directly or the battery. Therefore, over 20 years, the zone 1 PED supplies 71% of the energy consumed directly from on-site generation and additionally exports a large amount of PV power to the grid. On the other hand, the zone 5 PED in Fig. 10 shows a much smaller export-import ratio as well as a significantly larger grid import. This is visualised by the grey grid point in Figs. 9 and 10, where PED exports represent flows coming into the grid from the left and exports are represented by electricity flows coming out to the right. With only 26% of energy demand covered by local resources, the zone 5 PED is much more grid-dependent than the zone 1 PED. This is due to two main differences between zone 1 and 5. Firstly, the significantly superior solar influx allows the zone 1 PED to generate 55% more electricity despite having less installed capacity. Secondly, zone 5's heating demand is more than twice as high as zone 1's, while the much higher cooling demand of zone 1 is less crucial in absolute terms. Additionally, the cooling demand is well aligned with sun hours, while heating demand usually appears asynchronously to solar irradiance. However, while the PED in zone 1 has a higher self-coverage of its demand due to its sizeable excess PV power generation, the self-consumption of locally generated energy is only 26%, just as in zone 5 PED. Figs. 9 and 10 also show that compared to the electric boilers' capacities, their energy throughput is relatively small. The boiler needs to be sufficiently large to supply the peak DHW demand when the heat pump is in cooling mode. Therefore the heat pump can be smaller, and the boiler is used when the heat pump is supplying cooling or during cold days to cover the space heating peaks.

One of the major drivers of PEDs is the reduction of CO_2 emissions. Thus, this work closely analyses the emission saving potential of each zone. Fig. 11 illustrates the CO_2 reduction in relation to the respective status quo scenario of each zone. The status quo scenarios share the tariffs with their respective PED scenarios. However, the technology portfolio is the one defined in Section 3.4. This means that electricity is imported from the grid only, cooling is generated by standard AC devices and heating and DHW by gas boilers or district heating, depending on the zone. DH is assumed to be available in zone 3 and 5, while zones 1,2 and 4 rely on gas power heating in the status quo scenarios. Furthermore, the cost of the emission reduction in EUR/tCO_2 is shown. The graph underlines the south-north correlation in zones that share initial heating technology. Zones in the south of Europe, such as zone 1 and 2, show relative CO_2 reductions of just below 90% and a negative cost per tonne of emission. This means that in those southern zones, the CO_2 reduction is cost-effective and comes with a relative increase in the NPV over project time. The north-western zone 4 shows slightly less emission reduction than its southern counterparts and a positive abatement cost of approximately 30 EUR/tCO_2. As DH heating is assumed to become less carbon-intensive over time and cheaper than gas heating, relative emission reductions and cost of abatement are less favourable in zones 3 and 5. Relative emission reduction shrinks to below 60%, while the cost of emission reduction increases drastically to approximately 250 and 400 EUR/tCO_2 for scenarios 3 and 5, respectively. The northern location of both zones contributes to the lower CO_2 reductions and higher costs, as

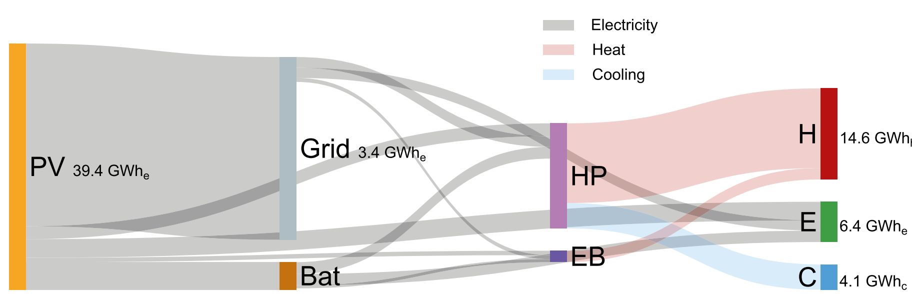

Fig. 9. Sankey energy flows over 20 years of the Zone 1 (Seville) PED including grid interaction; Bat - Battery, HP - Heat Pump, EB - Electric Boiler, H - Heating Demand, E – Electricity Demand, C - Cooling Demand.

