TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria

Energy Economics Group

Doctoral Thesis

Quantitative Tools to Support the Decision-Making Process for Energy Transition in Residential and Industrial Sector

submitted in satisfaction of the requirements for the degree of
Doctor of Science in Technical Sciences

---

by

Bottecchia, Luigi
Matr.Nr. 11934274

Supervisor

Univ. Prof. Dipl.-Ing. Dr. Reinhard Haas
Technische Universität Wien

Co-Supervisor

Dr. Pietro Zambelli
Eurac Research

Dipl.-Ing. Dr. Lukas Kranzl
Technische Universität Wien

Reviewer and Examiner

Prof. Dr. Fabian Scheller
Technical University of Applied Sciences Würzburg-Schweinfurt

Prof. Dr. Alessandro Prada
University of Trento

Wien, 03 March 2025

Abstract

In the context of the complex energy transition, this dissertation investigates methods to facilitate local energy transition in the residential and industrial sectors. On the one hand, the study examines local communities and Positive Energy Districts (PEDs). On the other hand, it analyzes the industrial sector's challenges in contributing to an economically viable energy transition. This research explores, develops, and applies methods and tools to address key challenges in the energy transition across residential and industrial sectors. It integrates simulation approaches, high-resolution spatial data, and economic analysis to support decision-making processes. By providing quantitative insights, it highlights how stakeholders can design effective energy intervention, understand the right solar potential in urban areas, and foster industrial symbiosis through actions like industrial waste heat integration into local district heating networks. To address these topics, this dissertation develops the Multi Energy System Simulator (MESS), a modular, bottom-up, multi-node simulation tool. As a first step, this dissertation investigates how simulation compares to optimization approaches in modeling district-level energy systems. By simulating non-optimal solutions, the MESS model highlights the dynamic behavior of energy systems and their uncertainties, supporting decision-makers in designing effective energy transition interventions. Compared to optimization tools, the faster resolution time of MESS allows the investigation of multiple scenarios almost instantaneously answering the *What happens if...?* question. On the contrary, an optimization approach is more indicated for investment planning models and macro energy systems analysis to understand what is needed to achieve a specific target. Consequently, combining optimization and simulation allows first to see the optimal solution and then investigate how non-optimal solutions, and often the reality is non-optimal, deviate from it. The study also explores the integration of spatial dimensions within energy system modeling. To do that, it exploits the value of high-resolution spatial data in assessing solar potential in complex urban environments such as the one of historic centers. The results show that in the historic center high-resolution spatial data are critical in improving solar irradiance estimates. In fact, considering them results in a 36% lower theoretical solar potential on a full year. These new insights are also critical to enable effective solar energy policy development and correct sizing of integrated systems. Finally, the dissertation integrates these technical insights with industrial project evaluation tools to investigate interventions that foster industrial symbiosis among industries, districts, and district heating operators (DHO). The research in this last step focuses firstly on a scenario where the industry acts alone without the DHO and then on three scenarios that see the cooperation between industry and DHO. The first evaluates the implication of introducing a support scheme on heat price, the second a financial incentive to cover the grid connection costs to be allocated to the DHO and finally a third scenario that combines the two. The findings reveal that the successful integration of industrial waste heat into district heating systems hinges on supportive policies and stakeholder coordination. By integrating simulation approaches, high-resolution spatial data, and economic analysis, this dissertation demonstrates how tailored methodologies can address technical, spatial, and economic challenges. Consequently, the presented methods and tools can support stakeholder decisions to pave the road for a sustainable energy transition.

Table of Contents

1 Introduction

The current energy transition is a critical challenge faced by modern societies. The main driver of this transition is the urgent need to reduce greenhouse gas emissions to mitigate the impact of climate change. Hence, it is essential to strengthen the interrelations between technological advancements, efficient energy management, supportive policy frameworks, and strong stakeholder symbiosis. In this context, energy systems models are key tools to better inform decision-makers on designing, using, and optimizing existing and new energy systems. However, the complexity and diversity of energy systems require different approaches to better capture their behavior. One of the most critical challenges is related to the interactions between residential and industrial sectors at urban scale. These sectors present unique technical and economic barriers, including integrating spatial data for urban planning and aligning stakeholder priorities in industrial symbiosis projects. In this context, this dissertation performs an in-depth literature review on open-source energy models. One of the main focuses of this review is to investigate optimization and simulation approaches. Given the scarcity of open-source pure simulation models, the author develops a novel simulation model called Multi Energy System Simulator (MESS). MESS is a modular, bottom-up, multi-node model that allows the investigation of non-optimal solutions by simulating the energy system. Consequently, this thesis investigates the potential of simulation approaches in modeling energy systems. Then, it evaluates the impact of high-resolution spatial data on modeling accuracy. Finally, it combines the findings to explore the role of policy interventions in fostering industrial symbiosis between industries and districts. By integrating simulation and optimization techniques, geographic information systems (GIS), and financial methods, this research offers robust and actionable insights to foster the energy transition and support decision-making in achieving sustainable urban development. The open-source and transparent nature of the methodologies adopted ensures that the findings are reproducible and accessible to a broader audience, promoting collaborative efforts in advancing the field of sustainable energy transition.

1.1 Motivation

In 2015, the Paris Agreement Nations 2015 set ambitious goals in the fight against climate change. However, despite the efforts of the last decades, the situation is still critical. The Intergovernmental Panel on Climate Change (IPCC) is currently working on its sixth assessment report, and the preliminary results show a worrying situation where emissions are still rising (even if at a lower rate), posing a severe risk for the whole world IPCC 2022. The European Union is a crucial stakeholder in the fight against climate change. In this context, essential policies and plans have been implemented in the last few years. Among these, the last ones are the European Green Deal Commission 2019 with which the European Commission (EC) aimed at carbon neutrality by 2050, and the REPowerEU Commission 2022 that, in light of the energy crisis caused by the war in Ukraine, aimed at accelerating the process towards energy independence of the EU.

In this context, the energy system has to undergo a profound transformation to become mainly based on renewable energy sources while guaranteeing security of supply, fairness, and sustainability. To do that, all sectors must implement radical changes to decrease their impact.

According to Eurostat, in 2021, almost 30% of the final energy consumption in the EU was accounted to the household sector, second only to the transport one, making it a key sector for analyzing opportunities to cut consumption and consequently emissions Eurostat 2022. Similarly, the industrial sector accounts for almost the same percentage (ca. 26%), making it equally relevant to the European Commission's decarbonization strategy.

Starting from the household sector, in recent years, particular attention has been given to cities and districts to achieve an efficient energy transition. Smart cities combine efficient energy management systems with analysis that aims to improve the quality and equity of the lives of their citizens Batty et al. 2012; Hoppe and Bueren 2015; Kheloufi et al. 2021. However, the current trend is to apply measures and initiatives initially designed for a city scale, also at a lower spatial resolution, e.g., districts or communities. In this sense, districts and concepts like energy communities facilitate the implementation process and become a testing environment to scale them up Lindholm et al. 2021; Hedman et al. 2021a. In the same way, also single buildings can be used as demonstration cases, for example, by analyzing how smart energy management systems can combine photovoltaic panels and electric batteries optimally Song et al. 2022.

This environment is where the concept of Positive Energy Districts (PEDs) was born. This concept was first introduced in 2018 by the Strategic Energy Transition Plan 3.2 2018 to support the development of 100 PEDs in Europe by 2025. Since then, the definition of PEDs has evolved until 2020 when JPI Urban defined them as *"energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net-zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy"* Europe 2020. To achieve the goal of a positive energy balance, PEDs use renewable energy sources (RES) coupled with smart energy management systems, as well as storage and flexibility options. Additionally, as well explained by Casamassima Luca 2022, the PED concept integrates these technical aspects with the social implications of the energy transition, adopting one of the goals of the new European Green Deal, which is to have sustainable growth and transition where nobody is left behind. Although most people will benefit from this transition, it has also some drawbacks. Thus, it is essential to try to foresee these, understand their distribution as they might not be equally spread among a city and its population, and mitigate them.

Looking at the industrial sector, in recent years, the primary focus has always been the sector's decarbonization or the efficiency improvement of the most energy-intensive processes. In this sense, some of these efforts go into increasing the share of renewable energy technologies toward a carbon-free or neutral approach Demartini et al. 2022. Instead, others are more innovative and focus on identifying and analyzing the interrelations between processes in the same industry or across different ones Fraccascia et al. 2020; Chertow 2003. The former can be considered as that field often referred to in literature as industrial symbiosis. Additionally, incentives and support schemes have been implemented to increase the share of renewable energy technologies.

Hence, while individually these two sectors have worked intensively to reduce their impact on climate and emissions, the interrelation between the two remains largely untapped. However, the potential synergies between the two sectors are key to achieving the goals of concepts like

Positive Energy Districts (PEDs) and the local energy transition.

In this context, district heating is a crucial technology, offering a sustainable and efficient way to distribute thermal energy within urban environments. By leveraging district heating technologies, communities can reduce their reliance on fossil fuels, lower greenhouse gas emissions, and improve energy efficiency. An additional opportunity within district heating is the potential to supply it with industrial waste heat. Industrial processes often produce substantial amounts of excess heat, which, if harnessed, can significantly enhance the efficiency and sustainability of district heating systems. By integrating industrial waste heat, districts can use a readily available energy source, reducing the need for primary energy inputs and furthering energy transition goals. Several factors must be considered to integrate district heating systems successfully. Buildings should undergo high-efficiency renovations to guarantee appropriate indoor comfort. Industries and district heating operators (DHOs) must collaborate closely to incorporate industrial waste heat into the district heating network, thus maximizing resource utilization and minimizing energy wastage. Policymakers, in turn, should facilitate these collaborations through tailored intervention measures that support and incentivize such symbiotic relationships.

In this context, the area of investigation of this work stands. The main objective is to provide quantitative tools and methods to facilitate the energy transition in the residential and industrial sectors. To achieve this, a simulation tool that models the energy system and integrates it with the spatial dimension is developed. The developed tool, called Multi Energy System Simulator (MESS), is a modular, bottom-up, multi-node model that allows to investigate non-optimal solutions by simulating the energy system. More specifically, it follows a logic that, based on a user-defined priority level for each technology, solves the energy balance of each node at each time step and, afterward, the overall network in analysis. This tool serves as a method to enhance the understanding of current energy dynamics and to demonstrate the impact of different interventions and scenarios on the analyzed context. By doing so, this approach can be used to foster industrial symbiosis between industries, districts, and local grid operators within the framework of district heating, providing valuable insights for policymakers.

1.2 Research Questions

Within this context, the main research questions are:

How does a simulation approach compare to an optimization one in modeling district-level energy systems to support decision makers in designing effective energy transition interventions?

Given the complexity of the decision-making, we would like to investigate how different modeling approaches, within the context of district-level energy systems, can better support policymakers. Particularly, the focus will be on the differences between optimization and simulation approaches to try to understand when and where one should use simulation rather than optimization.

Going into more detail, to answer this question the following sub-questions have been considered:

1. How do simulation approaches enhance the understanding of the dynamic behavior of energy systems compared to optimization methods?
2. What are the limitations of simulation models in capturing the complexity of real-world energy systems?
3. What computational resources are required for implementing simulation-based models compared to optimization-based ones?

This research question is answered in the first contribution of this thesis *The Potential of Simulating Energy Systems: The Multi Energy Systems Simulator Model.* Bottecchia, Lubello, Zambelli, et al. 2021

What is the quantitative impact of high spatial resolution data in assessing solar potential at district level?

Despite the increasing need and requests for high-resolution data, these are often hard to gather, more costly, and require more computational power. With this question we would like to investigate the real need of high-resolution spatial data at urban and district level. Particularly, the goal is to quantitatively assess the impact of such data using the context of the effect of the horizon height in evaluating the solar potential.

The following sub-questions were used to answer this point:

1. How does the resolution of spatial data affect the accuracy of solar potential estimation at urban and district levels?
2. What are the trade-offs between the costs of acquiring high-resolution data and the benefits they provide in energy system modeling?

This research question is answered in the second contribution of this thesis *Discussing the needs of high resolution data: their impact in evaluating solar potential considering the horizon height.* Bottecchia, Dallapiccola, et al. 2023

What is the required support level to facilitate industrial symbiosis in the context of industrial waste heat utilization to supply local district heating?

Given the context presented in the previous research questions, the aim here is to make use of the methods investigated above to understand how policy intervention can drive industrial symbiosis between industries, districts and local grid operators in the context of waste heat utilization in district heating networks. In this case the analysis is carried out by integrating modeling approaches with industry project evaluation methods to assess the viability of such integration as well as the effect of policy interventions.
To achieve this goal, these sub-questions were considered:

1. What are the key barriers that policy instruments need to address to encourage the adoption of industrial symbiosis initiatives?
2. What tools and methods can be used to identify the level of support?
3. How can the symbiosis between industries and districts favor the energy transition?

This research question is answered in the third contribution of this thesis *Driving Industrial Symbiosis: Evaluating Policy Intervention Effects on Waste Heat Utilization in Local District Heating Networks* Bottecchia, Kranzl, et al. 2024

1.3 Structure of the Work

This dissertation is the result of various publications. Among them, the main ones that will be used in this dissertation are:

- *The Potential of Simulating Energy Systems: The Multi Energy Systems Simulator Model.* - Luigi Bottecchia, Pietro Lubello, Pietro Zambelli, Carlo Carcasci, Lukas Kranzl. Bottecchia, Lubello, Zambelli, et al. 2021
- *Economic, social, and environmental aspects of Positive Energy Districts — A review.* - Luca Casamassima, Luigi Bottecchia, Axel Bruck, Lukas Kranzl, Reinhard Haas. Casamassima Luca 2022
- *Discussing the needs of high resolution data: their impact in evaluating solar potential considering the horizon height.* - Luigi Bottecchia, Mattia Dallapiccola, Lukas Kranzl, Pietro Zambelli. Bottecchia, Dallapiccola, et al. 2023
- *Driving Industrial Symbiosis: Evaluating Policy Intervention Effects on Waste Heat Utilization in Local District Heating Networks* - Luigi Bottecchia, Lukas Kranzl, Pietro Zambelli Bottecchia, Kranzl, et al. 2024

Figure 1 shows the relationships between aim, topic examined and research questions.

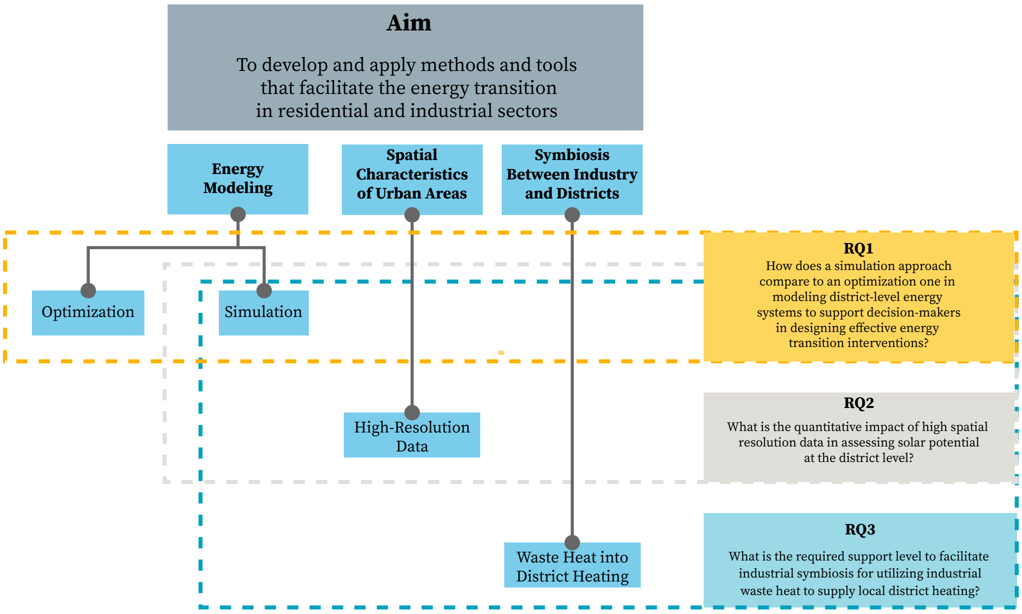


Figure 1: Relationship between aim, topic examined, and research questions.

In order to answer the research questions, the structure of this thesis is the following:

- **Section 2** presents the relevance of the specific contribution of this dissertation and shows the major literature review on the topics investigated. Firstly, **Section 2.1** presents the main concepts and definitions, **Section 2.2** illustrates the state of the art of the topic analyzed. Then, **Section 2.3** introduces a detailed overview of PEDs and their characteristics in comparison with similar urban concepts. **Section 2.4** presents a deep dive into energy system models to clarify why a novel tool has been developed. Finally, **Section 2.5** illustrates how this dissertation goes beyond the state of the art.

- **Section 3** presents the methodology adopted in the work. Firstly, **Section 3.1** provides an overview of how the developed model works and how it is structured. **Section 3.2** shows how the impact of the horizon height was calculated and integrated within the model. **Section 3.3** presents the financial analysis performed to assess the impact of utilizing the waste heat within the district heating both from the perspective of industries and district heating operators. Finally, **Section 3.4** presents the main data and sources utilized for the analysis performed.

- **Section 4** will present the results of the analysis performed. Particularly:
  - **Section 4.1** presents the results of the first contribution of this thesis, which is to investigate the potential of simulating an energy system rather than optimizing it.
  - **Section 4.2** will show what is the actual impact of considering the horizon height in evaluating the solar potential by exploiting the results of the second contribution of this thesis.

- **Section 4.3** describes the role of policy intervention in fostering industrial symbiosis between industries, districts and district heating operators. This part derives from the third main contribution of this thesis.

