Dissertation

On the feasibility and techno-economic values of Positive Energy Districts in Europe

in fulfilment of the requirements for the degree of
Doktor der technischen Wissenschaften

submitted at the
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Faculty of Electrical Engineering and Information Technology
Technische Universität Wien

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Vienna, July 2023

Acknowledgements

Accomplishing a research project such as this one is always dependent on the surrounding people and the local setting. Thus, I would like to take the time to thank those who contributed with any kind of support to this document. Without any of you the thesis as it is would not have been possible.

Firstly, I would like to thank my mother Anke, my father Martin and my brother Felix. Their moral support made me push through tough times and I am indefinitely happy for the special bond I have with my family. I would like to thank my two grandmothers Elisabet and Gerlinde with whom I am in close contact despite the large geographical distance. Special thanks also to my grandfather Karlheinz who brought me in contact with mathematics and physics in my early days and unfortunately passed away some year ago.

I would like to thank my supervisors Santiago Díaz Ruano from the Instituto Tecnologico de Canarias and Hans Auer from TU Vienna for the great support and freedom during my research. Also many thanks to Lucía Dobarro Delgado, who was in charge of managing the MSCA program at the ITC. Additionally, I thank Prof. Dr. Theocharis Tsoutsos and Prof. Dr. Kostas Galanakis for reviewing and examining this thesis.

Additionally, I express my gratitude to my colleagues at TU Wien, especially Sebastian Zwickl-Bernhard, Antonia Golab and Theresia Perger, my coworkers at the Instituto Tecnológico de Canarias and the peers from the H2020 project "Smart-EEjS". Here, I would like to highlight Ardak Akhatova, Luca Casamasissima and Luigi Bottecchia.

I would like to specifically acknowledge Benedikt Köpfer from the Fraunhofer Institute who kindly supplied me with valuable data for my research.

I would like to thank all my Canarian friends that welcomed me on the island and made it my home. They were always there for me if I needed distraction. Furthermore, I thank all my close friends from my studies, in particular Felix Sippel and Sultan Aliyev. Finally, I also thank those friends that I know since the very beginning: Paul Glade, Luis Karger, Stefan Bub and Kevin Beierlein.

In the end, I would like to thank the Atlantic Ocean. On and below its surface I could find the disconnection and tranquility that I needed to finish such a long-lasting project.

Abstract

Cities majorly contribute to the European Union's (EU) primary energy consumption and carbon emissions. While they require a large amount of energy resources, they hardly contribute to generating local renewable energy to cover their demand. The European Commission introduced the Positive Energy District (PED) concept to address this imbalance and decarbonise urban areas. A PED is a neighbourhood that generates more local renewable energy than it consumes from the surrounding grid. The EU-wide goal is to have 100 PEDs established, planned or under construction by 2025. This thesis contributes to the uptake of the PED concept by investigating the concept's feasibility and values across the EU. To do so, a tailor-made mathematical programming model has been developed. This thesis applies the model to three cases to study the feasibility of electrified PEDs across the EU, unveil PED-crucial external parameters for policy design and elaborate on how important passive retrofitting measures are to achieve PED status. The thesis concludes that PEDs are most cost-efficient in southern, warm climates with a dynamic electricity tariff. On the other hand, in cold climates, where often centralised solutions such as district heating are already installed, the PED concept is not economically feasible. Moreover, a high energy efficiency of the building stock through, e.g. envelop retrofitting is crucial in cold climates and densely populated districts to actually achieve a positive energy balance. In warmer climates, the cost-efficiency of passive retrofitting in PEDs is a case-by-case decision and is mostly optional for PED feasibility. This thesis proposes a threshold indicator to support this case-by-case decision. Finally, this work emphasises the significance of maintaining an acceptable amount of grid exchange not to strain the already often congested power grid but rather to provide flexibility.

Kurzfassung

Städte tragen in hohem Maße zum Primärenergieverbrauch und zu den Kohlenstoffemissionen der Europäischen Union (EU) bei. Während urbane Regionen eine große Menge an Energieressourcen benötigen, tragen sie kaum zur Erzeugung lokaler erneuerbarer Energie bei, um diesen Bedarf zu decken. Die Europäische Kommission hat das Konzept der Positiven Energiedistrikte (PED) eingeführt, um dieses Ungleichgewicht zu beseitigen und die städtischen Gebiete zu dekarbonisieren. Ein PED ist ein Stadtteil, der mehr lokale erneuerbare Energie erzeugt, als er aus dem umliegenden Netz verbraucht. Das EU-weite Ziel ist es, bis 2025 100 PEDs zu errichten, zu planen oder zu bauen. Diese Thesis trägt zur Verbreitung des PED-Konzepts bei, indem sie die Durchführbarkeit und den Wert dieses Konzepts in der EU untersucht. Zu diesem Zweck wurde ein maßgeschneidertes mathematisches Programmiermodell entwickelt. In dieser Arbeit wird das Modell auf drei Fälle angewandt, um die Durchführbarkeit von elektrifizierten PEDs in der EU zu untersuchen, die für PEDs entscheidenden externen Parameter für die Politikgestaltung aufzudecken und herauszuarbeiten, wie wichtig passive Nachrüstungsmaßnahmen sind, um den PED-Status zu erreichen. Die Arbeit kommt zu dem Schluss, dass PEDs in südlichen, warmen Klimazonen mit einem dynamischen Stromtarif am kosteneffizientesten sind. In kalten Klimazonen hingegen, in denen häufig bereits zentralisierte Lösungen wie Fernwärme installiert sind, ist das PED-Konzept wirtschaftlich nicht vorteilhaft. Darüber hinaus ist eine hohe Energieeffizienz des Gebäudebestands, z. B. durch Sanierung der Gebäudehülle, in kalten Klimazonen und dicht besiedelten Bezirken entscheidend, um tatsächlich eine positive Energiebilanz zu erreichen. In wärmeren Klimazonen ist die Kosteneffizienz der passiven Nachrüstung in PEDs eine Entscheidung die von Fall zu Fall zu treffen ist und meist optional für die PED-Machbarkeit. In dieser Arbeit wird ein Schwellenwertindikator zur Unterstützung dieser Einzelfallentscheidung vorgeschlagen. Schließlich unterstreicht diese Arbeit die Bedeutung der Aufrechterhaltung eines akzeptablen Umfangs des Netzaustauschs, um das ohnehin oft überlastete Stromnetz nicht zusätzlich zu belasten, sondern um diesem Flexibilität zu gewährleisten.

Contents

Abbreviations

CO_2	Carbondioxide
AS	Air Source
ASHP	Air Source Heat Pump
BAT	Battery
CAPEX	Capital Expenditure
CCHP	Combined Cooling Heat and Power
CHP	Combined Heat and Power
COP	Coefficient of Performance
DER	Distributed Energy Resource
DH	District Heating
DHI	Diffuse Horizontal Irradiance
DHW	Zero Energy District
DHW	Domestic Hot Water Contribution
DNI	Direct Normal Irradiance
EB	Electric Boiler
ECI	European Cooling Index
EHI	European Heating Index
ESCO	Energy Service Company
EU	European Union
FIT	Feed In Tariff
FSI	Floor Space Index
GFA	Gross Floor Area
GGS	Grid Generation Mix Scenario
GHG	Greenhouse Gases
GHI	Global Horizontal Irradiance
GIS	Geographic Information System

GS	Ground Source
GSHP	Ground Source Heat Pump
GTS	Grid Tariff Scenario
HP	Heat Pump
HS	Heat Storage
HVAC	Heating Ventilation and Air Conditioning
KG	Köppen Geiger
MAE	Mean Absolut Error
MFB	Multi Family Building
MILP	Mixed Integer Linear Programming
NDC	National Determined Contribution
nZEB	Nearly Zero Energy Building
nZED	Nearly Zero Energy District
PEB	Positive Energy Building
PED	Positive Energy District
PEF	Primary Energy Factor
PES	Power Exchange Scenario
PV	Photovoltaic
PVPC	Voluntary Price for the small consumer
R	Rural
REE	Red Eléctrica de España
RES	Renewable Eenergy System
RMSE	Root Mean Squared Error
SET	Strategic Energy Technology
SoA	State of the Art
SOC	State of Charge
SVS	Space Variation Scenario
ToU	Time of Use
TSO	Transmission Grid Operator
U	Urban
ZEB	Zero Energy Building
ZEC	Zero Energy Community

1. Introduction

1.1. Motivation

Human activity is likely responsible for approximately 1.0ºC of global warming beyond pre-industrial levels by today. Without strictly limiting carbon emissions, global warming will rise to levels that endanger life on planet Earth in various ways [1]. Therefore, in 2016 the "Paris Agreement" came into force as an international treaty to keep global warming below 2.0ºC [2]. The European Union (EU), as one of the participating regions, aimed for a reduction of not less than 40% of greenhouse gas emissions (GHG) by 2030 over 1990 as part of their initial nationally determined contribution (NDC). This NDC was revised in 2020 with a much stricter goal of a 55% emission reduction by 2030, in line with the famous European "Green Deal" that was presented end of 2019 [3, 4]. To achieve the Green Deal's overarching goal of carbon neutrality by 2050, the EU focuses on various areas, such as the environment and oceans, agriculture, food, transport, industry, energy generation and renovated and efficient buildings [4].

The usage of fossil fuels for energy generation is one of the many drivers of GHG emissions. On the one hand, cities cause almost 70% of the EU's primary energy consumption [5]. On the other hand, those dense urban areas barely contribute to the generation of renewable energy [6]. Furthermore, the Worldbank predicts urbanisation to grow from today's 56% to 70% by 2050 [7]. Due to space and resource limitations in cities, urban areas will have to rely on renewable energy generated elsewhere, which implies transport costs and losses [8]. Additionally, new electrified urban mobility solutions increase the risk of grid congestion, as cities' distribution grids were not designed for such capacities [9]. The requirement for more renewable energy in the electricity mix increases this issue due to the intermittency of most renewable energy sources such as solar or wind. Thus, urban neighbourhoods are encouraged to reduce the risk of grid congestion by flexibility and high self-consumption via storage solutions and demand-response, eg. with electric vehicles [10, 11, 12].

Regarding final energy consumption, the residential sector was responsible for roughly $\frac{1}{4}$ in 2019 in the EU. More than half of this final residential energy demand was natural gas (32%) and electricity (25%), which were mainly used in space heating and domestic hot water, as well as for appliances, respectively. 78% of the domestic energy was used for space heating and domestic hot water (DHW), mainly fueled by gas and other combustibles. Electricity-based heating played an insignificant role [13]. The urge for decarbonisation and increasing fossil fuel prices prognosticate a rising share of electricity in the heating mix as more cross-sectoral energy generation [14].

Buildings emit more than one-third of the EU's CO_2 emissions. One major problem is the age of the European building stock, where approximately 75% is regarded as inefficient. Dwelling inefficiency usually goes hand in hand with high energy consumption, which can lead to energy poverty for the tenants. Therefore, the European Commission intends to improve building retrofitting [15, 16]. To enhance the legislative backbone for increasing the EU's rate of building retrofitting, the EU updated their directives on energy performance of buildings and on energy efficiency in 2018 [17, 18]. Moreover, as part of the aforementioned "Green Deal" the European Union initiated the "renovation wave" including specific strategies and actions to speed up building retrofitting. Community-level solutions shall play an essential role by accumulating single building projects into district-scale ones [19].

Addressing the aforementioned energy-related challenges of (1) low urban renewable generation vs high urban energy demand, (2) demand for energy flexibility and (3) the need for energy efficiency of buildings, the European Union initiated the *Positive Energy District* (PED) concept as part of their Strategic Energy Technology (SET) Plan Action 3.2 in 2018 to decarbonise urban areas. A PED must generate more renewable energy locally than it imports from outside the district borders while being carbon neutral. The EU aims towards 100 PEDs by 2025 [20, 21]. Research and development activities around the PED concept are increasing thanks to dedicated working groups[1] and EU-funded projects[2], which create a high public interest for PEDs.

Based on the aforementioned points, this thesis aims to examine the feasibility and the techno-economic values of Positive Energy Districts in Europe. Therefore, mixed integer linear programming (MILP) is used to create a mathematical optimisation model for PEDs. This model is applied to different case studies to evaluate where PEDs are best situated. Additionally, the importance of building retrofitting for the PED project is highlighted in this study.

1.2. Research questions

This thesis consists of three major research questions and is consequently divided into three parts. Each part focuses on one particular topic that contributes to the overarching theme of the feasibility and techno-economic values of PEDs. All three research questions are answered as first-author publications in international scientific and peer-reviewed journals. Figure 1.1 overviews the three aforementioned research questions and their respective scientific publications [30, 31, 32]. The individual questions build upon each other and are further elaborated on in this section.

The first contribution to the thesis tests the newly developed PED linear programming model. It presents a novel and dynamic approach to the energy balance that takes into account the share of renewable generation in the surrounding grid mix on an hourly basis and therefore should provide more flexibility. Furthermore, it compares an urban and rural settlement regarding their PED feasibility using a real case study from the Spanish island La Palma [30]. This leads to the first research question of this thesis.

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[1] Annex 83 [22] and PED-EU research network [23]

[2] "Smart-BEEjS" [24], "Atelier" [25], "MAKING CITY" [26], "POCITYF" [27], "+CityxChange" [28] and "SPARCS" [29]

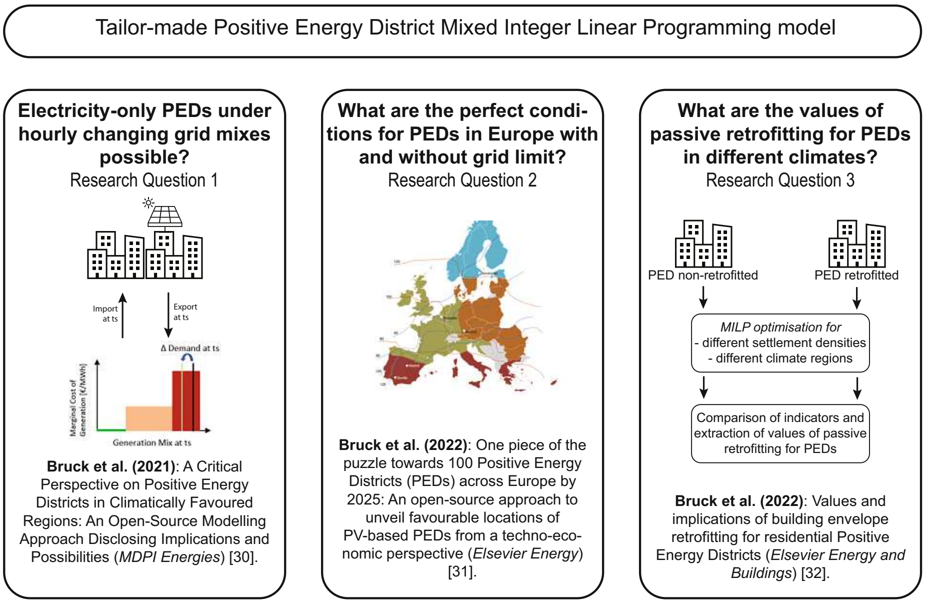

Figure 1.1.: Overview of the sub-research questions and respective publications

Research Question 1. *Are electricity-only PEDs feasible under hourly changing grid mixes with different renewable penetrations?*

Positive Energy Districts are a European concept. However, Europe is a large agglomeration of countries and is very diverse regarding climate and energy costs. Knowing where PEDs add the most value and are most likely feasible, as well as knowing tools to increase their cost efficiency would benefit urban planners and local decision-makers. Thus, building up on the first publication [30], the second contribution extends the scale of the application to investigate those conditions that would be most preferable for PEDs in Europe in terms of climate and electricity tariffs. Therefore the PED model was extended to a MILP model to accommodate space heating and cooling as well as domestic hot water. Additionally, the second contribution addresses how limiting the grid impact would affect the PED cost and optimised technology portfolio [31]. Therefore, the second research question is:

Research Question 2. *What are the perfect conditions in terms of climate region and energy tariff structure for multi-energy PEDs across Europe with* *and without grid exchange limitations?*

Finally, a low energy consumption of the district is the first and most significant step towards energy positivity, especially in areas with a high space heating demand. Additionally, one of the major PED pillars is energy efficiency. Therefore, the third contribution to this document examines how important passive building retrofitting is before turning a district into a PED, depending on different climates and available space for solar energy generation. Furthermore, this contribution determines a specific threshold cost of building envelope retrofitting that can be interesting as a rough indicator for urban planners [32]. Thus, the third research question is defined as follows.

Research Question 3. *What are the values of passive retrofitting for PEDs under different climate and settlement density conditions?*

Two additional publications to which I contributed are used for the literature review of this thesis but do not pose individual research questions [33, 34].

1.3. Structure of the thesis

The thesis is structured as follows. Chapter 2 elaborates upon the literature that is relevant for this thesis. This includes the definition of Positive Energy Districts and existing work on this topic, different optimisation techniques of district-scale energy systems and passive retrofitting research.

Chapter 3 addresses the mixed-integer linear programming model that is developed throughout this thesis. The focus is laid on the PED-specific energy positivity constraint which can be interpreted in several ways. Furthermore, the modular design that allows adding further technology to the MILP model and extend it therefore is elaborated in detail.

Chapter 4 tackles the three research questions by applying the MILP model to specific case studies. Thus, case by case, the value and feasibility of PEDs in Europe is unveiled in this thesis.

Finally, Chapter 5 presents a synthesis of the results and discusses them and Chapter 6 concludes the work and proposes directions for future investigation.

2. State of the art and progress beyond

After motivating the thesis topic in Chapter 1, this section provides the scientific basis of this dissertation. This thesis is based on three scientific publications that address different topics to answer the research question. Thus, this chapter is divided into several sub-chapters to provide a solid scientific background for this dissertation.

2.1. Positive Energy Districts

2.1.1. The development of the Positive Energy District concept

The Positive Energy District concept gradually developed over time from building and building-block concepts and is meant to eventually evolve into Positive Energy Cities or Regions in the future to become climate neutral by 2050 [33, 35]. In the 1970s first considerations about reducing the energy consumption of buildings were raised, which were fueled by the first oil crises and associated high fuel prices [33]. The initial focus was put on passive solar gains and reduction of heat demand, which led into the establishment of the passive house standard in the 1990s [36]. Subsequently, the concept zero energy buildings (ZEB) increased the requirements on passive energy savings and introduced the need for active and local, renewable generation such as solar PV to cover the entire building's demand. ZEBs became more popular around the turn of the millennium for example in the UK and US [37, 38]. The concept of nearly zero energy buildings (nZEB) is mainly used by the

EU. According to the revised Energy performance of buildings directive each new building after 2020 will have to be a nZEB [39]. The ZEB concept got quickly extended to the community/district level and the concept of the Zero Energy Community (ZEC) was born [40]. The logical next step was a positive energy balance by generating more energy than demanded. This concept was first introduced at building scale through Positive Energy Buildings (PEB) until it got extended to Positive Energy Districts [41, 20].

2.1.2. The definitions of the Positive Energy District concept

The PED concept was initially defined by the European Commission in the SET-Plan Action 3.2 “Smart Cities and Communities” in 2018 [20]. 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 [20]. 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 [21]. 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-sufficient. The virtual PED opens the spatial boundaries of the districts to allow off-site renewable generation [42, 43]. Initiatives such as the PED specific subgroup Annex 83 of the International Energy Agency [22] and the PED-EU research network [23], as well as EU-funded projects such as "MAKING CITY" [26], "ATELIER" [25], "+CityxChange" [28], "POCITYF" [27], "SPARCS" [29] or "Smart-BEEjS" [24] spark a strong research interest around PEDs. The Annex 83 works on PED stakeholder involvement, definition refinement, identification of technical solutions and modeling tool creation, as well as sustainability impact assessment of PEDs [22]. Also, academic literature approaches the PED concept from many diverse disciplines beyond the technical one. [44] for example, present a framework towards justice and inclusion, and the authors in [45] analyse potential justice problems in PED development. [46] investigate PEDs as forms of sustainable business models to answer the question of how various stakeholders add value to the community.

2.2. Distributed Energy Resources in PEDs

Distributed Energy Resources (DERs) include the local generation of energy from various sources, the local storage of this energy and demand response activities [47]. DERs are essential for PEDs as centralised approaches usually do not fit in densely populated urban areas such as PEDs. Without local distributed renewable energy generation that generates more energy than demanded by the district a dynamic PED would not be technically possible in the urban environment. Furthermore, without local storage options, a PED would not be able to fulfill its flexibility function.

Thus, all techno-economic work that is available on PED or PED-like concepts includes DERs to some extend. Authors of [48] consider combinations of PV and DHW energy communities consisting of PV generation, heat pumps and boilers as well as hot water storage as crucial to achieve Positive Energy District uptake. [49] deducts that DERs such as distributed generation and storage are a necessity to transform industrial parks into positive energy industrial parks and compare the concept with the PED concept. Authors of [50] analysed the technological solutions used in PEDs in different geographical areas in Europe through literature review, questionnaires and interviews. DERs such as solar PV, electric vehicles, electric and/or heat storage were considered to be of high significance across the spectrum of cases in the EU, often combined with centralised solutions such as district heating.

2.3. The value of passive retrofitting for PED-related concepts

The positive energy district is a highly ambitious neighbourhood concept. For achieving an annual positive energy balance while having net-zero carbon emissions, energy efficiency and local renewable generation are two essential pillars [21]. In dynamic PEDs with constrained district borders and therefore limited local generation potential, low energy consumption is important [43]. As the importance of passive retrofitting has not been discussed for PEDs yet, this section of the literature review focuses on concepts that share aspects with PEDs to some extent and that can be considered its predecessors. Typical concepts include nearly zero Energy buildings/districts (nZEB/D) or zero energy buildings/districts (ZEB/D) [33].

Building retrofitting has been particularly discussed in the context of nZEBs. According the to European Parliament, nZEBs shall have a very low energy demand that should be covered predominantly by local renewable resources [51]. kWh-specific details were defined by the EU-member states and therefore are not coherent across the EU [52]. Authors of [53] analyse the retrofit of an old soviet building in Estonia towards the nZEB standard. They conclude that the combination of building envelop retrofit and active measures makes the concept achievable and economically viable. Authors of Ref. [54] study the retrofit options of a building in Italy. Building envelope improvements are less financially attractive than active measures but necessary to lower the building energy demand sufficiently to fulfil the nZEB requirement. Ref. [55] study several existing renovation cases towards nearly zero energy buildings regarding their direct benefits and co-benefits. The authors conclude that benefits of retrofitting beyond economic ones, such as social, health and aesthetics, must be included in policy design and individual decision-making. Ref. [56] analyses the optimal refurbishment of buildings for the nZEB status across various European climates. It states that envelope retrofitting is more crucial in central and northern Europe, where it reduces the need for active refurbishment strategies for cost-optimal solutions. Study [57] assesses the needs of a modern Greek and an ancient Italian coastal house to become an nZEB by coupling energy simulation and genetic algorithm-based optimisation. They conclude that passive interventions are less cost-efficient than PV panels and improvements in the HVAC systems but essential to reach nZEB status. Thus, financial incentives are proposed to achieve this goal. Authors of [58] investigate a domestic building in Malta regarding retrofitting towards the nZEB status. They conclude that passive retrofit actions are less cost-effective than active measures regarding the nZEB indicators due to the warm climate. Ref. [59] investigate retrofit strategies for a Dutch neighbourhood. The study concludes that to achieve nZEB status, building envelope improvements beyond the current standards are required, reducing cost-effectiveness. Authors of [60] propose a strategy for nZEBs in Mediterranean climates based on the optimisation of a case study in Malaga. They suggest first reducing the energy demand by adapting the building envelope, then reducing the total energy consumption by applying efficient HVAC systems and lighting and thirdly, back the system with local renewable generation.

Zero Energy Buildings or Districts can be considered almost equal to PEDs from an energy balance perspective. Ref. [61] uses a genetic algorithm optimisation to investigate the optimal retrofit solution for an office building in five Italian climates toward a zero energy building. None of the combinations achieved the ZEB status due to limited PV area and non-sufficient retrofitting options. [62] optimise the district refurbishment for a case study in northern Spain using MILP. Results show that active measures such as CHP and district heating are more significant towards achieving the ZED goal than envelope improvements, which are not even selected in one of the three scenarios.

Thus, apart from some exceptions, passive retrofitting is crucial for high standard building or district concepts, while less economical.

2.4. Assessment of energy systems across large geographical areas

Energy system analysis is often applied to a specific case study with tight geographical boundaries. However, this limits the significance of the study to the respective location, as energy systems are highly dependent on spatial criteria. The PED concept is established by the European Commission and therefore, this work aims to deduct significant results for Europe and not only one specific geographic case. In literature, the potential of various types of renewable energy systems or technologies is assessed for large areas according to a common approach. The method segregates a large country or continent into smaller areas that share a common, mainly climate-related index and evaluate representative cities. Widespread examples in the literature are analyses of China, the United States (US) or Europe. For representative cities in the typical five Chinese climate zones, authors in [63] techno-economically assess multi-family buildings with grid-connected PV installations. [64] studies the potential of an innovative building envelope in those zones using established energy modeling software. Authors of [65] optimise solar-powered combined cooling, heating and power (CCHP) systems with a genetic algorithm in the Chinese climate areas. Authors in [66] divided the US into seven zones with a representative city each according to heating/cooling degree days, temperature and precipitation. Using particle swarm optimisation, they study the optimal size of a PV and solar thermal-backed CCHP plant for three different commercial building types. [67] creates eight zones of the US according to the Köppen-Geiger climate zones[1]. The authors determine the performance of off-grid, PV and fuel cell power plants fed by locally generated biogas. Authors in [69] created ten heating and cooling degree day based zones for the US to model the climate change impact on today's Net-Zero Energy buildings (NZEB). [70] and [71] use an approach developed by the PVSites Consortium [2][72] to divide Europe in 5 zones. The method uses a mix of Köppen-Geiger climate zones and the European Heating and Cooling Indices. [70] takes 38 representative cities spread over the five zones to determine the impact of climate change on residential buildings. Authors in [71] take one representative city per climate zone to investigate the potential of a residential PV, wind and heat-pump system with fixed capacities.