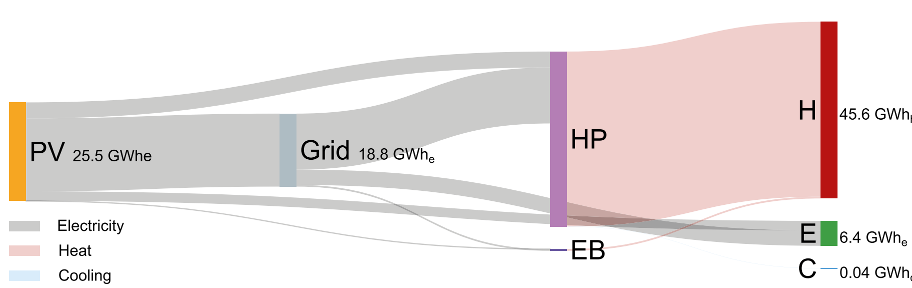

Fig. 10. Sankey energy flows over 20 years of the Zone 5 (Stockholm) PED including grid interaction; Bat - Battery, HP - Heat Pump, EB - Electric Boiler, H - Heating Demand, E – Electricity Demand, C - Cooling Demand.

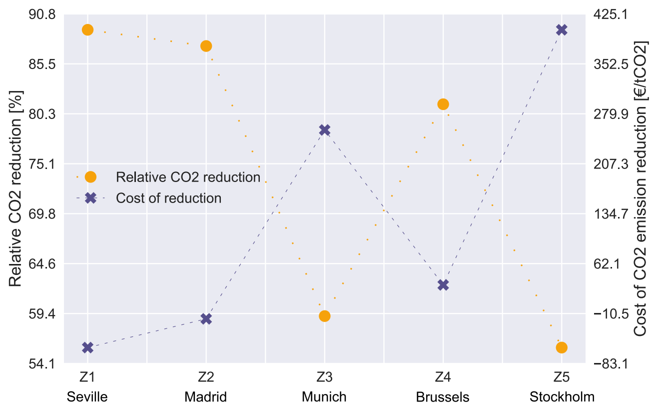

Fig. 11. Relative CO_2 emission reduction and associated cost of each PED compared to the status quo of each zone.

fewer solar resources are available and supply and demand are increasingly asynchronous. Fig. 11 deducts that PEDs in southern regions that replace decentralised gas heating with electrified heating are most cost-effective in emission abatement. This effect would be even greater if more polluting and expensive fossil fuels were replaced, such as oil, which is still used in some residential heating systems, according to Fig. 1. The replacement of DH with electrified heating, on the other hand, is less cost-efficient in this study as DH is assumed to become less carbon-intensive under the pressure of the European Green Deal.

The initial scenarios suggest that closer proximity to the equator within Europe is positive for the economic viability of the PED concept. Here, the PED concept is the optimal solution for a full electrification scenario and does not have to be imposed on the district. Additionally, districts at low altitudes and close proximity to the sea seem more economical than those in higher regions. An explanation for this could be the higher temperature extremes that lead to larger required installed equipment capacities. Finally, districts already supplied by district heating have a significantly higher cost per reduced tonne of carbon emission. This is caused by lower operating costs and a higher potential of corresponding emission reduction of DH compared to the individual supply of heat by fossil fuel boilers.

4.3. Sensitivity parameter analysis

While the initial scenarios assume equal cost of electricity and tariff structures for the entire EU, tariffs vary significantly among countries. To show this effect on an electrified PED, this study evaluates the extreme cases of very low and very high static electricity tariffs, a dynamic time of use tariff and CO_2 cost inclusion per kWh. Furthermore, this chapter discusses the potential negative grid impacts of high PV power generation and electrification of heating in PEDs.