- **Section 5** sums up the work presented by critically discussing it.
- **Section 6** presents the main conclusion of the whole thesis.

2 Literature Review, State of the Art and Progress Beyond

This chapter provides a comprehensive review of the literature, outlining the current state of the art and highlighting how this work goes beyond the current progress. The structure of this chapter is illustrated in Figure 2

Figure 2: Structure of the literature review.

Firstly, **Section 2.1** introduces the key concepts and definitions relevant to this dissertation. This section is crucial for two main reasons: it ensures that readers and the author share a common understanding of specific terminology, and it improves the transparency and replicability of the work.

Following this, **Section 2.2** delves into the current developments in the field, focusing both on the residential and industrial sectors.

Afterward, there are two sections with specific deep dives.

- **Section 2.3** is an extract of one of the contributions of this thesis Casamassima Luca 2022 and is essential to depict the various characteristics of Positive Energy Districts (PEDs) and related urban concepts.
- **Section 2.4** reviews various energy models, examining their features and classifications to understand the need for developing a new tool to reach the main objectives of this dissertation.

Finally, **Section 2.5** built from the previous ones to explicitly highlight the specific contribution of this dissertation and how it goes beyond the state of the art.

2.1 Concepts and Definitions

In order to improve the transparency of the work, as suggested by Pfenninger, Hawkes, et al. 2014, this section aims to provide the definition of the most important concepts considered in this thesis. It should be noted that the aim here is not to provide new definitions of the concepts investigated rather to clarify what the author considered for this dissertation. Additionally, it should ensure that the author and the readers share a common understanding of the main terminology. Part of this section is also part of Bottecchia, Lubello, Zambelli, et al. 2021 which is one of the contributions that will be presented in this thesis.

Energy System

The Fifth Assessment Report of the IPCC Allwood et al. 2014 defines an energy system as a system comprehending all components related to the production, conversion, delivery, and use of energy. Similarly, Jaccard 2006 refers to an energy system as the combined processes of acquiring and using energy in a given society or economy. Building on these two definitions and also following the terminology used by Pfenninger and Pickering 2018, in this work, the following definition is adopted:

An energy system is the combination of processes and technologies related to the production, consumption, conversion, and transmission of energy in a given society, economy, or location.

A location can be considered a site that contains multiple technologies and other locations. This means that a location can be either a single building with its own technologies, or as a district composed by multiple buildings. In this way, an energy system is seen not only from a mere technical point of view but also from the spatial and socio-economic dimensions.

Model

Given the definition of an energy system, it is then necessary to define what a model is. In this sense, Rosen 1991 considers a model as the formalized representation of a natural system with its own rules. Keirstead et al. 2012 added that, within the energy and engineering fields, the formalization is to be intended in the form of mathematical models and computer codes. In this work, we will adopt this definition as follows:

A model is the representation of a (natural) system with its own rules through the use of a mathematical formulation.

Optimization Model

In the context of energy system modeling, multiple approaches can be considered. One of the main distinctions is between optimization and simulation models. Within the field of water reservoir models, Wurbs 1993, speaks about optimization to refer to a mathematical formulation where an algorithm is used to set the values of a set of decision variables to optimize an objective function subject to constraints. Following up, Lund, Arler, et al. 2017 consider the optimization approach, and this will be the definition adopted in this work, as follows:

An optimization approach makes use of a mathematical formulation to find out the optimal solution of a given problem.

The problem is generally defined by an objective function subject to multiple constraints. Both the objective function and the constraints are dependent on a set of decision variables whose values are set during the optimization process. The objective function can be related to emissions, system costs, or other aspects related to the system.

Simulation model

In opposition to optimization, both Wurbs 1993 and Lund, Arler, et al. 2017 define a simulation model as the representation of a system used to forecast its behavior under certain given conditions. Both works highlight that simulation models are meant to be used to understand the performance of a certain system under a given set of assumptions. For the purpose of this work, the adopted definition is:

A simulation model is a representation of a system that is used to reproduce and understand its behavior, under given conditions, without looking for an optimal solution.

In particular, it was decided because of the author's belief that the first purpose of simulation tools should be to reproduce the behavior of a given system rather than to forecast it. Indeed, forecasting can be thought of as a subsequent step, to be performed through scenario analysis or similar approaches. In this regard, a simulation model could be used to evaluate the consequences of a given choice, whether it might be technical, political, or social.

Urban and Urban Scale

Given that a common trend identified in the literature is the shift from single-building to urban scale analyses Bisello and Vettorato 2018, and that one of the purposes of this work is to develop a tool that works at an urban scale, a clarification on the usage of the expression urban scale has been given in the following. Eurostat provides common definitions for the European geographical areas starting from the concept of *degree of urbanization*. According to this definition, the degree of urbanization provides a classification for local administrative units (LAUs) obtained from the combination of geographical proximity and population density Eurostat 2018a. The classification is made by considering a raster cell of 1 km^2. LAUs can then be cities (densely populated areas), towns and suburbs (intermediate density areas), or rural areas (sparsely populated areas). Urban areas are represented by the first two classes: cities and towns and suburbs Eurostat 2018b. At this point, the non-trivial aspect to consider is the integration of the *urban* concept in the energy system definition. Keirstead et al. 2012; Alhamwi et al. 2017 exploited the approach used by Ramaswami et al. 2011, called *geographic-plus*, which does not only consider the energy flows but also the geopolitical boundaries of a system. Hence, in the current work, and more in general in the context of energy system modeling, the definition of urban scale is as follows:

An urban scale is considered the resolution incorporating districts and cities, while an urban area is an area with an intermediate or high density of population.

In this way, an energy system model is considered to be able to perform analysis at urban scale when it has a spatial resolution that goes down to the district level, allowing to consider urban areas composed of small, medium, and large cities.

Solar Potential

Solar potential refers to the theoretical, technical, or practical amount of solar energy that can be used in a specific area Kabir et al. 2018. It is determined by several factors, including geographic location, meteorological conditions, available surface area, and the efficiency of solar technologies. Solar potential can be categorized into different levels:

- **Theoretical potential**: The maximum amount of solar energy that could be captured, assuming optimal conditions with no technical or practical limitations.
- **Technical potential**: The portion of theoretical potential that can be harnessed using current technology, considering conversion efficiencies and other technical constraints.

- **Practical potential**: The part of the technical potential that can realistically be exploited after accounting for socio-economic, regulatory, and environmental factors.

In the context of energy system modeling, solar potential is a key parameter for determining the contribution of solar energy to the overall energy mix.
Within this work, we refer to solar potential as follows:

Solar potential is the practical amount of solar energy that can be harnessed in a specific area independently of the technology considered.

Horizon Height

Horizon height is a parameter used in solar energy studies that describes the angular elevation of the horizon as observed from a specific location. It is determined by the surrounding topography, buildings, and other obstructions that can block direct sunlight. The horizon height is expressed in degrees and is crucial in calculating the solar exposure of a site, as it affects the periods during which the sun is visible and, therefore, the practical potential for solar energy generation. Following this, in this work, we refer to the horizon height as follows:

The horizon height is the angular elevation of the horizon from a specific location and, depending on the topography, can block the direct sunlight.

Industrial symbiosis

Industrial symbiosis refers to a collaborative approach where different industries within a region or cluster exchange materials, energy, water, and by-products in a way that benefits all parties involved Fraccascia et al. 2020; Chertow 2003. This concept is part of the broader framework of circular economy and seeks to optimize resource efficiency by turning waste from one process into a resource for another.
Industrial symbiosis involves the identification of synergies among industries, leading to cost savings, reduced environmental impact, and enhanced sustainability. It is often facilitated by geographic proximity and the presence of complementary industrial activities. An area of industrial symbiosis, still underexplored, is the interrelation between industries and districts.
Within this work, we refer to industrial symbiosis as:

industrial symbiosis is the interrelations between processes either in the same industry or across different ones or between industries and districts.

In energy system modeling, industrial symbiosis can be represented by integrating cross-sectoral energy flows, where waste heat, biogas, or other by-products from industrial processes are used to meet the energy needs of other sectors, thereby contributing to decarbonization goals.

2.2 State of the Art

In recent years, there has been growing attention on the decarbonization of energy systems, leading to notable advancements in technological innovation and strategic planning. As already mentioned, the residential and industrial sectors together contributes to ca. 56% of the final energy consumption in the EU. Within the residential sector, concepts such as Positive Energy Districts (PEDs), Smart Cities (SC), and Energy Communities (EC) have become central to these developments. These concepts emphasize the integration of renewable energy sources and the efficient management of energy flows across different scales. In parallel, the industrial sector focused mainly on the improvement of the efficiency of the most energy-intensive processes. While much progress has been made in analyzing individually these two sectors, the synergies between them — especially the potential of industrial symbiosis to achieve a more efficient local energy transition — remain underexplored.

This section reviews the current state of the art in these fields, focusing on the interrelation between urban and industrial energy systems. By examining existing literature on energy-based industrial symbiosis, the world of energy system models, the influence of policy interventions, and the integration of spatial dimensions into energy models, this review identifies key developments, challenges, and opportunities within the field. The aim is to provide a thorough understanding of how cross-sectoral synergies and available tools can be utilized to optimize these interactions, contributing in this way to the local energy transition.

As mentioned above, the residential sector is one of the major contributors to the final energy consumption in Europe. For this reason, numerous attempts have been made to establish frameworks that would facilitate the energy transition and help achieve the European and global climate goals. One of the most recent of such frameworks (or "concepts", as we refer to them throughout this dissertation) is Positive Energy Districts (PEDs). The Strategic Energy Transition Plan (SET-Plan) first introduced the concept in 2018 Strategic Energy Transition Plan 3.2 2018. Its definition has evolved to "energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net-zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy" JPI Urban Europe 2020. However, it distinguishes itself from other concepts (including Net Zero, nearly Zero, Plus Energy and Emission Districts/Neighborhoods) by its more holistic approach that includes social concerns, inclusiveness, and energy poverty Good et al. 2017; Hedman et al. 2021b; Bottecchia, Gabaldón, et al. 2022. As there is a richer body of research on at least technical aspects of achieving energy savings on a neighborhood or community level Amaral et al. 2018; Carlisle et al. 2009; Marique and Reiter 2014; Koutra et al. 2017; Ala-Juusela et al. 2016; Sørnes 2017, PEDs can profit from the previous studies.

As for the industrial sector, one innovative approach to achieving decarbonization goals is industrial symbiosis. Within the context of energy-based industrial symbiosis, three main groups have been identified Fraccascia et al. 2020: (*i*) energy cascade, (*ii*) fuel replacement and (*iii*) bioenergy production. While the first occurs when waste heat produced by one process is used by another one, the second occurs when waste materials are used to replace traditional fuels in existing processes. The last is similar to the fuel replacement one but focuses on exploiting bio or organic kind of waste. In this context, different modeling approaches and focuses have been considered to describe and analyze industrial symbiosis. Jiao and Boons 2014; Lybæk et al. 2021 investigated how policy intervention can foster and facilitate industrial symbiosis. Maes et al. 2011 focused instead on possible energy strategies to support the implementation of industrial symbiosis approaches in eco-industrial parks.
However, despite these developments, the connection between industries and districts re-

mains underexplored in the existing literature Fraccascia et al. 2020; Chertow 2003; Neves et al. 2019. Still, some studies have tried to bridge this gap. Caballero et al. 2023 analyzed an urban-industrial sustainable energy community solely from an electrical perspective, focusing on the sharing of energy from PV panels between an industrial park and a nearby district. Additionally, Dou et al. 2018 evaluated the opportunity to use waste heat for district heating. In this case, the aim was firstly to propose a spatial approach to evaluate the effects of urban planning on energy symbiosis from a land use perspective and secondly to evaluate and propose a set of land use policies. Manso-Burgos et al. 2022 developed a model to optimize local energy communities. While the study investigated the implication of having both residential and commercial activities within the community, the relationship between the district and industry was not considered. Maturo et al. 2021 also investigate the sustainability of energy-independent communities but only within the agricultural sector. This suggests that the opportunity of adopting a symbiotic approach between industries and districts has not been exploited in depth. In particular, there is a match between two different needs. On the one hand, concepts like PEDs, SC, and EC often rely on microgrids or district heating to supply the heating needs. On the other hand, particularly in countries where the manufacturing sector is a key element in the economy, there is an asset of energy-intensive industries that have the availability of waste heat.

Evaluating the Net Present Value (NPV) of utilizing this waste heat from industrial processes can provide critical insights into the economic viability and long-term benefits of such energy recovery initiatives. As pointed out by Pärssinen et al. 2019, few studies highlighted the benefits of such energy recovery initiatives. Wahlroos et al. 2018; Davies et al. 2016 presented cases on the use of waste heat coming from data centers showing, together with Pärssinen et al. 2019, the potential benefits of such initiatives. Similarly, Fierro et al. 2020 analyzed the use of waste heat in cement industries, also pointing out that NPV and the overall economic performance are significant. However, as mentioned above, limited literature is available in the context of integrating waste heat with local communities as well as the impact of NPV analysis.
In light of this, energy system modeling can be an efficient support tool in the process of planning and designing the future energy system also at district level as well as a promising tool to investigate more in detail industrial symbiosis.

In this sense, in the last years, a large number of tools have been developed, updated, and adopted to have a better understanding of emerging challenges. Most of these tools are techno-economic models able to represent in a detailed way an energy system. There are several works that reviewed not only the models themselves but also the challenges and trends of this area of study. (Section 2.4 will also provide an in-depth review of different models.) In particular, Pfenninger, Hawkes, et al. 2014 pointed out how it is essential to improve the transparency of the various tools through an open-source approach coupled with open access to the data used too. In this way, the tool is not only an instrument tailored for experts in a specific field but can be better utilized also by other people as well and each study can be more easily replicated, favoring, in this way, the transmission of best practices. Additionally, the increased interest in renewable energy technologies makes it necessary to have at disposal high temporal and spatial resolution data. Following the work of Chang et al. 2021 reviewed a number of energy models to identify current trends. The analysis showed that even though progress has been made in terms of cross-sectoral synergies, growing attention to transparency, and in the utilization of high temporal resolution data, there is still an area of improvement with regards to adopting approaches that also look into non-optimal solutions as well as in integrating more deeply spatial data.

Within energy system modeling, when talking about spatial dimension, we refer to the ability of the model to include and consider aspects related to the geographical characteristics of an energy system. As pointed out by Martínez-Gordón et al. 2021, the integration of spatial dimension in an energy system model normally requires the use of Geographic Information System (GIS) tools. This reflects in various aspects. On the one hand, this can be related to the inclusion of climate conditions of a specific area of interest in order to model technologies and the system itself in light of this. This is also linked to how the demand is shaped. On the other hand, the spatial dimension is also related to the geographical characteristics of a place, aiming to answering and/or providing information on several aspects. An example of this is the potential of renewable energy sources in a specific location. Moreover, the complexity of urban environments makes it crucial to have a more detailed understanding of these areas' geography and spatial characteristics to assess the possibilities arising from the energy transition. The different possibilities range from which energy sources should be used to cover the energy demand to optimally designing a system at the building level accordingly.
In this context, it is also essential, as depicted in one of the contributions of this dissertation Bottecchia, Dallapiccola, et al. 2023, to understand, in such complex environments, how the shapes and elevation of the surrounding areas affect how shaded will be a specific location. As already pointed, out the need for high-resolution data is a key aspect in modeling energy systems Pfenninger, Hawkes, et al. 2014; Sun et al. 2014; Chang et al. 2021. This necessity has a dual implication: from a temporal perspective and a spatial one. On the one hand, there is a need for high detail of data from a temporal point of view to depict the fluctuation of RES. On the other hand, it is essential to spatially represent and investigate the areas in exam to properly assess the potential of solar energy in a given location, as pointed out by Freitas et al. 2015.
Several tools are used to evaluate the potential of solar energy in a given location. Among them renewables.ninja Pfenninger and Staffell 2016b allows running simulations that provide hourly data in terms of power production but also irradiance for a selected location. Pfenninger et al. validated the tool by conducting an in-depth analysis of long-term PV output in Europe Pfenninger and Staffell 2016a. Nevertheless, this tool does not consider or evaluate the impact of the horizon height on the solar potential. On the contrary, other tools like PVGIS JRC 2012 evaluate the solar potential, considering the horizon height through a 100 mt resolution map. The work has been adequately validated as presented in Huld et al. 2012. Nevertheless, none of these widely used tools considers the nearby horizon (e.g., one of the nearby buildings). Another study proposed a model to identify solar energy and daylight on tilt planes considering the CIE (International Commission on Illuminance) standard skies Lou et al. 2020. However, the authors mentioned a significant limitation of the work: the fact that the approach is limited to unobstructed environments only. Bognár et al. 2021 developed a model to calculate solar irradiance without shading geometry using a point cloud-based method. In particular, they started with a high-resolution Digital Surface Model (DSM), with a 0.5 mt resolution, to remove the need for 3D surface geometry. They also demonstrated their results in two case studies. Additionally, one of their outcomes was that the only way to achieve this result was to consider a very high-resolution DSM. Nonetheless, there was no consideration

of when it is necessary to use high-resolution data. This is of particular importance given that the need for high-resolution data is in contrast with their availability. High-resolution data are, in fact, hard to gather, but they are usually also more costly Pfenninger, Hawkes, et al. 2014; Chang et al. 2021.

Another aspect that is linked to the spatial dimension regards the distributional effects of policy/interventions as well as what are the socio-demographic characteristics of the area in exam. In this sense, another fundamental aspect is to investigate the role of policy intervention within the local energy transition and how these can foster industrial symbiosis between industries, districts, and local grid operators, particularly in the context of waste heat and district heating projects. However, before delving into the literature showing the potential of policy intervention, it is crucial to understand the nature of these interventions.