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[1] Most frequently applied climate classification system [68]

[2] EU Horizon 2020 research project about building-integrated PV

2.5. Modeling of district/community-wide energy systems

2.5.1. Techno-economic modeling of energy district and community projects

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 [45]. The district/neighbourhood/community-wide modeling 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 modeled 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 [73]. Authors of [74] 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. [75] 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 [76] 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 is the use of multi-node MILP models [77] to include more spatial detail, bi-level optimisation [78] to account for the objectives of two parties, or the inclusion of game theory [79, 80] to integrate multi-agent behaviour. This, however, can raise the complexity of the modeling 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 technological detail [73]. Therefore, each approach to community modeling serves a specific aim that needs to align with the research questions and shifts priorities to different aspects of modeling.

2.5.2. Techno-economic modeling of Positive Energy District and similar concepts

Despite the relative novelty of the concept, techno-economic analyses of PEDs are being actively discussed in the scientific literature. In [81], the authors assess obstacles of using existing energy modeling 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 of district parts are the key challenges that make existing modeling software not applicable to PEDs. Therefore, most existing literature is based on self-developed PED assessment approaches such as the one proposed by [82]. 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. [83, 84] 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 [85], 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. Finally, [86] presents the loads and technologies, spatial boundaries, temporal resolution and the objective function as key factors of modeling specifically important for PEDs. The authors highlight that evaluating the modeling goal and target audience is the initial step that shapes the four aspects.

2.6. Contribution to the progress beyond the state of the art

Putting the three research questions from Section 1.2 into perspective with the PED-related SoA reveals this work's contributions to literature which is presented in the following Section.

Concerning the first research question, a linear programming optimisation model was developed that integrates different approaches towards the realisation of the annual positive energy balance. Compared to the SoA, the approach elaborated in Section 4.1 adds to the literature through the following points:

- Firstly, case study one discusses perspectives of Positive Energy Districts that go beyond the annual positive energy balance using the case study approach. This includes the problem of available space for local renewable energy generation, particularly in urban areas, which is the target zone of the concept. Therefore, a rural area is compared with an urban one in climatically very advantageous conditions (a high renewable energy potential and predominant electricity demand; no space heating and cooling needed), which favour the creation of PEDs. Furthermore, the distribution grid impact is examined. While it might be possible to supply more than the annual energy demand from local and renewable resources, how this energy is supplied and exchanged with the grid is of significant importance to actually add value to the entire energy system instead of straining it.

- Secondly, and most importantly, the approach introduces an electricity import and export mechanism based on hourly changing primary energy factors of the grid according to its current technology mix. This novel approach in energy system planning and scheduling is tailored explicitly for district concepts that are constrained by a primary energy balance such as the PED and aims to provide flexibility in two ways. On the one hand, the dynamic mechanism provides flexibility to the district concept itself. The district scheduling can consider times with high grid mix primary energy intensity for export and low grid energy intensity for import. Thus, the district reduces its primary energy export requirements over the year and, therefore, also the need for expensive technology investment. On the other hand, this dispatch behaviour would also add flexibility to the surrounding grid. Considering that the grid primary energy factor is high during low renewable generation and vice versa, district electricity export during high primary energy grid mixes and import during low ones can stabilise the grid. This approach demonstrates the potential of primary energy arbitrage in PEDs and discusses its possibilities beyond the PED scope for island systems that do not have their own electricity market. Finally, by adding this approach to energy system planning and scheduling, primary energy intensity gets reduced, contributing to one of the primary goals of the European Union in the energy transition, namely increasing energy efficiency [87].

For the second research question, the model has been extended to a mixed-integer linear programming model to accommodate DHW, heating and cooling alongside the electricity demand. Furthermore, a machine learning model was developed to generate demand profiles for several locations across Europe. The total approach is described in Section 4.2 and contributes with the following novelties:

- Firstly, this work adds to the field of PED and PED-like techno-economic modeling by discussing all four major energy demand services, namely electricity, domestic hot water, space heating, and space cooling demand, with a tailor-made PED optimisation model. While previous PED research used to be highly case-study based, as shown in Section 2.5.2, this work goes beyond the approach of specific local case studies and focuses on deriving techno-economic statements on PEDs in the European context, covering different climate zones and energy costs.

- Additionally, this study contributes with an innovative method to approach the energy performance of large geographic areas, combining machine learning and integrating further indicators such as the cost of energy beyond the climate. This allows to derive generalised statements of which parameters to tweak in which part of Europe to have a well-performing PED.

To answer the third and last research question, further heating technology was added to the mathematical model and the value of a highly energy efficient building envelope was brought into the conversation of PEDs. The methodology is presented in Section 4.3 and adds the following points to the existing literature:

- This study approaches the determination of the value of retrofitting from a more general view. Most scientific studies, however, address the value of retrofitting through specific actions such as window replacement or insulation thickness. Nevertheless, each retrofitting scenario requires different actions to achieve the desired reductions in energy demand. Thus, this work provides the value of retrofitting bound to the energy demand reduction, independent of specific interventions. Through this approach, this study deducts a threshold cost per reduced unit of energy demand. This cost can be used very versatile as an indicator of the cost-effectiveness of retrofit interventions in the early planning stage.

- On a more PED-specific point, this study adds the value of retrofitting to the PED concept, where high energy efficiency is crucial. However, this work brings this into perspective with the climate and the settlement density.

- Finally, this study not only focuses on the economic value of retrofitting but additionally on the environmental and grid-related values building envelope renovation can add across Europe.

3. Optimization model for assessing Positive Energy Districts

This thesis is based on a tailor-made MILP optimisation model called PEDso (Positive Energy District system optimiser). This model has been developed within the three main publications on which this thesis is based on [30, 31, 32]. It optimises the technology portfolio needed to become a PED and the energy flows per time step by minimising its annualised costs (AC) or maximising its Net Present Value (NPV). PEDso is written in Python using the Pyomo optimisation framework [88, 89] and published under an open-source license [90]. PEDso is developed to be applicable to any district, regardless of its size or location. The following sections of the thesis describe the architecture of PEDso, its mathematical definition and how the model is applied to solve this thesis' research questions.

3.1. The architecture of PEDso

Figure 3.1 shows an overview of PEDso's architecture. Depending on the user's choice, the model can either be solved to maximise the NPV or to minimise the AC. This choice can, for example, depend on the available calculation capacity, as maximising the NPV requires significantly more time. An integral part of PEDso is the definition of the positive energy balance, which requires the district to export more energy annually than it imports from the regional energy system. PEDso allows to choose from various interpretations of this positive energy balance as further explained in Section 3.2.

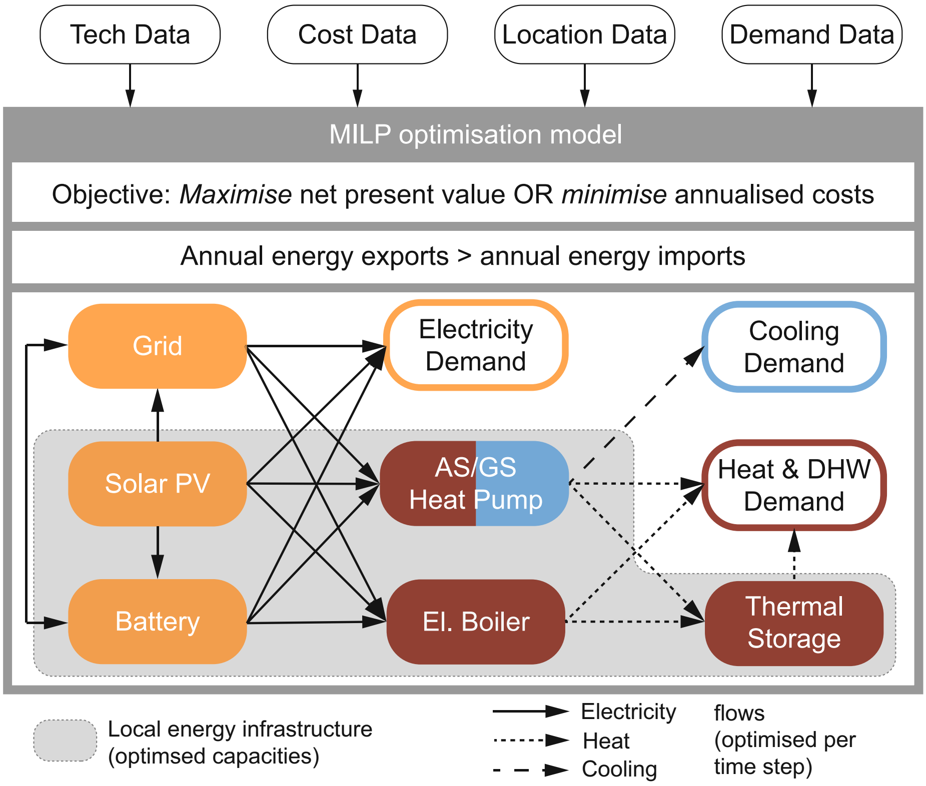


Figure 3.1.: Architecture of PEDso

The user can choose between only considering the electricity demand or, in addition as well account for space heating & DHW and space cooling demand. To cover these demands at each time step, a list of energy generation, transformation and storage technology is available. It can be selected to include solar PV, battery storage, air and/or ground-source heat pumps, electric boilers and thermal storage, as this thesis focuses on electrified PEDs. Section 3.3 describes the technology and further required model constraints mathematically.

A large amount of input data is necessary to describe a specific case study. Technical data includes the efficiencies and coefficients of performance of the technologies. Cost data represents the specific fixed and variable costs of the technologies as well as the tariff data, supporting various tariff schemes, feed-in tariffs and capacity tariffs. Location data includes the actual coordinates, hourly global horizontal, direct normal and diffuse horizontal irradiance (GHI, DNI, DHI) and temperature, as well as the available roof space for PV power generation at various roof angles and orientations. Demand data includes the load per chosen time step for electricity and options to include heating, DHW and cooling loads. Section 3.4 further elaborates on the model inputs.

3.2. The definition of energy positivity in PEDso

Energy positivity is directly defined in PEDso as a constraint. There are three types of balance constraints to choose from, the *non-PED balance*, the *static balance* and the *dynamic balance*.

If the *non-PED balance* is chosen, the PED status will not be opposed on the energy community. In this case, PEDso will optimise the district's energy portfolio without the need to export more energy then import annually. Districts will only become PEDs if this is the optimal solution in any case.

If *static balance* or *dynamic balance* is chosen, the district needs to fulfil the energy positivity constraint throughout the year. The primary energy factor (PEF) is used to compare different kinds of energies crossing the district borders. Even though this thesis focuses on electrified PEDs, electricity also has different PEFs. In the *static balance* approach, the imported PEF_{im} is set to be the average PEF of the grid mix. As per PED definition, it is only allowed to generate local renewable energy. Thus, the exported electricity needs to be renewable. Therefore, PEDso treats the exported electricity as avoided imported electricity with the same factor as PEF_{im}. Thus, if considering an electrified PED, PEF_{im} and PEF_{ex} are equal according to the static approach. This approach does not require knowledge of the regional energy generation mix in high resolution. The *dynamic balance* approach can be chosen if high-resolution electricity mix data is available. Here, each time step considers specific PEFs for imported and exported electricity depending on the regional marginal cost curve of the electricity generation mix. The comparison in Figure 3.2 shows that the export at time step ts reduces the regional electricity demand at ts. Thus, in the dynamic case, the $PEF_{ex}(ts)$ equals the PEF of the generated electricity that gets substituted. According to the marginal cost curve, this would be the most expensive one used at the specific ts. For the imported electricity from the regional system to cover the PED's electricity load, $PEF_{im}(ts)$ is assumed to be the PEF of the grid mix at ts. For any import that does not cover the load but, for example, is used to charge batteries, the PEF of the most expensive technology is taken. This is necessary as the model would otherwise trade back and forth between the batteries and grid, improving its energy balance, which is not a desired effect.

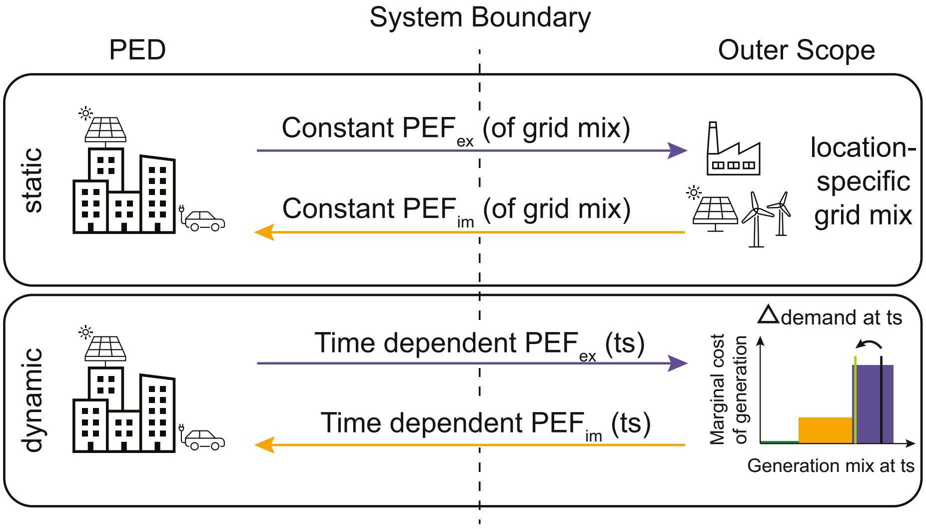


Figure 3.2.: Architecture of PEDso

3.3. Mathematical definition of PEDso

This section describes the mathematical formulation of PEDso. The objective of PEDso is always to achieve the most cost-optimal PED. This can be achieved by maximising the NPV (Equation 3.1) or minimising the AC (Equation 3.2). I_0 and I_{an} are the investment cost and the annualised investment cost, respectively. R is the revenue, $Cfix$ are the fixed costs and $Cvar$

the variable costs. Y is the lifetime of the project and y the actual year.

$$\max_{v\in V} NPV = \max_{v\in V}(-I_0 + \sum_{y=1}^{Y}(R_y - Cfix_y - Cvar_y) * (\frac{1}{(1+i)^y})) \tag{3.1}$$

$$\min_{v\in V} AC = \min_{v\in V}(I_{an} + Cfix + Cvar - R) \tag{3.2}$$

In the following, apart from the investment costs, all equations are the same for the NPV maximising and the AC minimising model, only that the AC model does not iterate over the years, so $Y = 1$ in all following equations for the AC case. In the NPV model the investment cost is the technologies' capacities cap_{tec} times their respective specific investment costs $cspec_{tec}$ as shown in Equation 3.3. For the AC model the investment cost is annualised as shown in Equation 3.4. Equation 3.5 shows the revenue earned by grid sales, and Equation 3.6 and 3.7 describe the fixed and variable cost, respectively. The power variable $p_{x_e,z_e,y,ts}$ shows the power flow from a device that can export electricity x_e to one that takes in electricity z_e. Heating and cooling flows are equally defined using $h_{x_h,z_h,y,ts}$ and $c_{x_c,z_c,y,ts}$, respectively. All three variables are being solved for each time step.

$$I_0 = \sum_{tec}^{TEC} cap_{tec} * capex_{tec} \tag{3.3}$$

$$I_{an} = \sum_{tec}^{TEC} cap_{tec} * \frac{capex_{tec}}{a_{tec}} \tag{3.4}$$

$$R_y = \sum_{ts}^{TS}\sum_{x_e}^{X_e} p_{x_e,grid,y,ts} * \frac{dt}{60} * tf_{y,ts} \tag{3.5}$$

$$Cfix_y = \sum_{tec}^{TEC} cap_{tec} * cfix_{tec} \tag{3.6}$$

$$Cvar_y = \sum_{ts}^{TS} \sum_{z_e}^{Z_e} (p_{grid,z_e,y,ts} * \frac{dt}{60} * t_{y,ts}) \tag{3.7}$$

Equation 3.8 and 3.9 show the previously described static energy balance and dynamic energy balance. In the static example the PEFex and PEFim are equal and constant, while in the dynamic balance, the PEFs get updated each time step.

$$\sum_{ts}^{TS} \sum_{x_e}^{X_e} p_{x_e,grid,y,ts} * \frac{dt}{60} * PEFex > \sum_{ts}^{TS} \sum_{z_e}^{Z_e} p_{grid,z_e,y,ts} * \frac{dt}{60} * PEFim \tag{3.8}$$

$$\sum_{ts}^{TS} \sum_{x_e}^{X_e} p_{x_e,grid,y,ts} * \frac{dt}{60} * PEFex_{ts} > \sum_{ts}^{TS} \sum_{z_e}^{Z_e} p_{grid,z_e,y,ts} * \frac{dt}{60} * PEFim_{ts} \tag{3.9}$$

Equations 3.10, 3.11 and 3.12 assure that the electric, heating and cooling loads are covered at each time step.

$$loadE_{y,ts} = \sum_{x_e}^{X_e} p_{x_e,loadE,y,ts} \tag{3.10}$$

$$loadH_{y,ts} = \sum_{x_h}^{X_h} h_{x_h,loadH,y,ts} \tag{3.11}$$

$$loadC_{y,ts} = \sum_{x_c}^{X_c} c_{x_c,loadC,y,ts} \tag{3.12}$$

Solar photovoltaic panel

Photovoltaic (PV) arguably is one of the most crucial renewable generation technology for PEDs as it can be applied to existing rooftops, carports or bus stations. Thus, it hardly competes with other ground usage, such as living or recreational space, which is important in urban areas. PV is separated into PV for flat surface applications and PV for tilted rooftops in PEDso. Equation 3.13 describes the PV power generated at each time step. $A_{az,\beta}$ defines the area used for PV power generation depending on the azimuth and tilt angle. This area includes installations that have already been installed before. $Irr_{az,\beta,y,ts}$ is the tilted irradiance in kW/m^2 at each time step and for each angle constellation. It is calculated from the global horizontal, the direct normal and the diffuse horizontal irradiance for each azimuth and tilt angle constellation of the district, depending on the exact location of the PED, the time of the day and the day of the year according to [91, 92]. η_{pv} is the efficiency of the PV module, and PR the performance ratio of the PV system that accounts for losses such as from the inverters.

$$\sum_{z_e}^{Z_e} p_{pv,z_e,y,ts} = A_{az,\beta} * Irr_{az,\beta,y,ts} * \eta_{pv} * PR \tag{3.13}$$

Equation 3.14 assures that the area used for PV power generation is smaller or equal than the available area of the district. GCR is the ground coverage ratio and accounts for PV panel spacing to avoid too much shading, especially in flat roof installations.

$$A_{az,\beta} \leq A\_avail_{az,\beta} * GCR \tag{3.14}$$

Equation 3.15 defines the total installed PV capacity in kW_p under STC conditions as a sum of all angle constellations.

$$cap_{pv} = \sum_{az}^{AZ} \sum_{\beta}^{TILT} A_{az,\beta} * \eta_{pv} \tag{3.15}$$

Battery storage

The battery storage is essential for the PED's flexibility, which is one of its three pillars. Equation 3.16 describes the charging and discharging behavior of the battery storage using the round-trip efficiency η_{bat}.

$$batSOC_{y,ts} = batSOC_{y,ts-1} + \sum_{x_e}^{X_e} p_{x_e,bat,y,ts} * \sqrt{\eta_{bat}} * \frac{dt}{60} - \sum_{z_e}^{Z_e} \frac{p_{bat,z_e,y,ts}}{\sqrt{\eta_{bat}}} * \frac{dt}{60} \tag{3.16}$$

Equation 3.17 ensures that the battery state of charge (SOC) cannot not exceed the installed battery capacity.

$$batSOC_{y,ts} \leq cap_{bat} \tag{3.17}$$

Heat pumps

Equations 3.18 - 3.29 describe the air-source (ashp) and ground-source heat pump (gshp). In PEDso, a PED can either choose ashp or gshp, which is ensured by Equations 3.23 and 3.29 and the binary variable *bhp*. Furthermore, at any given time step the heat pump can only produce heat or cold, which is arranged by Equations 3.19, 3.20, 3.25 and 3.26 and binary variables $bashp_{y,ts}$ and $bgshp_{y,ts}$.

$$\sum_{x_e}^{X_e} p_{x_e,ashp,y,ts} = \sum_{z_h}^{Z_h} \frac{h_{ashp,z_h,y,ts}}{COPhas_{y,ts}} + \sum_{z_c}^{Z_c} \frac{c_{ashp,z_c,y,ts}}{COPcas_{y,ts}} \tag{3.18}$$

$$\sum_{z_h}^{Z_h} h_{ashp,z_h,y,ts} \leq M * bashp_{y,ts} \tag{3.19}$$

$$\sum_{z_c}^{Z_c} c_{ashp,z_c,y,ts} \leq M * (1 - bashp_{y,ts}) \tag{3.20}$$

$$\sum_{z_h}^{Z_h} h_{ashp,z_h,y,ts} \leq cap_{ashp} \tag{3.21}$$

$$\sum_{z_c}^{Z_c} c_{ashp,z_c,y,ts} \leq cap_{ashp} * \frac{COPcas_{y,ts}}{COPcas_{y,ts} + 1} \tag{3.22}$$

$$cap_{ashp} \leq M * bhp \tag{3.23}$$

$$\sum_{x_e}^{X_e} p_{x_e,gshp,y,ts} = \sum_{z_h}^{Z_h} \frac{h_{gshp,z_h,y,ts}}{COPhgs} + \sum_{z_c}^{Z_c} \frac{c_{gshp,z_c,y,ts}}{COPcgs} \tag{3.24}$$

$$\sum_{z_h}^{Z_h} h_{gshp,z_h,y,ts} \leq M * bgshp_{y,ts} \tag{3.25}$$

$$\sum_{z_c}^{Z_c} c_{gshp,z_c,y,ts} \leq M * (1 - bgshp_{y,ts}) \tag{3.26}$$

$$\sum_{z_h}^{Z_h} h_{gshp,z_h,y,ts} \leq cap_{gshp} \tag{3.27}$$

$$\sum_{z_c}^{Z_c} c_{gshp,z_c,y,ts} \leq cap_{gshp} * \frac{COPcgs}{COPcgs + 1} \tag{3.28}$$

$$cap_{gshp} \leq M * (1 - bhp) \tag{3.29}$$

The COPs of the GSHP is assumed to be constant while the one of the ASHP is temperature dependent according to [93].

Electric boiler

Equations 3.30 and 3.31 describe the dispatch behavior and the capacity of the electric boiler, respectively.

$$\sum_{z_h}^{Z_h} h_{eb,z_h,y,ts} = \sum_{x_e}^{X_e} p_{x_e,eb,y,ts} * \eta_{eb} \tag{3.30}$$

$$\sum_{z_h}^{Z_h} h_{eb,z_h,y,ts} \leq cap_{eb} \tag{3.31}$$

Heat storage

The hot water storage is defined in Equations 3.32 and 3.33 in analogy to the battery storage. η_{self} is the self-discharge of the heat storage per time step. This work assumes a temperature difference of 30ºC between storage inlet and outlet

$$hsSOC_{y,ts} = hsSOC_{y,ts-1} * \eta_{self} + \sum_{x_h}^{X_h} h_{x_h,bat,y,ts} * \sqrt{\eta_{hs}} * \frac{dt}{60} - \sum_{z_h}^{Z_h} \frac{h_{bat,z_h,y,ts}}{\sqrt{\eta_{hs}}} * \frac{dt}{60} \tag{3.32}$$

$$hsSOC_{y,ts} \leq cap_{hs} \tag{3.33}$$

3.4. Model inputs

PEDso requires many input data to determine the optimal PED for each specific case. Most of this is fed to the model in Microsoft Excel files and can therefore be easily adapted to specific case studies.

Energy demands

The energy demand per defined time step is an important model input that is one major factor of the required energy technology. PEDso considers electricity demand, domestic hot water and space heating demand as well as space cooling demand. However, not all of the demands are needed, as the model can be used in e.g. electricity-only mode as well. This thesis uses both, real demand from a national TSO and synthetically generated demand data for specific cases.

Technology specific data and costs

The technology considered by the model needs to be described in terms of techno-economic parameters such as efficiencies, specific investment costs in $\frac{EUR}{kW(h)}$ and specific maintenance and operation costs.

Tariffs

A dedicated file feeds in the tariff structure to the model. It is possible to mix a tariff, feed-in tariff and tariff per connected capacity. All tariffs can be dynamic or static and need to be provided as time series with a length depending on the chosen ts.

Meteorological data

Reliable and local meteorological data is crucial for the calculation of renewable energy generation. PEDso requires time series of the global horizontal, the direct normal and the diffuse horizontal irradiance as well as the outdoor temperature to establish the PV power generation as well as e.g. the heat pump efficiency per time step.

Available space for PV

Finally, it is important to know how much space is available for PV power generation in the district and how is it distributed in different azimuth and tilt angles. PEDso takes in a matrix of different aggregated areas of various definable azimuth angles and tilt angles. Those roof areas can either be automatically measured in geographic information systems or manually in e.g., Google Maps.

3.5. PEDso applied

Section 4 shows three case studies in which PEDso is applied to answer the research questions about Positive Energy Districts. As PEDso was developed over time to answer those specific questions, each case study only applies the part of PEDso that is needed for the particular case. Figure 3.3 shows the "differentiation sheet" that is used in each case study to highlight, which specific parts of PEDso are used. It distinguishes between six different technology assets, the two balance types (static vs. dynamic), the two objectives (NPV vs AC) and four energy demands (electricity, DHW, space heating and cooling).