Fig. 12 compares the change of NPV (left) and CO_2 emissions (right) between the PED district and the status quo district for each zone - tariff parameter combination. The aforementioned south-north relation holds for any discussed tariff option for the NPV and the emission change. In both matrices, southern zones are shaded green, which illustrates a more beneficial relative economic and environmental development by changing the status quo district to a PED. Districts that used to have district heating installed in the status quo assumptions can be seen in purple (Z3 and Z5) due to their decreased NPV (left matrix) and especially lower CO_2 emission reductions (right matrix). However, while not all zone-tariff combinations increase the NPV compared to their respective status quo scenario, all combinations achieve between 56 and 93% emission reductions. It has to be mentioned that this study works with the average European grid CO_2 factor. Therefore countries that deviate strongly towards a lower or higher factor, such as Sweden or Poland, have higher or lower relative savings through electrified PEDs, respectively. Reversely, higher carbon intensity of DH also goes in hand with higher relative CO_2 savings in this zone.

Focusing on the NPV matrix on the left in Fig. 12, areas with a dynamic ToU tariff have the strongest economic motivation to convert a district to a PED among the four tariff options (initial, low, high and ToU). In southern districts, the ToU tariff has a specifically high benefit on the NPV. The ToU PED saves around 40% on battery capacity compared to the PED with a flat 0.2134 EUR/KWh tariff in zone 1. An explanation for this would be that the low off-peak price makes it uneconomical to save energy for those night times compared to selling it to the grid during the day. Additionally, the battery is used to buy energy at night and use it to cover high-peak times. This additional flexibility in the tariff is also why northern PEDs have high battery installations in the ToU cases, whereas they (almost) have none in the static standard tariff scenarios. Because of these increased battery installations in northern districts, the ToU tariff is not the most economically beneficial. There, due to higher requirements of grid import and lower PV generation compared to installed capacity, a low flat tariff is most beneficial. The addition of a carbon price on the electricity, gas and district heating depending on the respective carbon intensity has a positive economic effect across all zones compared to the initial scenario. The carbon price increases the cost of the status quo scenarios significantly more than the cost of the electrified PEDs. The importance of battery installations gains strongly, and some capacity of the electric boilers is shifted to more heat pumps. Through the increased battery capacity, the PEDs can focus more on self-consumption of PV power to decrease the electricity import that becomes more expensive due to the CO_2 cost. The severe punishment of fossil fuel usage by carbon pricing makes the CO_2 cost a suitable tool to create a driver towards a high electrification rate, in combination with one of the tariff options.

The matrix on the right in Fig. 12 clearly illustrates that a high tariff yields the highest CO_2 emission reductions of a PED compared to the status quo in all zones except zone 5. Regions with high electricity tariffs provoke large battery installations to increase the self-coverage of the electricity demand. Reversely, in areas with a low electricity tariff, battery installations are not incentivised, and thus, electricity consumption related carbon emission savings are lower as more power is imported. In districts with a ToU tariff, the CO_2 savings in southern zones are relatively low as increased electricity import occurs to take advantage of the dynamic pricing to cover peak demands more economically.

Fig. 13 shows a zone - parameter combination matrix of the cost of emission reduction in EUR/tCO_2. It combines the matrices in Fig. 12 and therefore illustrates the economic efficiency of carbon emission abatement. In southern areas of the EU with ToU tariffs, PED implementations have the lowest cost of carbon reduction among the tariffs. For the presented PED, approximately 123 EUR/tCO_2 would be gained compared to the status quo. However, while the cost efficiency of abatement is very high, the actual emission reduction is among the lower ones, as the ToU tariff incentivises increased grid exchange. Even though, more emission associated grid import takes place at first glance, the grid import can also be advantageous for the distribution grid. If the dynamic tariff is well designed, low prices that incentivise electricity import are distributed over times that typically have a low demand or a high renewable energy share of generation. PEDs in zones with ToU pricing always perform relatively good. However, the further north the zone is located, the more interesting it seems to be if the PED is