Abdmouleh et al. 2015 categorize renewable energy policies into five broad types: financial (e.g., funding, grants, loans), fiscal (e.g., tax exemptions, energy/environmental taxes), legislative (e.g., power purchase agreements, grid access, Feed-in Tariffs, Feed-in Premiums, tendering), political (e.g., national/regional/local renewable energy plans), and technological (e.g., funding for research and development in renewable energy). Taking a more precise economic approach, as suggested by Wiese et al. 2018, policies can be further classified into market-based instruments (e.g., energy taxes, tradable emission certificates), financial incentives (e.g., subsidies, measures to improve access to capital such as grants and loans), regulatory measures (e.g., codes and standards), information and feedback mechanisms (e.g., information provision), and non-regulatory measures (e.g., voluntary agreements).

Within the context of this work, we will focus on specific categories of policies, primarily considering the following taxonomy:

- Support Schemes and Regulatory policies: encompassing market-based instruments, support schemes such as Feed-in Tariffs (FIT) and Feed-in Premiums (FIP), as well as codes and standards.
- Financial policies: focusing on incentives, subsidies, and measures to enhance access to capital.

There are several studies that explore the potential of policy intervention. Maturo et al. 2021 highlights the significance of integrated energy strategies for sustainable development, emphasizing the role of renewables and energy efficiency in agricultural communities. Similarly, Bianco and Sonvilla 2021 investigates the optimization of local energy communities, emphasizing the importance of policy support to enhance energy sustainability. Other studies instead tried to analyze policies and/or electricity consumption patterns to identify opportunities for better interventions Selvakkumaran et al. 2021; Li et al. 2022; Vaquero et al. 2020. On a different level, Wenninger et al. 2022 investigates the factors influencing retrofits and the role of explainable AI in policymaking, suggesting the feasibility of replicating successful retrofit policies and considering income-based CO2 taxes. Moser and Jauschnik 2023 performed a survey on the Austrian area to identify characteristics and business models of projects where industrial waste heat was used in district heating. One of the outcomes is that policymakers play a crucial role in making such projects more viable. While these studies offer a holistic perspective on policy interventions in the energy sector, providing valuable guidance for policymakers, there is limited literature quantitatively evaluating the effect of such policy interventions Zhang et al. 2021. Hence, there is a nice area of study not only in terms of industrial symbiosis between industry and districts but, more importantly, in quantitatively assessing the effect of policies in this context.

2.3 PEDs and Urban Concepts

This section provides an overview of PEDs and their characteristics focusing also in comparing in with related urban concepts. In particular, it is based on *"Economic, social, and environmental aspects of Positive Energy Districts - A review"* Casamassima Luca 2022, which is a study carried out during the work of this Ph.D. thesis.
Table 1 shows the main concepts of this section and their respective primary reference. This analysis utilises the three pillars of sustainability (Social, Economic, Environment) to analyse Positive Energy District. This system can enable an interdisciplinary approach Purvis et al. 2019; Campbell 1996, which is essential given the intrinsic holistic nature of Positive Energy Districts. Based on this approach, a "Triangle of sustainability" is built similarly to the work of Bakari 2021.

Concept name	Abbreviation	Literature
Positive Energy District	PED	Strategic Energy Transition Plan 3.2 2018; JPI Urban Europe 2020
Positive Energy Block	PEB	Cartuyvels 2021
Zero Energy Community	ZEC	Carlisle et al. 2009
Net-Zero Energy Neigbourhood	NZEN	Marique and Reiter 2014
Net-Zero Energy District	NZED	
Positive Energy Building	PEB	Magrini et al. 2020
Nearly Zero Energy Building	NZEB	

Table 1: Major literature used in the analysis

History of PEDs and similar concepts

The first concerns about households' expenditure started to appear in the literature during the early 70s (Wessling Jr. 1974), in conjunction with the first oil crisis. However, the first actual increase in publications containing methodologies to improve residential buildings' energy performance came in 1979. The initial designs focused mainly on improving thermal efficiency and lowering heat demand in buildings through solar gain and thermal storage. Some of the methods utilised were solar thermal panels, Trombe walls, thermal wall storage, to mention some Lee 1979; S. Nichols and W. Nichols 1979; Noll et al. 1979; Block and Hodges 1979; Plumb 1979; Munday 1979; Tymura 1979; Kieffer 1979; Casperson and Hocevar 1979. With time the focus shifted towards superinsulation. In the '90s, the Passive House concept was established. It embraced superinsulation completely as a cornerstone of its design, together with controlled air ventilation and carefully designed solar gain and shadings Schnieders et al. 2015. A similar approach is that of Nearly Zero Energy Building (NZEB). The concept has many different variations regarding methodologies and design for calculation. Still, high-efficiency materials

and local renewable generation are necessary due to the high thermal efficiency required Petcu et al. 2017. The European Union has included its own definition of NZEB in the Energy Performance of Buildings Directive (EPBD). It states that "Nearly Zero Energy Building" means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby European Parliament 2018. The last amendment to the EPBD states that all governmental and public buildings will have to be NZEB by 2018, and starting from the year 2021, all new buildings of any nature will have to be NZEB European Union 2010. However, the Member States' detailed implementation of NZEB definition is being done with different indicators, methods, and calculation procedures. Some Member States have a numerical indicator of specific primary energy use requirement to qualify as NZEB, whereas others do not. Analogously, not all Member States mandate any requirements regarding renewable energy BPIE 2021. With an even stricter energy balance, Positive (or Plus) Energy Buildings are a direct evolution of NZEBs. However, while the European Commission firstly proposed the concept of NZEBs in the EPBD, Positive Energy Buildings already existed before that time. As Cole and Fedoruk 2015 defined it, a Positive Energy Building produces more than it can use and exchanges that energy where it is most needed. They consider both electricity and heat exchange as a possibility. In 2009 the NREL published “Definition of a Zero Energy District” and defined a Zero Energy Community (ZEC) as “one that has greatly reduced energy needs through efficiency gains such that the balance of energy for vehicles, thermal and electrical energy within the community is met by renewable energy”. Although the paper provides concrete definitions and measures, the term community still remains vague.
Several studies support broadening the boundary from a single construction to a district level. By assembling different building and end-users typologies, it is possible to reduce district heating and cooling costs. At the same time, different demand patterns can help to shave the load curves and reduce and move peaks (Paatero 2009 Koch et al. 2012 Pachauri and Reisinger 2008). In 2014, Marique and Reiter 2014 proposed smaller units called “urban blocks” that would compose a whole district. In a similar fashion, Positive Energy Districts would also be composed by Positive Energy Blocks.

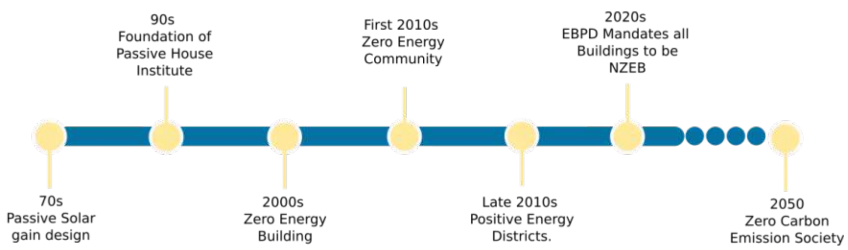


Figure 3: Path towards Positive Energy Districts

In 2017, the discussion veered over to Positive Energy Districts, when Nzengue et al. 2018 presented a method for archetyping districts and facilitating the implementation and replication of large-scale refurbishment plans within the Sinfonia project. This article refers to PEDs as Low Energy Districts and sees PEDs as a way of achieving a Smart City (SC). Though the idea of Smart Cities has evolved according to different needs and goals that equally evolved through time, there is a strong link between Positive Energy Districts and Smart Cities. The

European Innovation Partnership (EIP) on Smart Cities and Communities defines a Smart City as a "system of people interacting with and using flows of energy, materials, services and financing to catalyse sustainable economic development, resilience, and high quality of life" European Innovation Partnership on Smart Cities and Communities 2013. The EIP ambition is to use these concepts to develop and transform current districts into "zero/plus energy/climate-neutral status" by integrating local renewable energy technologies through smart energy networks, virtual power plants, storage systems and demand control. Hence, smart cities are a means to achieve "energy positivity" and not PEDs per se. PEDs might achieve energy positivity/neutrality from renewables by drawing from knowledge developed through the years in the frame of Smart Cities. Figure 3 points out the significant milestones and summarises how energy savings concepts have evolved towards Positive Energy Districts.

Criteria for Analysis of the Concepts

In order to analyse the PEDs and their similar concepts according to techno-economic, environmental and social criteria, those three pillars of sustainability will have to be broken down into relevant sub-themes. Therefore, as proposed in Bakari 2021, a sustainable development triangle approach is used, to account for the three pillars holistically. Figure 4 shows the selected criteria of analysis included within the three main pillars.

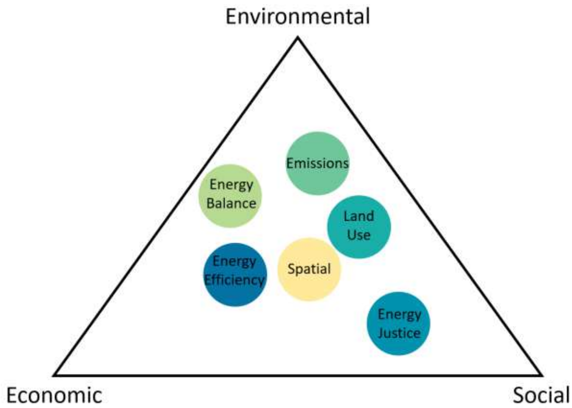


Figure 4: Criteria of analysis within the triangle of sustainability

All of the six criteria of sustainability relate to each pillar of sustainability. Spatial aspects have repercussions on the economics of a project, the environmental and social impacts. Similarly, this is true also regarding emissions, land use, energy balance, efficiency and justice. Chapter 2.3 discusses these aspects in more detail. The authors are aware that other factors such as costs, policy interventions and governance, to mention a few, can influence the development and the diffusion of Positive Energy Districts or other similar concepts. It is also clear how policy interventions and governance are strongly related to social concerns while total costs also connect to economics. On the other hand, costs can vary significantly between sites and projects. Lindholm et al. 2021 studied the availability of renewable energy potentials between different countries in Europe and their associated costs. Governance and policies are also strictly connected to countries. As this study aims to enable a comparison between different energy concepts, the choice was limited to the criteria listed in the following sections. These criteria are less dependent on geographical location and countries, thus allowing a more direct comparison.

Evaluation of the concepts

Basing the analysis on the sustainable triangle approach allowed identifying some major areas of interest that helps in defining commonalities and differences that different concepts have compared to PEDs.
Table 2 provides an overview of the main differences and similarities of the various analyzed concepts based on the selected criteria.

Table 2: Concept categorization.

	Spatial	Energy Balance			Energy Efficiency	Land Use	Emissions	Energy Justice
Abbreviation		Balance	Temporal	Calculation basis				
PED	District	Positive	Annual	Primary Energy	B + I	S	GHG	x
PEB*	Block	Positive	Annual	Primary Energy	B (+ I)	—	GHG	x
ZEC	District	Zero	Annual	Multiple	B + I	E + EN	GHG, O	~
NZEN	District	Zero	Annual	Primary Energy	B	—	GHG	—
PEB**	Building	Positive	Annual	Primary Energy	B + I	—	GHG	—
NZEB	Building	nearly Zero	Annual	Primary Energy	B	—	GHG	—

B = Building Efficiency, I = Infrastructure Efficiency, S = social, E = economic, EN = environmental
GHG = Greenhouse gases, O = NO_x + SO_x, PM = particulate matter
~ = only mentioned
* = Positive Energy Block
** = Positive Energy Building

One can see a strong correlation between a lot of the concepts analysed. NZEC, PEB, PED and NZEN are all very similar. The major distinction lies in the energy balance and energy justice. While PED requires an annual positive energy balance by definition, the other concepts only expect a zero or nearly zero balance.

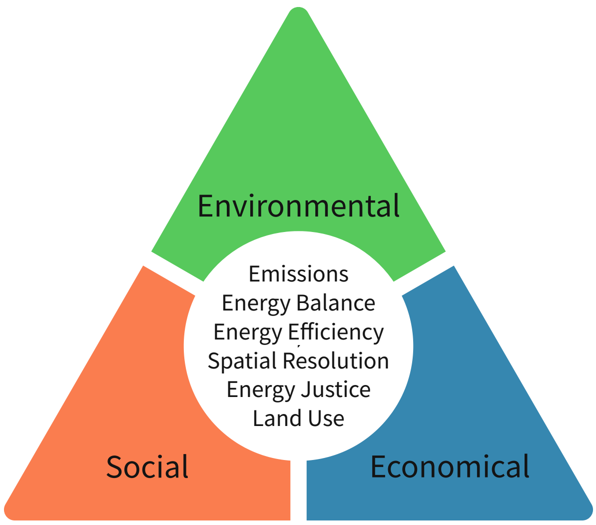


Figure 5: Hierarchical representation of the analysed concepts according to their attributes

Figure 5 further shows an hierarchical representation of the different concepts considered in this work as the results of the analysis performed. As one can see, the PED concept stands on top of this upside-down pyramid because it includes all the aspects and attributes considered. Then, the concepts are sorted as they gradually do not consider some attributes. Zero Energy Communities differs from PED because of the balance, but they also miss energy justice aspects. On the other hand, while Positive Energy Blocks have a positive balance, they are not dealing with land use considerations. Finally, the concepts at the bottom of the pyramid only consider emissions and overall efficiency neglecting land use and energy justice. Additionally, some of them only relate to a single building rather than a district scale.
Despite the relevance of these topics for the purpose of this work we will only present the discussion related to the spatial resolution.

Spatial Resolution

As one can see from the results in Table 2, most of the concepts analyzed relate to the spatial dimension. By talking about small scale urban areas such as districts or communities, geographical boundaries are essential to understand what is inside or outside of a given system. PEDs exploit this aspect due to the various definitions currently in place. Lindholm et al. 2021 present the three definitions of Autonomous/Dynamic/Virtual PED that all include considerations with a geographical nature. These are mainly related to PED's boundaries and whether technologies must only be located within the boundaries or can also be outside the district. More precisely, Autonomous PEDs have a well and strictly defined geographical boundary. They are entirely energy independent and cannot import energy, although they can export. Hence, Autonomous PEDs have to meet all their energy demand internally. A Dynamic PED also has clear geographical boundaries. It can export and import energy as long as the overall balance remains positive throughout the year. The exchange of energy can happen between other PEDs or the external grid. Finally, Virtual PEDs have a geographical boundary, but they can also import and export outside of it. In Virtual PED, energy can be exported and imported. It can also have renewable energy systems and storage outside the district's geographical boundaries. Thus the name "virtual". Of course, the positive balance restriction applies here as well; therefore, the total amount of energy produced outside and within the district must be larger than the imported. These three spatial definitions of PED also affect the energy balance. An autonomous PED, for example, will have a strict positive balance at any time. In contrast, the other two will be allowed to have a momentary negative balance as long as the overall yearly total remains positive. Thus, this also reflects on the temporal resolution considered for the energy balance. Lindholm et al. 2021 point out how, theoretically it could be possible, by properly combining the three kinds of PEDs to achieve a positive balance also at a larger scale. Additionally, JPI Urban Europe 2020 mentions that the terms "regional" and "local" have been left open to allow some flexibility. The complexity of the system of a district may lead to different boundaries for each end-user sector considered. In the report "Towards Nearly Zero Energy Buildings", Hermelink et al. 2013 describe the characteristics related to the system boundaries and they present how this has been considered in different cases around Europe. They point out how the system boundaries' definitions are needed to understand the available renewable energies options: on-site PhotoVoltaic (PV) or renewables, nearby installation financed by user or off-site renewable like a biomass power plant. Additionally, they further exploit the analysis by also consider eventual power purchase agreements (PPA).

Furthermore, Hermelink et al. 2013 exploit the difference between system and physical boundaries. This refers to whether we are talking about a single building, a cluster of buildings or a city. Article 2.2 of the EPBD European Union 2010 defines NZEB as a building where *"nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby"* which means that also off-site renewable generation is allowed. Carlisle et al. 2009 mentioned that when talking about energy communities, except for the case of islands, the boundaries are arbitrary and can be either geographically but also politically defined. The National Institute of Building Sciences 2015 defines the site boundaries as the *"Line that marks the limits of the building site(s) across which delivered energy and exported energy is measured."*

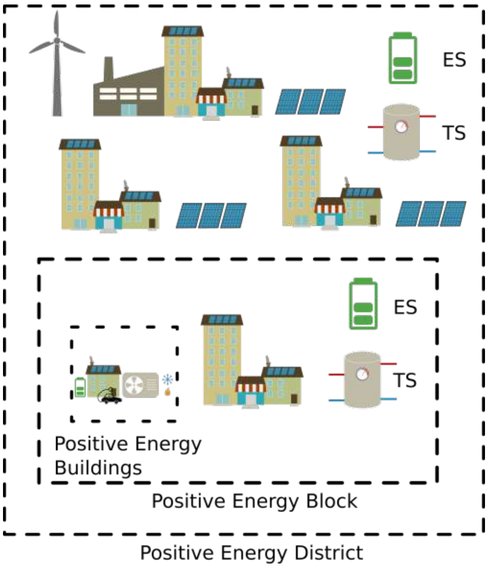


Figure 6: Spatial resolution for Positive Energy Districts. TS = Thermal Storage, ES = Electrical Storage

Figure 6 shows a possible spatial structure of a Positive Energy District. In this example, each building is a Positive Energy Building. Two or more Positive Energy Buildings produce a Positive Energy Block, which themselves form a Positive Energy District. Each specific resolution can produce more energy than it needs and export to other buildings, blocks and districts. Each block or district can contain a variety of different end-users, including industrial, commercial and residential buildings.