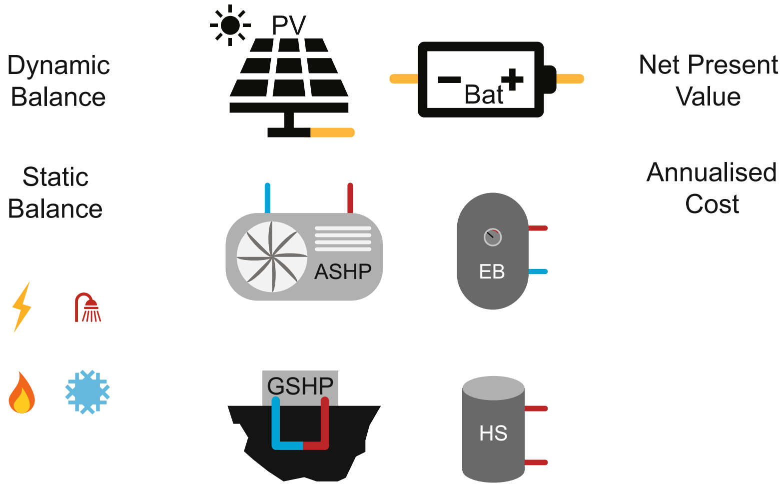


Figure 3.3.: Differentiation sheet for case studies

3.6. Nomenclature

Sets

AZ	Roof azimuth angles
TEC	Technology portfolio
$TILT$	Roof tilt angles
TS	Time steps per year
X_c	Technology with cold output
X_e	Technology with electricity output
X_h	Technology with heat output
Y	Years
Z_c	Technology/load with cold input
Z_e	Technology/load with electricity input
Z_h	Technology/load with heat input

Model expressions and variables

$A_{az,\beta}$	Area covered by PV panels at azimuth and tilt angle az and β
AC	Annualised costs
$bashp_{y,ts}$	Binary variable of heating or cooling mode of air-source heat pump at time step ts and year y
$batSOC_{y,ts}$	Battery state of starge at time step ts and year y
$bgshp_{y,ts}$	Binary variable of heating or cooling mode of ground-source heat pump at time step ts and year y
bhp	Binary decision variable between air or ground source heat pump
$c_{x_c,z_c,y,ts}$	Cold flow from x_c to z_c at time step ts in year y
cap_{tec}	Optimised capacity of each technology
$Cfix_y$	Fix costs at year y
$Cvar_y$	Variable costs at year y

GCR	Ground coverage ratio
$h_{x_h,z_h,y,ts}$	Heat flow from x_h to z_h at time step ts in year y
$hsSOC_{y,ts}$	Heat storage state of starge at time step ts and year y
I_0	Investment cost at year zero
I_{an}	Annualised investment costs
NPV	Net present value
$p_{x_e,z_e,y,ts}$	Power flow from x_e to z_e at time step ts in year y
R_y	Revenue at year y

Parameters

η_{bat}	Efficiency of the battery storage (roundtrip)
η_{eb}	Efficiency of electric boiler
η_{hs}	Efficiency of heat storage (roundtrip)
η_{pv}	Efficiency of the PV panels
η_{self}	Self discharge of heat storage at each time step
$A\_avail_{az,ts}$	Available area for PV installations at each angle constellation
a_{tec}	Annuity factor for each technology tec
$capex_{tec}$	Specific investment cost of each technology tec
$cfix_{tec}$	Annual fix costs of each technology tec
$COPcas_{y,ts}$	Coefficient of performance of ASHP in cooling mode at time step ts and year y
$COPcgs$	Coefficient of performance of GSHP in cooling mode
$COPhas_{y,ts}$	Coefficient of performance of ASHP in heating mode at time step ts and year y
$COPhgs$	Coefficient of performance of GSHP in heating mode
dt	Duration of one time step
i	Interest rate
$Irr_{az,\beta,y,ts}$	Irradiance on tilted surfaces with the azimuth angles az and the tilt angle β at each time step ts in year y
$loadC_{y,ts}$	Cooling load at each time step ts and year y

$loadE_{y,ts}$	Electricity load at each time step ts and year y
$loadH_{y,ts}$	Heat load at each time step ts and year y
M	Large M parameter for binary variables
$PEFex$	Primary energy factor of exported energy
$PEFim$	Primary energy factor of imported energy
PR	Performance ration of PV system
$t_{y,ts}$	Tarrif at time step ts and year y
$tf_{y,ts}$	Feed-in tarrif at time step ts and year y

4. Techno-economic investigation of the feasibility and values of PEDs in Europe in three case studies

This chapter aims to answer the three research questions from Section 1.2 with three studies that have been published in peer-reviewed journals [30, 31, 32]. Together, the studies contribute to the overall thesis topic of feasibility and values of PEDs in Europe.

4.1. Case Study: Electricity-only PEDs under hourly changing grid mixes

The first case study aims to answer the research question *"Are electricity only PEDs feasible under hourly changing grid mixes with different renewable penetration?"*. Additionally, this case study investigates how rural or urban settlements influence the PED portfolio and how a lowered grid impact affects the PED's technology portfolio and its costs. Therefore the study focuses on electricity only PEDs in regions that do not require heating nor cooling due to favorable weather conditions. This case study tests the functionality of the dynamic balancing algorithm and its potential value in island systems by comparing the PED establishment on a fossil-based island with the one on a highly renewable penetrated island. The study is published in MDPI Energies [30].

4.1.1. Method and case study description

In the following section, the first case study and its methodology is described. This study tests the functionality of the PED model PEDso and its different approaches towards the positive energy balance with real data. The chosen sites are an urban and a rural district on the island of La Palma, in the town Los Sauces. The various location specific input parameters are described and scenarios are defined.

4.1.1.1. Mathematical optimisation model

The mathematical optimisation model used in this study is a small part of PEDso, including only the PV panels and electricity storage as possible energy assets to optimise a purely electrical PED. This model focuses on the functionalities of the dynamic energy balance approach and is therefore chosen for model evaluation. Figure 4.1 shows the included constellation of PEDso in this first case study. For the mathematical formulation please refer to Section 3.3.

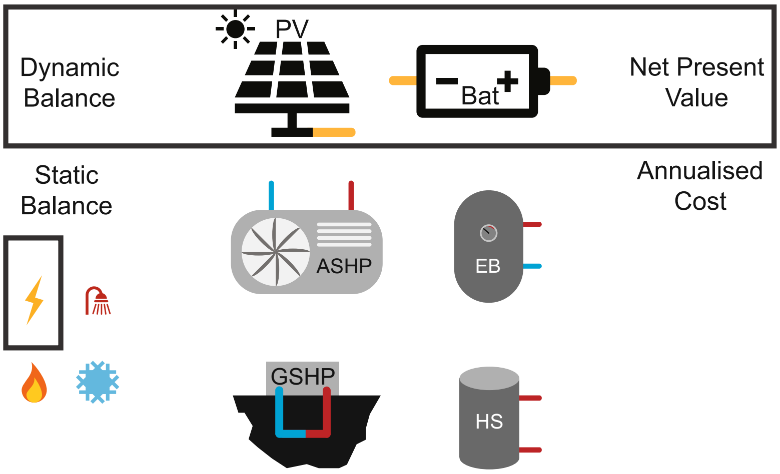


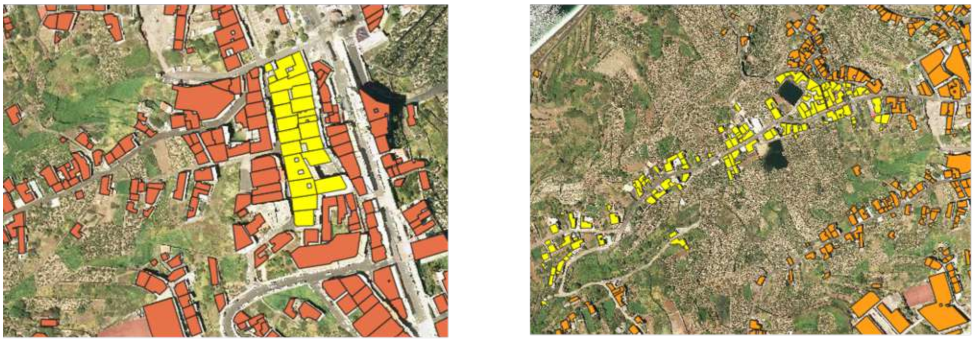
Figure 4.1.: PEDso usage in case study one

4.1.1.2. Location

Figure 4.2 describes the location of the rural and urban test site, which are located very close to each other in Los Sauces. La Palma has been selected as an initial case study due to its favourable climate conditions. Those allow to only focus on electricity demand and neglect heating and cooling for now. Furthermore, the islands that are not connected through underwater cables (Gran Canaria, La Palma, El Hierro) can be considered a closed system, making them very interesting from the standpoint of the grid generation mix. The grid generation mix of all islands, except El Hierro, is dominated by fossil fuels, mainly in the form of diesel. Thus, renewable focused projects gain interest in the sun-, and wind-rich archipelago to cut on diesel derived electricity to reduce CO_2 emissions, cost and dependency. Among the Canarian Islands, La Palma is one of those with the least stable grids [94]. Therefore, a PED project that values flexibility would be a valuable addition. Regarding selecting the town of Los Sauces, a local initiative called La Palma Renovable is currently planning the first steps of the island's energy transition in exactly this location. A floating PV power-based energy community with a 100 kW_p installation on a water storage is proposed in the area shown in Figure 4.2 (**d**) [95]. This would generate renewable electricity locally and reduce the evaporation of water from the storage. Thus, as the town of Los Sauces is already in the centre of interest for energy communities, this case study is applied there as well.

a) Position of La Palma among Canary Island

b) Area of Los Sauces - Case study



c) Urban housing block

d) Rural housing block

Figure 4.2.: Location of case study: (**a**) Location of La Palma in the North-West of the Canarian Archipelago (red circle). (**b**) Location of Los Sauces in the North-East of La Palma (red circle). (**c**) Urban buildings considered for urban PED example (labeled in yellow). (**d**) Rural buildings considered for rural PED example (labeled in yellow)

Both sites have an aggregated gross floor area (GFA) of approx. 15,800 m^2, despite the large difference in surface area. Thus, the floor space index mentioned before as an indicator of PED feasibility lies around 3 and 0.68 for the urban and rural district, respectively. The gross floor area is derived from the Spanish open kataster data in QGIS. Tables 4.1 and 4.2 show the available space for PV power installations for the urban and the rural district, which has been derived manually in QGIS.

Table 4.1.: Space available for PV generation on flat surfaces.

Occupation	Area urban [m^2]	Area rural [m^2]
Flat roof	678	3138
Terrace	2150	2295
Water Storage	0	2190
Total	2828	8323

Table 4.2.: Space available for PV generation on tilted roofs with tilt angle of 30º.

Azimuth Angle [º]	Area urban [m^2]	Area rural [m^2]
0	40	235
45	0	195
90	29	270
135	0	170
180	40	240
225	0	215
270	90	250
315	0	155

4.1.1.3. Timeseries Data

Time series, location-specific input data include the electricity demand, the tariffs, the grid generation mix and meteorological data. Demand, generation and tariff data are taken for the year 2019 not to be affected by COVID-19. The electricity demand is approximated as a share of La Palma's electricity demand, considering the gross floor area of the district. Since the urban and rural GFA is equal, both districts' electricity demand is assumed to be similar. The GFA share of all buildings in La Palma is 0.0159%. This value is applied to calculate the hourly demand of both districts. The hourly island-wide load is derived from [96], which is an open data register of the Spanish system operator Red Eléctrica de España (REE). There are two types of dynamic grid tariffs for consumers below 10 kW capacity in Spain (default and two periods; TARIFF 2.0 A and TARIFF 2.0 DHA, respectively), beyond the somewhat static tariffs. The dynamic tariffs, called "voluntary price for the small consumer" (PVPC), represent the cost of electricity generated and are thus very well suited for PED projects that are supposed to supply flexibility. The PVPC tariff is composed of the day ahead and intraday market price, cost of ancillary services, distribution and transmission tariffs, capacity payments and other fees. Additionally, the PVPC mechanism offers a surplus compensation for PV production according to the electricity generation cost. As this dynamic feed in tariff was introduced the 6th of April 2019 by the royal decree 244/2019 [97], the tariff for the beginning of the year is calculated according to the average difference to the default tariff during the rest of the year. The grid tariffs are also derived from [96]. Generation mix data for each island is obtained from [98]. Figure 4.3 shows a graph of the 2.0 DHA tariff (chosen for this study) as well as the feed-in tariff and of the generation mix during a specific day. Here, the strong dependency on expensive diesel fuel of the island of La Palma becomes very apparent. Meteorological data, such as global horizontal, direct normal and diffuse irradiance, and temperature and wind speed, is taken from [99]. All further necessary data is shown in Appendix B.

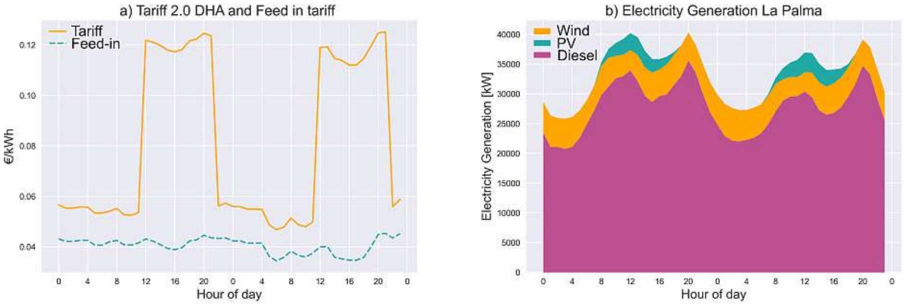


Figure 4.3.: a) Tariff 2.0 DHA and feed-in tariff during 24th and 25th of August 2019; b) Generation mix during 24th and 25th of August 2019.

4.1.1.4. Initial Scenarios

This section describes the initial scenarios for the urban and rural PED analysis, which are summed up in Table 4.3. At first, for comparison, the status quo is calculated. Since there are no pre-existing PV installations and the demand is the same for the urban and rural district, only one status quo scenario is needed for both districts. The status quo scenario will show the cost of doing nothing and therefore the cost of electricity purchase only. Next, for the urban and the rural district, an optimisation is done without the requirement of being a PED allowing for all the area, including terrace and water pond surface for PV power generation. This is then compared to the same optimisation with the requirement of having a positive energy balance, to see if the PED scenario would be the generally preferred solution. As it is pretty unlikely that all of the available space would be used for PV generation because the owners would want to use it otherwise or because they do not want to participate in, e.g. an energy community, an urban and rural scenario where only roof area and potential carports are used, that has no other possible occupation. The PED status is required in these variations. If any of those two scenarios cannot fulfil the PED requirement sensibly due to space restrictions, 25% of terrace space is allowed for PV panel installations as a third variation scenario.

Table 4.3.: Description of initial scenarios with the respective scenario number (S) and variation in available space for PV power generation with its respective space variation scenario number (SVS) for the rural (R) and urban (U) cases

S #	Description
1	R & U: status quo
2	R: no PED
3	U: no PED
4	R: PED
5	U: PED
SVS #	**Description**
1	R: PED; no terrace or water storage for PV generation
2	U: PED; no terrace for PV generation
3	U/R: PED; 25% of terrace allowed if no PED possible in SVS 1/2

4.1.1.5. Sensitivity Scenarios

Beyond the aforementioned variation in space available for PV generation, variation in grid power exchange (PES), grid generation mix (GGS) and grid tariff (GTS) is applied to specific scenarios. The grid power exchange restriction is used for the urban and rural district that uses the least amount of space and fulfils the PED requirement sensibly. Here, the grid connection power is restricted to 2, 1.5 and 1 times the maximal load at a time step, to decrease negative grid impact by the PED. Subsequently, the two aforementioned urban and rural scenarios are tested in a grid mix with very high renewable penetration to evaluate if this has an impact on the PED's NPV due to the lower primary energy intensity of the grid. Here, the grid mix of El Hierro is used, which had a renewable share of electricity generation of 67% compared to 10% on La Palma in 2019 [94]. Figure 4.4 shows the generation mix of El Hierro on the 24th and 25th of August in 2019. These two days are chosen because the generation mix of El Hierro is completely renewable at some times, while supported by diesel at other times. This allows for an in-depth assessment of the influence of extreme changes of the grid mixes PEF, as shown in section 4.1.2.3. Overall it can be seen that the electricity generated during this day is mainly renewable wind power that is partly stored by pumped hydro storage to bridge low wind generation. Electricity used for the pumped hydro storage is represented as negative values, while discharging the hydro-basins is shown positively in Figure 4.4. Finally, it is investigated how a grid tariff increase of 2%[1] and 4% annually affects scenario S1, urban PED scenario with least space used and with a grid power exchange limit of factor 2. The recently introduced [2] version of the PVPC tariff supports the assumption of an increasing and more fluctuant electricity cost [101].

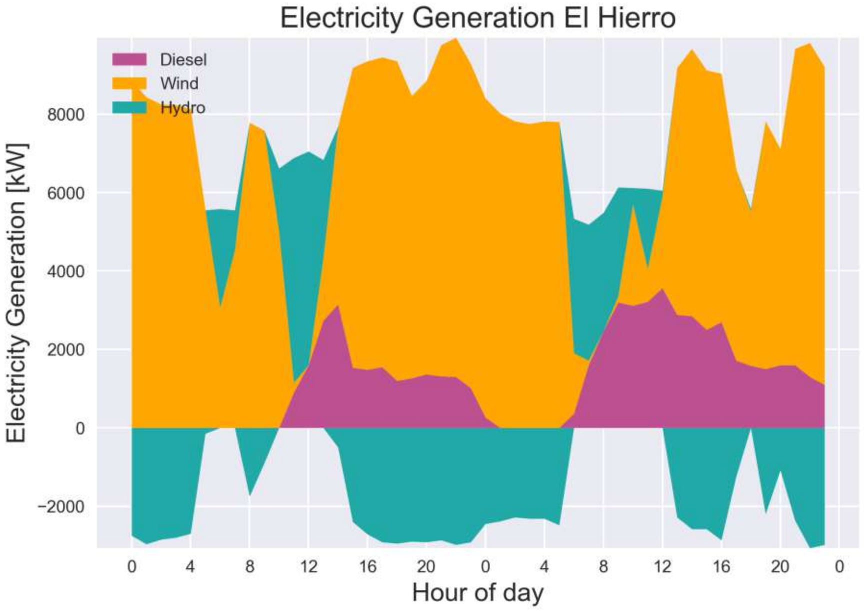


Figure 4.4.: Generation mix on the 24th and 25th August on Island of El Hierro

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[1] average annual tariff increase in Europe 2008-2020 [100]

[2] PVPC 2.0 TD got introduced on the 31st of May 2021

4.1.2. Results and discussion

4.1.2.1. Rural vs. urban and variation of roof space available

Figure 4.5 illustrates the net present value of each considered scenario as well as its composition by CAPEX, fixed cost, variable costs and revenue from grid sales. Table 4.4 shows the NPV, optimised technology portfolio for each scenario, as well as the respective electricity export/import ratio and the CO_2 emissions associated with the grid import. In the status quo scenario, no electricity generation is available, and the NPV is solely composed of variable cost, which in this case is the grid tariff only. Since the CO_2 emissions are only associated with the grid mix (time-dependent), S1 has the highest CO_2 emissions. As solar PV is very profitable under the given climate conditions, the rural and urban "no PED" and "PED" scenarios are identical and utilise all of the available area for PV installations. The NPV increases by €150,851 for the rural PED and by €136,696 for the urban equivalent over status quo. For the rural scenario, where no pond or terrace surfaces are considered for PV installations the NPV decreases around €10,000 from the rural scenario where all area is selected, due to decreased solar PV electricity generation. However, the PED solution is still economically superior over the status quo.

Table 4.4.: NPV, optimised technology portfolio, electricity export/import ratio and CO_2 emissions of respective scenarios.

Scenario	**NPV [€Mio]**	**PV_flat [kW$_p$]**	**PV_tilt roof [kW$_p$]**	**Battery [kWh]**	**Export/ Import**	**CO_2 Emissions [t]**
S 1	-0.483	0	0	0	-	1971
S 2 & S 4	-0.332	1265	86	0	12.60	978
S 3 & S 5	-0.346	430	17	0	3.29	1047
SVS 1	-0.342	477	86	0	4.47	1025
SVS 2	-	-	-	-	-	-
SVS 3 - urban	-0.357	185	25	0	1.04	1134

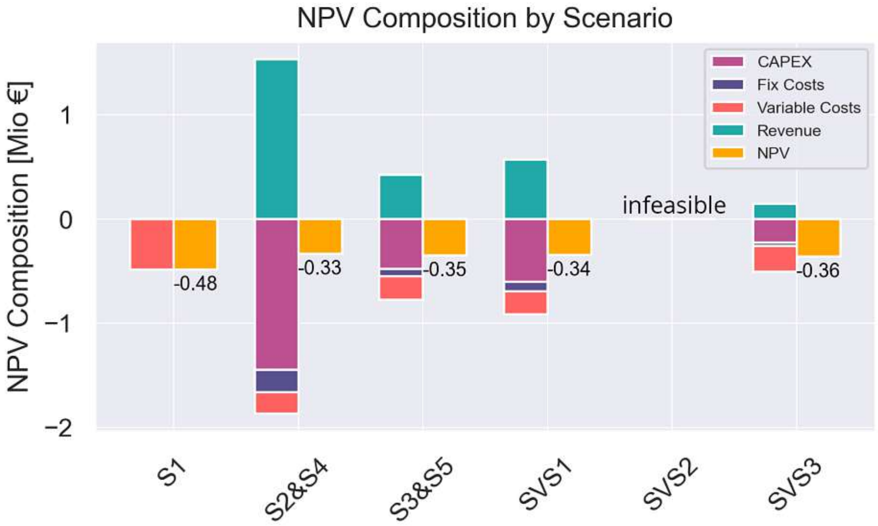

Figure 4.5.: Composition of the net present value by scenario in CAPEX, fixed costs, variable costs and revenue.

On the other hand, in the urban scenario, where rooftop terraces are not taken into account, a PED is considered to be infeasible by the optimization, as not enough area is available for PV power generation. Thus, 25% of terrace usage has been allowed for PV generation in the urban scenario, which has an increased NPV of €125,643 over the status quo scenario. SVS3 has the lowest electricity export/import ratio with 1.04, as it provides the least space for local generation. Among the scenarios with PV systems, it can be seen that the NPV only changes very little. This is due to the relatively low feed-in tariff that does not allow for high revenues compared to the capital expenditure. Thus, the significant increase in the NPV results from self-consumption and not from excess sales to the grid. This also explains the low difference in associated CO_2 emissions for the scenarios with a PV system, as emissions are only omitted by reducing grid import. For further considerations, the scenarios SVS1 and SVS3 are used, representing the rural PED only using roofs and possible carports and for the urban case only roofs plus 25% of terrace space for PV power generation, respectively. As it is unlikely that 100 % of the available space for PV generation will be used, this is also a more realistic assumption.

While both SVS1 and SVS3 satisfy the PED restriction in terms of having a positive energy balance, they do not contribute to grid stability. This becomes specifically apparent when looking at the distribution of PED import and export power as done for SVS3 in Figure 4.6. It can be seen that grid power export observations are spread over a much larger spectrum of power and reach maximum values of up to 221 kW. On the other hand, the grid import spectrum is much tighter, and most observations are located in the area around 40 kW, while the maximum value is 65 kW. Considering that the scenario depicted in Figure 4.6 is the PED scenario with the lowest installed capacity of PV power, all the other scenarios will have even higher export power values. As for comparison, SVS1 and S2/4 have a maximum export power of 676 kW and 1.6 MW, respectively, compared to the same import power maximum of 65 kW. This ratio does not contribute to grid stability but would instead destabilize the grid.

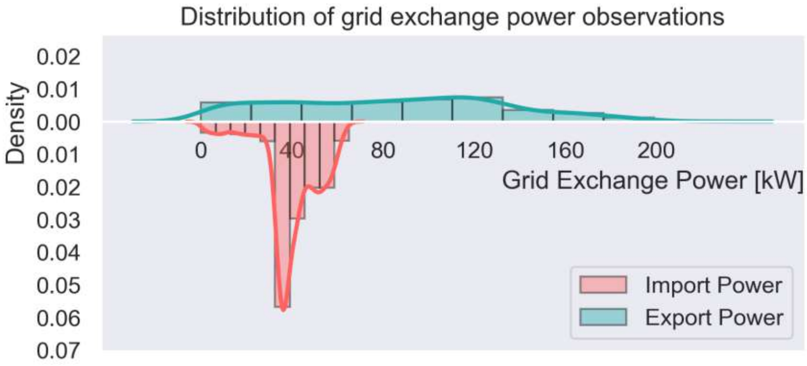

Figure 4.6.: Density of grid import and export power without zeros over year one of SVS3 - urban.