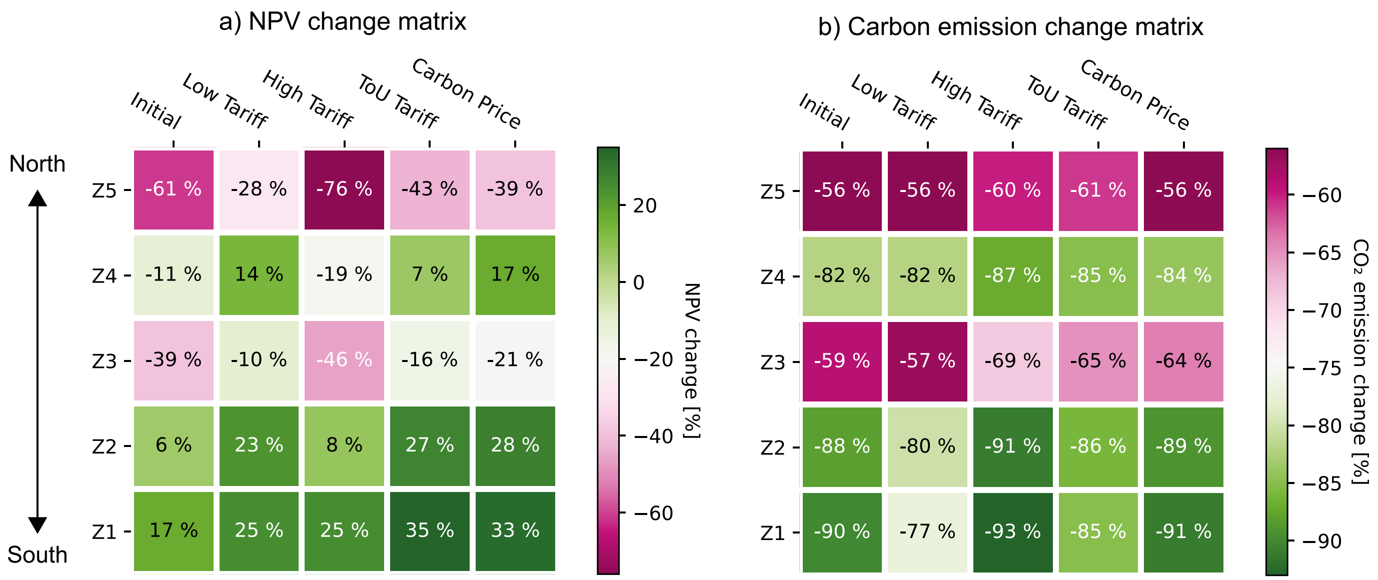

Fig. 12. (a) Change of net present value (NPV) per parameter set and zone compared to the respective status quo; (b) Change of CO_2 emissions per parameter set and zone compared to the respective status quo.

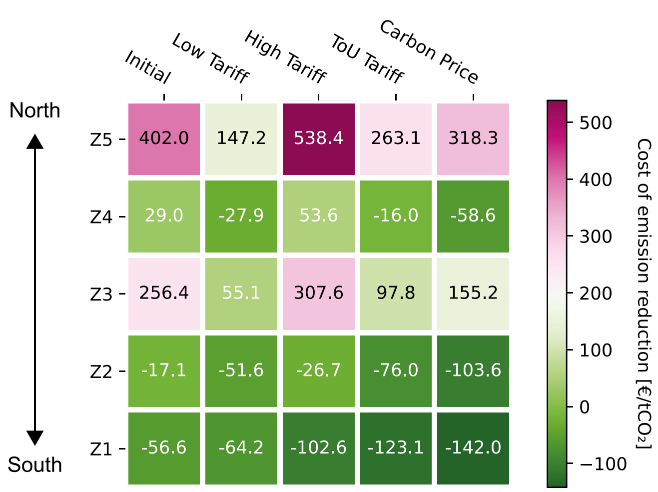

Fig. 13. Cost per reduced tonne of CO_2 emission in EUR per parameter set and zone compared to the respective status quo.

created in low-cost electricity regions, as the sun just cannot be used cost-efficiently. In the areas that do not use DH in the status quo but gas boilers, a carbon price on top of the initial tariff yields the best emission abatement efficiency. In general, the study shows that PEDs are specifically cost-effective for CO_2 reduction in southern EU countries that have a high ToU tariff and potentially carbon pricing, as well as rely on gas or oil for individual heating. Finally, all the PED cases that this work investigated have sizeable solar power generation and increased electricity import because of the electrification of heating. This can be very problematic in urban areas, where the electricity grid is often congested. Fig. 14 illustrates this problem using box plots of zone 1 districts' non-zero, hourly power exchanges with the grid. On the left, the status quo power exchange illustrates that no electricity export occurs as no PV installation is assumed, and grid import mainly appears in a small power window with occasional outliers, peaking at 152 kW. The PED scenario in zone 1 shows high power grid exports, mainly between 200 and 650 kW, reaching almost 1 MW at its peak. Also, the import of electricity increased to a peak of over 400 kW, while most values remain in a relatively small window. The rightmost power exchange plots illustrate the PED with a limit of export and import of 304 kW (twice the initial grid usage). It drastically reduces the grid exports to this maximum and halves its interquartile range. Additionally, the grid import distribution is slightly more desirable.