Take out

This analysis aims to investigate the interconnections between Positive Energy Districts (PEDs) and other similar concepts, provide a thorough analysis, improve clarity, avoid repetition, and homogenise terminology. This work carried out an analysis based on six main criteria of interest in the context of urban/district analysis: spatial resolution, energy balance, emissions, land use, energy efficiency and energy justice.
The main and most obvious characteristic that makes PEDs stand out is their positive energy balance. In this sense, it is worth mentioning that its estimation is consistently affected by

the three aforementioned typologies (Autonomous/Dynamic/Virtual). Even though a district generating more energy than it needs has a higher appeal, which may facilitate its replication, further studies will be needed to evaluate it. Intense and immediate production of energy from PEDs can allow a district-wise positive balance, but also put further strain on the grid if not utilised immediately or stored. Battery storage and demand response, to name a few, need careful design and thought to allow proper utilisation of the energy surplus and avoid curtailing and shedding. The annual character of the energy balance does not capture seasonalities. Thus, a we propose a stricter balance resolution of 8 hours to account for seasonal differences in energy generation and demand but also those throughout the day.

Both NZEC and PEDs consider energy efficiency at a building or district level. However, the approach needs to be also extended to the infrastructure, including its utilisation, capacity and management. All concepts considered in this review consider GHG emission as an important factor. They all tend to reach a near or completely zero-carbon balance.

However, although carbon emissions are incredibly important, other emission types seem to be missing in all the concepts investigated. Particulate matters, Nitrogen Oxides and other forms of pollutants are known to cause damage and issues to the respiratory apparatus and therefore should be considered with more care. Other kinds of emissions should also be considered, such as grey emissions (embodied emissions) but also contaminants relative to extraction and production of raw material utilised to build PVs, batteries and other materials utilised to produce RESs and increase energy efficiency. Positive Energy Districts only contemplate land use from a social perspective and end-users perspective. NZEC have a more economical approach to the issue, considering the differences from an economic and technical perspective of utilising brownfield or greenfield for renewable energy generation. Both approaches are valuable, and Positive Energy Districts could include considerations regarding utilisation and even reclaiming brownfields. Citizen participation is key to Positive Energy Districts. With a proper framework it is possible to include and work on all pillars of Energy Justice. Although also other concepts favour citizen participation, the current research on energy justice in Positive Energy Districts seems to gain an edge.

From a technical standpoint, as of now, Positive Energy Districts are defined as an urban area that produces more locally generated energy than required over one year span, aiming at net zero carbon emissions. This goal is achieved by implementing a combination of highly energy-efficient buildings, renewable energy generation and smart grid management interconnection. Moreover, energy justice plays a crucial role in making the transition possible and fair through citizen participation and targeted interventions.

To conclude, given the novelty and high appeal that PEDs currently have, the authors believe that this concept should include, as mentioned above, aspects that are now poorly investigated. In particular, more attention to land use and emissions beyond GHG emissions should be encouraged. Additionally, the higher attention PEDs give to the energy balance and energy justice is a crucial aspect that should be strengthened even more by linking them with a more specific and standardised economic framework and analysis. By doing this, it is then possible for PEDs to become a reference in the current urban scale energy transition, including all the different aspects considered by its predecessors.

2.4 Energy Models

The second step of the literature review is providing an overview of the energy models. In particular, the goal is to investigate open-source models that either optimize or simulate energy systems. This section is based on *The potential of simulating energy systems: The Multi Energy System Simulator model* Bottecchia, Lubello, Zambelli, et al. 2021, the first publication of this Ph.D. thesis.

As highlighted by Pfenninger, Hawkes, et al. 2014, a possible solution to overcome the issue of increasing complexity in energy system modeling is to be able to investigate non-optimal solutions. As for the definition given in Section 2.1, using a simulation approach allows for exploring these kinds of solutions. Further, developing the considerations made by Lund, Arler, et al. 2017, the authors decided to analyze the potential of using a simulation approach in modeling energy systems at urban scale. Having clarified what simulating an urban energy system means, a review of 40 different open-source models, mainly based on the list provided by the Open Energy Modeling Initiative (openmod) openmod 2020 was performed. The review considered three main aspects. First, the sectors covered by the model. Second, the type of model, i.e., optimization or simulation, as for the definition provided in Section 2.1. Last, the model should be able to simulate energy systems at urban scale. The review focused on clustering those tools that allow modeling multiple energy vectors (at least electricity and heat ones) at urban scale.
Table 3 presents the complete list of investigated models.

Table 3: List of models reviewed.

Model	Sectors*	Math modeltype	Timeresolution	Georesolution	Urban Scale	modeling Software
Backbone	All	Optimization	Hour	Depends on user	Y	GAMS
Balmorel	El. , Heat	Optimization	Hour	NUTS3	N	GAMS
CAPOW	El.	Simulation	Hour	Zonal	N	PYTHON - PYOMO
Calliope	User-dependent	Optimization	Hour	User-dependent	Y	PYTHON - PYOMO
DESSTinEE	El.	Simulation	Hour	National	N	EXCEL - VBA
DIETER	El. and Sector Coupling	Optimization	Hour	Node	N	GAMS - CPLEX
Dispa-SET	El.	Optimization	Hour	NUTS1	N	PYTHON - PYOMO, GAMS
ELMOD	El. , Heat	Optimization	Hour	Network	N	GAMS
EMLab-Generation	El. , Carbon	Simulation	Year	Zones	N	JAVA
EMMA	El.	Optimization	Hour	Country	N	GAMS
ESO-X	El.	Optimization	Hour	Node	N	GAMS - CPLEX
Energy Transition Model	El., Heat, Transport	Simulation	Year	Country	N	RUBY - RAILS
EnergyNumbers-Balancing	El.	Simulation	Hour	National	N	FORTRAN
EnergyRt		Optimization			N	GAMS - CPLEX
EnergyScope	El., Heat, Transport	Optimization	Hour	Country	N	GLPK - CPLEX
Ficus	El. , Heat	Optimization	15 Minute			PYTHON - PYOMO
FlexiGIS	El.	Opti., Simulation	15 Minute	Urban	Y	
Genesys	El.	Opti., Simulation	Hour	EUMENA, 21 regions	N	C++
GridCal	El.	Opti., Simulation				PYTHON
MEDEAS	El. , Heat	Other	Year	global, continents, nations	N	PYTHON
NEMO		Opti., Simulation	Hour	NEM regions	N	PYTHON
OMEGAlpes	El. , Heat	Optimization			Y	PYTHON
OSeMOSYS	All	Optimization	Day	Country	N	PYTHON
Oemof	El., Heat, Transport	Opti., Simulation	Hour	Depends on user	Y	PYTHON - PYOMO
OnSSET		Optimization	Multi year	1 km to 10 km	Y	PYTHON
PowNet	El.	Opti., Simulation	Hour	High-voltage substation	N	PYTHON - PYOMO
PowerMatcher						JAVA
PyPSA	El., Heat, Transport	Opti., Simulation	Hour	User dependent	Y	PYTHON - PYOMO
REopt	El. , Heat	Optimization	Hour	Site	Y	JULIA - JuMP
Region4FLEX	El. and Sector Coupling	Optimization	15 Minute	Administrative districts	Y	PYTHON
Renpass	El.	Opti., Simulation	Hour	Regional (only DE) or Country.	N	R
SIREN	El.	Simulation	Hour		N	PYTHON
SciGRID	El. , Transmission	Simulation		nodal resolution		PYTHON
SimSES	El.	Simulation	Minute		N	MATLAB
StELMOD	El.	Optimization	Hour	Nodal resolution		GAMS
Switch	El.	Optimization	Hour	buildings, to continental	Y	PYTHON - PYOMO
Temoa	All	Optimization	Multi year	single region	N	PYTHON - PYOMO
TransiEnt	El., Heat, Gas	Simulation	Second	Hamburg	N	MODELICA
URBS	User-dependent	Optimization	Hour	User-dependent	Y	PYTHON - PYOMO
City Energy Analyst	El. , Heat	Optimization, Simulation	Hour		Y	PYTHON
Total						40

*Electricity is here abbreviated to "El.".

Based on the above-mentioned criteria, Figure 7 shows the number of models as the result of the different queries.

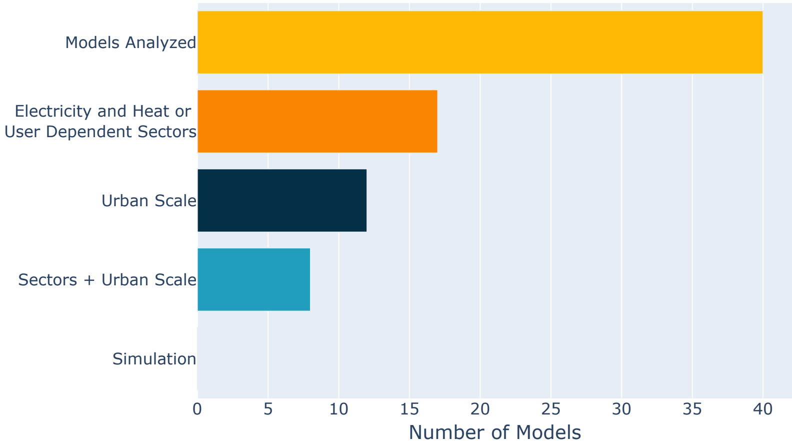


Figure 7: Results of the query of the different models reviews.

Particularly, Table 4 shows the list of the models that match both the *Urban Scale* criteria and the *Sectors* one.

Table 4: List of models that allow modeling of multiple sectors and at urban scale.

Model	Sectors*	Model Type	Urban Scale
Calliope Pfenninger and Pickering 2018	User-dependent	Optimization	Y
OMEGAlpes Delinchant et al. 2018	Electricity, Heat	Optimization	Y
Oemof Hilpert et al. 2018	El., Heat, Transport	Optimization, Simulation	Y
PyPSA Brown et al. 2018	El., Heat, Transport	Optimization, Simulation	Y
REopt Cutler et al. 2017	Electricity, Heat	Optimization	Y
URBS Dorfner et al. 2019	User-dependent	Optimization	Y
CEA Fonseca et al. 2016	Electricity, Heat	Optimization, Simulation	Y
Backbone Helistö et al. 2019	All	Optimization	Y

*Electricity is here abbreviated to "El.".

The model type column in Table 3 and 4 presents the entries originally provided by openmod. However, considering the definition of simulation given in Section 2.1, none of the models listed allows actual simulations to be performed. A possible explanation of this finding is to be found in the generic use of the word simulation. Indeed, it is often used as a general term to indicate a standard run of any model. However, in this work, the authors considered simulation as that model type that allows the analysis of an energy system without looking for an optimal solution. Thus, despite the existence of well-known simulation tools for the analysis of urban energy systems (e.g., EnergyPLAN Lund, Thellufsen, et al. 2021, HOMER Energy HOMER Energy LLC 2021), to the authors' knowledge, there is a lack of open-source simulation tools meeting the criteria aforementioned. These criteria include the provided definition of simulation model and the possibility of performing analysis considering multiple sectors at urban scale. This absence suggests a niche for the development of such models in the field of energy system modeling.

2.5 Progress Beyond the State of the Art

This work builds on the current state of the art by addressing some identified gaps in the literature. This dissertation, following a step-by-step approach, aims to tackle these critical gaps to understand how synergies between districts and industries can lead to a more efficient local energy transition.

As already mentioned, one of the challenges of energy modeling is the silos approach focusing only on specific aspects. In this context, many modeling tools adopt an optimization approach to find the optimal solution for a given set of constraints. Additionally, these tools and methods are often evaluated individually. This work comprehensively compares these methods, offering new insights into their strengths and limitations. Focusing on district-level energy transition, this work aims to identify how the flexibility of a simulation approach can support policymakers in designing more effective energy transition policies. To do that, given the lack of purely simulation tools, we developed a new energy model that uniquely simulates energy systems using a multi-node approach and the same principles of existing optimization tools. On the one hand, it allows to see the impact of using a simulation approach in supporting policymakers. On the other hand, it also helps understand how using both simulation and optimization approaches together is possible.

Moreover, adding the spatial dimension to energy models is one of the field's challenges. This research also contributes to the ongoing debate on the need for high-resolution spatial data in district-level energy modeling. In this context, this work aims to address the need for high-resolution data when evaluating solar potential. In particular, one key aspect is to provide novel insights based on real case studies to understand whether and when high-resolution spatial data are needed. The impact of the shading caused by the horizon height of the surrounding areas (e.g., close-by buildings), as well as the more distant obstacles (e.g., mountains), on evaluating the solar potential in a given location is assessed starting from a high-resolution (2.5m) Digital Surface Model (DSM). Such analysis provides a novel understanding of the trade-offs of using high-resolution spatial data in an urban context. Hence, it is possible to analyze how the horizon height affects the dynamics of energy availability (e.g., daily seasonality). This is crucial to understanding how to design and size systems that integrate PV panels at the district level, thus providing more cost-effective modeling strategies and advising policymakers on supporting the local energy transition.

One of the common links between these different aspects is understanding how to support policymakers in achieving a more efficient local energy transition. In this context, this work wants to advance the understanding of industrial symbiosis between districts, industries, and local district heating operators to use industrial waste heat as a source of district heating to achieve this transition. It is true that studies evaluating the economic viability of energy recovery initiatives are available. In fact, this study does not want to provide innovative financial evaluation tools to evaluate these initiatives. It wants to offer a novel perspective on quantifying the level of support required to facilitate these interactions by integrating energy modeling with the industry's project evaluation methods. Identifying which interventions are best suited for the final purpose is essential to achieving this goal. Consequently, it is essential to focus on the barriers to effectively utilizing industry waste heat for local district heating networks.

While many options exist, a policy intervention's success is linked to how it addresses specific impediments. In this context, one challenge is the usually long payback period associated with many projects, including those related to waste heat, in industries. It is important to remember that the normally accepted payback in industries is below 3 years, with some exceptions that can go up to 5. All projects above 5 years are usually rejected unless the company has specific needs to invest in such projects. These are some of the challenges that policy intervention should address. Moreover, waste heat is often not a primary focus for industries and regulators, so it is normally excluded from policy intervention design. Another aspect to consider in this sense is the likely chance that district heating companies will disincentivize third parties from accessing the network to reduce the level of competition. In this sense, recognizing and strategically addressing these barriers is the first step in designing policies that, on the one hand, allow us to overcome or at least mitigate these challenges and, on the other hand, pave the way for a sustainable and effective implementation of waste heat recovery initiatives.

Given this context, this work considered two different policies to quantify their impacts in favoring the abovementioned symbiosis:

1. **Constant Feed-in Premiums on the district heating price from industry to districts.**
   This would decrease the investment risk for industries and would increase economic incentives. This scenario will be called "FIP". While in this study a simple tariff scheme is proposed, it should be mentioned that such support scheme could also be upgraded by systematically considering both temperature levels of waste heat and security of heat delivery from the industry.

2. **Financial incentive to support the connection costs of industry to district heating to be given to district heating operators.**
   In this case, the policy addresses the barrier of market competition. In this situation, while the investment cost of the project is still in charge of the industry, the grid connection costs, which is a yearly OPEX, are in charge of the district heating operator (DHO) that will receive a financial incentive to partially cover these costs. The price at which the heat is sold from the industry is lower than the previous scenario, so the DHO recovers its investment thanks to the margin obtained by selling the heat at a higher price than the one at which it bought it. By incentivizing this, it is possible to lower the risk that prevents companies from entering this market. In this way, industries may find additional opportunities to utilize waste heat while DHO enlarges their revenue streams. We will refer to this scenario as "FIC".

This dissertation integrates these policies with the developed simulation tool, the effect of the horizon height, and industry's project evaluation tools. This approach provides quantitative insights for policymakers to promote industrial waste heat utilization in local district heating networks and, ultimately, achieve a more efficient local energy transition.

Through these contributions, this dissertation not only addresses existing gaps in the literature but also paves the way for future research and policy development in the field of energy transition.

3 Methodology

In light of the background information provided in the previous chapter, this section aims to explain this thesis's methodological approach. The interdisciplinary aspects involved in this work require particular attention.

For this reason, it was decided to have a bottom-up approach, trying, step by step, to increase the complexity of the analysis in order to be able to answer the main research questions of this work. Following this, the main approaches utilized were modeling methodologies to analyze energy systems as well as the impact of horizon height and common industrial project evaluation tools to provide more precise insights on how to foster industrial symbiosis between districts, industries and local grid operators. Additionally, these two main methods have been integrated together by using the output of modeling approaches as the input of the financial assessment and feasibility analysis.

Thus, considering the main aspects touched, Figure 8 shows the structure of this section.

Figure 8: Subdivision of the methodology.

The first part presents the developed techno-economic model in detail. It starts with the rationale behind the leading choices and ends with the more practical aspects of the model's functioning. The second part provides insights on how to consider the horizon height. It mainly shows the effect of adopting a spatially explicit approach in evaluating solar potential. Finally, the last section describes the financial analysis and feasibility methodology utilized.

3.1 The Multi Energy System Simulator: MESS

This section first presents the model developed and then focuses on the methodology applied to perform the comparison with Calliope Pfenninger and Pickering 2018, an existing optimization tool. Additionally, it is based on *The potential of simulating energy systems: The Multi Energy System Simulator model* Bottecchia, Lubello, Zambelli, et al. 2021, the first publication of this Ph.D. thesis.