4.1.2.2. Variation of grid exchange power

Therefore, a sensitivity analysis, where the grid exchange power has been limited to 2, 1.5 and 1 times the maximum demanded power over the year (66 kW, up-rounded). Without a requirement to achieve PED status, this restriction would simply reduce the PV installed capacity to match the power exchange requirement. However, in combination with the PED constraint, high PV installed capacity is required to generate sufficient electricity, and almost always, storage has to be engaged to adjust and distribute the export power. The negative development of the NPV with reduced power exchange to the grid can be seen in Figure 4.7 (a) and (b) for the rural and urban scenario, respectively. This reduction in the net present value over the project time of 20 years is mainly due to increasing storage requirements to spread the PV power export over a more extensive period. This can also be observed in the required technology portfolio in Table 4.5, where battery capacity grows with lower power exchange allowance. Additionally, for the rural case, installed PV capacity is strongly restricted by the grid exchange limit. Furthermore, it can be seen that the rural PES lim2 and 1.5 as well as the urban PES lim2 are still economical superior or at least similar to the status quo scenario. It becomes apparent that the rural scenarios have a better NPV than the urban ones. Looking at Table 4.5, this is due to the higher requirement of battery storage in the urban scenarios. The rural PES lim2 does not even require battery storage at all. This is due to the higher abundance of tilted roof surfaces in rural areas that induce a higher peak PV power generation diversity throughout the day. However, as urban rooftops are mainly flat, this diversity could be manually induced by varying tilt and azimuth angle of the panels to achieve an optimal self-consumption instead of the highest aggregated power generation throughout the year. This reveals that the optimal tilt and azimuth angle is not in any case the preferred option. In this case study and in most of today's tariff systems, the feed-in compensation for excess PV generation is very low compared to the grid import tariff. Thus, in most cases, it appears to be more economical to reduce consumption with a slightly less optimal PV plant set-up in terms of aggregated energy generation than setting up panels in an optimal way to then sell the excess electricity cheaply.

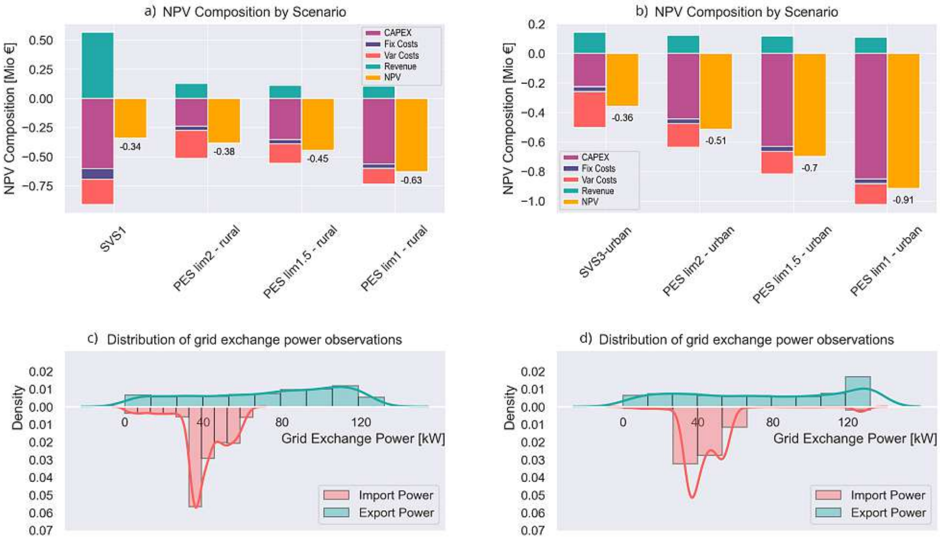

Figure 4.7.: (**a**) NPV composition with power exchange limitations of the rural PED; (**b**) NPV composition with power exchange limitations of the urban PED; (**c**) Distribution of grid exchange power observations of PES lim2 rural; (**d**) Distribution of grid exchange power observations of PES lim2 urban .

Furthermore, Figure 4.7 (c & d) show a more cohesive export power of PES lim2 rural compared to Figure 4.6. In (c), this is achieved by reducing PV power generation and a more diverse portfolio of azimuth angles of PV panels. On the other hand, in (d) batteries are installed, which also explains the grid import at approximately 120 kW. Generally, the import is less when batteries are installed and at economically more preferable times due to the very dynamic grid tariff. Thus, the grid limit exchange scenarios fulfil the PED requirement while not straining the grid as the initial scenarios and, in the case of battery installations, even supply further stability by reacting to price signals and shed expensive peak loads. Additionally, it can be seen in Table 4.5 that the export/import ratio of electricity is below one. Due to the high cost of batteries, the model sizes the district now just to reach the PED requirement and thus, the primary energy import/export balance is slightly bigger than one. It can also be seen that with increasing battery capacity and the same primary energy balance, the electricity balance decreases. This is due to the primary energy arbitrage that is performed by the battery to reduce the required storage size and, therefore, the CAPEX to achieve PED status. Finally, also CO_2 emissions associated with the grid import decrease with increasing battery size as less electricity is imported.

Table 4.5.: NPV, optimised technology portfolio, electricity export/import ratio and CO_2 emissions of respective PES.

Scenario	**NPV [€Mio]**	**PV_flat [kW$_p$]**	**PV_tilt roof [kW$_p$]**	**Battery [kWh]**	**Export/ Import**	**CO_2 Emissions [t]**
PES lim 2 - R	-0.385	38	185	0	0.942	1110
PES lim 1.5 - R	-0.445	34	192	148	0.937	944
PES lim 1 - R	-0.631	29	200	424	0.928	867
PES lim 2 - U	-0.514	175	29	301	0.932	1014
PES lim 1.5 - U	-0.698	175	29	551	0.930	976
PES lim 1 - U	-0.907	176	29	842	0.926	894

4.1.2.3. Variation of local generation mix

The PEF of the electricity generation mix is strongly dependent on its share of renewable energy. Therefore, PED scenarios have been investigated under the very renewable grid mix of the island of El Hierro, compared to the very diesel-based mix of La Palma as of today. As it can be seen in Table 4.6, a renewable generation mix favours the PED concept when assessed dynamically. This is due to the low PEF of the import-electricity and the still high PEF of the export power when fossil generation is running and therefore replaced. Thus, less battery capacity is needed, and significant savings can be made in most scenarios when compared to Table 4.5. Furthermore, it can be seen that the export/import ratio of the grid exchange restrained scenarios is significantly lower than in the same scenarios considering a more fossil-based grid mix. This can be explained by higher fluctuations between the PEFs of time steps. Thus, in the very renewable heavy grid mix of El Hierro, there is more opportunity to take advantage of the primary energy difference and therefore reduce the amount of actually required export electricity. Finally, the grid associated CO_2 emissions increase with grid exchange power restrictions under the assumption of El Hierro's grid mix. This is due to the decreased time when PV power can cover the entire electricity load, and thus more grid import is necessary.

Table 4.6.: NPV and optimised technology portfolio of S1&3 as well as all PE scenarios within a high RES penetrated grid mix.

Scenario	**NPV [€Mio]**	**PV_flat [kW$_p$]**	**PV_tilt roof [kW$_p$]**	**Battery [kWh]**	**Export/ Import**	CO_2 **Emissions [t]**
SVS1 - R	-0.342	477	86	0	4.467	476
PES lim 2 - R	-0.370	74	108	0	0.727	536
PES lim 1.5 -R	-0.393	19	172	15	0.714	567
PES lim 1 - R	-0.493	8	180	178	0.671	529
SVS3 - U	-0.357	185	25	0	1.036	530
PES lim 2 - U	-0.392	159	11	61	0.696	563
PES lim 1.5 - U	-0.495	132	29	183	0.646	586
PES lim 1 - U	-0.667	130	29	407	0.626	592

Additionally, Figure 4.8 illustrates the differences in the energy dispatch considering a low renewable energy local grid mix and a high renewable energy local grid mix. In both scenarios, night-time is covered by electricity from the grid due to the price advantage. For expensive and fossil-heavy evening peaks, the battery is used. In the low RES case, due to the higher battery capacity, the evening peaks in the two chosen days can be completely covered by the battery. In the high RES scenario, the battery size is considerably smaller, and therefore the evening peaks are only partly supplied by the battery to support the grid. Furthermore, it can be seen that even if PV power is available, sometimes the grid is used to cover the load before noon. This is due to the very cheap tariff during this time and the favourable PEF of the grid mix. In the low RES scenario on the second day, the morning PV power charges the battery to be used later during the day. In the high RES scenario, the grid covers the demand and the PV power generated is sold to the grid because this results in a positive balance of primary energy exchange according to the dynamic definition in Figure 3.2. The low RES scenario does not show this behaviour to this extend because the primary energy balance gains are only marginal and mainly get outweighed by the negative cost balance of feed-in tariff to grid tariff. While the PV power distribution behaviour under the low RES scenario is more logical due to the low cost of electricity until that time, the distribution under the high RES scenario is unwanted. This undesirable phenomenon also contributes to the explanation of increasing CO_2 emissions in the high RES scenario under grid exchange restrictions. Furthermore, it can be seen that the grid is used much more frequently to charge the battery in the high RES scenario than in the low RES scenario, which is also explained with the more favourable grid mix of El Hierro, which on the other hand is reasonable behaviour.

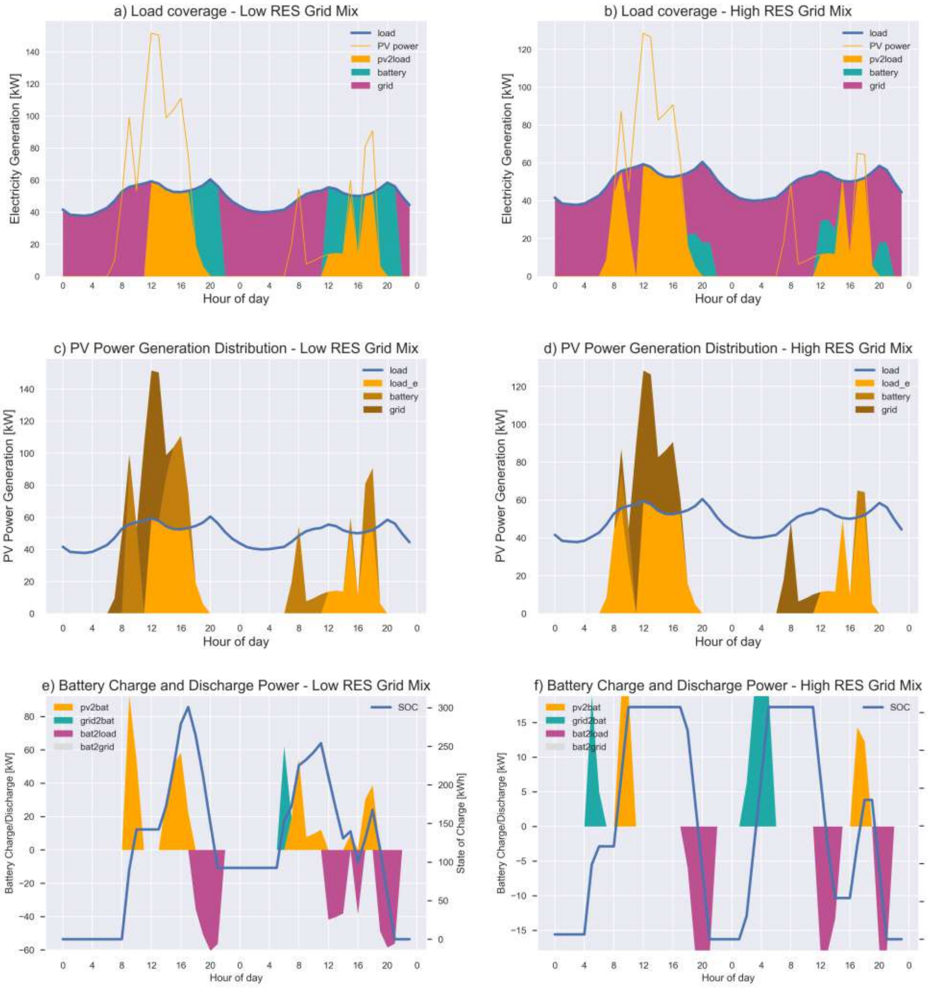

Figure 4.8.: Electricity dispatch on the 24th and 25th of August 2019 considering a) load coverage under the low RES La Palma grid mix, b) load coverage under the high RES El Hierro grid mix, c) PV power distribution under the low RES La Palma grid mix d) PV power distribution under the high RES El Hierro grid mix, e) Battery Charge and Discharge Power under the low RES La Palma grid mix and f) Battery Charge and Discharge Power under the high RES El Hierro grid mix. Considered is the urban scenario with a grid exchange limit of 132 kW (PES lim2 - U)

4.1.2.4. Variation of the electricity price

Figure 4.9 shows the sensitivity of the status quo scenario, the SVS3 scenario and the PES lim2 - 2 scenario towards an increase in the electricity tariff. Since the status quo scenario is only considering electricity import to cover the load, it is the most sensitive of the three towards an annual increase in electricity tariffs. Even with only the yearly 2% growth that resembles the average annual tariff increase in Europe, the status quo scenario has the lowest net present value over a lifetime. On the other hand, the grid power exchange limited scenario is the least affected by an increasing electricity price, given the used, dynamic tariff scheme. Being the only scenario among the three having a > 300 kWh battery installed, it can effectively reduce price peaks compared to the SVS3 scenario, which is dependent on the fluctuant behaviour of the sun.

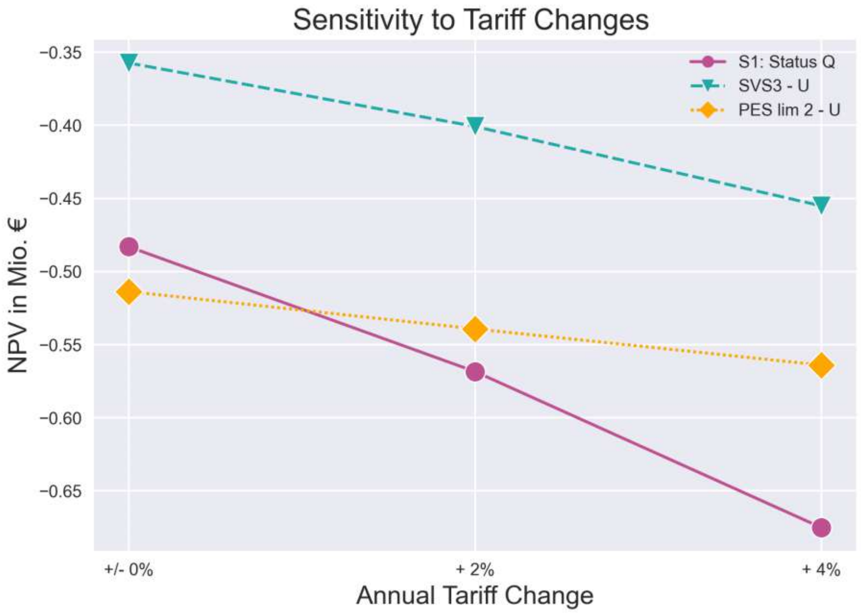

Figure 4.9.: Sensitivity of the status quo (S1), the SVS3 - U and the PES lim 2 - U towards tariff increase .

4.1.3. Resume Case 1

This work shows that Positive Energy Districts can be spatially feasible and economically superior over plain grid import in climatically favourable conditions, considering electricity demand only. This has been elaborated by applying a tailor-made linear programming model to an urban and rural case study with the same gross floor area on the island of La Palma. The rural area is more straightforward to convert to a PED due to its low floor space index. The much denser urban area with its higher FSI had to use some of the terrace space for PV power generation to achieve an annual positive energy balance. Thus, the FSI as an indicator for PED feasibility was confirmed, as already mentioned in [83]. However, due to the excellent climatic conditions, PV panels are sized until the limit of available space. While this favours the energy transition, it can be problematic for the grid, as amplitudes of power export fluctuations increase with higher PV installed capacity. This strains the grid, requires frequency regulations and potential expensive grid updates. A PED should contribute to neither of those, and thus, the grid export was restricted in this work to a multiple of the maximum demand. In most scenarios, this requires battery installations and PV power installed capacity is reduced. Furthermore, the model tries to distribute the azimuth angle of PV installations more evenly to spread the PV power generation over the day and therefore reduce expensive battery installations. Especially the battery addition reduces the net present value of a PED significantly. Only in some rural cases (more flexible PV installation distribution), the NPV stays above the one of status quo, as no/less battery is required compared to the urban scenarios.

The novel dynamic primary energy balancing mechanism appears promising for optimising PEDs or other collective energy systems, with some sort of energy storage for flexibility. The positive annual energy balance based on hourly changing PEFs of the grid mix provides an economic incentive to reduce primary energy consumption, which should be one of the central energy supply related goals of current times. This holds specifically for closed island (-like) systems such as the Canary Islands with no own electricity market. Thus, the price signals of the electricity tariff do not correspond to the local generation situation. Thus, it adds additional value over the static PEF approach proposed for PED evaluation by [82]. When applying such dynamic primary energy balancing, one critical point is allocating primary energy factors to specific export and import power streams, as this significantly affects the power exchange with the grid. This is further explained in Appendix A, where the grid to battery power flow PEF has been misallocated and resulted in undesirably battery charge and discharge behaviour.

Due to the dynamic PEF balance, the grid power exchange limited PED can be implemented less expensively in areas with high renewable grid mixes. Here, the battery capacity can be reduced as the significant differences in PEFs result in an excellent opportunity for PEF arbitrage. However, slight "cheating" could be identified particularly in the high RES scenario, where PV power is exported to the grid instead of covering the load as the model found it more valuable in terms of PEF at some time steps. This underlines the importance of correct adjustment of the PEF for each power flow. The low RES scenarios did not show this phenomenon to the same extent, as the PEF gap was too small to make up for the economic loss of this behaviour. Finally, a feasibility analysis towards increasing electricity tariffs revealed that the PED is more future proof towards raising electricity cost than the status quo scenario. Here, the grid exchange limited scenario, including a battery, is the most unaffected by the change, due to the added flexibility to react to price peaks. Thanks to the novel dynamic PEF approach, this work contributes to both, PED planning and operation approaches and is therefore a perfect addition to the aforementioned Annex 83 [22].

For future work, the primary energy led operation optimisation will be adjusted to not allow for "cheating" in any scenarios, such as covering the load demand by the grid while PV power is exported. A primary focus on self-consumption will be included. This would propose a valuable addition to microgrid/energy community operation in closed systems that do not have economic incentives for primary energy-saving operation due to a missing own electricity market. Additionally, the model will be extended to a mixed-integer linear programming model to account for heating and cooling in addition to electricity. To do so, a heating and cooling power matrix, similar to the electricity power matrix presented in this chapter, will be introduced along with the mathematical description of each generation, conversion and storage technology. This will allow investigating less climatically favourable areas across Europe for their PED potential, including multi-energy demands. However, the introduction of binary variables and a much larger space of possible solutions will significantly increase the model-complexity. Finally, for reducing strain on the grid but still keeping up high renewable installation capacity, electric mobility addition to the modelling framework will be discussed in future research.

4.2. Case Study: Perfect conditions for PEDs in Europe with and without grid limit

The second case study aims to determine *the perfect conditions for electrified multi-energy PEDs in Europe, taking into consideration the grid impact*. Therefore, this study creates a matrix of climate zones and energy tariff options to determine the perfect combination. The study is published in Elsevier Energy [31].

4.2.1. Method and case study description

This section includes an overview of the methodology, followed by an in-depth elaboration of each specific methodological step. As shown in Figure 4.10, 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 4.2.1.1). The second step elaborates a random-forest based machine learning algorithm to generate the space heating and cooling demand to overcome data shortage (Section 4.2.1.2). In addition, 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. The part of PEDso used in this study is shown in Figure 4.13. The MILP modelling approach as the core of the methodology evaluates the optimal multi-energy portfolio and energy flows for the district. Finally, Section 4.2.1.4 introduces the initial scenarios that the work analyses. Section 4.2.1.5 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] [102]. SynPro is a load generator for the German market. To overcome the data gap for 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 by the Copernicus project as meteorological data for the defined zones [103].

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

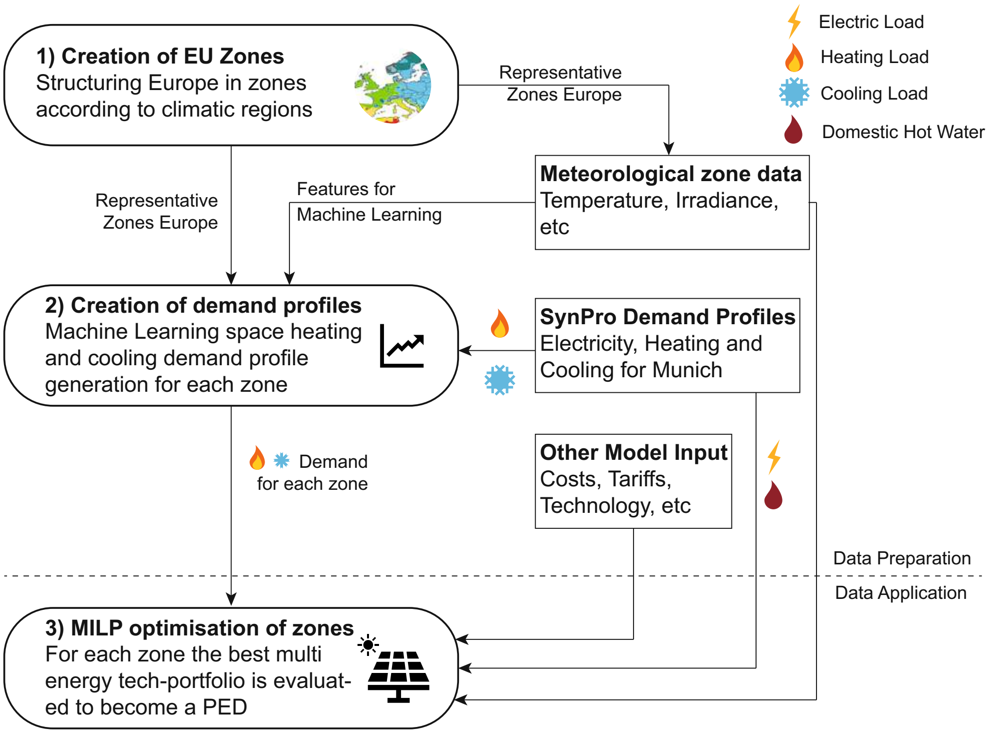

Figure 4.10.: Overview of the methodology

4.2.1.1. EU Zones

The climate is the leading indicator for zoning as it highly affects two types of energy uses, namely space heating and cooling [72]. A widely accepted classification system for climate zones is the Köpper-Geiger (KG) approach [68]. 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 4.7. Nearly zero-energy buildings require almost fulfilling the annual energy demand by local renewable generation and are therefore similar to PEDs. Thus, the presented methodology re-uses the five zones created by the PVSites consortium. Typically, a representative city per climate zone is chosen.

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

Table 4.7.: Zones for comparison according to [72]; highlighted cities are used in this work; colours represent zones in Figure 4.11

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

The most prominent KG zones in Europe 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 analysis compares Seville, Madrid, Munich, Brussels and Stockholm to create a modest 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. Figure 4.11 shows the aforementioned five zones on the map of the EU. The map mixes the KG approach with EHI and ECI [72]. 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 4.7.

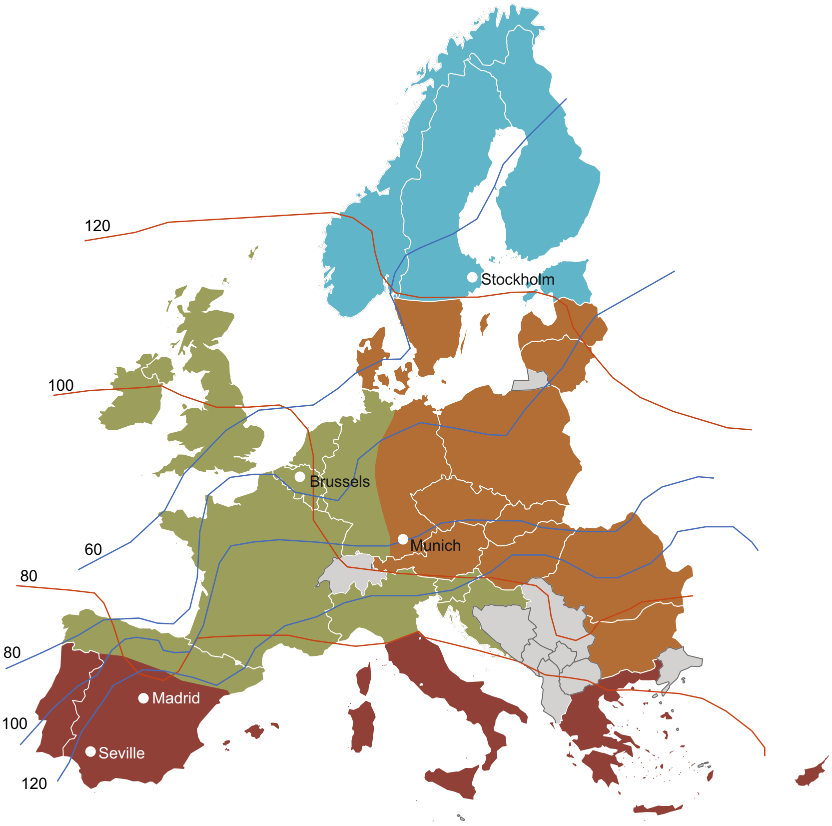

Figure 4.11.: EU zones map by [72] with European Heating Index (EHI) & European Cooling Index (ECI) on red and blue lines, respectively; 100 marks the "standard" heating/cooling line; each other line has a heating/cooling demand of X % compared to locations on the "standard" line, with X being the number on the line

4.2.1.2. 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 [104] 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 [105]. Figure 4.12 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.