Table 8 shows the NPV, the technology portfolio, the export/import balance, and the grid import-associated CO_2 emissions of the grid exchange limited PED for each zone. In zone 1 and 2, the limitation of the grid exchange has not very much effect on the NPV of the PED project. The optimal PV capacity is reduced, while the battery is slightly larger. In both cases, the export/import balance is still significantly larger than one but reduced compared to the grid limitless PEDs. The associated emissions barely change. This picture is very different for the remaining PEDs in zones 3, 4 and 5, where the NPV decreases more drastically due to large battery installations of up to 3.8 MWh for the most northern district in zone 5. On the other hand, the effect on the CO_2 emissions is very positive as less electricity gets imported.

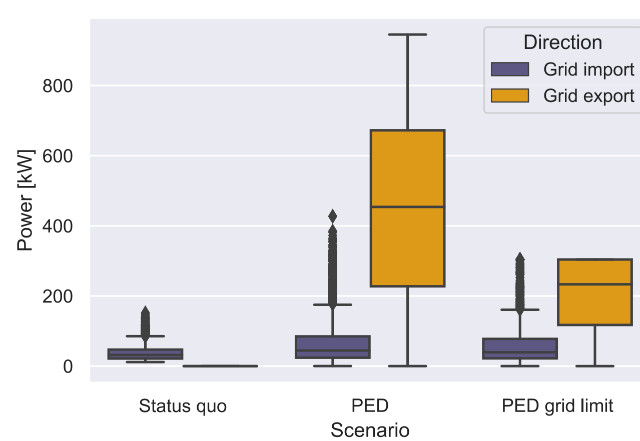

Fig. 14. Grid exchange power distribution for the Z1 (most southern) PED.

Table 8
NPV, technology portfolio, export-import ratio and CO_2 emissions for each zone for the grid exchange limited PEDs; Bat: Battery, B: Electric Boiler, HP: Heat Pump and Ex/Im: Export-Import ratio.

Zone	NPV [EUR]	PV_f [kW_p]	PV_t [kW_p]	Bat [kWh]	B [kW_p]	HP [kW_p]	Ex/In [−]	CO_2 [t]
1 PED	- 1,735,198	0	603	697	278	355	2.88	670
2 PED	- 2,385,026	152	468	777	271	486	1.50	1,128
3 PED	- 4,075,182	152	783	1,928	234	563	1.00	1,585
4 PED	- 3,754,548	152	749	1,787	203	518	1.00	1,396
5 PED	- 6,578,715	152	1274	3,808	256	619	1.00	2,313

Fig. 15 shows the Sankey diagram of the Z1 PED with a grid exchange limit of 304 kW. Comparing it with Fig. 9, which illustrates the energy flows of the same PED without the grid limit, visually reveals specific differences. While the self coverage of the energy demand remains unchanged at 71%, the self-consumption of generated PV power almost doubles to approximately 47% with the grid exchange limit. High self-consumption in combination with low maximum grid exchange power are parameters that a PED should strive for as it increases flexibility and resilience for the district and the distribution grid. Beyond the smaller PV power generation, the most apparent difference is the missing grid-battery power exchange in the initial Z1 PED scenario. With the grid limit, the grid has to supply electricity to the battery to be prepared for peak demand out of sun hours beyond the grid limit. Furthermore, the battery exports electricity to the grid when too much PV power is generated that is not needed to cover the demand, and further PV generation is anticipated in the upcoming hours to not surpass the grid limit. A rather negative point of the grid limited PED constellations is the reduced PV power generated and PV capacity installed compared to the non-restricted scenarios. Comparing Figs. 9 and 15, it becomes apparent that over the lifetime of the PED, almost 18 GWh less of PV power is generated in the grid restricted scenario. With the correct incentives, such as high CO_2 costs, the correct tariff scheme or direct subsidies, this difference could be used locally for behind the meter electric vehicle charging or even local H_2 generation without any additional grid impact. Thus, the available space for renewable energy generation would be used to its limits.