The Multi Energy System Simulator tool (MESS) is a modular, bottom-up, multi-node model that allows investigating non-optimal solutions by simulating the energy system. It is available in a public repository Bottecchia, Lubello, and Zambelli 2024.
In light of the already mentioned challenges of modeling energy systems Chang et al. 2021; Pfenninger, Hawkes, et al. 2014, MESS was developed with a set of design goals in mind and

was deeply inspired by Calliope Pfenninger and Pickering 2018. This choice was made to try to mitigate the consequences of an additional model in the literature and to improve the interoperability among multiple models. The main design goals in the development of MESS are:

1. the model has been built having in mind urban level analyses while maintaining a certain flexibility in terms of spatial resolution;
2. it should be possible to use the model without the need for coding but just by writing human-readable configuration files;
3. the model should be able to perform analyses on systems composed of multiple energy carriers (e.g., electricity, heat, fuels);
4. the model should have a flexible approach to temporal resolution and time series;
5. having a free and open-source energy system model written in Julia Bezanson et al. 2017.

The structure of this section is the following:

- Section 3.1.1 presents the functioning of MESS in detail. Explaining the rationale behind the tool's functioning is essential to improve the clarity of the model proposed. Additionally, it increases transparency and allows future users to better understand the tool's characteristics.
- Section 3.1.2 presents the configuration files required to run the model.
- Section 3.1.3 presents in detail the structure and architecture of MESS as well as its mathematical formulation.
- Section 3.1.4 introduces the comparison performed between MESS and Calliope to depict the potential of the simulation approach compared to the optimization one and describes the case study considered for the comparison.

3.1.1 Functioning of the MESS Model

In order to use MESS, the user has to set up three configuration files to define the system in analysis and the modeling options. The input files are written in YAML, as to ensure readability and allow the user to intuitively interpret them. Once this step is done it is possible to run the model by using the Julia REPL.
Additionally, MESS offers a library of predefined technologies to be included by the user in the model. Each technology is part of a group of technologies that show similar behavior in terms of energy fluxes. This categorization has been taken from Calliope and, as in Calliope, the groups are called parents. MESS has six parents: *demand*, *supply*, *supply_grid*, *conversion*, *conversion_plus*, *storage*. A comparison between the parent categories used in Calliope and MESS is given in Table 5.

Table 5: Parent technology groups - Comparison between Calliope and MESS.

Parent	Calliope	MESS	Description
demand	Yes	Yes	Energy demand for the defined carrier
supply	Yes	Yes	Supplies energy to a carrier
supply_plus	Yes	No	As supply, with additional constraints
supply_grid	No	Yes	As supply, energy from national grid
storage	Yes	Yes	Stores energy
transmission	Yes	No	Transmits energy from one location to another
conversion	Yes	Yes	Converts energy, one carrier to another
conversion_plus	Yes	Yes	Converts energy, N carriers to M carriers
Total	7	6	

In summary, MESS has one parent technology less than Calliope. In particular, this is the result of not considering *supply_plus* and *transmission* parents but considering the *supply_grid* one.
Looking at parents category more in detail, *demand* technologies represent energy sinks. The energy carrier to be considered must be defined and a Comma-Separated Values (CSV) file detailing the demand for that carrier at each time step is required. Technologies with *supply* as a parent represent energy sources. Renewable energy sources as solar photovoltaic or wind turbines are the most evident examples for this parent. The carrier considered and technology-specific parameters should be defined. Different modeling options might be considered for each technology. Technologies belonging to the *supply_grid* parent represent energy sources from distribution grids not modelled in the analysis, as, for example, national distribution grids or district heating grids. The energy carrier of the energy source must be defined in this case as well. Then, *conversion* technologies are defined by a single carrier in and a single carrier out (e.g. natural gas-fed boilers), while *conversion_plus* technologies are defined by multiple energy carriers in and/or out (e.g., combined heat and power technologies). Both categories require the definition of technology-specific parameters. Finally, *storage* technologies are defined by the same carrier in and out and, depending on the state of charge and the energy balance, might act as energy sink or energy source.

3.1.2 Input files

The general configuration parameters for the simulation are set in a specific file named *model_specs.yaml*. It allows the user to define the name of the model, the timespan and time step to be used, as well as if the local electricity network is to be solved and the type of solver to be used. The *techs.yaml* file is used to define and set the input parameters of all different technologies that might be included in the model. Each technology is defined by three subsets of parameters: essentials, constraints and monetary, plus the priority index. In the essentials' subset, fundamentals parameters are to be declared, as the user-defined technology name, the color to be used for plotting, the parent and input and/or output carriers. The constraints' subset contains the parameters used to set the technical characteristics of the technologies and the ones to be specified are technology dependent. In the monetary category costs related to the technology are to be defined, as the Capital Expenditures (CAPEX), the Operational Expenditures (OPEX), interest rate etc. The priority parameter is an integer input that sets the

priority of each technology i.e., the order in which technologies are to be called by the solver, hence allowing the user to define different ways of solving the model. The *locations.yaml* file describes the nodes composing the network to be studied and which technologies each node hosts.
For each technology, additional node specific data can be set, as installed capacity or time series files (e.g., demand curves, capacity factor series), or specific parameters can be superscripted on the general ones defined in the *techs.yaml* file. In addition to the configuration files, input files might be needed for demand profiles, non dispatchable power sources generation profiles, energy prices etc.

3.1.3 MESS structure

MESS is divided in four major steps, that are: *(1)* Pre-processor, *(2)* Core, *(3)* Post-processor and *(4)* Plotting.

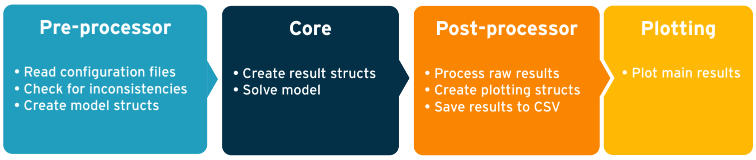


Figure 9: Four steps of MESS.

Pre-processor In the pre-processor stage, all the modules required for the execution of the following steps are loaded. This includes loading the exceptions and structures modules. The former module contains all the exceptions that might arise in the program, while the latter all the data structures used.Some of the structures here defined contain the constraints allowed per each category of technology (or, following MESS's and Calliope's terminology, per each parent) as well as the structures that defines the model characteristics. All these information are then combined with the input files in order to create the model structure to be used in the core module.

Core In the core stage the model is solved. Solving the model is a three-step process. In the first step the single locations are solved at each time step, in the second step the solutions of each location are considered together and the local network is solved. Finally, in the third step the details of the exchanges with higher level grids (i.e. national grid) are defined. Figure 10 shows a schematic diagram representing the functioning of this phase in MESS.

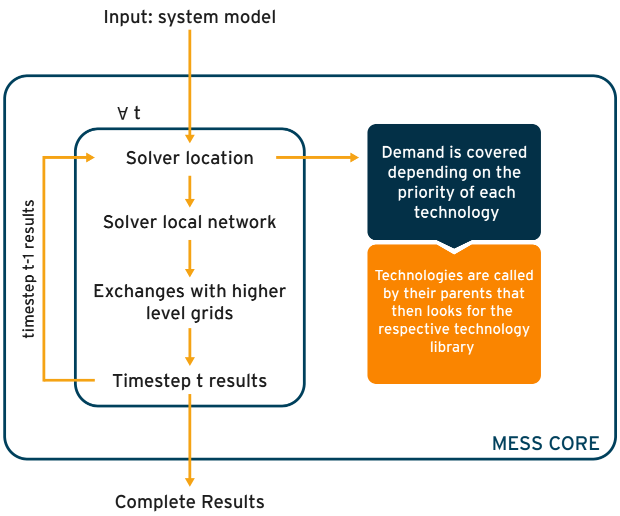


Figure 10: Functioning of the Core phase of MESS.

As briefly introduced, the first step solves each location at each time step. The energy balance is initialized at zero at each time step and is progressively updated while the technologies are solved in each location. Generally speaking, demands are the first to be added to the balance and then the different technologies are used to cover the demand based on their priority. This means that the technologies with the highest priority (lower index value) are the first one to be used to cover the demand. Once that the highest priority technology has been called by the solver, it proceeds searching for the second highest one and so on, until the demand is covered. In this phase, using this approach means that non dispatchable renewable energy technologies might lead to an overproduction of energy. This solving strategy adds the possibility of considering counter-intuitive control strategies for each location, expanding the range of scenarios that can be defined and investigated by the user, nonetheless it should be used with caution, since it might lead to unrealistic behaviors. Once that all locations have been individually solved the local network is considered in the second step of the core phase.

The following equations represent the mathematical formulation of this first step.
Firstly, the sets considered are presented:

$$\begin{aligned} t &: \text{Time steps, equals to hourly resolution} \\ x &: \text{Locations} \\ i &: \text{Technologies} \\ T &: \text{Total number of time steps} \\ X &: \text{Total number of locations} \\ I &: \text{Total number of technologies} \end{aligned}$$

Then, the main variables considered:

- $D_{x,t}$: Demand at location x and time step t
- $Dres_{x,t}$: Residual demand at location x and time step t
- $P_{i,x,t}$: Maximum possible production from technology i at location x and time step t
- $EP_{i,x,t}$: Actual energy produced by technology i at location x and time step t
- $OP_{x,t}$: Over-production caused by non-dispatchable renewable energy technology at location x and time step t

And then the mathematical formulation of this first step of the core of the MESS model. Firstly, the residual demand in each time step is depicted as shown in Equation 1.

$$Dres_{x,t} = D_{x,t} \qquad \forall x \in X, \forall t \in T \quad (1)$$

At this point, the model starts iterating through each technology to meet the residual demand (which has a negative sign convention). For each technology i in order of priority (i.e., from highest to lowest priority) firstly, the Energy Production is depicted following Equation 2.

$$EP_{i,x,t} = \min(Dres_{x,t}, P_{i,x,t}) \forall i \in I, x \in X, t \in T \quad (2)$$

Then the residual demand is updated as per Equation 3

$$Dres_{x,t} = Dres_{x,t} - EP_{i,x,t} \forall i \in I, x \in X, t \in T \quad (3)$$

At this point, if $Dres_{x,t} = 0$, then the loop for the time step t breaks.
This means that demand is always covered by production at each time step following Equation 4

$$\sum_{i=1}^{I} E_{i,x,t} \geq D_{x,i} \forall x \in X, \forall t \in T \quad (4)$$

The *"greater or equal then sign"* is place because, in case of non-dispatchable renewable energy technologies, there might be cases of overproduction as shown in Equation 5.

$$OP_{x,t} = \sum_{i=1}^{I} EP_{i,x,t} - D_{x,t} \quad \text{if} \quad \sum_{i=1}^{I} EP_{i,x,t} > D_{x,t} \forall x \in X, \forall t \in T \quad (5)$$

If there are imbalances in the single locations and the option of considering the local network has been considered, the local grid is solved. In this second step, the solver does a simple summation of the positive and negative imbalances of the single locations estimating the amount of energy exchanged. In the third and final step of the core phase the exchanges with higher level grids (i.e. national grid) are defined.

Post-processor and Plotting After having solved the model in the core stage, the generated solution is processed by the post-processor. The objectives of this step are multiple. It allows processing data to obtain aggregated indicators of performance, looking at the whole timespan considered and not only at the time step resolution (e.g. hourly) imposed. At the same time, it allows to process the data as to proceed with the plotting and to save the results in CSV files that can be used by the user to perform further analyses.
The plotting phase has been considered as a separate step from the post-processing one, even though the two being highly interlinked. Plotting in MESS is handled using the PlotlyJS package *JuliaPlots/PlotlyJS.jl* 2021 that creates interactive HTML files allowing the user to analyze the generated plots by zooming in and out and highlighting the single values navigating on the plot. At the current status, the plotting phase automatically generates two different kinds of plots. The first one shows the overall results at each time step, for each location, in terms of electricity, heat and gas balance. The second one uses the aggregated results for each location to show how demand is covered in percentage by each technology available in the different locations.

3.1.4 MESS vs Calliope

Developing and presenting a new model requires a comparison with an existing tool in order to identify its peculiar characteristics and different usage purposes with respect to a renowned standard. Therefore, a comparison between MESS and Calliope Pfenninger and Pickering 2018 has been conducted. Calliope is an energy system model that allows to investigate energy systems with high spatial and temporal resolution. It permits to analyse different scenarios from urban scale to countries. The choice of Calliope as benchmark model was made due to several reasons. Calliope has proven to be a largely utilized tool, with high standards of code testing and with an approach that is both user-friendly, since no coding is required by the user, and rigorous. At the same time, Calliope is an optimizer and comparing MESS with it allows evaluating what is the potential of simulating against optimizing a system. Indeed, as mentioned by Lund, Arler, et al. 2017 these two approaches have different strengths and purposes. Optimization tends to be more indicated for bottom-up models with a high level of technical details and for being used by planners and engineers. Nonetheless, due to its characteristics and the long computational times that are usually required, it might show some limitations in certain applications. Using a simulation approach results in lower computational times - due to its simpler approach - and might allow a more dynamic and productive interaction with policymakers.
Calliope offers three different modeling options: *(i)* planning mode allows to perform an investment decision analysis to find the optimal configuration of a system in terms of installed capacity via the minimization of an objective function, *(ii* the operational or dispatch mode is meant to perform an optimization on the economic dispatch of the model. In this case, installed capacities of the different technologies are fixed, and the model finds the optimal way of satisfying the demand while minimizing the objective function. Last, *(iii)* SPORES mode allows investigating sub-optimal solutions around the optimal one. In this work, the first two modes have been employed, while the SPORES one has not been considered.
The comparison between MESS and Calliope has been performed following the steps illustrated in Figure 11.

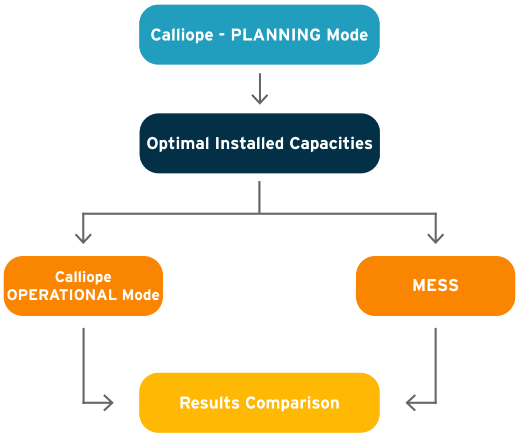


Figure 11: Schematic of the steps performed in the comparison between MESS and Calliope.

First, using the planning mode of Calliope allowed to obtain the optimal level of installed capacities of the different components. The timespan considered (i.e., the horizon used in the run) was one year at hourly resolution. Then, the operational mode of Calliope and MESS have been run with given installed capacities obtained from running Calliope in planning mode. Afterwards, the analysis has been focused on comparing the results obtained from the two models.
The comparison of the two models has been performed through a case study composed of three locations. A more detailed overview of the data employed is presented in Section 3.4. Figure 12 shows the case study considered.

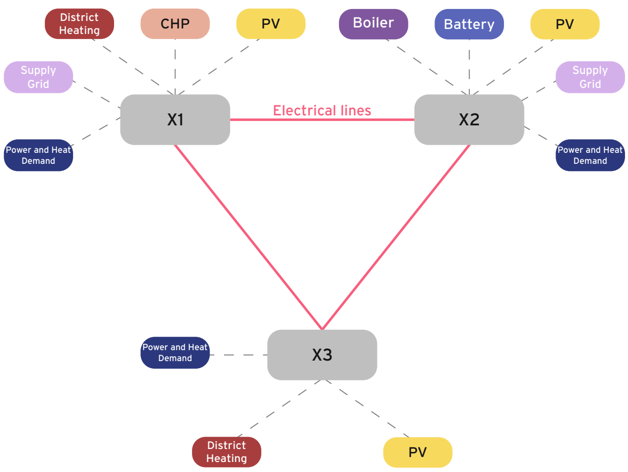


Figure 12: Case study example

In particular the figure shows the three locations considered, *X1*,*X2* and *X3*, with the respective demand and technologies. As an example, location *X1* is characterized by both power and heat demands, the connection to the national grid (Supply Grid) and to the District Heating network, by the presence of a combined heat and power (CHP) unit and by a PV unit. All three locations are connected to each other through electrical power lines.

3.2 Horizon Height Overview

As mentioned before, this works aims at assessing the need of high spatial resolution data at building level to evaluate the potential of solar energy when the horizon height is considered. This section is based on *Discussing the needs of high resolution data: their impact in evaluating solar potential considering the horizon height.* Bottecchia, Dallapiccola, et al. 2023 which is the second article published within this thesis.

Solar radiation can be divided into three main types as can be seen in Figure 13. The first one *(a)*, the direct radiation, happens when the light from the sun hits an object directly. In case the sunlight is screened by clouds then the radiation is called diffuse *(b)*. It should be noted that diffuse radiation can also happen due to scattering related to vapor and other gases (Rayleigh scattering) as well as fine particles in the atmosphere. In fact, there is normally also a minimum diffuse component even under clear sky conditions. Finally, there is also the reflected radiation *(c)* by the surfaces that surrounds an object. These three, summed together returns the Global Horizontal Irradiance (GHI). For the purpose of this work, the reflected radiation has been neglected.

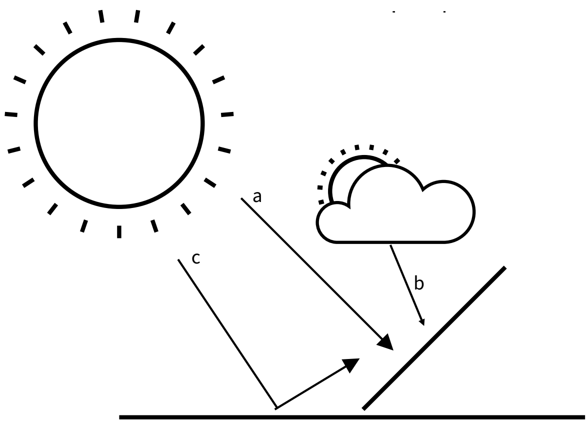


Figure 13: Type of solar radiations: *(a)* direct radiation, *(b)* diffuse radiation, *(c)* reflected radiation.