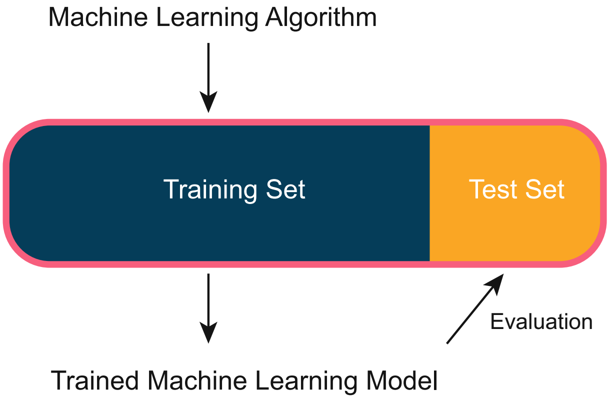

Figure 4.12.: Machine learning training and evaluation process

80% of the 365 days of time-series data is used for training while the remaining 20% are taken for evaluation [106]. 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 [107]. A model is created for the heating and cooling demand label, each with the same input features. The used features are shown in Table 4.8. The values predicted for the two hours 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 mathematically described in Equations 4.1 and 4.2.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - y_i'| \tag{4.1}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - y_i')^2} \tag{4.2}$$

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

Table 4.8.: 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

4.2.1.3. Mixed Integer Linear Programming PED Model

As this case study includes electrified heating and cooling, beyond the electricity demand the PEDso asset portfolio is extended for air-source heat pumps and electric boilers in addition to PV panels and batteries. The static energy balance approach is taken as no hourly generation data for the five different places are available. The objective function is the maximisation of the NPV to generate the cost optimal Positive Energy District for each scenario. Figure 4.13 shows the PEDso constellation used in this case study. For the mathematical description of the MILP model please refer to Section 3.3.

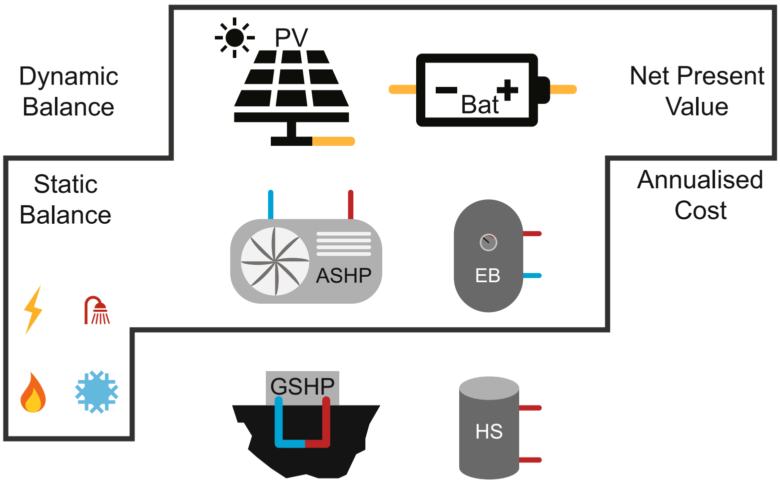

Figure 4.13.: PEDso usage in case study two

4.2.1.4. 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 than they demand from the grid annually. A district of 20 multi-family houses is assumed in all cases.

PV generation space available Each house is assumed to have 250 m^2 meters of free north and south-facing roof area available. In addition, each house has 50 m^2 meters 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.

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 [100]. 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 [108]. District heating is assumed to cost approximately 0.05 EUR/kWh of heat delivered [74]. Electricity, gas and DH tariffs are assumed to grow 2% each year.

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 [109]. Additionally, for the status quo scenario, the CO_2 factor of natural gas is 198 gCO_2/kWh_{gas} [110]. [74] 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 analysis 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 [111].

Technology available Table 4.9 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). Figure 4.14 illustrates the four technologies in an exemplary building of the PED. Derived from [112, 113], 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 B.

Table 4.9.: 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	+			+		

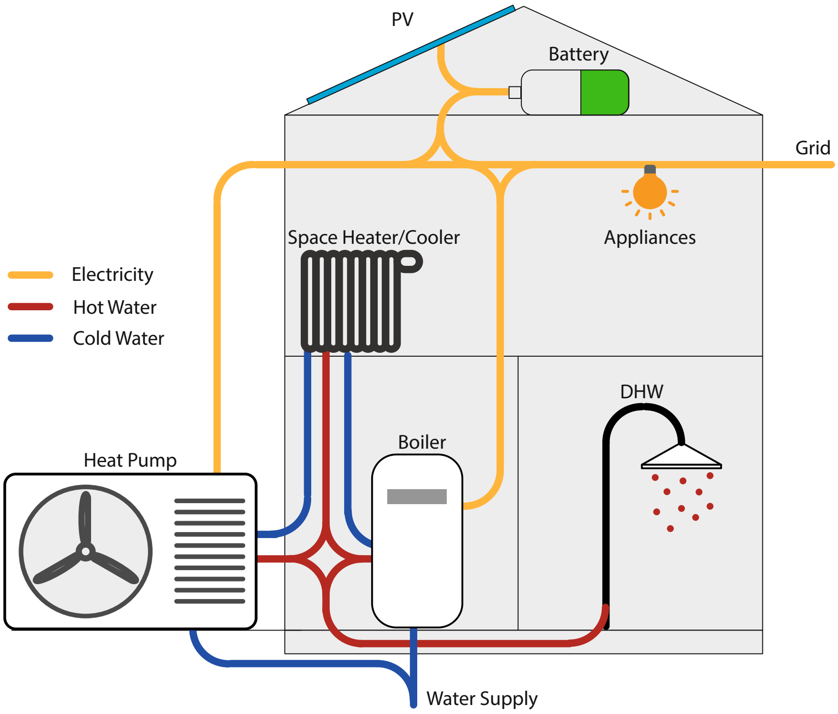

Figure 4.14.: Simplified sketch of available technology for the district buildings

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

4.2.1.5. Sensitivity Parameters

In order to determine what set of electricity cost parameters supports the diffusion of the PED concept best, 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 [100]. 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 [114]. This work 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 C. 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 [115]. Taking a current CO_2 price of 60 EUR/tCO_2 our analysis assumes an annual growth of the carbon price of 9.75% [116]. Finally, electrification of heating and large solar PV installations can adversely effect the grid [117]. 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 4.10 gives an overview of the sensitivity analysis cases. In the sensitivity analysis, only the PED cases are investigated.

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[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 [115].

Table 4.10.: Sensitivity parameters

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

4.2.2. Results and discussion

This section presents the results of the previously elaborated study and discusses them. Firstly, in Section 4.2.2.1, the machine learning-based space heating and cooling demand generator results are shown. Section 4.2.2.2 shows and discusses the results of the PED potential under the initial scenario assumptions, and Section 4.2.2.3 integrates further variables such as variation of electricity cost and structure, CO_2 cost and grid limitation.

4.2.2.1. Space heating and cooling demand generation

The following section presents the results obtained by the Random Forest Regressor (RFR) for demand generation. Table 4.11 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 to 3.6 kW, 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 hours of the year, heating is not zero during 6335 hours. 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 hours of the entire year in the Munich data set.

Table 4.11.: 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

Figure 4.15 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 it can be seen in Figure 4.15, even though the cooling demand is less accurate.

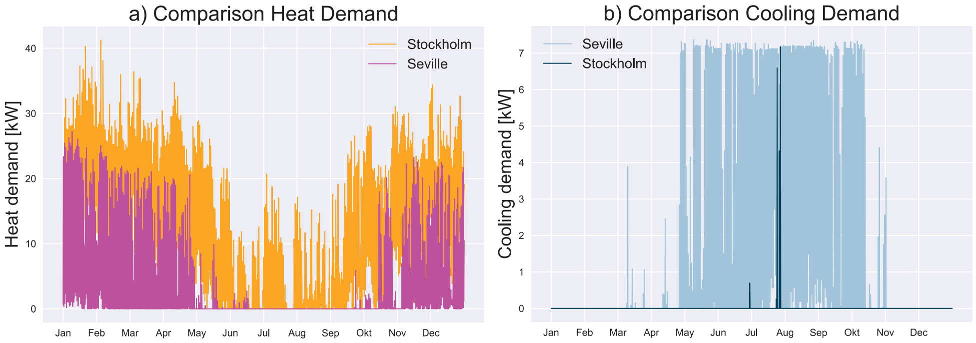

Figure 4.15.: Comparison of space heating and cooling demand of the two most extreme zones

4.2.2.2. PED potential across the EU

Table 4.12 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 4.12.: 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

Table 4.13 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 in these zones 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 Mu-

nich 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.

Table 4.13.: 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

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. Figure 4.16 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.

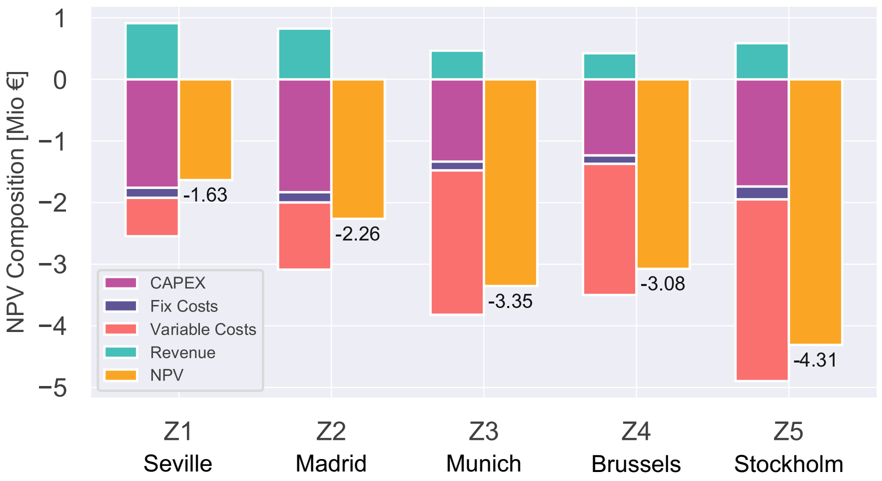

Figure 4.16.: Net present value composition of the PED for each zone

Comparing Figures 4.17 and 4.18 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 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 Figure 4.18 shows a much smaller export-import ratio as well as a significantly larger grid import. This is visualised by the grey grid point in Figures 4.17 and 4.18, 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 from 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. Figure 4.17 and 4.18 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.

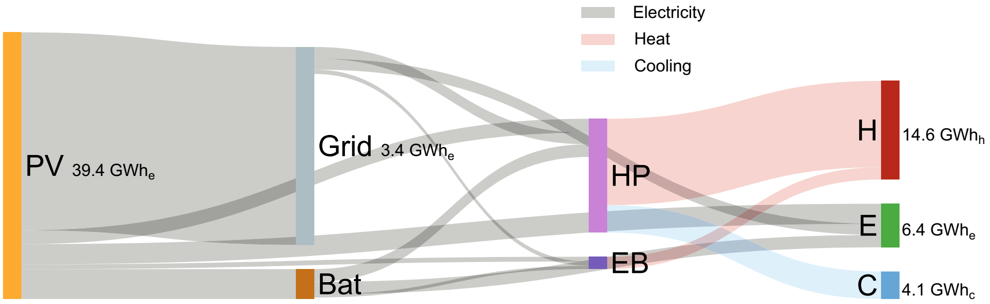

Figure 4.17.: Sankey energy flows over 20 years of the Zone 1 (Seville) PED including grid interaction; Bat - Battery, HP - Heat Pump, EB - Electric Boiler, H - Heating Demand, E - Electricity Demand, C - Cooling Demand

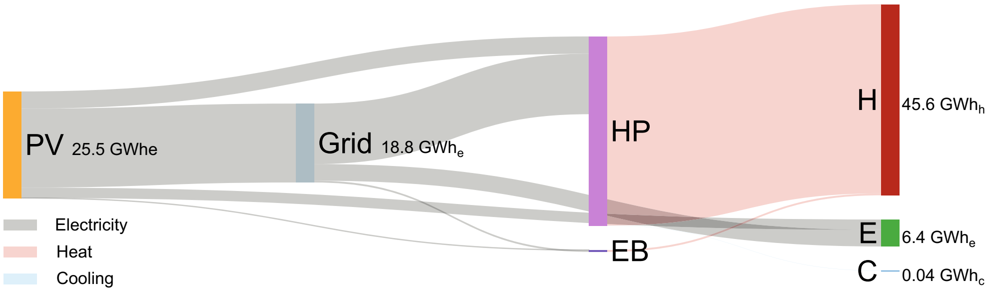

Figure 4.18.: Sankey energy flows over 20 years of the Zone 5 (Stockholm) PED including grid interaction; Bat - Battery, HP - Heat Pump, EB - Electric Boiler, H - Heating Demand, E - Electricity Demand, C - Cooling Demand

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. Figure 4.19 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 4.2.1.4. 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 fewer solar resources are available and supply and demand are increasingly asynchronous. Figure 4.19 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. The replacement of DH with individual 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.

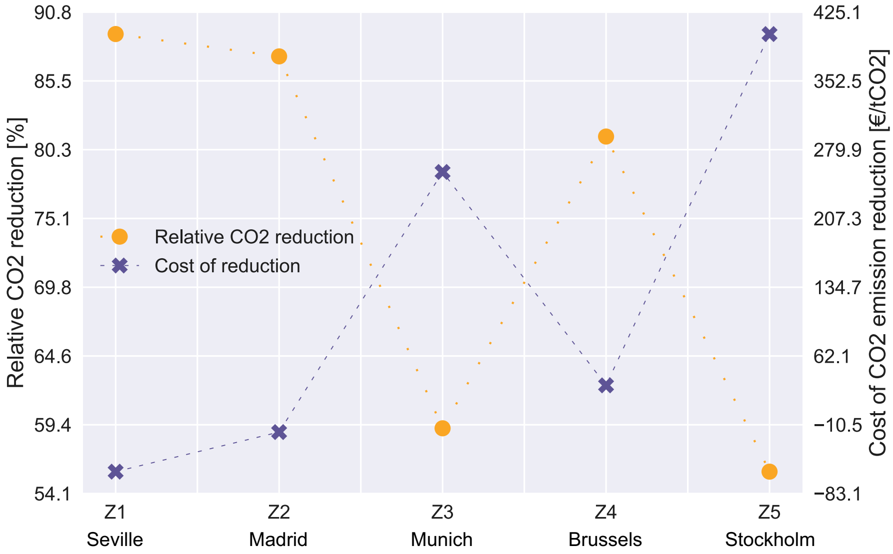

Figure 4.19.: Relative CO_2 emission reduction and associated cost of each PED compared to the status quo of each zone

The initial scenarios suggests 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 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.

4.2.2.3. 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.

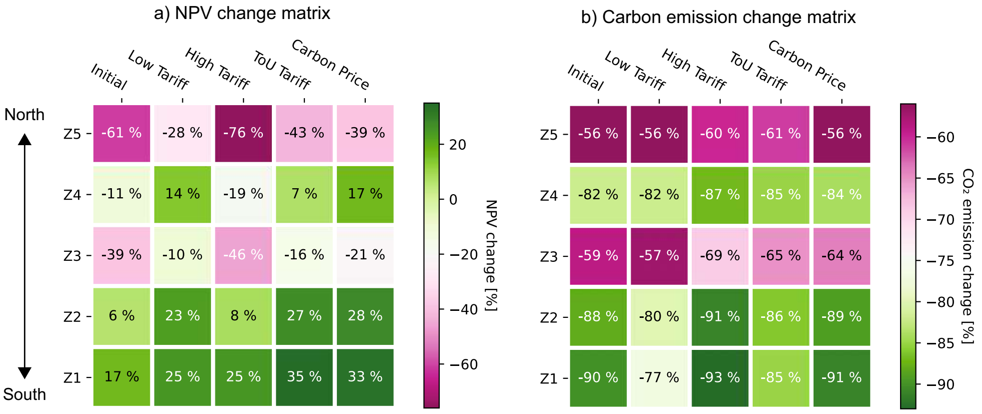

Figure 4.20.: (a) Change of net present value (NPV) per parameter set and zone compared to the respective status quo; (b) Change of CO_2 emissions per parameter set and zone compared to the respective status quo

Figure 4.20 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 - 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 Figure 4.20, areas that have 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 at 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. 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 Figure 4.20 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.

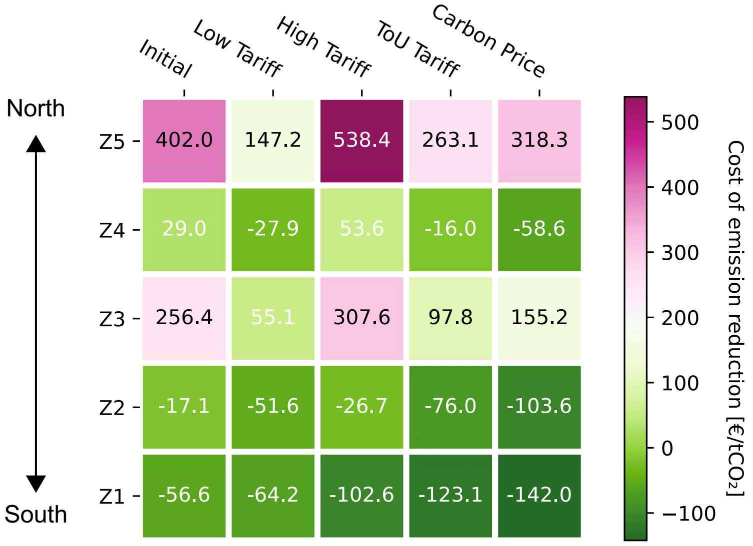

Figure 4.21.: Cost per reduced tonne of CO_2 emission in EUR per parameter set and zone compared to the respective status quo

Figure 4.21 shows a zone - parameter combination matrix of the cost of emission reduction in EUR/tCO_2. It is a combination of the matrices in Figure 4.20 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 created in low-cost electricity regions, as the sun just cannot be used cost-efficiently. In the areas that do not use DH for heating 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. Figure 4.22 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.

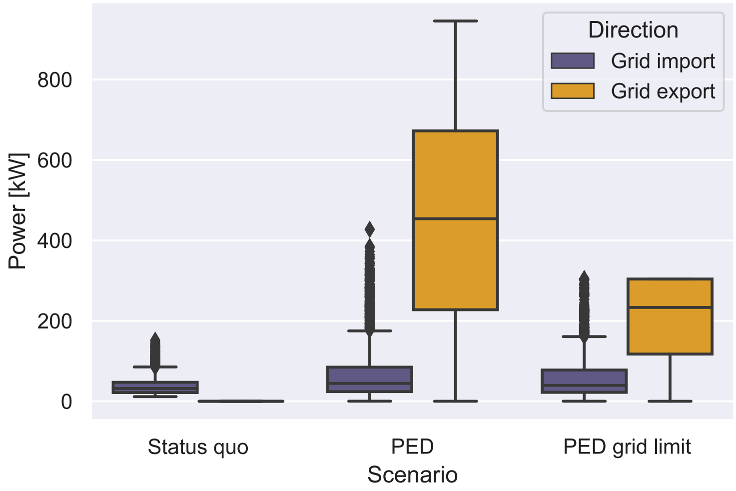

Figure 4.22.: Grid exchange power distribution for the Z1 (most southern) PED

Table 4.14 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.

Table 4.14.: 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

Figure 4.23 shows the Sankey diagram of the Z1 PED with a grid exchange limit of 304 kW. Comparing it with Figure 4.17, 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 non-existent 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. 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 Figures 4.17 and 4.23, it becomes apparent that over the lifetime of the PED, almost 18 GWh less of PV power are 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.

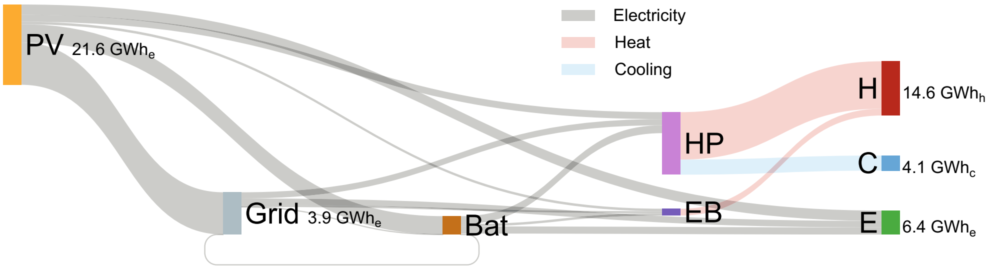

Figure 4.23.: Sankey energy flows over 20 years of the Zone 1 PED (Seville) including grid interaction with a grid limit of 304 kW; Bat - Battery, HP - Heat Pump, EB - Electric Boiler, H - Heating Demand, E - Electricity Demand, C - Cooling Demand

While the grid limitation reduces the negative impact that PEDs can have on the distribution grid, there is still a seasonal unbalance of the grid-PED power exchange. 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.

4.2.2.4. Limitations of the work

Given that 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 of the electricity load. Both aforementioned limitations have also been used in literature, e.g. by [69]. 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 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 [118, 93, 119].

4.2.3. Resume Case 2

The answer of 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 (ToU) tariff scheme [101]. 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 a 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 analysis has potentially negative impacts on the distribution grid. High electricity exports during short times and large electricity imports to cover the electrified heating in evenings amplify the already existing grid issues. Limiting the power exchange between the PED and the grid partially reduces this issue without significantly affecting the NPV and the carbon impact for 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.

4.3. Case Study: Values and implications of building envelope retrofitting for residential PEDs

The third case study reveals the values and implications of building envelope retrofitting for residential PEDs across three different climate zones. This study is published in Elsevier, Energy and Buildings [32].

4.3.1. Method and case study description

Figure 4.24 illustrates an overview of this case's approach to determining the value of building envelope retrofitting for PEDs. The methodology is composed of three main steps. Firstly, the data preparation creates all the scenarios needed for the analysis. This includes determining the cost and technology data, which does not vary among the scenarios, as well as the tariff data. The meteorological data, such as solar influx and outdoor temperature, describe the different climatic locations across Europe considered in this study. As presented in Section 4.2 Europe can be climatically divided in five zones depending on a mix of Köppen-Geiger (KG) zones and the European Heating and Cooling Indices [72, 68]. These five climate zones have been used by Refs. [31, 70, 71] to evaluate how energy systems perform differently across Europe. To determine the climatic dependency of building envelope retrofitting while keeping data scarcity and practicality in mind this study takes a representative city of the coldest and most northern, the warmest and most southern and one central zone. The cities chosen to represent cold, continental and hot European climate are Stockholm (northern Europe), Munich (central Europe) and Seville (southern Europe), respectively. The associated KG climate zones are Dfc, Dfb/Cfb and Csa[7] [68, 120]. While this does not draw a representative map of entire Europe, it shows how retrofitting in Europe is dependent on warmer or colder climates. Furthermore, to distinguish different settlement densities of the districts, the Floor Space Index (FSI) is varied through the available roof space for PV power generation. Finally, the

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[7] Dfc: Subarctic cliamte, Dfb: Warm-summer humid continental climate, Cfb: Temperate oceanic climate, Csa: Hot-summer Mediterranean climate [68, 120]

space heating and cooling demand define the building envelope retrofitting status.

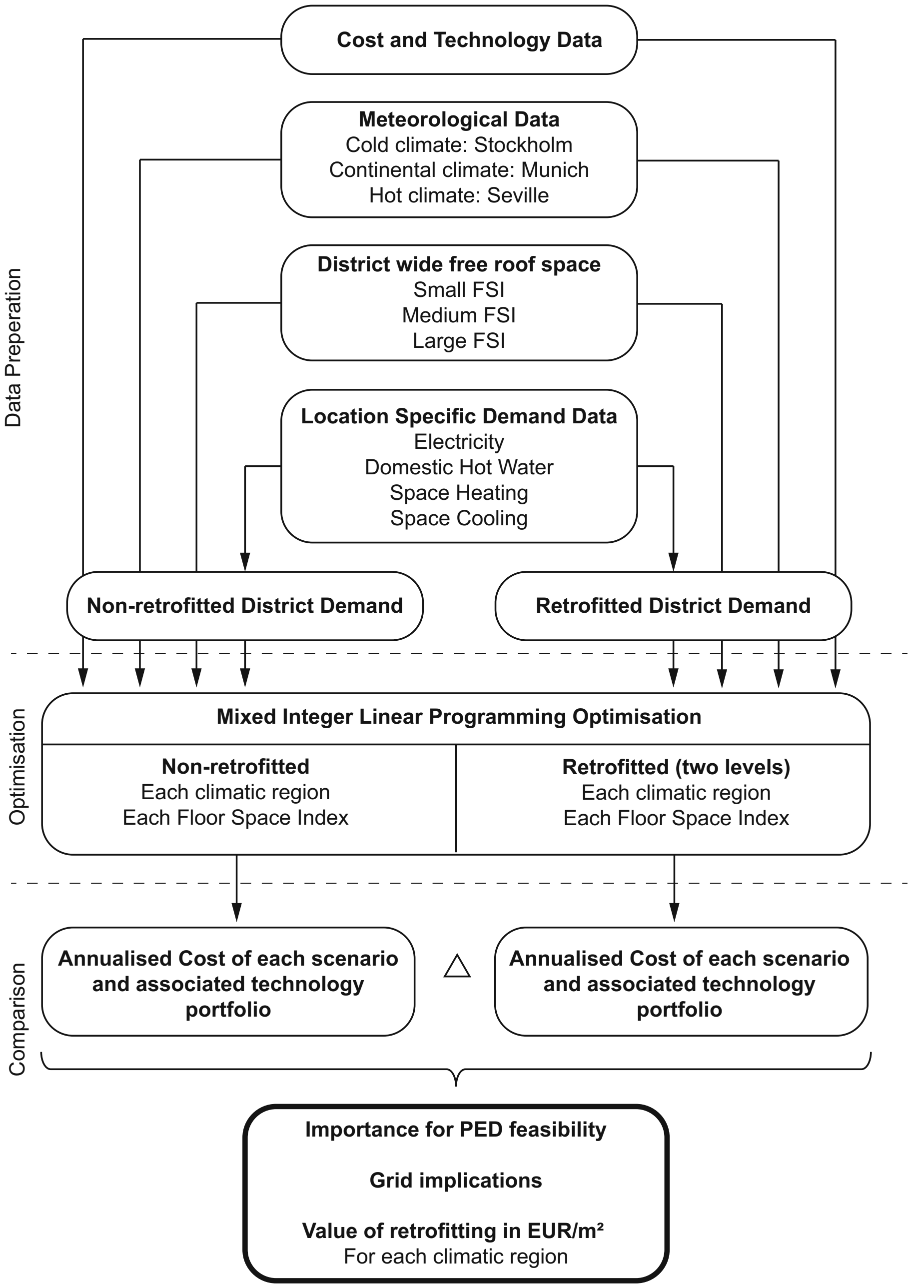

Figure 4.24.: Overview of the applied methodology

The prepared data feeds into the optimisation model, which is the second step of the methodology. The tailor-made PED MILP model determines the optimal solution for each given scenario. In a third step, for each location and settlement density scenario, the non-refurbished and refurbished solution is compared to extract the value of retrofitting for each scenario.