While the grid limitation reduces the negative impact that PEDs can have on the distribution grid, there is still a seasonal imbalance of the grid-PED power exchange. Figure C1 in Appendix C depicts perfectly that the PED exports most of its power in summer months and imports most electricity in the winter. This imbalance gets more prominent the further north the PED is located.

4.4. Limitations of the work

Given that this work covers a large geographical area in its analysis, certain limitations need mentioning. Firstly, this study assumes the building stock to be equal across the EU for space heating and cooling demand. However, different areas have different building styles regarding materials used, roof types and even inhabitant density. On the other hand, one could argue that the buildings are more likely to be similar for the suburban building type used in this study than in city centres. Furthermore, this work uses equal electricity loads across Europe for the district. Due to variations in inhabitant behaviour, the load could vary locally. Location-specific habits such as very late dinners in southern European countries contribute to a variation in the electricity load. Both aforementioned limitations have also been used in literature, e.g. by Ref. [49]. The third limitation also addresses the building stock. The building that makes up the districts of this study are assumed to be old, existing, unfurnished buildings. Renovation of these buildings is not part of this study, even though building efficiency improvements would most likely be the first step towards converting an existing district into a PED. However, this discussion goes beyond the scope of this study and leaves room for important future work. Finally, also the applied technology portfolio is a limiting factor in this work. While the combination of PV and air-sourced heat pumps might be a legitimate choice in mild regions, it does definitely not favour cold areas with few sun hours, such as northern Europe. However, by complying with the definition of an urban, dynamic PED, many other viable technology options are ruled out. Wind power generation, for example, is not included as it is typically not applicable in an urban, residential context. Waste incineration is also unlikely to be part of a residential district and therefore excluded as a local source of electricity and heat. Biogas is rarely to be locally sourced in an urban, residential district and would therefore have to be imported, which is not the purpose of a PED. Of course, residential energy generation by PV, battery, heat pumps and boilers is not the only viable constellation for PEDs, but one that is frequently discussed in current literature [62,73,74].

5. Conclusion and future research

The answer to where to go to cost-efficiently accomplish 100 solar-based and electrified Positive Energy Districts (PEDs) in Europe by 2025 is south and to zones where no district heating is already in place. This study shows that southern areas with a dynamic tariff system provide the best basis for a PED with high cost-effectiveness of CO_2 abatement. A great example would be southern Spain, as the country recently introduced a dynamic time-of-use

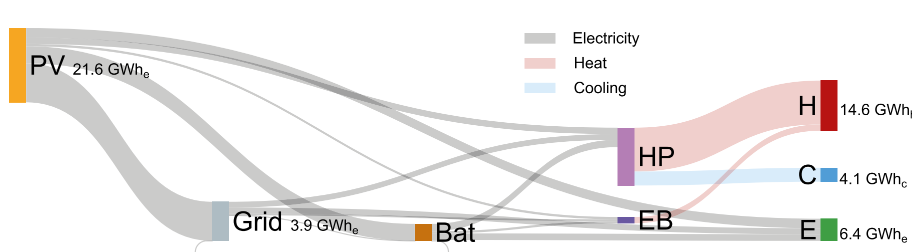

Fig. 15. Sankey energy flows over 20 years of the Zone 1 PED (Seville) including grid interaction with a grid limit of 304 kW; Bat - Battery, HP - Heat Pump, EB - Electric Boiler, H - Heating Demand, E − Electricity Demand, C - Cooling Demand.