Given these different types of radiation, the way the horizon height impacts the global is the following: when the solar elevation is below the horizon height, then the only radiation that reaches a solar panel is the diffuse one and not the direct.
In order to evaluate this impact, the analysis focuses on three locations in Bolzano, Italy. The three locations are:

- **The weather station:** both because monitored data of irradiance are available and because it is characterized by large fields in the surroundings and almost no obstacles on the horizon. (lat/long: 46.977/11.3128)
- **Passeggiata dei Castani**: Because of its particular location close by a mountain. (lat/long: 46.48071/11.346785)
- **Historic Center**: a location in the historic city center considered to evaluate the impact of close by buildings. (lat/long: 46.498973/11.355298)

The choice of the three location was explicitly made to understand how the need of high resolution data changes accordingly to different situation. For these locations the following data have been used to perform the analysis using 2019 as reference year.

- Hourly data of GHI from renewables.ninja Pfenninger and Staffell 2016b using the MERRA-2 dataset Rienecker et al. 2011.
- Hourly data of GHI from PVGIS JRC 2012 using the SARAH2 dataset Pfeifroth et al. 2017.
- Hourly data from the weather station in Bolzano and then adapted for each location based on their horizon Agenzia per la Protezione Civile 2016.

In order to assess the impact that the horizon height has in the evaluation of solar potential, several aspects were investigated. Particularly, geospatial aspects are related to mathematical models that allows to evaluate the solar irradiance in a given location. In order to do that, some software and libraries were used in this work. For the spatial analysis GRASS GIS Neteler et al. 2012 was used to work on geo-spatial data as well as for calculating the horizon height. Instead, for the evaluation of solar potential, pvlib Holmgren et al. 2018 has been used to work on the data obtained from the weather station in order to decompose the GHI in its components.
Finally, it should be mentioned that all the scripts, the data utilized as well as a documentation to guide users are available in a public repository Bottecchia 2022. The work presented can be divided in three main steps. These are summarized in Figure 14.
As can be seen, the initial input data requirements are a Digital Surface Model (DSM) of the area in exam that allows to evaluate the orography of the location under analysis. From this, the first step was called GIS application. Here, a set of geo-spatial analysis and operations were performed to been able to calculate the horizon height. Secondly, data of the weather station, namely the global horizontal irradiance - (GHI), were processed to obtain the radiation with horizon height included and divided in global irradiance, direct irradiance, and diffuse irradiance. Finally, this data has been compared with the data obtained from renewables.ninja and PVGIS. The following sections will explain more in details these three steps.

3.2.1 GIS Application

Figure 15 shows the details of the first step of the workflow where GIS data are handled by running GRASS GIS in python. This step can be divided in two main parts. The first one applies when instead of a single DSM file, multiple files that must be merged are available. In this case, the script takes as input these files and, after creating a GRASS location, patch them

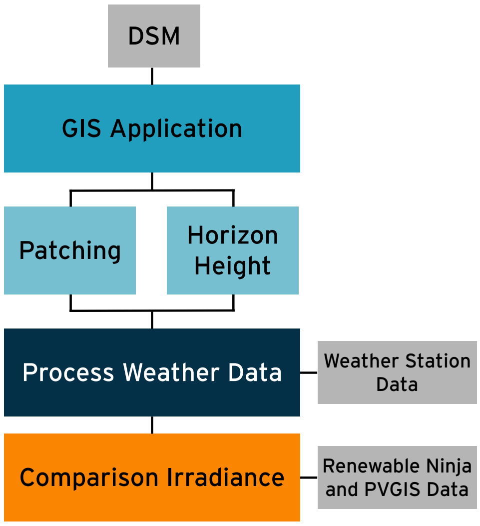


Figure 14: Three steps of the workflow adopted.

together into a single DSM map. Once this is done, another script that takes both this single DSM map and the coordinates of the location in exam to calculate the horizon height, of the location itself. To do that the r.horizon function of GRASS GIS is used. This creates a comma-separated values (CSV) file with the horizon height of the location for each degree (0-360) of solar azimuth.

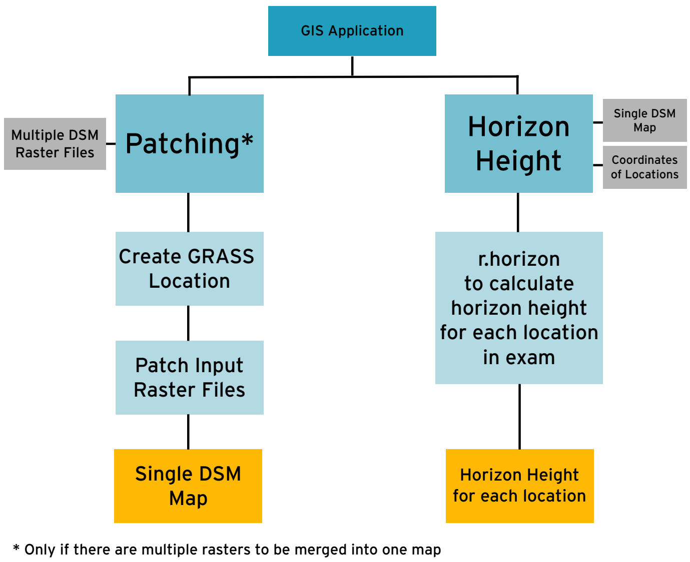


Figure 15: The GIS Application workflow.

3.2.2 Process Weather Data

Figure 16 presents in details how the data of the weather station were processed. For this step the initial input data required are: (i) a CSV file with GHI of the weather station as well as (ii) the coordinates of the location in exam and the year of the analysis (iii). Using these data the first step is to create a pvlib location, then using the hourly dates associated with each data the solar position in the selected location is computed by using the get solarposition function of pvlib Development Team 2021. At this point, using the solar position and the GHI of the weather station it was possible to decompose the radiation into its different components (i.e. direct and diffuse). Firstly using the dirint model from pvlib Ineichen et al. 1992 the direct normal irradiance, which is the radiation that hits an object which is always perpendicular to the sun, was calculated.

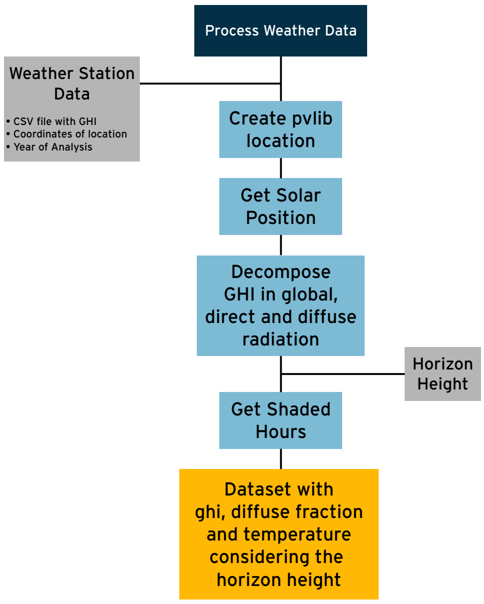


Figure 16: The process weather data workflow.

Then, the ERBS model Erbs et al. 1982 was used to calculate the diffuse radiation using the following equation:

$$DNI = \frac{GHI - DHI}{cos(\theta_z)} \tag{6}$$

where:

- DNI: is the direct normal irradiance
- GHI: is the global horizontal irradiance
- DHI: is the diffuse horizontal irradiance
- θ_z: is the Zenith angle

Consequently, it was possible to calculate the direct irradiance by subtracting the DHI from the GHI. At this point the horizon height calculated in the GIS application step was used to understand in which hours the solar elevation was lower than the horizon height. Once this was done it was possible to adjust the radiation information accordingly. In particular, when the solar elevation is lower than the horizon height there is a situation of shadow and then the GHI is equal to the DHI and the direct irradiance is equal to zero. One should also consider that in complex orographic areas (i.e. mountain areas) the ground radiation is reduced also by orographic obstacles that impacts the calculation of diffuse radiation. In all the other cases, hence when the solar elevation is higher than the horizon height, the radiation remains the same (i.e. with both the direct and diffuse components).

Mathematical Formulation

This section presents the mathematical formulation of the analysis described in the previous section.

The direct normal irradiance (DNI) is calculated using the DIRINT model based on the global horizontal irradiance (GHI) and the solar zenith angle. The formulation is given by:

$$\mathrm{DNI}_{\mathrm{DIRINT}} = \mathrm{DIRINT}(\mathrm{GHI}, \theta_z, t) \tag{7}$$

where:

- GHI is the global horizontal irradiance,
- θ_z is the solar zenith angle,
- t is the time index.

The radiation components are decomposed as follows:

- The diffuse horizontal irradiance (DHI) is calculated by:

$$\mathrm{DHI} = GHI - \mathrm{DNI} \cdot \cos(\theta_z) \tag{8}$$

- The direct horizontal irradiance (DNI on a horizontal plane) is given by:

$$\mathrm{DNI}_{\mathrm{horizontal}} = GHI - \mathrm{DHI} \tag{9}$$

These radiation components are converted from W/m^2 to kW/m^2 by dividing by 1000. Finally, shaded hours are determined by comparing the apparent solar elevation with the horizon height. The hours when shading occurs are identified by:

$$\text{Shaded Hours} = \{t \mid E(t) < H(t)\} \tag{10}$$

where:

- $E(t)$ is the apparent solar elevation at time t,
- $H(t)$ is the horizon height at time t.

3.2.3 Comparison Irradiance

The sub-steps performed in the Comparison Irradiance step are shown in Figure 17. In this step, the input data required were the raw weather data, the dataset coming from the Process Weather Data Step, the data coming from renewables.ninja, the one from

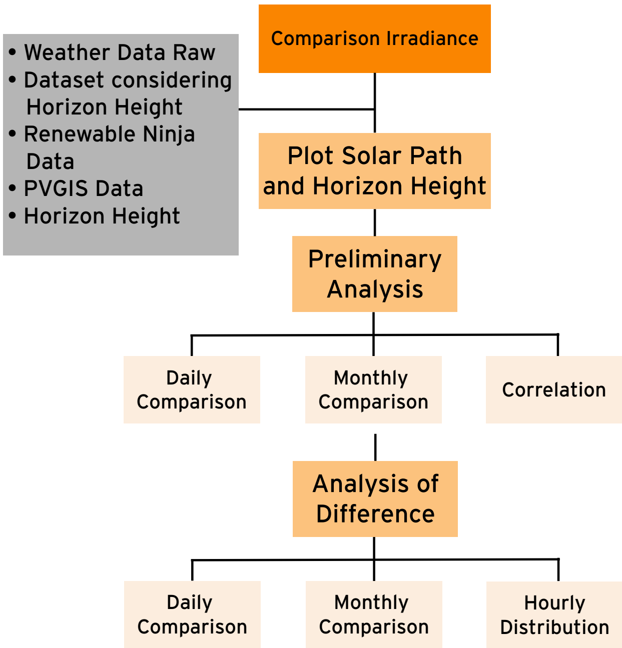


Figure 17: The Comparison Irradiance workflow.

Thus, firstly the horizon height for a given location was plotted above the solar path making it possible to visualize the hours of shading. Secondly, a preliminary analysis was performed. In this phase the Pearson correlation between the data from renewables.ninja, and the weather station with and without Horizon Height included was investigated. Moreover, also an initial statistical analysis on daily and monthly radiation was performed by evaluating indicators (e.g. mean value, standard deviation, and the different quartiles, etc...). In the last step of the comparison the difference between the various datasets were considered. Also in this case the daily and monthly difference was evaluated as well as the hourly distribution of this difference

3.3 Financial Analysis for Industrial Project Evaluation

This section shows the methodology applied to the financial analysis and feasibility assessment performed in Bottecchia, Kranzl, et al. 2024.

3.3.1 Cash Flow Analysis

The analysis of the Net Present Value or the equivalent Discounted Cash Flow (DCF) is the standard framework in performing feasibility assessment and industrial project evaluation. The rationale behind is on comparing the costs and benefits of a project over a defined time span and discounting them to make them comparable. Thus, the first step performed in the analysis was to evaluate the different Cash Flows (CF) of the project.
Starting from an industry perspective the first CF considered were the Revenues from selling the waste heat. In this case the amount of heat sold both to the district heating network and to other industries is considered and then multiplied by the heat price as per the following equation:

$$Revenues_y = (Heat_{DH,y} + Heat_{IND,y}) \cdot p_{h,y} \tag{11}$$

Were the subscript y represent the fact that revenues are calculated each year y and $p_{h,y}$ is the heat price at the year y in €/MWh. The second CF considered regards the operational expenses (OPEX). These are represented by the Operational & Maintenance (O&M) costs of the system and by the connection costs to the district heating network. The following equation is used to evaluate the O&M costs.

$$O\&M_y = (Heat_{DH,y} + Heat_{IND,y}) \cdot O\&M_{var,y} + IC_{HEX} \cdot O\&M_{fix} \tag{12}$$

were:

- $O\&M_{var,y}$ are the variable O&M costs each year in €/MWh
- IC_{HEX} is the installed capacity of the Heat Exchanger in kW
- $O\&M_{fix}$ are the fixed O&M costs depending on the size of the system and thus in €/kW/y

The third CF considered is the investment one, occurring at the year 0. At this point it is possible to evaluate the Net Cash Flow (NCF) commonly known as the Earnings Before Interests, Taxes, Depreciation and Amortization (EBITDA) as:

$$EBITDA_y = (Revenue_y - O\&M_y) \tag{13}$$

At this point the yearly depreciation (DA_y) is calculated dividing the total CAPEX by the lifetime (10 years) that is also the time span considered in the analysis. Consequently, the CAPEX is to be considered as a cash-out in year 0, but a depreciation of the assets are considered for the 10 years analysis. While 10 years might be small for certain technologies (i.e. grid lifetime is longer) in industry investment analysis this is what is usually considered as depreciation time. Hence, the Earnings Before Interest and Taxes (EBIT) is calculated as follows:

$$EBIT_y = EBITDA_y - DA_y \tag{14}$$

That represents the taxable income. From this CF it is possible to calculate the payable taxes (PT_y) by multiplying the $EBIT_y$ with the Corporate Tax Rate. Hence, the Free Cash Flow (FCF) is:

$$FCF_y = EBIT_y - PT_y \tag{15}$$

To obtain the DCF it is necessary to multiply the FCF with the discount factor (DF):

$$DCF_y = FCF_y \cdot DF_y = FCF_y \cdot \frac{1}{(1+r)^y} \tag{16}$$

Where r is the discount rate that corresponds, for the purpose of this analaysis, to the Weighted Average Cost of Capital (WACC). It is possible at this point to calculate also the Cumulated DCF as:

$$CumulatedDCF_y = DCF_y + DCF_{y-1} \tag{17}$$

Where at $y = 0$ the Cumulated DCF is equal only to the DCT at $y = 0$.

3.3.2 Financial Indicators

At this point it is possible to evaluate the three main indicators the Net Present Value (NPV), the Internal Rate of Return (IRR) and Pay Back Time (PBT). The NPV can be calculated using the following formula:

$$NPV = -FCF_{y=0} + \sum_{y=0}^{Y} \frac{FCF_y}{(1+r)^y} = -FCF_{y=0} + \sum_{y=0}^{Y} DCF_y \tag{18}$$

While the IRR is the discount rate at which the NPV results equal to 0 and is obtained solving the following equation:

$$0 = -FCF_{y=0} + \sum_{y=0}^{Y} \frac{FCF_y}{(1+IRR)^y} \tag{19}$$

Finally the evaluation of PBT has been done considering that the cash flow of the investment would happen at half of the year (July) in order to have the system ready to go in the winter season.

3.3.3 Financial Impact of Policy Intervention

As mentioned above, in the FIC scenario the participation of the DHO in such projects is evaluated and assessed. In this scenario the investment on the heat exchanger (to transfer the waste heat to the district heating) is still in charge of the industry. However, all the grid connection costs and distribution costs are in charge of the DHO that receive a Financial Support covering these annual costs. At the same time the price at which DHO buys heat from company is lower so that, the revenues obtained by selling the heat to final consumers allows the DHO to cover its investment costs.

In this case it is possible to define the $EBITDA$ of the DHO as follows:

$$EBITDA_{DHO,y} = (Revenue_{DHO,y} - O\&M_{DHO,y}) \tag{20}$$

Where:

$$Revenue_{DHO,y} = Heat_{sold} \cdot p_{h,y,fc} \tag{21}$$

$$O\&M_{DHO,y} = GridConnectionCosts_y + Heat_{bought} \cdot p_{h,y,ind} \tag{22}$$

Where, as mentioned before $p_{h,y}$ is the heat price each year y. The fc subscript denote the heat price for final consumer and the *ind* one the heat price at which DHO buys heat from industry. The relationship between these two prices is as follow:

$$Heatprice, fc > Heatprice, ind \tag{23}$$

Hence from DHO perspective there is not a so called investment but rather some recurrent Revenues and OPEX. Thus, while for the industry perspective the main outcome of the feasibility assessment is the evaluation of the NPV, IRR and PBT for the DHO will be mainly the DCF to understand the yearly yield of such a project.

At this point it is also possible to see how the selected policies will affect the cash flows of both Industry and DHO. The FIP tariff will be applied to the heat price at which the industry and the DHO sells the heat.

$$p_{h,y,FIP} = p_{h,y} \cdot (1 + FIP) \tag{24}$$

Where FIP is a percentage. On the other hand, the financial incentive works on lowering the grid connection costs as follow:

$$GridConnectionCosts_{y,FIC} = GridConnectionCosts_y \cdot (1 - FIC) \tag{25}$$

Where also in this case FIC is a percentage.