4.3.1.1. Data and Scenario Preparation

This section defines the four input data aspects from Figure 4.24 and thus, creates the scenarios.

Costs and technology The technology cost and specific data are constant across all scenarios and shown in Appendix B. This study uses a dynamic Time-of-Use (ToU) tariff because it proved a beneficial tariff option for cost-efficient CO_2 abatement in PEDs according to Ref. [31]. Furthermore, dynamic tariffs induce certain demand-side flexibility and are therefore crucial in a renewable-rich electricity mix in the future [114]. This study works with a baseline cost of 0.2 EUR/kWh, a shoulder tariff of 0.3 EUR/kWh and a peak cost of 0.4 EUR/kWh. For the time-dependency of the ToU tariff, refer to Appendix C. Additionally, electricity sold to the grid is valued at 0.05 EUR/kWh. For the status quo scenarios, natural gas boilers with an efficiency of 0.9 are assumed for Domestic Hot Water (DHW) and space heating in this study. Thus, this work only focuses on areas not connected to district heating, as Ref. [31] showed low feasibility of switching from district heating to decentralised electrified heating. This study works with a gas tariff of 0.1 EUR/kWh gas. Standard air conditioning units supply cooling with a COP of 2.5.

Meteorological data This work uses meteorological data to calculate PV power generation and the outdoor temperature-dependent air-source heat pump COP. Essential parameters to do so are the global horizontal, the direct normal and the diffuse irradiance, as well as the outdoor temperature in an hourly resolution. All data is taken from the ERA5 database by the

Copernicus project for the year 2019, and the three representative cities, Seville, Munich and Stockholm, [103].

District wide free roof space This study analyses multiple building scenarios of suburbs that affect the available space for roof-based PV power generation. The floor space index (FSI) is an important parameter for PED feasibility [83]. The FSI is defined by the gross-floor area divided by the plot size of the building. To relate the FSI more to the roof space available, this study adapts the definition to FSI_{roof} shown in Equation 4.3. Roof space includes the surface of garages.

$$FSI_{roof} = \frac{GrossFloorArea}{RoofSpace} \tag{4.3}$$

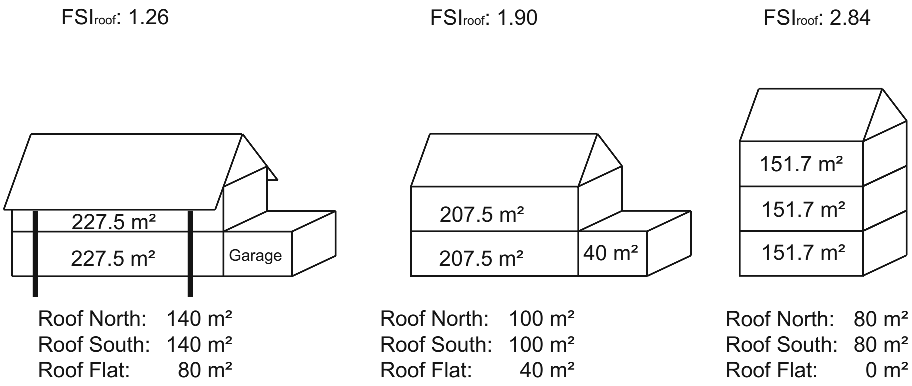

Figure 4.25.: Different roof areas available for PV generation per building of district and associated FSI

Figure 4.25 shows the considered roof spaces. Each district is made up of 50 equal buildings. All configurations have equal gross floor area (455 m^2). The house with FSI_{roof} 1.26 is the only multi-family house with a garage. The other two building types have underground or on-street parking.

Location specific demand data The hourly load demand for electricity, DHW, space heating and space cooling is provided by the Fraunhofer Institute's in-house stochastic model for load generation called "synPro" [102]. SynPro is based on the norm "DIN EN ISO 13790", "Energy performance of buildings — Calculation of energy use for space heating and cooling" [121]. Specific thermal transmittance values for the building envelope parts are associated with different building renovation standards to obtain the heating and cooling loads of differently renovated buildings. The load profiles are available for the three locations (Stockholm, Munich and Seville) for an old, non-retrofitted building, as well as for a highly retrofitted building. The retrofitting standard is the passive house standard. Thus one building should have approximately $15\frac{kWh}{m^2}$ or less of space heating demand [122]. To focus on the building envelope only, the electricity and DHW demand profile is kept unchanged over all scenarios as it depends more on the tenants' behaviour. Only the space heating and cooling demand varies across locations and retrofitting status. The demand is scaled to 455 m^2 living surface per building for each scenario for comparability.

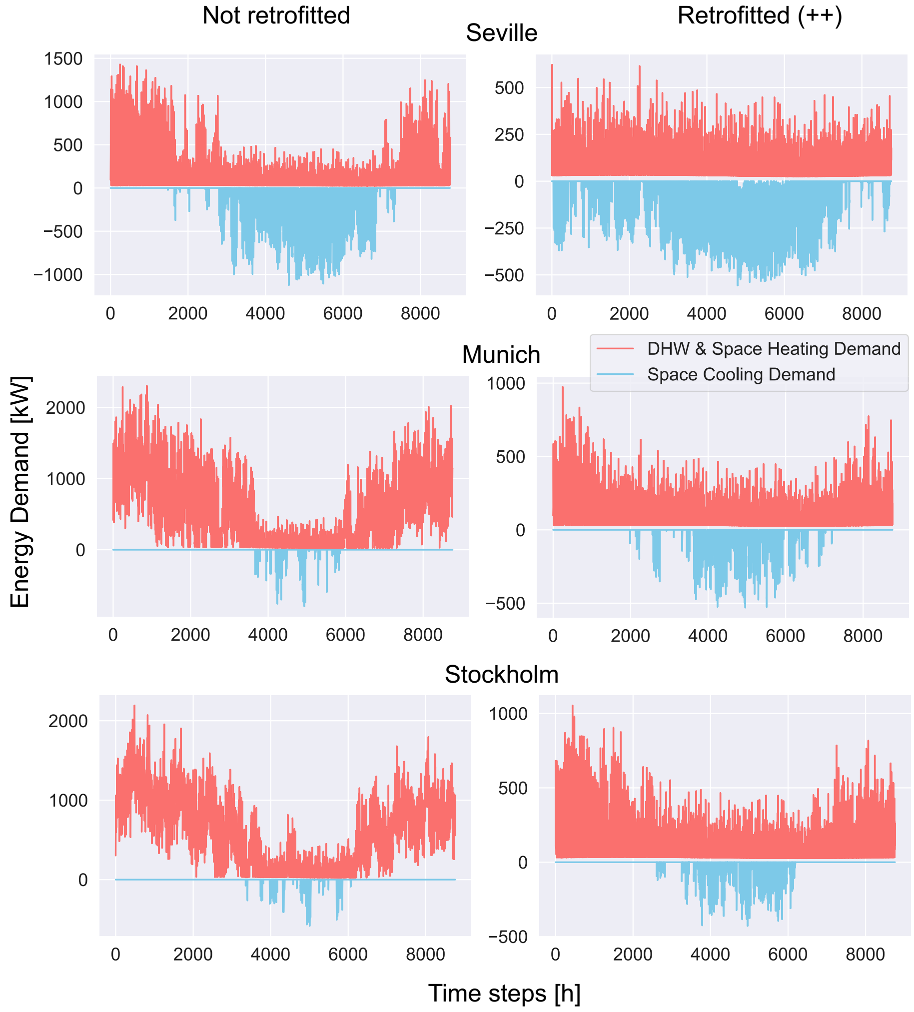

Figure 4.26.: Visualisation of the DHW, space heating and space cooling demand of each climate zone before and after retrofitting

Figure 4.26 shows the living area adapted heating and cooling demand of a 50-house district in Stockholm, Munich and Seville, representing cold, continental and hot European climates, respectively. In all cases, the heating demand is significantly reduced and less seasonal in the retrofitted districts. In Seville, space heating is no longer needed, and the heating demand is only domestic hot water. On the other hand, cooling is required on more days throughout the year, but the peak demand is lower. Furthermore, a less ambitious retrofitting scenario is created by taking the mean of hourly retrofitted and non-retrofitted heating/cooling values, respectively. Table 4.15 shows the significant differences in space heating and cooling demand with and without retrofitting. The southern area represented by Seville decreases its heating demand from 30 to 0 $\frac{kWh}{m^2}$, while the cooling demand remains relatively stable. Munich and Stockholm achieve reductions of 166 and 174 $\frac{kWh}{m^2}$ from non-retrofitted to the passive house standard, respectively. In both cases, the cooling demand increases with higher retrofitting standards.

Table 4.15.: Space heating and cooling demand per scenario (+ identifies the medium level retrofitting, while ++ identifies the passive house standard retrofitting)

Region	Heating $[\frac{kWh}{m^2}]$	Cooling$[\frac{kWh}{m^2}]$
Seville	29.8	44.6
Seville +	14.9	43.1
Seville ++	0.0	41.6
Munich	175.5	3.7
Munich +	92.4	8.6
Munich ++	9.3	13.3
Stockholm	191.6	3.1
Stockholm +	104.8	6.1
Stockholm ++	18.1	8.9

4.3.1.2. Mathematical Optimisation

This case study optimises a large number of different parameter constellations. Additionally, the possible technology portfolio includes also ground-source heat pumps and heat storage in form of hot water tanks to the previous cases. To reduce the calculation time, this case uses the annualised cost minimisation as the model objective. The PEDso design parameters are shown in Figure 4.27. For further mathematical formulations of the MILP model PEDso please refer to Section 3.3.

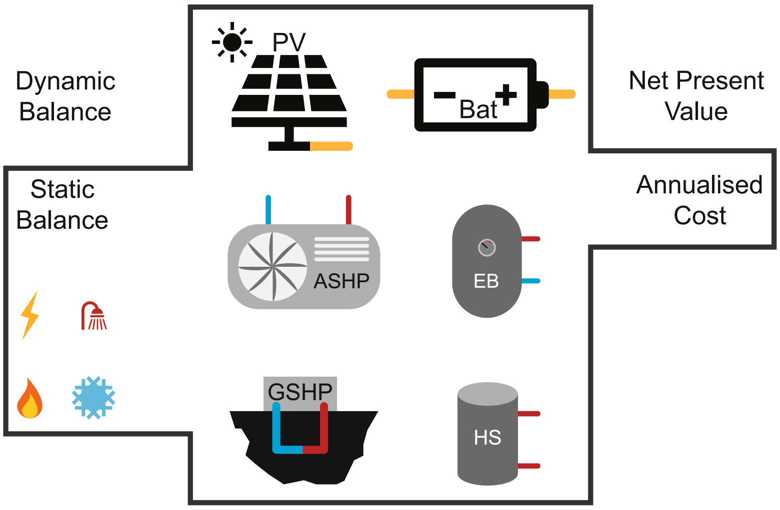

Figure 4.27.: PEDso usage in case study three

4.3.1.3. Sensitivity Analysis

To see how factors of the electricity tariff affect the economic feasibility of building envelope retrofitting this study investigates the effects of the following tariff changes on the PED in Munich in the small density case:

- Increase and decrease cost of electricity: +/- 20% of each tariff step
- Integrate cost per kW of connection needed: It is assumed that a plus of 20% of the used connection is contracted for safety. The cost used in this work is 0.1 $\frac{EUR}{kW day}$.
- Dynamic feed in tariff: 25% of original electricity tariff at each tariff step

Tariff changes are attractive means of adjustment as public and private utility companies can adapt them. Thus, the design of the tariff structure and its implications on the energy infrastructure of PEDs can significantly influence the uptake of PED projects and related retrofitting actions.

4.3.2. Results and discussion

This section discusses the results of the third case study. Section 4.3.2.1 presents the costs and energy demands of the status quo. This is required to compare the PED scenarios with the assumed current status of gas heating and no renewable energy generation in the district. Section 4.3.2.2 shows the results of the initial case studies. This section explains the importance and values of building envelope retrofitting for PEDs depending on the climate and the district density. Additionally, this section introduces the energy saving-specific economic value of retrofitting. Finally, Section 4.3.2.3 shows the dependency of the previously introduced economic value of retrofitting on various energy cost components.

4.3.2.1. Status Quo

Table 4.16 shows the status quo scenarios (non-retrofitted and the two retrofitting levels) and their associated annualised costs and electricity import-related CO_2 emissions. It can already be seen here that retrofitting the building envelope has a powerful effect on the districts located in Munich and Stockholm. The annualised cost decreases by 47% and 48%, respectively and the CO_2 emissions associated with the electricity import by 61% in both locations in the case of ++ retrofitting. On the other hand, the cost and emission reductions are lower in the case of Seville with only 15% and 22% reductions of AC and CO_2 emissions, respectively.

Table 4.16.: Energy demand (El - Electricity, H - Space & DHW heating, C - Space cooling), CO_2 emissions, and annualised costs of each districts' status quo and after renovation without its associated renovation cost

District	AC_{gas} [EUR]	CO_2 [t]
Seville	578,651	703
Seville +	536,264	624
Seville ++	494,029	546
Munich	832,743	1330
Munich +	635,817	926
Munich ++	438,892	522
Stockholm	871,551	1409
Stockholm +	660,240	982
Stockholm ++	448,928	555

4.3.2.2. The value of renovation in PEDs and the associated technology portfolio

Table 4.17 shows the results of the PED optimisations for each area and each settlement density and retrofitting level (none, medium, passive-standard). The table shows two clear trends at first glance. Deep retrofitting of the building stock gains importance with increasing settlement density and latitude. While in Seville, all scenarios result in possible PED compositions, in Munich and Stockholm, densely populated districts require retrofitting to fulfil the PED requirements. In the densest scenario in Stockholm, not even the passive house standard retrofit is sufficient to reduce the energy demand to match the available low solar resources. All scenarios have a lower annualised cost than the respective status quo scenarios in Table 4.12. Therefore, if the PED is spatially and technologically feasible, it is the economically preferable solution under the given assumptions, independent of the level of retrofitting. Retrofitting reduces the AC, especially in cold, northern areas. However, the cost of retrofitting is not included in the AC, and the final economic value, therefore, depends on the retrofitting cost.

Table 4.17.: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), HP (Heat Pump; Air-Sourced (AS) or Ground Sourced (GS)), Electric Boiler (EB), and Heat Storage (HS)) and CO_2 emissions for each district scenario

District	AC [EUR]	PV [kW]	Bat [kWh]	HP [kW]	EB [kW]	HS [m^3]	CO_2 [t]
Sev FSI s	283,560	1,938	1,212	(AS) 561	43	84	118
Sev FSI s +	258,810	1,938	1057	(GS) 410	189	41	96
Sev FSI s ++	224,125	1,938	1,037	(GS) 278	182	35	78
Sev FSI m	303,008	1,546	1,168	(AS) 561	43	82	129
Sev FSI m +	276,361	1,254	1072	(GS) 410	194	41	106
Sev FSI m ++	240,618	1,254	1,053	(GS) 278	198	35	86
Sev FSI l	321,637	1,520	1,062	(AS) 561	43	80	143
Sev FSI l +	293,702	1,197	991	(GS) 410	192	40	117
Sev FSI l ++	257,209	1,088	985	(GS) 278	196	34	99
Mun FSI s	625,440	2,203	798	(GS) 1,173	371	144	338
Mun FSI s +	446,512	1938	863	(GS) 669	290	88	227
Mun FSI s ++	287,411	1,672	897	(GS) 265	99	38	126
Mun FSI m	- infeasible -						
Mun FSI m +	466,822	1,876	793	(GS) 700	187	88	245
Mun FSI m ++	290,061	1,254	843	(GS) 265	106	38	144
Mun FSI l	- infeasible -						
Mun FSI l +	- infeasible -						
Mun FSI l ++	308,457	1,438	786	(GS) 265	81	39	155
Sto FSI s	740,030	3,014	671	(GS) 1,221	253	133	413
Sto FSI s +	524,183	2,049	727	(GS) 742	171	87	302
Sto FSI s ++	340,281	1,478	761	(GS) 265	203	45	192
Sto FSI m	- infeasible -						
Sto FSI m +	- infeasible -						
Sto FSI m ++	348,359	1,553	724	(GS) 278	181	47	196
Sto FSI l	- infeasible -						
Sto FSI l +	- infeasible -						
Sto FSI l ++	- infeasible -						

In all cases, retrofitting reduces the requirements regarding the technology portfolio. Less installed PV capacity is needed to fulfil the PED requirements, smaller heat pumps, and heat storage capacity. In southern and warm areas such as Seville, the battery capacity decreases with higher building standards as less electricity needs to be shifted to other times of the day, and cooling is more synchronous with solar irradiation. On the other hand, in Munich and Stockholm that have colder climates, the battery capacity slightly increases with the building standard. The retrofitted scenarios have increased solar gains and therefore less direct usage for generated solar PV power. Thus, more excess generation needs to be either sold to the grid or shifted to later, non-solar hours. Here, the low feed-in tariff and the high evening peak tariff incentivise a shift of the excess electricity to the evening hours. All scenarios apart from the Southern non-retrofitted ones opt for the ground source heat pump. In Munich and Stockholm, the COP of the GSHP for heating in the winter is much higher due to the stable ground temperature. For southern Europe, the case is not this clear, as the outdoor temperature is warmer and therefore favours the more economical air source heat pump in non-retrofitted cases with a balanced heating and cooling demand [123, 124]. In retrofitted cases, cooling is more used than heating (mainly only for DHW). The ground-sourced heat pump is advantageous in these scenarios. Finally, the grid-associated carbon emissions decrease with increasing retrofitting, especially compared to the status quo scenarios.

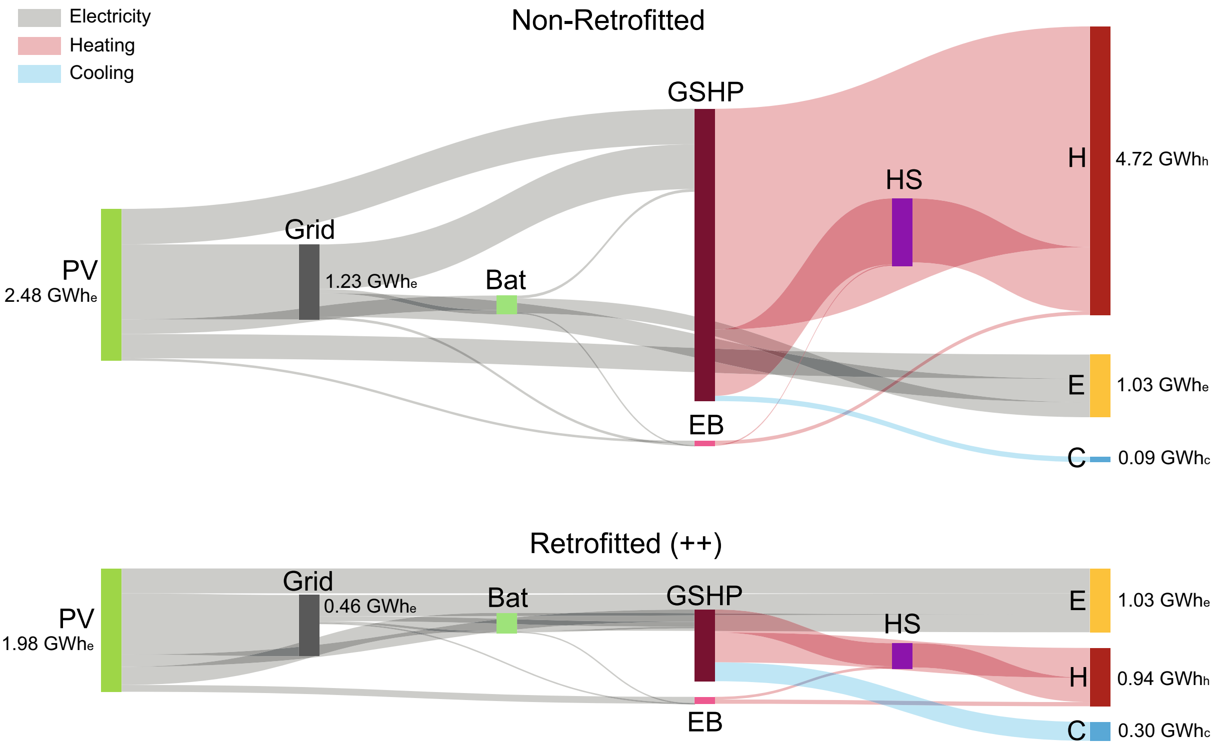

Figure 4.28.: Annual energy flow between the the energy infrastructure of the non-retrofitted and the retrofitted PED (small FSI) in Munich (PV: Photovoltaic, Bat: Battery, GSHP: Ground-Sourced Heat Pump, EB: Electric Boiler, HS: Heat Storage, E: Electric load (final), H: Heating load, C: Cooling load)

Figure 4.28 shows the annual energy flows as a Sankey diagram for the non-retrofitted and the passive house standard retrofitted PED in Munich. Be aware that the graph includes conversion from electric energy to heat or cooling, shown in red and blue, respectively. It is evident that electricity, heating and cooling demand is much more balanced in the retrofitted PED. Furthermore, the non-retrofitted PED exports and imports almost equal amounts of electricity and therefore fulfils the PED requirement only just. This indicates that without the enforcement to become a PED, this district would not have opted for the concept from an economical perspective. On the other hand, the retrofitted PED exports more than twice as much as it imports from the grid while generating less PV power. The self-consumption of the generated

PV power is equal, with 50% in both cases. However, the self-coverage of the demand is 51% and 68% for the non-retrofitted and the retrofitted PED, respectively. The deeply retrofitted PED has a more desirable performance, addressing PED values such as self-coverage and efficiency.

Another PED requirement is grid resilience. A highly electrified district with significant solar exports does not cover this requirement by nature as it would provoke fluctuant grid exports and imports. Figure 4.29 shows the grid exchange in the first January and July days of the non-retrofitted and highly retrofitted Munich PED in the lowest settlement density scenario, as well as the ToU electricity tariff. Clearly, the non-retrofitted PED draws significantly more electricity from the grid than the retrofitted one on winter days. Both districts try to avoid expensive morning and evening tariff times, using the battery for energy arbitrage. While both PEDs achieve this to some extent, the retrofitted district is better able to cut imports during peak tariff times. The non-retrofitted PED sometimes still imports electricity for 0.4 EUR/kWh in the evenings. Thus, the retrofitted PED is better prepared to adhere to electricity price signals. This could be used by, e.g. the distribution system operator to incentivise grid-positive import and export behaviour for grid stability.

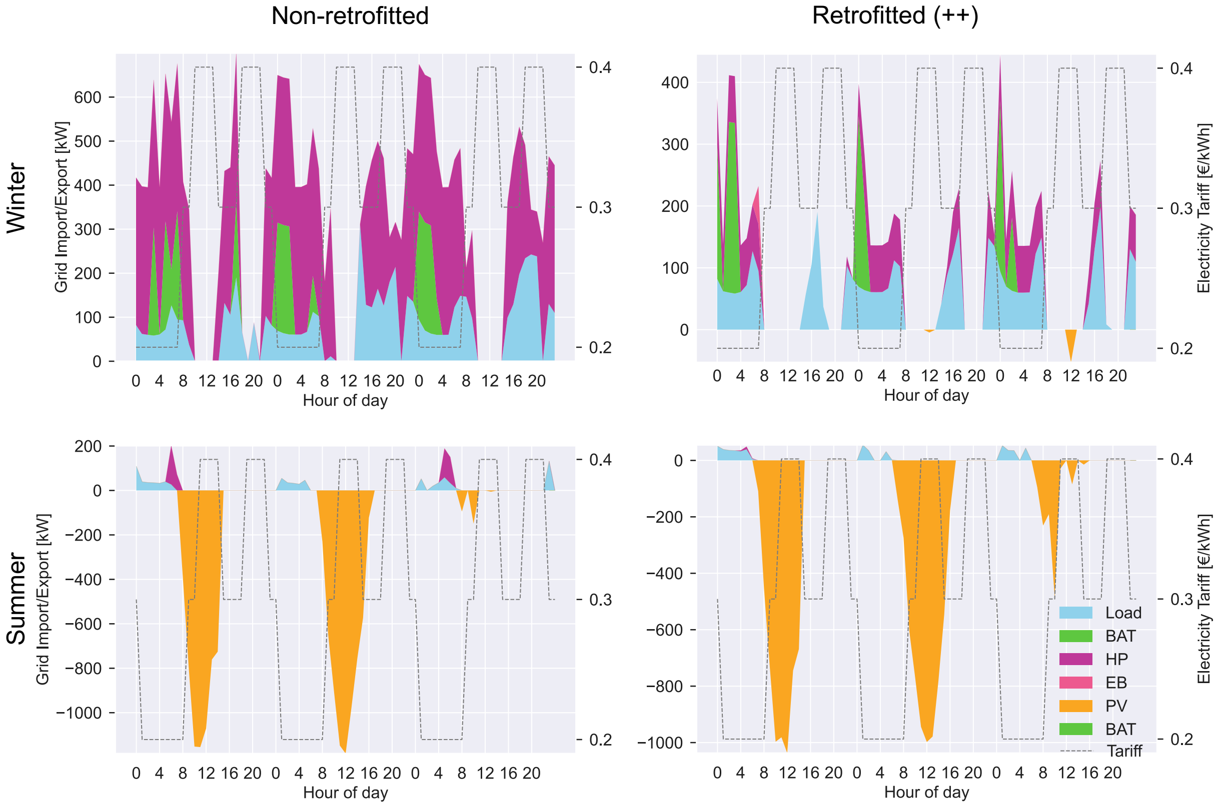

Figure 4.29.: Grid Exchange in the first 3 days of January and July in the Munich PED; BAT: battery, HP: heat pump, EB: electric boiler, PV: photovoltaic

In the summer, in both cases, not much import is needed. The non-retrofitted district imports slightly more electricity than the retrofitted one. The export peaks in the summer are more prominent in the non-retrofitted version, as the installed solar PV capacity is larger. However, both export peak powers are significant and could contribute to grid instability. Overall, the retrofitted PED shows a more grid-supportive behaviour, as shown in Figure 4.30. While in southern PEDs (Seville), the export distribution between the retrofitting levels is almost identical, the peaks are significantly lower in the retrofitted cases of northern and central Europe (Stockholm and Munich). In terms of electricity import, all areas reduce the peak power appearances thanks to retrofitting.