(ToU) tariff scheme [75]. Under those conditions, the PED with electrified heating and cooling through heat pumps and electric boilers is more economical and environmental than the status quo. An additional nudge towards increasing PED implementation can be given by including a CO_2 price on the fossil fuel and the electricity consumption of the final customer. This would make fossil fuel-based heating less attractive and the electrified PED more cost-efficient than the status quo. The further north a district is located, the less economically attractive the electrified PED becomes compared to the status quo. It has to be mentioned that the PV and air-sourced heat pump based technology portfolio in this study strongly favours southern regions. Potentially, in northern Europe, a virtual PED that allows off-site renewable electricity generation such as through community-owned wind farms or the inclusion of ground-sourced heat pumps are better options. However, the virtual approach would not assist the already struggling electricity grid, and ground-sourced heat pumps are associated with a high installation complexity in dense, urban areas.

The PED concept discussed in this paper has potentially negative impacts on the distribution grid. High electricity exports during short times and large electricity imports to cover the electrified heating in the evenings amplify the already existing grid capacity issues. Limiting the power exchange between the PED and the grid partially reduces this issue without significantly affecting the NPV and the carbon impact of southern districts. In northern districts, a grid limit significantly decreases the economic viability but, on the other hand, also reduces its associated carbon emissions. However, this study shows that the grid exchange power limit does not address the seasonality issue of PEDs in terms of high electricity exports in the summer and high imports during the winter. An adaption of the PED definition would be necessary to address this issue, away from requiring an annual positive export-import balance towards a daily or even 8-hourly balance. Moreover, the local generation of green hydrogen could help dealing with the grid restrictions and the seasonal imbalances by simultaneously making full use of the local space for PV power generation.

For future work, a closer look at the building stock will give further insides into the viability of the PED concept. This will include renovation towards a high energy efficiency but also different building structures and their influence on the PED concept. Thanks to its modularity, further technology options such as ground-sourced heat pumps, solar thermal panels, thermal storage, or even the application of locally produced green hydrogen can be included in the model to be less location-biased by default. Moreover, the innovative load generator presented in this study will be further developed, especially on the cooling demand side. Finally, the specific inclusion of electric vehicle charging and moving patterns and their effect on the district's PED balance will be an exciting evaluation point.

Author contribution

Axel Bruck: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Santiago Diaz Ruano**: Writing – review & editing, Supervision, Project administration. **Hans Auer**: Writing – review & editing, Supervision, Project administration

Data availability

Python code and an example data set for one scenario is available under: https://github.com/urbLexa/PEDso.

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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. Technology data assumptions

Table A1 shows the technological input data assumptions for the PV installations. Assumptions are taken from Ref. [76]. Due to the large roof size, the average of the small private and medium-sized commercial system cost is taken. PR stands for performance ratio and incorporates certain losses of a PV system, such as the inverters or shading. GCR is the ground coverage ratio of the PV plant and defines how much space of the available area is covered by panels.

Table A1
PV input data

Variable	Value	Unit
CAPEX	900.00	EUR/kW_p
OPEX	11.00	EUR/kWa
η_{pv}	19.00	%
PR	0.84	–
GCR flat	0.80	–
GCR tilt	1.00	–

Table A2 explains the cost and technical assumptions for the lithium-ion battery storage. Refs. [35,62,77] are used for battery costs. A range of 500–1000 EUR/kWh is stated. This work therefore uses 750 EUR/kWh as a value in between.

Table A2
Battery input data

Variable	Value	Unit
CAPEX	750.00	EUR/kWh
OPEX	0.00	EUR/kWa
η_{bat}	95.00	%
Capa2power	0.30	–
$SOC_{1,0}$	0.00	kWh

The heat pump and electric boiler cost data is taken from [62,78] and shown in Table A3 and Table A4, respectively. The values are slightly increased and compared with commercial products due to the different scale of application in Ref. [78].

Table A3
Heat Pump input data

Variable	Value	Unit
CAPEX	800.00	*EUR/kW*
OPEX	2.00	*EUR/kWa*

Table A4
Electric boiler input data

Variable	Value	Unit
CAPEX	100.00	*EUR/kW*
OPEX	1.00	*EUR/kWa*
η_{eb}	99.00	%

Appendix B. Time-of-use tariff structure

Similar to Ref. [79] this work uses a ToU tariff that consists of three times: off-peak, shoulder and peak. While the FIT stays static over the whole period, the grid tariff varies according to the times. The shoulder time corresponds to the EU average grid tariff of 0.2134 *EUR/kWh*. The off-peak and peak tariffs are equal to a 50% reduction and increase of the shoulder tariff, respectively. There is no peak tariff during the weekend but only shoulder during the day and off-peak during the night. Figure B1 shows the ToU tariff structure applied.