3.4 Data

A relevant part of the work carries out in this thesis regards the data used for performing the various analyses. This section aims at presenting the main data used in the three main contribution of this thesis (Bottecchia, Lubello, Zambelli, et al. 2021; Bottecchia, Dallapiccola, et al. 2023; Bottecchia, Kranzl, et al. 2024).

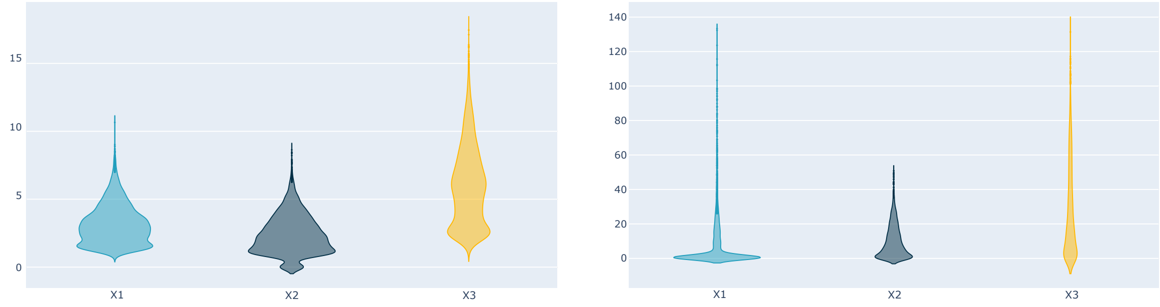
The data eployed has different nature and can be categorized in two main clusters:

1. **Technical Data:** This cluster encompasses various technical parameters, such as installed capacity, efficiency, resource data (e.g., load profiles for photovoltaic panels), and also demand data that, among the various things, represents also the data used in the MESS model.

2. **Economic and financial data:** This includes the marginal cost of production for each technology as well as electricity and district heating costs, financial data such as CAPEX, OPEX as well as WACC to evaluate the investment in connecting industries to districts. Additionally, also the levels of policies that were considered in (Bottecchia, Kranzl, et al. 2024) are included in this section.

3.4.1 Technical Data

The demand profiles considered and used in both Bottecchia, Lubello, Zambelli, et al. 2021 were obtained from the consumption data of three monitored multi-apartment buildings from the Sinfonia Project SINFONIA 2020 in Bolzano, Italy. Figure 18 show the distribution of both the power and heat demand in the three locations in exam.
As can be seen the thermal demand has a higher variability of distribution showing higher peaks rather than the power demand one.



(a) Power Demand. (b) Heat Demand.

Figure 18: Power and Heat Demand of the three locations in exam

As for the load profiles, in Bottecchia, Lubello, Zambelli, et al. 2021 the load profiles were obtained from Renewable.ninja setting Bolzano as location Pfenninger and Staffell 2016b.

However, as already presented in Section 3.2 in Bottecchia, Dallapiccola, et al. 2023 a more detailed analysis was carried out to define the impact of horizon height. In this sense, for the purpose of the work for each of the three locations investigated in that study the following data have been used:

- Hourly data of GHI from renewables.ninja Pfenninger and Staffell 2016b using the MERRA-2 dataset Rienecker et al. 2011.
- Hourly data of GHI from PVGIS JRC 2012 using the SARAH2 dataset Pfeifroth et al. 2017.
- Hourly data from the weather station in Bolzano and then adapted for each location based on their horizon Agenzia per la Protezione Civile 2016.

Moreover, in Bottecchia, Kranzl, et al. 2024 the load profiles utilized in the study were the ones utilizing the horizon height calculated in Bottecchia, Dallapiccola, et al. 2023. Figure 19 shows the distribution of the load profiles considered.

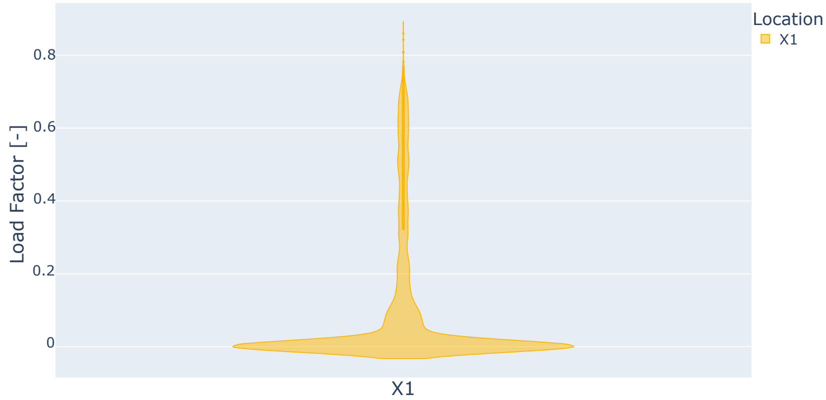


Figure 19: Load Profiles PV.

Both in Bottecchia, Lubello, Zambelli, et al. 2021 and Bottecchia, Kranzl, et al. 2024 different mix of technologies were considered for each location. In both cases the main technical data utilized in modeling these technologies were sourced from the Danish Energy Agency Technology Catalogs Agency 2023.
As for the District Heating, Bolzano's current system is composed by two different generation units. Two CHP for a total of 3.7 MWth of installed capacity and a waste to heat with a thermal capacity of 32 MWth Project 2019; *Termovalorizzatore Bolzano* 2023. The two in total are able to produce more than 50 GWh of thermal energy operating at a temperature level ranging from 80 to 95 °C. In order to evaluate the industrial district heating the assumption that the waste heat for district heating mainly comes from high energy intensive industries normally running 24/7 and almost for the whole year.

3.4.2 Economic and Financial Data

This section presents the economic data included in the MESS Model as well as in the financial and feasibility study. It is an extract of both Bottecchia, Lubello, Zambelli, et al. 2021 and Bottecchia, Kranzl, et al. 2024.

Looking at the power prices, the cost of electricity from the grid was obtained from the Italian authority responsible for managing electricity markets, Gestore Mercati Energetici (GME). Hourly resolution data for the national price (Prezzo Unico Nazionale - PUN) for the year 2022 were considered for this purpose *GME - Download - - EXCEL HISTORICAL DATA* n.d. As for the heating price, it was not possible to find district heating prices for at hourly resolution. Thus, general data of heat prices were obtained from GME. Since only daily values were available, electricity prices distribution was used to determine the hourly one of the heat. While it is widely known that 2022 represented a particular year in Europe in terms of energy prices, it should be also noted that from an industry perspective, investment are always evaluated at current prices and eventually using some forecasts for future year prices. In this sense in order to have a more precise evaluation of feasibility the average heat price was firstly calculated for 2022 and 2023. Then the evolution of Natural Gas Prices coming from TTF Exchange 2023 was used to define prices until 2027. After 2027 they were considered constant since no outlook was available. This evolution of prices is shown in Figure 20

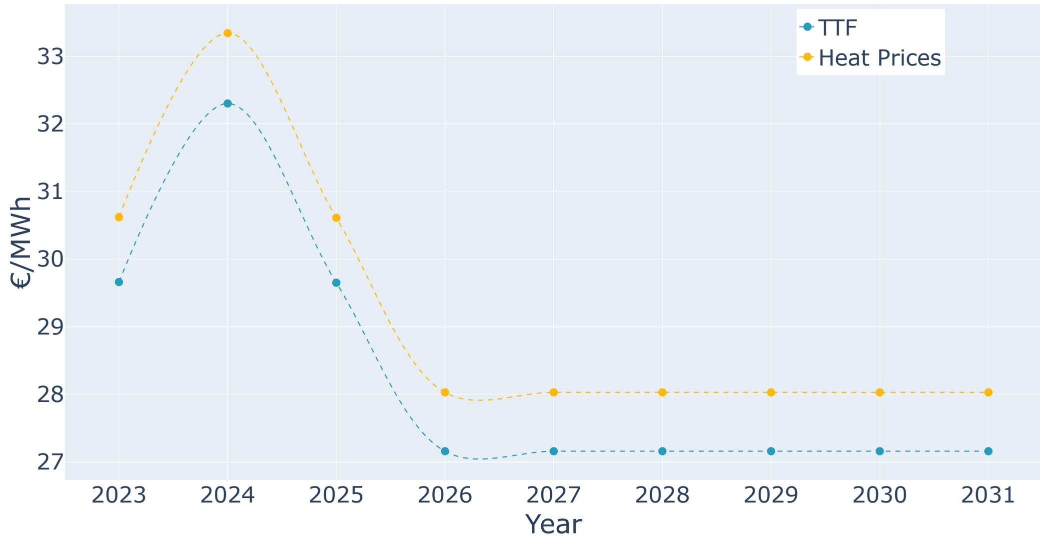


Figure 20: Heat Price Evolution.

In order to evaluate the investment in waste heat utilization for industries a set of data is necessary. From a technical perspective, to connect an industry to a district network a localized exchange substation must be installed. The easier way to implement such a system is to install a heat exchanger (could be either water to water or steam to water depending on the characteristics of the waste heat) so that the water of the district heating runs in a separate close loop. This is of particular importance because the waste heat from industry can often be contaminated and not clean. In analyzing the opportunity to connect an industry to a local district heating the foreseen costs to be considered regards the installation cost of a heat exchanger (HEX), the related operational expenditures (OPEX) as well as the cost for connecting the industry to the network. Table 6 presents these data used in the financial analysis.

Table 6: Main CAPEX and Opex of the Heat Exchanger Agency 2023; Saini et al. 2023.

Data	**Value**	**Unit**
Total Capex	310	€/kW
- o/w Heat Exchanger	90	€/kW
- o/w Mechanical & Hydraulic Connection	105	€/kW
- o/w Power Supply	45	€/kW
- o/w Cabling	35	€/kW
- o/w Commissioning	35	€/kW
Contingencies	10%	-
Cost of Grid Connection	10 000	€/year
Fixed OPEX	4	€/kW/year
Var OPEX	2.5	€/MWh

In addition to these also financial data to evaluate the single project and perform a feasibility analysis must be considered. In particular, a financial analysis should be made both from the industry perspective and from the DHO one. Table 7 shows the main financial data considered in the study in the industry calculations. Please consider that all the information, unless specified are considered for the specific case study in Italy. To evaluate the Weighted Average Cost of Capital (WACC) the following formula, from "Innovation Fund (InnovFund) Call for proposals Annex B: Methodology for Relevant Costs calculation Innovation Fund Large-scale Projects InnovFund-LSC-2021 Annex B: Methodology for Relevant Costs calculation Contents" n.d. was used:

$$WACC = \frac{E}{V} \cdot R_e + \frac{D}{V} \cdot R_d \cdot (1 - T_d) \tag{26}$$

Table 7: Main Financial Data considered in the industry calculations Damodaran 2023; "Innovation Fund (InnovFund) Call for proposals Annex B: Methodology for Relevant Costs calculation Innovation Fund Large-scale Projects InnovFund-LSC-2021 Annex B: Methodology for Relevant Costs calculation Contents" n.d.

Data	**Value**
T_d - Corporate Tax Rate	24%
R_e - Cost of Equity	10.7%
R_d - Cosf of Debt	6.1%
E/V - Equity over Total Value	73.5%
D/V - Debt over Total Value	26.5%
$WACC$	9.1%

These values were retrieved from Damodaran 2023 by taking the dataset updated the 05/01/2024 and by considering the average of the following industries: engineering, machinery, paper & forestry, rubber & tires, steel as a good representative view of the industrial sector of Bolzano. Similarly, the same data were retrieved for the DHO considering, in this case, the average of the following industries: green & renewable energy, utility. Table 8 shows the data utilized.

Table 8: Main Financial Data considered in the DHO calculations Damodaran 2023; "Innovation Fund (InnovFund) Call for proposals Annex B: Methodology for Relevant Costs calculation Innovation Fund Large-scale Projects InnovFund-LSC-2021 Annex B: Methodology for Relevant Costs calculation Contents" n.d.

Data	**Value**
T_d - Corporate Tax Rate	24%
R_e - Cost of Equity	8.9%
R_d - Cosf of Debt	5.7%
E/V - Equity over Total Value	52.6%
D/V - Debt over Total Value	47.4%
$WACC$	8.9%

These, together with the production data coming from the MESS model simulation are then used to perform a feasibility analysis and define the Net Present Value (NPV), Internal Rate of Return (IRR) and Pay Back Time (PBT) of the project. Lastly, the following information regarding the selected policy interventions are needed. The following table shows the initial assumption made in this sense. For the purpose of the study these data were then changed within the sensitivity analysis performed

Table 9: Main Data on selected policies intervention

Data	**Value**
Level of Constant FIP	15%
Level of support on Grid Connection Costs	60%

The last data worth to be mentioned is the fact that on the FIP scenario of the waste heat produced by an industry only a part goes to actual districts, the remaining part, assumed in this case to 30%, is considered to be sold by the industry itself to nearby industries as part of the most canonical industrial symbiosis. This is not happening in the FIC and COMBO scenario. In fact in this case since the DHO takes over part of the investment the industry sell directly all the waste heat to the DHO.

All the data, input files as well as the financial model are available in an open access repository Bottecchia 2024.

4 Results

Given the research questions and the methodology presented above, this section presents the main results of this work. Thus, following the structure of the methodology, Figure 21 shows the format of this section.

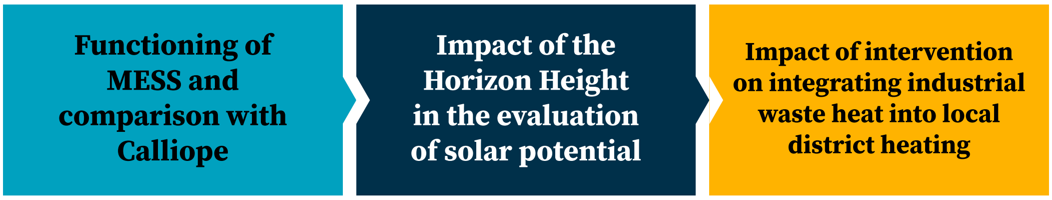


Figure 21: Subdivision of the results section.

The first part illustrates the results of the comparison between MESS and Calliope. This will help understand the potential of a simulation approach versus the optimization one.
The second part describes the implication of considering the horizon height in evaluating solar potential. Additionally, it shows when and whether high-resolution data should be used.
Finally, the last section presents the effects of policies and interventions on integrating industrial waste into the local district heating network viable for industries, DHOs, and districts.

4.1 Results of the functioning of MESS and the comparison with Calliope

In this section, the results obtained from Calliope and MESS are reported. Also, this part is based on *The potential of simulating energy systems: The Multi Energy System Simulator model* Bottecchia, Lubello, Zambelli, et al. 2021, the first publication of this Ph.D. thesis.
Calliope has been used both in planning (Subsection 4.1.1) and operational modes, while MESS has been compared to the results obtained from the latter approach (Subsection 4.1.2). Table 10 lists the execution times of the three simulations, considering a three-node system for a timespan of 1 year and an hourly time step, which have been conducted on a Linux machine running Ubuntu 18.04 with the 15 GB of RAM, and an Intel ® Core i7-8565U CPU @ 1.8GHz 64bit. The time reported in the table have been derived from a single-run, and include all the phases from pre-processing to plotting. Runs have been carried out using the case study presented in Figure 12.

Table 10: Comparison of the execution times for the three simulations.

Model	Execution time
Calliope - Planning	$\sim$45 min
Calliope - Operational	$\sim$11 min
MESS	$\sim$1 min

The absolute speed achieved does not represent the central aspect of this result. However, having a faster tool allows performing multiple scenarios analysis, making it possible to use it in a participatory process of decision-making.

4.1.1 Calliope - Planning mode

Planning mode has been employed to obtain the optimal capacities to be used as inputs for each technology for the following simulations. The obtained capacities are shown in Table 11. Given the costs imposed, the optimized results would tend not to include photovoltaic panels and batteries in the technology mix. Hence a lower bound on their capacity to be installed has been imposed. Given the constraints, locations X1, X2 and X3 result having respectively 5.0 kW, 10.0 kW and 7.0 kW installed of PV, while an energy storage system of 5.0 kWh has been imposed in location X2 as well. Locations X1 and X3 mainly rely on district heating to cover their thermal demand, with a minor contribution from CHP in X1, while a boiler unit is supplying thermal energy to X2.

Table 11: Calliope planning mode results, used as inputs for Calliope operational mode and MESS

Location	Technology	Installed capacity
X1	CHP	9.1 kW
X1	District heating	183.1 kW
X1	PV	5.0 kW
X1	Supply gas	22.5 kW
X1	Supply grid power	20.9 kW
X2	Battery	5.0 kWh
X2	Boiler	50.8 kW
X2	PV	10.0 kW
X2	Supply gas	59.8 kW
X3	District heating	131.4 kW
X3	PV	7.0 kW

4.1.2 Calliope - Operational mode and MESS

Given the capacities obtained from the investment planning optimization, the operational mode in Calliope and the MESS simulation have been run. This sections presents the results obtained. In particular:

- The first section presents the aggregated results at an annual level to identify differences between the two approaches at a macro level.
- The second section shows the results on a monthly-based scale to depict the differences, in the single months and hence in the seasonality, arising from how the two models work.
- The third section presents the results for four representative weeks (one each for winter, spring, summer, and autumn) at an hourly level. In this way, it is possible to have an overview of the differences between the two models in solving the hourly balance.