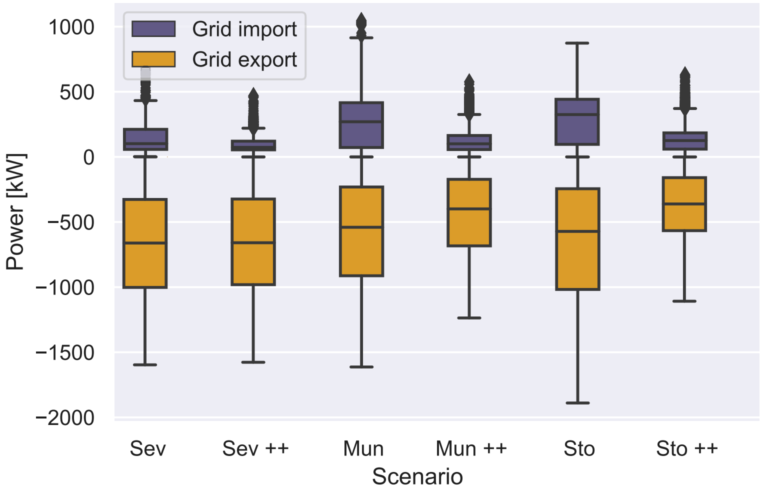

Figure 4.30.: Grid Exchange distribution for the low density PEDs for each area in the non-retrofitted and the passive house standard retrofitted version

So far, this work established that retrofitting can be crucial for making PEDs feasible in colder climates and densely populated areas and that it can benefit the distribution grid stability. However, if retrofitting is not required for PED feasibility, what would be its economic and environmental value and where and under which circumstances would it be the highest? Figure 4.31 shows a combination of the annualised cost of the entire PED project (not including any retrofitting cost) and its CO_2 emissions. Furthermore, the low population density status quo and PED districts in all retrofitting levels are added to the scatter plot. The graph shows clearly that the more south in Europe a district is located, the closer to the lower-left corner the districts are drawn on the graph, showing lower cost and lower emissions. Retrofitting decreases the CO_2 emissions in all scenarios. However, the steps are more significant in the status quo scenarios. In the PED cases, the heating and cooling demand reduction effect is less crucial in emission abatement because the PED does not use any fossil fuels and the only emissions are those associated with electricity import. The plainly economic value of retrofitting between a non-retrofitted and a passive house standard (++) retrofitted PED is quantified in Figure 4.31. For a reduction of 29.8, 166.2 and 173.5 $\frac{kWh}{m^2}$ annual (Seville, Munich and Stockholm), the difference in annualised costs are 59, 338 and

400 kEUR, respectively. The direct investment cost threshold[8] per m^2 gross floor area translates to 47.5, 271.3 and 320.8 $\frac{EUR}{m^2}$ in Seville, Munich and Stockholm, respectively, assuming a lifetime of 50 years of the retrofitting. Thus, per m^2 of living area, the building envelope retrofitting costs shall not surpass those thresholds for the respective space heating demand reductions. Otherwise, the retrofitting intervention would not be economically feasible. Thus, a variety of measures to retrofit the building envelope can be chosen on a case by case basis to achieve the desired energy demand reduction, while intending to stay below the threshold cost.

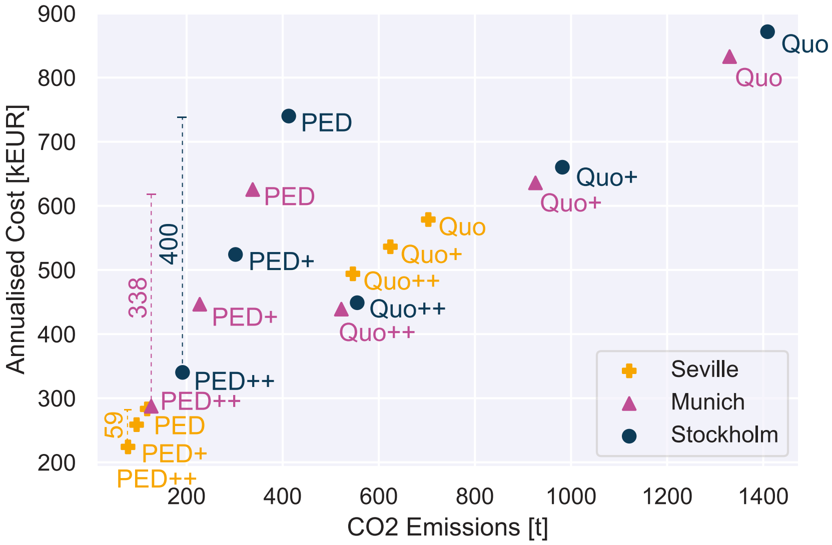

Figure 4.31.: Annualised cost and CO_2 emission development of the low density cases; cost of building refurbishment is not integrated

For further generalisation, Figure 4.32 shows the value of retrofitting in EUR per gross floor area and kWh reduced space heating demand for the three areas in the lowest settlement density. For Seville, the high settlement density district is also accounted for to assess the effects of a large FSI. A higher settlement density increases the value of retrofitting according to the two cases of Seville. In both cases, the value of retrofitting in the status quo

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[8] Investment cost that should not be exceeded to from an economical perspective

scenario[9] has the highest value per square meter and reduced space heating consumption. In the PED cases, the passive house standard retrofit has a higher specific value than the intermediate solution. The picture changes in central Europe (Munich) and especially northern Europe (Stockholm). In Munich, the retrofitted status quo district still shows the highest retrofitting value, but it is significantly reduced compared to Seville. Furthermore, the intermediate retrofitting option among the two PED scenarios appears to be the more valuable one. In Stockholm, the intermediate PED solution has the highest value of retrofitting. Comparing the low-density solutions of the three climates, the value of the intermediate retrofitting increases relatively constant. The passive house retrofit value raises less significantly, specifically between Seville and Munich. The plain value of retrofitting without PED interventions in the status quo cases decreases between Seville and Munich and then slightly increases again between Munich and Stockholm.

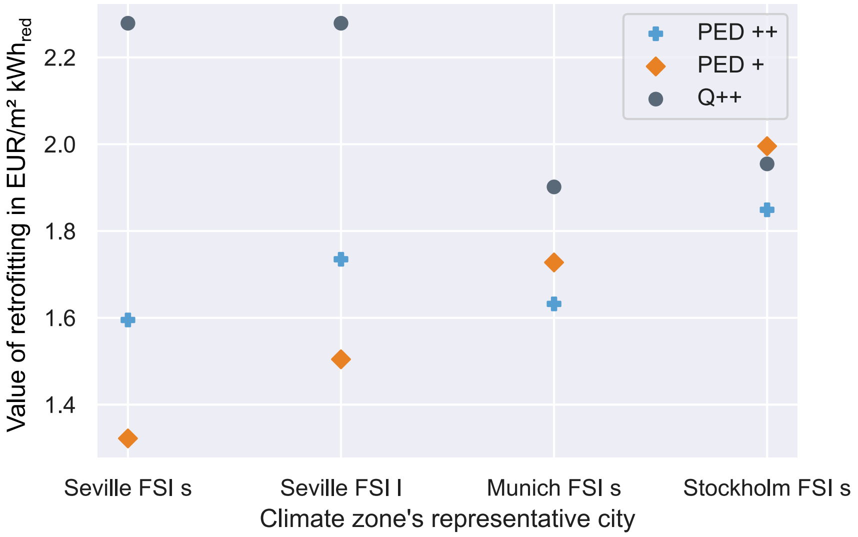

Figure 4.32.: The economic value of high standard building retrofitting for PEDs per $m2$ gross floor area and reduced kWh of space heating demand → the cost of building retrofitting should be below the respective point to be economically feasible

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[9] no PED interventions - just building envelope retrofitting

The difference in the retrofitting value of the status quo scenarios can be explained by the different effects on the cooling demand and the increased ability to harvest solar gains in southern Europe. In Seville, cooling demand decreases slightly with reduced space heating demand. More cooling time steps are required, but the peaks are lower, as the building can keep room temperature more stable. On the other hand, in Munich and Stockholm, cooling increases significantly by reducing the heating demand. This is specifically true for Munich, which has the highest differences in extreme temperatures (46 °C) due to its relatively high altitude. Stockholm and Seville have a difference in extreme outdoor temperatures of 42 °C and 37.5 °C in the sample year, respectively. This suggests that low outdoor temperature differences throughout the year increase the value of retrofitting due to lower cooling demand growths. This effect is visible even though reduction/increase in cooling demand is not integrated in the metric. However, the differences in cooling demand affect the value of retrofitting through the costs to cover this cooling demand. In southern Europe, the value of retrofitting in PEDs is less than in central and northern Europe in the low settlement density cases. This is because there is much less difference in the technology portfolio. Because of very favourable solar resources, the flat and south-facing roof area is maxed out in any case in Seville. In the more northern zones or where less roof area is available, less efficient north-facing PV panels need to be installed in the non-retrofitted cases. Those less cost-efficient north-facing PV panels can be reduced or are not needed through retrofitting.

4.3.2.3. Influencing electricity tariff factors on the value of building envelope retrofitting in PEDs

This section analyses the sensitivity of the retrofitting value and the districts' optimised technology portfolio of the small FSI PED in Munich on changes in the electricity tariff structure. Table 4.18 shows the values of the PED with the standard tariff structure and the changes in % of each case for the respective retrofitting standard. A rise of 20% in the electricity tariff also increases the annualised cost of all PED scenarios. However, this increase in the AC is lower in the case of the highest standard retrofit, while it yields the highest decrease in CO_2 emissions. This is achieved by additional investments in the storage infrastructure (battery and hot water) to improve the capacity for electricity arbitrage. Furthermore, the PV infrastructure for the passive house standard retrofitting PED rises by 16%, while for the other building envelope standards, the PV infrastructure remains almost equal. An explanation for this is that in the case of the lower building standards, the south-facing and flat roof areas are already used to their maximum, and installations on north-facing roofs do not seem economically feasible under the assumptions. Electricity to heating infrastructure also increases to cover the higher capacity of the heat storage. A reduction in the tariff cost of 20% triggers a reverse action. The annualised cost decreases in all renovation scenarios, and storage and generation infrastructure is highly reduced. The grid import-associated emissions increase strongly compared to the initial scenarios. While the emission increase is very similar in absolute terms, relative to the initial scenarios, the high standard retrofitting case suffers the most substantial increase in emissions.

Table 4.18.: Optimised Annualised Cost (AC), associated technology portfolio (Photovoltaic (PV), Battery (Bat), GSHP (Ground-sourced Heat Pump), Electric Boiler (EB), and Heat Storage (HS)) and CO_2 emissions for the sensitivity analysis scenarios in the FSI small cases in Munich

Case	AC $[EUR]$	PV $[kW]$	Bat $[kWh]$	GSHP $[kW]$	EB $[kW]$	HS $[m^3]$	CO_2 [t]
Standard	625,440	2,203	798	1,173	371	144	338
Standard +	446,512	1,938	863	669	290	88	227
Standard ++	287,411	1,672	897	265	99	38	126
+20% tariff	9%	2%	19%	2%	-18%	13%	-6%
+20% tariff +	8%	0%	19%	4%	2%	15%	-8%
+20% tariff ++	6%	16%	23%	0%	11%	8%	-18%
-20% tariff	-10%	0%	-61%	-4%	11%	-17%	14%
-20% tariff +	-9%	-3%	-50%	-6%	14%	-17%	22%
-20% tariff ++	-9%	-20%	-54%	0%	-15%	-3%	43%
kW tariff	4%	-1%	-3%	5%	-25%	13%	-2%
kW tariff +	4%	0%	-6%	6%	-21%	11%	-1%
kW tariff ++	4%	7%	-2%	0%	-2%	3%	-2%
Dyn. feed-in	-6%	1%	-6%	-1%	5%	-9%	1%
Dyn. feed-in +	-8%	0%	-8%	1%	-6%	-9%	4%
Dyn. feed-in ++	-15%	16%	-7%	0%	-8%	-3%	3%

A cost of 10ct per kW contracted per day of the year causes the AC of all PED scenarios to rise slightly. To combat this variation in the tariff cost structure, the PEDs try to shift the heating peak by investing in more heat storage equipment. As heating is less relevant in the highly retrofitted districts, lower investments in additional storage equipment are needed. This results in slight emission reductions. Finally, a dynamic and increased feed-in tariff reduces investments in storage capacity and fills the available PV generation area apart from northern roofs. Thus, the AC drops significantly, especially in the highly retrofitted scenario, but the carbon emissions slightly increase as less PV power is used to cover the local demand directly.

Figure 4.33 illustrates the change in the value of building envelope retrofitting according to the sensitivity criteria per reduced kWh of heat demand and per m^2 gross floor area. A growing electricity tariff logically increases the value of retrofitting as the resulting retrofitted PED requires less electricity import. Reversely, a lower energy tariff goes in hand with a reduced value of retrofitting. A tariff on the power contracted also increases the value of retrofitting as electrification of heating increases this peak. A dynamic and increased feed-in tariff has little effect on the value of retrofitting in this case.

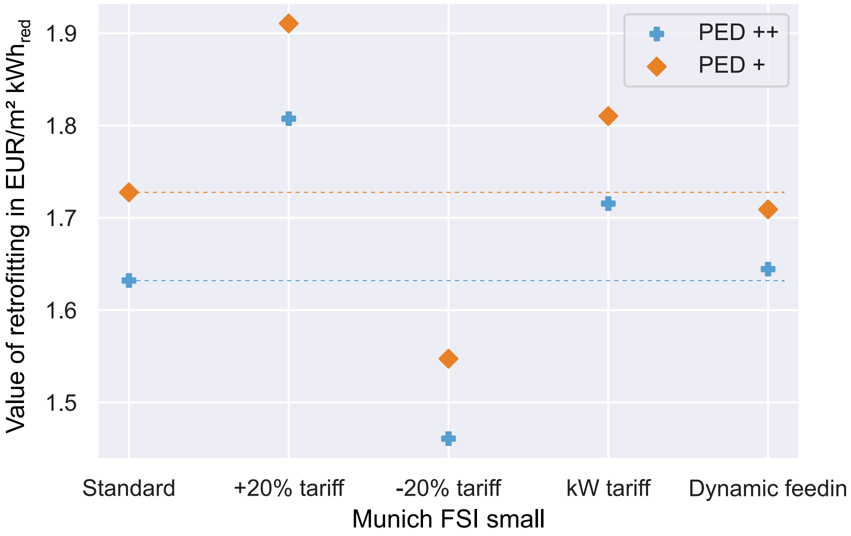

Figure 4.33.: The economic value of high standard building retrofitting in the Munich PED for the small FSI constellation for different sensitivity cases per $m2$ gross floor area and reduced kWh of space heating demand → the cost of building retrofitting should be below the respective point to be economically feasible

The value of retrofitting can also be interpreted as a threshold cost of the renovation. Thus, in areas where the electricity costs are relatively high, PED retrofitting has a higher cost threshold than in lower tariff regions. One can argue that those high electricity prices generate an incentive for retrofitting. This could be used by public authorities such as public utilities that intend to accelerate the renovation wave and support PED development. However, retrofitting comes with a high upfront investment that not everybody is capable of paying. Thus, if high electricity costs or peak tariffs are used as an instrument to generate a push towards high standard retrofitting, further steps need to be taken to avoid injustice. Authors of [125] show that low cost of capital is crucial for high uptakes of retrofit activities and that public finance can play a key role. Thus, for people and communities with low economic power, financing options would be needed to omit the high upfront cost of the retrofitting investment. Various financing options for retrofitting residential buildings are reviewed in [126].

The influencers of the value of retrofitting Table 4.19 qualitatively summarises this study's findings. It shows the identified influencers and their effect on the value of retrofitting of Positive Energy Districts as well as the influence on the grid import-related CO_2 emissions. It clearly shows that no matter which climate, energy efficiency measures of the building envelope positively affect the district's carbon emissions. However, the economic value of retrofitting increases with colder temperatures and decreases with warmer conditions. An increasing district density also increases the value of retrofitting because the scarcer space for PV panels is more likely to be sufficient. In general, in some very dense and cold scenarios, a PED is technically not feasible without retrofitting. Increasing electricity tariffs positively affects the retrofitting value and the carbon reduction, while decreasing tariff costs affects both values negatively. A capacity connection cost per kilowatt increases the economic value of retrofitting PEDs but has virtually no effect on the associated CO_2 emissions under the assumed costs and conditions. The slightly increased and dynamic feed-in tariff barely impacts the retrofitting value or the carbon emissions. The qualitative effects of the influencers have to be interpreted with care, as they are strictly bound to the exact conditions of the cases. A high enough increase of the feed-in tariff, for example, might affect the retrofitting value and the CO_2 emissions.

Table 4.19.: Qualitative summery of influencers on the value of retrofitting PEDs and their electricity import associated carbon emissions

Influencers	Effect on Retrofitting Value	Effect on CO_2 reductions
Colder climate	+	+
Warmer climate	-	+
Higher settlement density	+	-
Lower settlement density	-	+
Higher electricity tariff	+	+
Lower electricity tariff	-	-
kW electricity tariff	+	o
Dynamic and higher feed-in tariff	o	o

4.3.3. Limitations of this work

Due to the high dependency of PEDs on external factors, this work includes limitations to reduce the complexity of the study. Firstly, this analysis works with an equal DHW and electricity demand across all scenarios and only focuses on space heating and cooling changes. Here, variations in electricity and DHW due to country-specific differences or differences in building standards are not included. Furthermore, the housing design is limited to 3 types with similar roof shapes. Results could slightly differ for other roofs, such as flat roofs only.

Furthermore, the specific value/threshold cost of building envelope retrofitting in PEDs is assessed per kWh of reduced heat demand per m^2. This work does not integrate cooling into this indicator. The integration of cooling in the specific value of retrofitting would most likely slightly favour southern countries, as the cooling demand is reduced there, while it increases in northern countries.

4.3.4. Resume Case 3

Building envelope retrofitting, such as insulation and multi-glazed windows, strongly affects the technical feasibility of Positive Energy Districts (PEDs), their optimal technology portfolio and their environmental footprint. However, the value of retrofitting is not equal and depends on many factors. This work shows that the further north (the colder the climate) a PED is located in Europe and the denser it is populated, the more critical retrofitting becomes to achieve an annual positive energy balance, one of the PED requirements. Without retrofitting, turning an existing, old district into a PED would not be possible in those areas.

This study shows that retrofitted PEDs have a higher self-coverage of the energy demand and react more flexibly to changes in the electricity tariff. Furthermore, retrofitted PEDs show lower peak exchanges with the grid, potentially contributing to grid resilience. Energy flexibility, energy efficiency and grid resilience are central parts of the PED definition; thus, retrofitting a district before PED creation would be very much in line with its core values.

If PED feasibility is not dependent on the retrofitting status, such as in southern European areas or districts with a low population density, a value of retrofitting can be calculated per square meter of gross floor area and per kWh of reduced heat demand. This study determines the value of retrofitting for PEDs between 1.5 and 2 $\frac{EUR}{m^2 * kWh_{red}}$ depending on the climate zone, settlement structure and energy tariff. The value of retrofitting can also be seen as the threshold cost for PED retrofitting and, therefore, as an initial indicator for urban planners as a cost limit for building envelope retrofitting interventions in PED projects. The value increases with colder climate and denser urban environments. Through the cost of electricity, local authorities could try to push for retrofitting activities while always keeping energy justice in mind.

From an environmental point of view, the higher the retrofitting standard, the lower the grid electricity-related carbon emissions. Furthermore, retrofitted PEDs require less energy infrastructure, which saves internalised emissions and valuable raw materials. On the other hand, retrofitting material must also be produced and installed.

Future work could cover how retrofitting affects districts that are not solely residential but include commercial end-users such as supermarkets or offices. Furthermore, due to retrofitting, the installed PV capacity is reduced. Including additional electricity consumers or potential innovative and community-driven storage solutions such as EV charging and hydrogen would round out the PED planning. Additionally, solar thermal solutions competing with PV panels regarding the available roof space would be an exciting addition to the model. Moreover, a study with lower resolution data but all of Europe's representative climate zones could map the value of building envelope retrofitting on a finer spatial scale. Finally, a study on how the costs and responsibilities within the PED are distributed according to social parameters such as income will be a crucial addition to the literature in energy-community concept planning.

5. Discussion and synthesis of results

This chapter synthesises and discusses the results generated in this thesis. Section 5.1 answers the research questions defined in Section 1.2 using the findings of this work. Section 5.2 puts the findings into perspective and discusses potential implications on the PED definition, policy design and the PED realisation across Europe. Finally, Section 5.3 discusses the strengths and limitations of this thesis, as well as potential directions for future research.

5.1. Answers to the research questions

This work's overarching objective is to uncover and analyse the feasibility and values of Positive Energy Districts in Europe. The objective is broken down into three research questions presented in Section 1.2. Those research questions are investigated in the three case studies of Chapter 4. This section summarises the key findings regarding each research question.

Thus, the first research question is stated as follows:

Research Question 1. *Are electricity-only PEDs feasible under hourly changing grid mixes with different renewable penetrations?*

This case study uses a mathematical linear programming model to investigate if PEDs are feasible if only the electricity consumption is considered. Furthermore, the work proposes a novel approach using the primary energy factor of the regional energy mix on an hourly basis to calculate the energy balance and its effects on the PED. The method is applied to a real case of a Spanish town on the Island of La Palma, where the climate conditions do not require space heating or cooling. Results indicate that a rural district of the town can easily be converted to a PED and will be more cost-effective than buying electricity from the grid. However, PED development is more complicated in a more urban and densely populated district due to the undesirable ratio of available space for PV power generation to energy demand. If certain roof areas (eg. terraces) could not be used for PV power generation, a positive energy balance over the year was impossible to achieve, indicating a strong dependency of the PED feasibility on the floor space index. The analysis furthermore shows that the PEDs in question have extremely high electricity import and especially export peaks, which can lead to grid instability. Reducing this phenomenon by limiting the import and export power with the underlying energy system harms the economic feasibility, as much more investment in battery capacity is needed to spread the import and exports over a larger time frame. Finally, applying an hourly changing primary energy factor to the PED balance proves beneficial in island-based systems with a high penetration of renewable energy. The approach incentivises the export of energy in times of low renewable penetration and the import during high renewable penetration, which can support stabilising the grid.

The second research question of this thesis extends the regional boundaries and investigates PEDs across the EU:

Research Question 2. *What are the perfect conditions in terms of climate region and energy tariff structure for multi-energy PEDs across Europe with and without grid exchange limitations?*

To answer this question, the tailor-made mathematical optimisation model was extended to a mixed integer linear programming model that considers electricity, DHW, space heating and cooling demand. Different scenarios were created by appointing five different sites with representative climate conditions across Europe and generating respective energy demand profiles through machine learning. The PEDs considered were all PV-powered and heat-pump/electric boiler-based systems. Across all sites, an equally sized, 20-building district was compared, applying different tariff structures and costs. While in southern regions of Europe, a PED is more cost-effective than the assumed status quo, the PED concept is economically not feasible in northern regions, especially those considered to have district heating. Results demonstrate that the cost per unit of CO_2 abated is lowest (even negative) in PEDs in southern Europe with a dynamic tariff structure and additional carbon pricing. This abatement cost increases the more north a district is located and especially if the district is assumed to have district heating previously available. The district heating-based neighbourhoods would be better off decarbonising the districts with a centralised heating approach. Limiting the grid exchange to reduce the strain on the distribution grid has different effects in different climates. While in northern regions, the grid limit has only small adverse effects on the net present value, the northern regions suffer drastically from decreasing NPVs because of the need for much larger battery capacities. Additionally, the self-consumption rate of the PV power generated in the PED almost doubles through the grid limit in southern Europe. Concluding, PV-powered and electrified, decentralised PED solutions shall focus on southern to central Europe, where no centralised heating is already in place. High and dynamic tariffs could actuate as a push towards PEDs in those areas. Other approaches and concepts, such as virtual PEDs, might be more sensible for decarbonisation in the remaining areas.