Appendix C. Seasonal Export Import Imbalance

Figure C1 depicts the imbalance of export and import within the seasons of the first year. The graph of the Z3 PED with 304 kW grid exchange limit shows well that most grid export happens during the summer months, while most import takes place in winter.

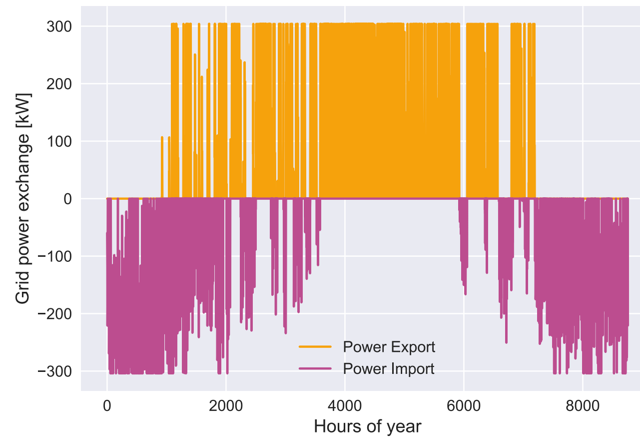

Fig. C1. Seasonal imbalance of power export and import in Z3 (Munich) PED under grid limitation of 304 kW maximum

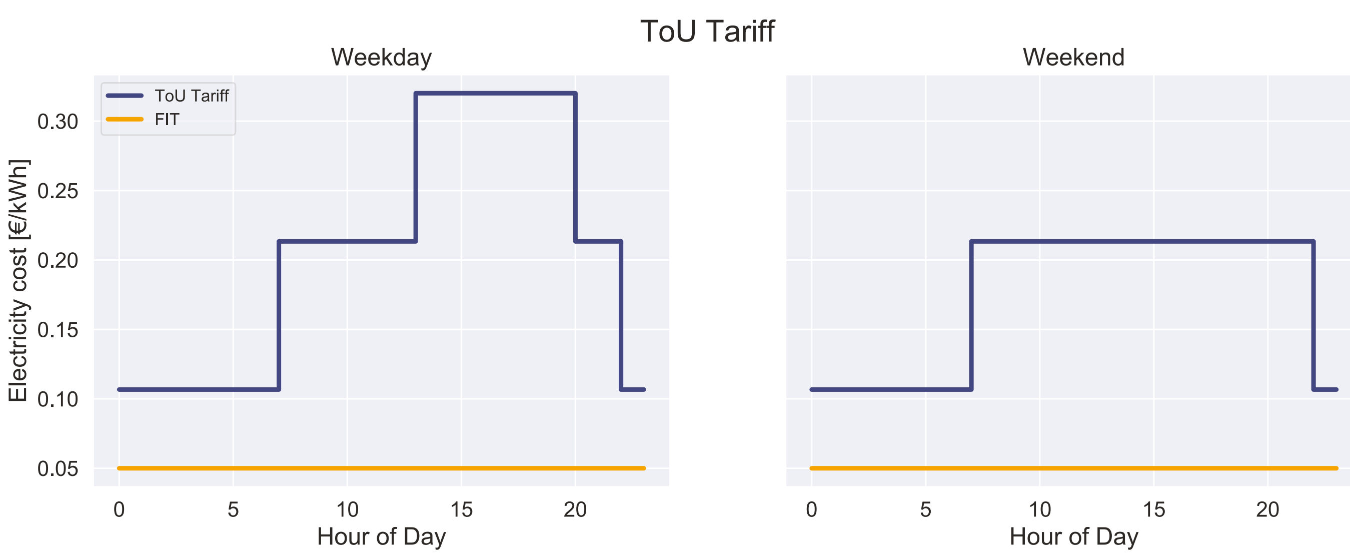

Fig. B1. ToU tariff at weekdays and weekends

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