The final research question of this thesis integrates building envelope retrofitting:

Research Question 3. *What are the values of passive retrofitting for PEDs under different climate and settlement density conditions?*

This question is answered by comparing PEDs with and without retrofitting in three climate zones and different settlement densities. The comparison shows that passive retrofitting is crucial for developing PEDs, especially the colder the climate and the denser the district is. In those cold and densely populated areas, non-retrofitted districts cannot achieve the dynamic PED standard as the solar PV power generated over the year within the district is not sufficient to cover the high demands for space heating. Logically, the self-consumption of the generated PV power is higher in retrofitted PEDs, which can be positive for the regional grids. Generally speaking, the retrofitted district is more flexible in following electricity price signals and, therefore, can be valuable for the distribution grids. By comparing retrofitted and non-retrofitted and optimised districts, the value of retrofitting has been quantified in $\frac{EUR}{m^2 * kWh_{red}}$. In the considered cases, the value ranges between approximately 1.4 to 2.2 $\frac{EUR}{m^2 * kWh_{red}}$ being low in warmer and high in colder climates. The climate, the settlement density and the electricity tariff development affect the value of retrofitting in PEDs. The value increases with colder climates, higher settlement densities, and higher electricity prices. Moreover, it can be used as a threshold. Anything lower than this threshold would be a cost-efficient investment in passive retrofitting if only economic values are considered. In contrast, anything beyond the specific value would be more expensive than not doing any envelope enhancements. However, beyond the plain economic value, passive retrofitting can significantly impact reducing CO_2 emissions, and decisions should, therefore, not only be made on an economic basis.

5.2. Implications on policy design and PED realisation

The results of the cases have potential implications for the design of EU energy policy, the PED realisation in Europe and the redefinition of the PED concept.

5.2.1. Policies to support the PED development

The European Union is pushing the PED concept as one of many approaches to decarbonise urban areas. A supportive regulatory framework and incentives to realise such concepts could play a crucial role in large-scale adaption and sensible realisation. National and regional laws and programs are essential to creating an optimal environment for PEDs depending on the local conditions. The results of this work's three case studies show that high and dynamic energy prices, as well as the pricing of district-associated CO_2 emissions favour the PED concept, especially in southern Europe. Thus, municipalities that want to push the PED development locally should implement PED-friendly, dynamic energy tariffs through public utility companies.

Furthermore, on an EU level, the cost of carbon-emitting energy technology has to rise to generate a push towards concepts such as the PED. This can be done by directly increasing the cost of the respective fossil fuels for the final consumers or raising taxes on fossil-based energy generation technology such as gas heating. While increasing the cost of energy and making prices more volatile might favour the Positive Energy District concept, it might be detrimental for those final consumers that cannot afford the increasing cost of energy nor the high investment barrier that come with PEDs and therefore fall into energy poverty. In the official PED definition, the European Commission states that PEDs must be inclusive and should not leave anybody behind by tackling issues such as energy poverty and affordability [20, 21]. Thus, this work proposes that while local, regional and national governments need to increase the cost of fossil-based energy and make final energy tariffs better reflect the actual cost of generated energy through dynamic tariffs, they need to ensure that those nudges towards the PED concepts are not harming vulnerable parts of our society. To do so, PEDs must be inclusive concepts that provide affordable living. Some approaches towards more inclusive PEDs could be public investment in such concepts for social housing projects, facilitating the creation of energy communities and tax exemption or subventions for renewable energy technology such as PV, passive retrofitting or heat pumps, among others. In the end, the final customer would profit in the long run economically and environmentally from living and investing in PED concepts. However, many will require public or private support to overcome the hurdle of the high initial investments.

5.2.2. Most sensible regions for electrified, dynamic PEDs

PV-based, electrified PEDs are one of the most typical dynamic PEDs, as solar energy is easy to capture on the districts' roofs, wind energy is rarely practical in the urban environment, and other heating resources such as biofuels can usually not be sourced in cities. According to this thesis, this specific kind of PED solution is most viable in southern European countries from a technical, economic and environmental point of view due to a combination of better solar energy resources and more favourable heating and cooling demands. With colder climates and less solar irradiation, the economic value of PV-based and electrified PEDs reduces until they are not even technically feasible anymore. Additionally, the further north and the denser the district is, the more critical passive retrofitting becomes to be technically able to achieve a positive energy balance. Thus, this thesis deducts that the effort of PV-based, electrified PEDs should be centralised in southern Europe, where the economic and ecologic value is the greatest compared to the associated costs. The colder and darker the climate, other decarbonisation concepts or different forms of PEDs might become more sensible, such as the virtual PEDs with community-owned wind parks. Moreover, if a neighbourhood is already part of a centralised solution such as district heating, decarbonisation is more economical via decarbonising the centralised energy technology equipment rather than through individual approaches. For the specific case of island-based systems, where the energy price does not at all reflect the local cost of generation, PEDs could use an hourly re-evaluation of the primary energy factor to nudge towards a more grid-favourable behaviour.

5.2.3. Expanding the PED definition

Furthermore, this work shows that the definition of the Positive Energy District needs to be specified better. While flexibility and grid resilience is mentioned in some definitions, the goal of exporting more energy than importing on an annual basis is the overarching objective. However, as shown in this thesis, the most cost-effective way to achieve this in PEDs with electrified heating, results in extremely high export and import powers as well as significant differences in electricity import and export across the seasons. Both behaviours can contribute to grid instability and are exactly what a PED should avoid. Thus, contribution to grid stability needs to become a more central role in an official definition of Positive Energy Districts. Some proposals are:

- Reducing the period for energy positivity: By reducing the compliance to have a positive energy balance from one year to one month, one week, one day or even 8 hours, the strong fluctuations in electricity import and export, especially on a seasonal scale, would be reduced. On the other hand, this approach reduces the feasibility of PEDs, and where still technically possible, it would make them financially unattractive with every reduction of the period.

- Limiting the export and import power of the PED not to surpass, for example, the maximal power demand of the district, as done in this work, significantly reduces grid impact and increases flexibility.
- A compulsory high self-consumption rate of the locally generated electricity would also reduce the electricity exchange with the grid and increase the local flexibility of the district as storage investments will be necessary.

Ultimately, a mix of the proposed approaches would make a sensible addition to the PED concept definition as they enforce the investment in otherwise expensive storage equipment that increases the district's flexibility. Combined with the right incentives, e.g. tariff schemes, such PEDs would be a lot more valuable to the energy transition as they could actually contribute to grid stability and could reduce the need for expensive grid upgrades in congested areas.

Moreover, the PED definition needs a clear methodology towards district development. Considering all results of this thesis, the transition towards PEDs from existing districts should start with building envelope retrofitting as long as it is cost-efficient according to the proposed threshold. As a second step, an optimisation model, such as the proposed PEDso model needs to be used to determine the most cost-effective technology portfolio under the local grid exchange constraints that complies with the autonomous or dynamic PED definition. Only if under those steps a PED is technically not possible, the virtual PED should be considered. Along all these steps, the citizens need to be involved to raise acceptance and define the final "legal" version of the district, such as a energy cooperative in the role of an aggregator.

5.2.4. Qualitative summary of the main findings

Table 5.1 indicates the parameters that influence the feasibility and techno-economic value of dynamic PEDs that are based on electrified heating. Furthermore, it presents those parameter values that are most likely creating the basis for a PED to thrive. Thus, the most PED-enabling parameter combination according to this work is a warm/hot cliamte, a relatively low settlement density, high and dynamic electricity tariffs, direct taxation of carbon emissions and a relatively high building standard. According to this, modern or modernised suburbs in cities such as Seville would be a perfect basis for extracting high value of the PED concept, especially since the electricity tariffs on the Iberian peninsula are relatively high and volatile.

Table 5.1.: Parameters that influence the feasibility and techno-economic value of electrified, dynamic PEDs

Parameters	PED-supportive value
Climate	hot
Settlement density	low
Electricity tariff	dynamic & high
CO_2 tax	high
Building standard	high

If a PED-supportive basis is created through the previously mentioned parameters, Table 5.2 shows the potential effects such a PED could have to different stakeholders. Firstly, if well optimised, an electrified PED can drastically reduce the energy-related expenses of the PED owner and/or citizens. Furthermore, due to the fact that a large part of the imported electricity gets replaced by locally produced, renewable electricity and fossil-based by electrified heating, those PEDs have a significantly improved CO_2 footprint. On a negative point, the PED creation is always associated with large investment costs that need to be sourced somehow. Thus, without extensive public or private investment or crowdfunding PED projects are not possible. As pointed out in this work, if well designed, a PED can significantly contribute to flexibility to the grid thanks to its generally large installed capacity of energy storage (electricity and heat). In addition to the dynamic pricing, as shown in this work, further grid resilience can be provided by the PED's high capacity of flexible assets through incentive-based demand response. However, if not taken care of, PEDs can also negatively affect grid stability, as the high PV power installations can lead to extremely high and volatile export events and to seasonal imbalances.

Table 5.2.: Potential effects of a PED on its stakeholders and surrounding

Parameters	Effect
Long-run cost-effectiveness	↗
Required investment	↗
Carbon emissions	↘
Flexibility	↗
Grid resilience	→

5.3. Strengths, limitations and a glimpse in the future

This section presents the strengths and limitations of the applied approaches in this thesis as well as potential work and ideas for future research in the area of Positive Energy Districts.

5.3.1. Strengths of the methods

Variety of crucial variables

One major strength of this work is the number of variables discussed that are significant for the techno-economic feasibility of Positive Energy Districts. This thesis addresses the influence of climate, different tariff structures and the cost CO_2, various district density constellations, thermal performance of buildings, grid stability support and even the renewable penetration of the surrounding energy system. Most of these parameters crucially influence the PED concept's technological, economic and/or environmental feasibility.

Therefore, by exploring the techno-economical performance of various combinations of the aforementioned parameters, this thesis provides a real value for the European PED concept by indicating conditions that allow PEDs to thrive. Thus, this work allows to either place the PED project in perfect conditions from a techno-economic standpoint or helps to identify which indicators need to be adjusted to enhance the project's value. To achieve this, throughout this work, various innovative approaches have been developed and indicators defined. The academic and practical value for a European concept, such as the PED, goes far beyond that of a single case study framed for a specific location. Ultimately, this approach allowed the work to deduct generalised statements about PEDs in Europe rather than those that are limited to a single area.

Optimisation model: Mulit-energy, open-source MILP model

A further strong point of this thesis is the tailor-made optimisation model. The mixed-inter linear programming model has been developed from scratch with modularity and flexibility in mind. The model already includes the relevant technology for electrified PEDs to cover the electric, DHW, space heating and cooling demand but can be easily extended by defining additional technology with respective input and output energy flows and constraints. This allowed the model to grow with each case study, providing a red thread throughout this thesis and helping to comprehend the approaches. Furthermore, the model is published under an open-source license and is thus accessible for everybody [90]. This increases the reproducibility of academic publications and the value of academia in general but also allows non-academic projects and endeavours to use the research that went into this work. One example is the European Commission's call for Horizon Europe Projects "Interoperable solutions for positive energy districts (PEDs), including a better integration of local renewables and local excess heat sources" that is explicitly advocating for the development of such planning tool solutions, as stated in the call's scope: "Develop tools and methods for planning and designing PEDs, that support PED developers and managers to optimise the mix of PED solutions depending on the local conditions" [127]. Also, other institutions, such as the Annex 83 by the International Energy Agency, call for

PED planning and operation tools and underline the importance of the topic [22].

Energy consumption profiles

One challenging topic in energy modeling is to source adequate input data, especially energy demand profiles. This challenge becomes even larger in multi-energy systems, where the electricity, the DHW, and the space heating and cooling demand profiles are needed. Using different climate locations and building standards, such as in this work, the amount of different demand profiles multiplies again. This thesis leveraged several solutions to obtain good quality energy demand data. In the first case, which was electricity-only and situated in Spain, the publicly available data by the TSO has been taken and broken down to the district [101]. In the second case study, synthetic demand data was created for one location by synPro, the Fraunhofer Institut's stochastic energy demand generator, and then transferred to other locations through machine learning. For the third and final case, all the demand data was generated from synPro directly [102]. Thus, this thesis showed three innovative ways of generating energy demand data for academic use. Even though the demand data is sourced differently, the final results regarding PED indicators, such as the climate or the available space, go in the same direction, thus validating the methodologies.

5.3.2. Limitations of the methods

Focus on one specific type of PEDs and exclusion of certain factors

The PED concept is vast and multifaceted. This thesis only focuses on dynamic PEDs that cover their heating and cooling demand via individual electrification. The dynamic PED allows for free energy exchange with the surrounding system but requires all the generation to be done locally. While this is the most feasible and grid-supportive approach for urban areas, this thesis does not discuss other possibilities. One of them is the virtual PED, which virtually expands the PED borders beyond the district's physical ones. Therefore, one of the limiting factors, the available space, becomes obsolete and opens the door for other, large-scale energy generation technology such as wind power. This concept would especially favour northern countries with difficulties supplying the energy needed by local PV power for a positive energy balance. This thesis focuses on the dynamic PED concept only, as it has the most considerable potential to support the stabilisation of the power grid. In contrast, the virtual PED concept might even destabilise it. However, the virtual PED could be considered in those northern regions where the dynamic PED is techno-economically not feasible.

This work makes two further limitations to the PED concept discussed in the case studies. Firstly, it only considers purely residential districts. While this is possible in some suburban parts of cities, many districts would likely have a more diverse profile, including shops, offices and public institutions such as schools. Secondly, this work does not include electric vehicles in the positive energy district equation. While the demand for EVs can be easily added to the electricity demand of the district, it has to be defined how EVs are treated, as one can see them as a moving batteries that can cross the district's borders. One could argue that an EV that is charged in the district and then leaves and uses the energy somewhere else is counted as an energy export. Reversely, an EV entering the district fully charged and then used for demand response while parked inside the district could be considered an energy import. These dynamics are not considered by the PEDso model so far.

Optimisation model: Single-level only

While the optimisation model is discussed as a strength in some of its points, it also has limitations. The major limitation of the MILP model developed for this thesis is its single-level-only character. While this allows to derive valuable statements about the district as a whole, it cannot represent the interaction of individual stakeholders, such as minimising the cost per individual PED inhabitant on a lower level and maximising the profit of a higher level aggregator. This thesis traded off the option of a bi-level optimisation for the inclusion of a large number of cases and variables.

5.3.3. A glimpse in the future

Research on PED-related techno-economic modeling is being strongly pushed by the European Union and other institutions through Horizon Europe calls [127, 128], terminated or currently running EU-projects [28, 25, 29, 24] and initiatives such as the Annex 83 by the International Energy Agency or the PED-EU-NET [22, 23]. Thanks to this high public interest in the concept and its potential extension to Positive Energy Cities [35], the research on Positive Energy Districts will continue.

Building up on this thesis, an extension of the PEDso model towards bi-level optimisation and the inclusion of electric vehicles in the PED-balance could reveal exciting information about the interaction between stakeholders and the value of further highly flexible assets in the districts.

Additionally, an extension towards more diverse districts in terms of energy demand could reveal the perfect district structure for newly developed districts, which has high value for early city and district planning. This could include offices, restaurants, supermarkets, schools or other public buildings, but also industrial areas.

A further topic that requires deeper research within the field of techno-economic analysis of PEDs is the decision between centralised technology or individual supply eg. district heating vs. individual heat pumps or central energy storage vs. indvidual storage. Another point for future research is the value of less common technology such as hydrogen storage for increased self-consumption of the locally generated energy or approaches for seasonal storage systems.

6. Conclusions and outlook

The concept of Positive Energy Districts (PED) aims to be one of the supporting pillars of Europe's energy transition and decarbonisation efforts in the urban environment. This thesis contributes to the relatively new topic of PEDs by proposing a tailor-made optimisation framework that is used to answer PED-related questions about the concept's feasibility, values and influential external factors. This chapter concludes the methods used in this thesis, discusses the PED's feasibility and techno-economic values and presents an outlook on future work.

There are two main methodological points in this thesis. On the one hand, the PED optimisation model itself and, on the other hand, how the model is applied to answer the research questions.

The open-source model PEDso presented in this thesis has been developed explicitly for the PED context to answer the research questions of this thesis. It is a modular mathematical optimisation model that grew with the different requirements of the three research questions to a multi-energy mixed-integer linear programming model. The model's core is the energy balance calculation, which has different approaches to consider the different primary energy factors (PEF) of the energy exchanged.

A dynamic version of the PEF balance was used, where the PEF changes hourly depending on the grid mix surrounding the PED, with real data from the Spanish islands La Palma and El Hierro. The high PEF during fossil-based electricity generation incentivised the PED to export energy, and the low PEF during a highly renewable grid mix made the PED store or self-consume their generated PV power or even shift grid imports to this time. This dynamic system proved to be an excellent incentive for PEDs in island systems without electricity markets, such as the Canary Islands. Since the energy cost in those systems does not reflect the cost of actual energy generation on the island, it cannot be used as a grid-stabilising tool. On the other hand, the dynamic PEF developed in this thesis for energy exchange between the PED and the regional energy system can incentivise flexibility and flexible behaviour of the PED to stabilise the grid.

In a second study, the PEDso model was used to assess under which conditions in Europe a PED would be most sensible. To do so, a representative city of the five major European climate zones was chosen. A machine learning algorithm was used to create the different heating and cooling demand profiles. PEDs under different energy cost and grid exchange limitation scenarios were investigated to create a matrix of carbon abatement costs for the PEDs under all climate-tariff combinations. Results show that the electrified PED is most cost-efficient in CO_2 abatement in southern Europe under a dynamic tariff system. Here, abatement cost is even negative, indicating economic profit per saved tone of CO_2. The least cost-effective scenarios for PEDs that use individual heat pumps are in northern areas with district heating already installed. Here it would be more sensible to reduce the carbon intensity of the already existing district heating system. Limiting the power exchanged with the grid eliminates the destabilising effect that a PED can have through its significant PV power exports and increases the self-consumption significantly. This comes with an additional cost of more storage capacity, especially in northern districts.

A third study used PEDso to investigate the value of building envelope retrofitting in the PED context. To do so, PEDs in three different climates, settlement densities, and specific energy demands were optimised and compared. From the results, a new indicator was deducted that quantifies the economic value of building envelope retrofitting in $\frac{EUR}{m^2*kWh_{red}}$. This indicator can be used as a threshold until passive retrofitting measures are economically sensible. In the PED context, building envelope retrofitting is crucial in cold climates, where the electrified, dynamic PED concept would otherwise not be possible. Furthermore, PEDs with a high building energy standard have a better electricity related CO_2 footprint, a superior energy self-consumption behaviour and react more flexibly to grid signals.

Generally speaking, this thesis shows that PEDs are technically feasible across Europe. However, they are most cost-effective in decarbonisation in southern Europe. In colder climates, the electrified, dynamic PED concept might not be economically profitable, and other solutions could provide more cost-effective decarbonisation. Local, regional and national governments can use parameters such as energy tariffs or carbon cost, as well as subsidies for building retrofitting to make the PED concept even more attractive. In all cases, the concept requires large amounts of initial investments. Thus, tailor-made business models will be needed to ensure a significant and socially responsible uptake of the concept, such as through ESCOs, energy communities, or cooperatives. It is specifically important not to create exclusive districts that only the wealthy part of the society can afford but establish an inclusive neighborhood that grants access to clean energy for everybody.

Future research is needed to investigate the specific influence of a high uptake of electric vehicles on the energy balance and find innovative ways to account for their dynamic nature. Additionally, a bi-level optimisation approach would enable representing different stakeholders, such as the single end-users of the districts, compared to the aggregating institution that participates in the electricity market. Furthermore, centralised solutions such as district-owned and operated district heating networks could increase the profitability in northern regions as well as the inclusion of virtual PEDs that allow for, e.g. district-owned wind farms out of the spatial borders of the neighbourhood.

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Appendices

A. Crucial allocation of the Primary Energy Factor in the dynamic balance

Figure A.1 shows the high importance of correct allocation of primary energy factors to power flows. In Figure A.1, all import power was treated the same way in terms of PEF, no matter if it was used to cover the load that existed before PED creation or added new parts to the load by charging the battery. The PEF was the *average* over the grid mix PEFs at the current time step according to their share in the mix. For grid export, it was the PEF of the *most expensive* technology on the marginal cost curve at a current time step, as this one would be "substituted" by the PED's electricity export. This would create the undesired behaviour of grid to battery power import contributing the negative average of the current grid mix PEF to the balance, while at the same time battery to grid export contributing with positively with the PEF of the marginally most expensive technology to the balance. This would leave a positive balance and therefore, reduce the need for battery installation in total, as the PED balance would be created partially by back and forth trading between battery and grid. Attributing also the PEF of the most expensive grid technology at a given time step to any electricity import that does not cover the load fixed this error. However, it shows the importance of correct attribution of the PEF to corresponding power flows to not create undesired dispatch behaviour.

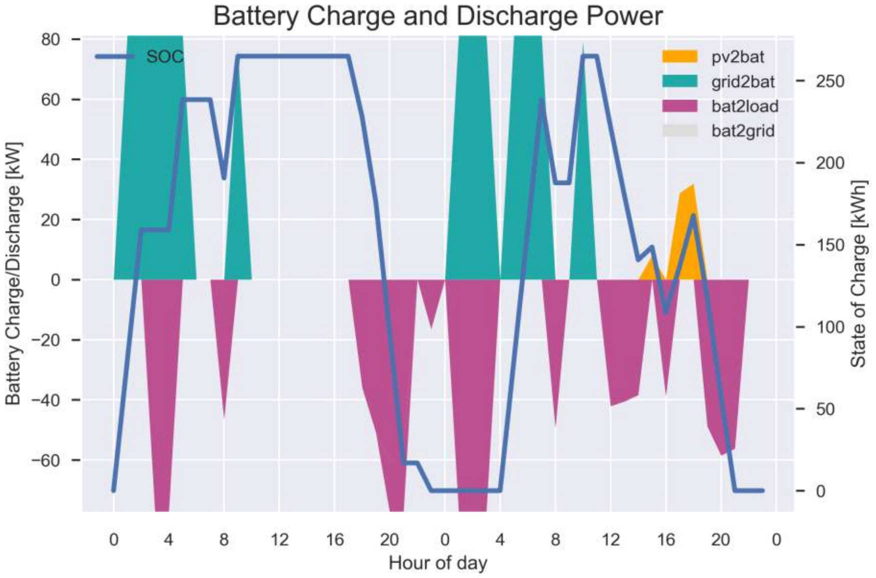

Figure A.1.: Battery charge and discharge power of PES lim2 scenario with wrong PEF for grid tp Battery power.

B. Technology data assumptions

Table B.1 shows the technological input data assumptions used for the PV installations. The data are taken from Ref. [129]. The average of the small private and medium-sized commercial system cost is taken. PR: performance ratio (incorporates losses of a PV system), GCR: ground coverage ratio of the PV plant.

Table B.1.: 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	-
Lifetime	25	a

Table B.2 shows the cost and technical assumptions for the lithium-ion battery. Refs. [74, 93, 130] are used for for battery costs.The studies state a range of 500-1000 EUR/kWh. Thus, this study opts for 750 EUR/kWh as a value in between.

Table B.2.: 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
Lifetime	15	a

The heat pump (air sourced and ground sourced) and electric boiler cost data is taken from Refs. [131, 93, 132, 133] and shown in Table B.3 and B.4, respectively. The costs are slightly increased and compared with commercial products due to the different scale of application in Ref. [131]. The ground source heat pump's COP for heating and cooling is constantly at 3.5 and 5 respectively. The air-source heat pump's COP for heating is dependent on the outdoor temperature according to Ref. [93] and the one for cooling is constant at 3.

Table B.3.: Heat Pump input data

Variable	Value	Unit
$CAPEX_{AS}$	800.00	EUR/kW
$OPEX_{AS}$	2.00	EUR/kWa
$CAPEX_{GS}$	1300.00	EUR/kW
$OPEX_{GS}$	6.00	EUR/kWa
Lifetime AS & GS	20	a

Table B.4.: Electric boiler input data

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

Finally, Table B.5 shows the technical and economic data of the heat storage.

The main sources used are Refs. [134, 135, 136].

Table B.5.: Heat storage input data

Variable	Value	Unit
CAPEX	57.00	EUR/kWh
OPEX	0.00	EUR/kWa
η_{tss}	95.00	%
η_{self}	0.9998	%/h
Capa2power	0.30	-
$SOC_{1,0}$	0.00	kWh
Lifetime	20	a

C. Time-of-use tariff structure

Figure C.1 shows the ToU tariff that Case Study 2 and 3 use. The ToU tariff is separated in three periods (low, middle and peak) throughout the day, peaking in the morning and the evening, while being flat during the weekend. The feed-in tariff is a flat tariff throughout every time step.

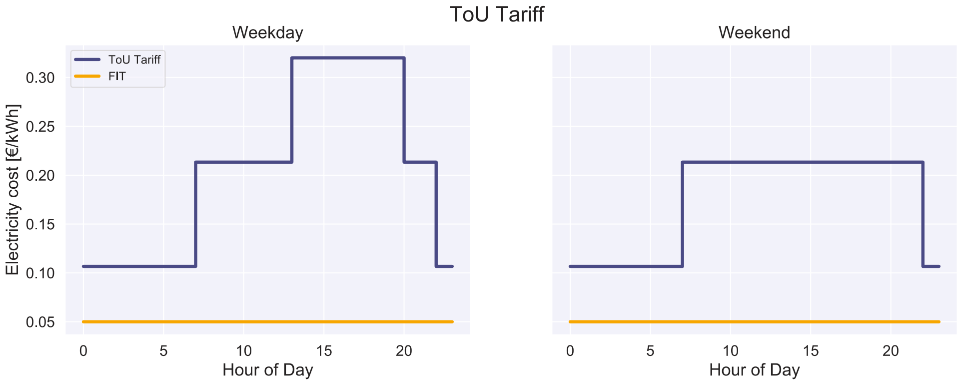

Figure C.1.: Time of use tariff and feed-in tariff of this study