Annual aggregated results Figures 22 and 23 show the results aggregated for the whole timespan considered (8760 hours, 1 year). Each bar in Figure 22 shows the total amount of electricity obtained from each technology: blue bars represent Calliope's results, while the green bars show MESS' ones. The energy produced by the PV panels is exactly the same in all three location. This should not be surprising given the straightforward functioning of a non-dispatchable technology and the simple models employed. Differences can be noted both for the CHP (∼16%) in location X1 and for the battery in location X2 (∼35%). In the former case, such a difference might be ascribed to the CHP producing electricity not only for location X1, but for the other locations as well, in the case of Calliope. Indeed, this possibility is yet to be implemented in MESS: dispatchable technologies can only be controlled by the demand of the location where the technology is installed. In the case of the battery, in Calliope, its usage depends on an economic optimization of the system as a whole, while in MESS, it only tends to maximize the electricity self-consumption of the location where it is installed. Finally, the most evident difference is in the electrical energy imported from the national grid. Looking at Calliope's results, electricity is only imported in location X1: this is because the connection to the grid is placed there, and electricity is then distributed to X2 and X3 from X1. In the case of MESS, no electricity is imported in X1 since the location is self-sufficient, while substantial imports are present in X2 and X3 since all locations are supposed to be connected to the grid.

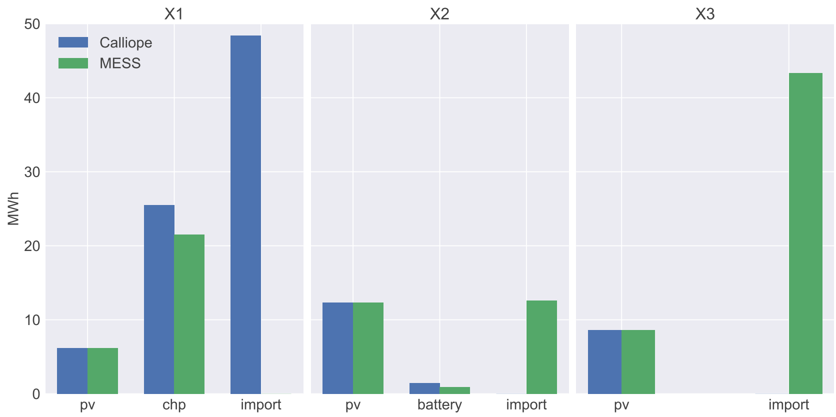


Figure 22: Annual electricity generation per technology for the three location X1,X2 and X3 - Calliope and MESS comparison

Similar considerations can be made for Figure 23. The boiler in X2 and district heating in X3 are the only heat sources for their locations and the results obtained from Calliope and MESS match completely. The differences highlighted for the CHP in the electricity case have repercussions on the heating part for location X1 as well. The CHP is operated in the electrical load following mode, hence the higher quantity of electricity generated in Calliope's solution translates in a higher production of heat as well, which is compensated by MESS with an higher quantity of heat purchased from the district heating grid.

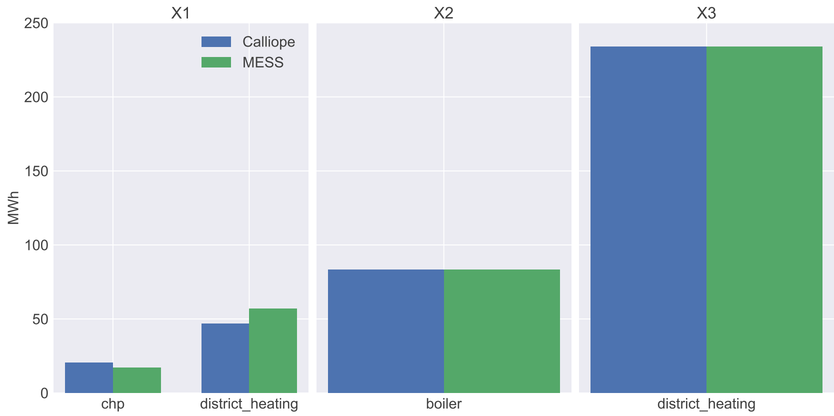


Figure 23: Annual heating generation per technology for the three location X1,X2 and X3 - Calliope and MESS comparison

Monthly aggregated results Monthly aggregated results are shown here for location X1. The same results for locations X2 and X3 can be found in Appendix 6.
Figure 24 shows the monthly amount of energy derived from different technologies for Calliope (left-hand side graph) and MESS (right-hand side graph).

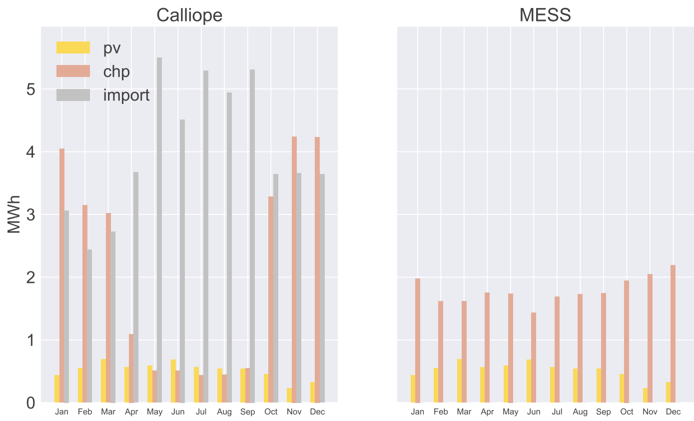


Figure 24: Monthly electricity generation per technology: Location X1 - Calliope and MESS comparison

As seen before, the differences between the two models are in how the CHP works and the reliance on imported energy. Calliope shows a greater utilization of CHP in winter months, while and heavier reliance on electricity import in the summer. This could be ascribed to the higher thermal demand of the winter months: in that case it would make more economic sense to have the CHP running rather than buying electricity from the grid, since the CHP could provide both electrical and thermal energy. On the other hand, MESS shows a more regular behavior of the CHP throughout the year. As seen in the previous paragraph, the CHP in MESS works in electrical load following mode, hence its behavior is only dictated by the electricity demand and the PV production, resulting in a more even behavior. Moreover, no electricity is imported from the grid, since the CHP size is enough to cover, together with the PV panels, the electricity demand. The graphs in Figure 25 confirms it.

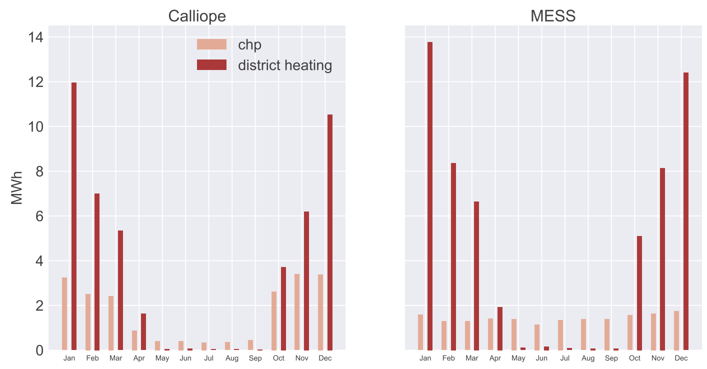


Figure 25: Monthly heating generation per technology: Location X1 - Calliope and MESS comparison

Indeed, the results obtained with Calliope show a higher heat production from the CHP in the winter and a way lower production in the summer. Instead, MESS relies more heavily on the district heating in colder months and has an excess production of heat in the warmer ones, heat that hence is discarded. Details of the monthly behavior for all the locations are presented in Appendix 6.

Hourly results - Typical weeks Finally, the results obtained from the two modeling tools are shown on an hourly basis for four representative weeks of the year. Figure 26 shows the results obtained via Calliope for a week in winter, spring, summer, and autumn, while Figure 27 shows the same results for MESS.
Looking at Figure 26, it is possible to notice a similar behavior for the winter and autumn weeks and for the spring and summer ones. The main difference between the two pairs is the behavior of the CHP. In the colder seasons, the CHP has a major role since it allows to cover both the electrical and thermal demands, as seen also in the previous paragraphs. The reliance on the grid is much heavier in the warmer seasons, since the contribution of the CHP is almost negligible. The electricity demand is always exceeded by the electrical energy produced or imported from the grid. This is because location X1 acts as a connection point for all three locations to the national grid. In winter and autumn, the CHP tends to reach its peak production and the remaining electricity demand from locations X2 and X3 is covered by buying electricity from the grid. In spring and summer, since the thermal demand is lower, it makes more economic sense to buy electricity from the grid, and the CHP is used much less. Another thing worth noticing is the unmet demand at the beginning of the spring week. In this case, the electricity demand in X1 is actually met, but not from a combination of the technologies seen so far, but from an excess of PV electricity from the other locations since it happens in the central hours of the day.

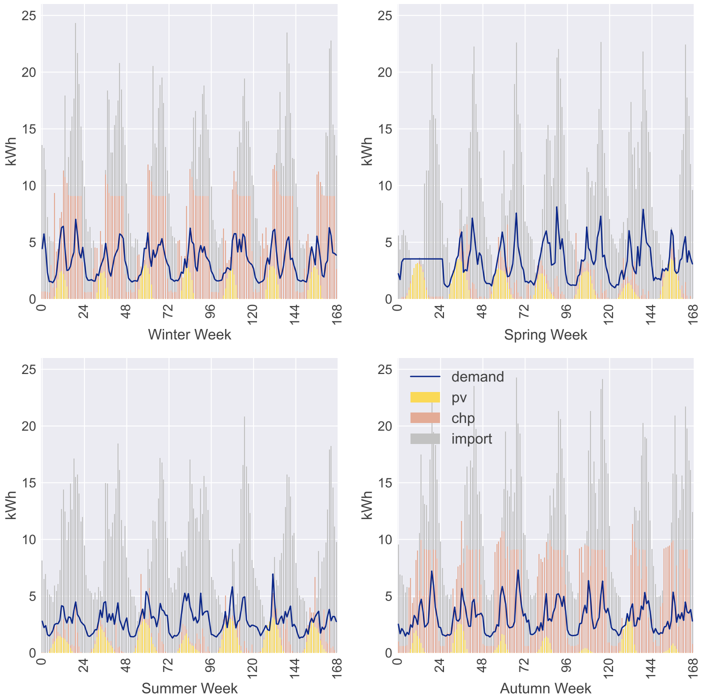


Figure 26: Hourly electricity generation of four representative weeks: Location X1 - Calliope

In the case of MESS, the interpretation of the results shown in Figure 27 is more straightforward since each location tends to be more independent and, in general, less reliance is made on the local grid.

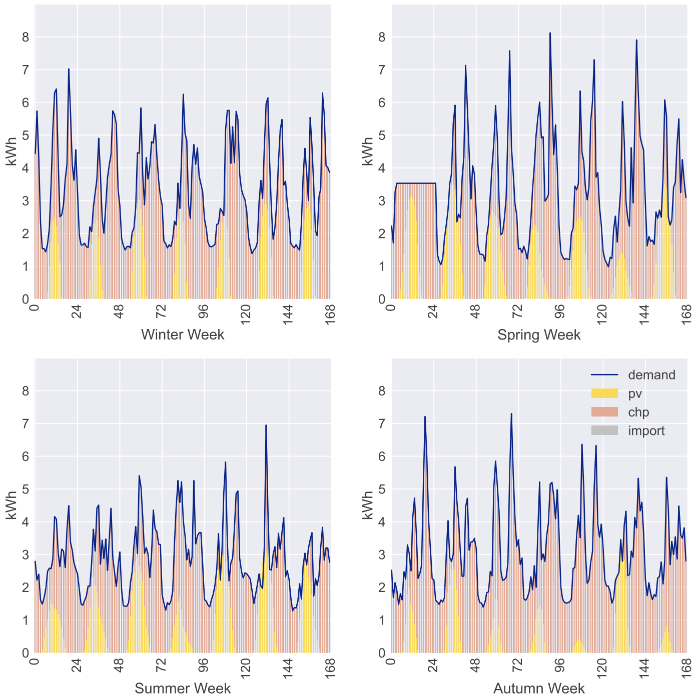


Figure 27: Hourly electricity generation of four representative weeks: Location X1 - MESS

In the considered weeks, the demand is completely satisfied by the combination of PV panels and CHP. Priority is here given to the non-dispatchable electricity produced by the PV panels, while the CHP covers the remaining demand. Given a good superposition of production and demand and the size of the solar panels, almost no excess electricity is produced in the analysed weeks, except for a very few hours in the summer. In that case, the excess electricity is exported to the locations, if required, or otherwise sold to the grid. In Appendix 6, it is possible to see the weekly results for the other two locations.

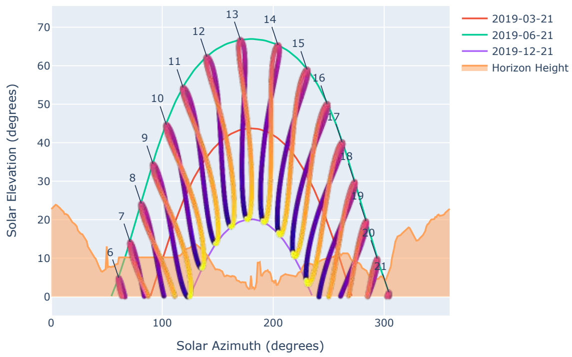
4.2 Impact of horizon height in evaluating the solar potential

This section presents the results of investigating the impact of considering the horizon height when evaluating the solar potential. This is based on *Discussing the needs of high resolution data: their impact in evaluating solar potential considering the horizon height.*, Bottecchia, Dallapiccola, et al. 2023 which is the second article published within this thesis.

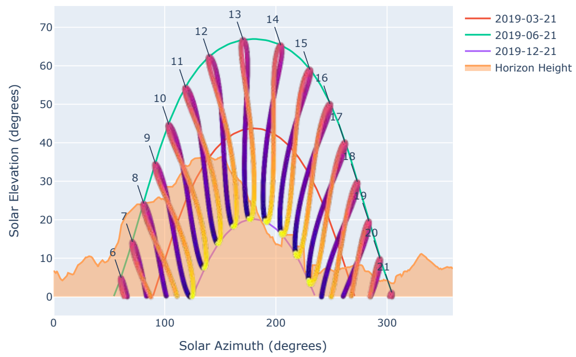
In particular, the results of the comparison between renewables.ninja, PVGIS and the data coming from weather station including or not the horizon height are presented. At the same time, the results will be critically evaluated and discussed.

4.2.1 The Horizon Height and the Solar Path

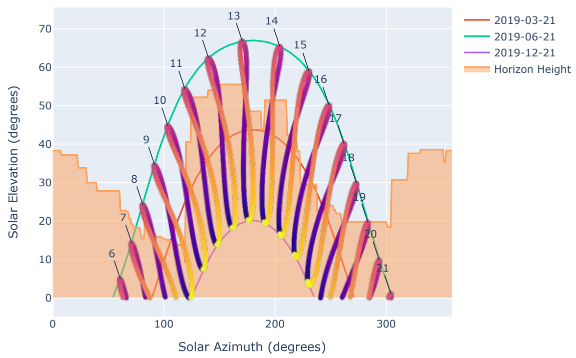
Firstly, it is relevant to look at the differences of the horizon height in the three locations. Figure 28 shows the horizon compared with the solar path in each hour for the weather station (28a), Passeggiata dei Castani (28b) and the Historical Center (28c). As can be seen, Passeggiata dei Castani is characterized by a significant impact of the surrounding mountains that results in a constant shading for a great part of year during morning while in the Historical Center the shading is mainly the results of the nearby buildings. On the other hand, the location of the weather station is not characterized by obstacles in the horizon suggesting that shades won't have a large impact on evaluating solar potential.



(a) Weather Station



(b) Passeggiata dei Castani



(c) Historical Center

Figure 28: Horizon Height and Solar Path for the three locations under investigation.

In light of this, it appears even more relevant to analyze how this affects the solar potential. Initially, the analysis focused on the exact location of the weather station. Both data from renewables.ninja, PVGIS and the weather station itself both considering and not considering the horizon height were compared. Table 12 shows the difference of the yearly irradiance for the weather station. As one can see, the differences at yearly level are almost irrelevant in each case suggesting that in situation when there are no major shadings of the surroundings, the use of high resolution data to assess the impact of the horizon height is not needed.

Table 12: Percentage Difference of yearly irradiance for the Weather Station.

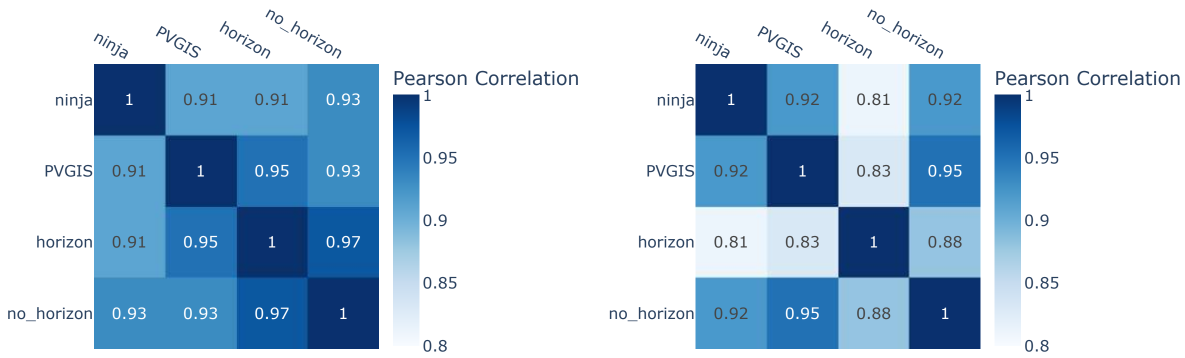
renewables.ninja vs. No Horizon	PVGIS vs. No Horizon	Horizon vs. No Horizon
0.93%	3.05%	-0.09%

In order to further investigate these findings, the focus was switched to the other two location. Table 13 presents the yearly irradiance in Passeggiata dei Castani and the Historical Center for the different approaches and data sources utilized in this work.

Table 13: Yearly Irradiance Comparison [kWh/(m^2*yr)].

	renewables.ninja	PVGIS	Horizon	No Horizon
Passeggiata dei Castani	1390	1264	1267	1382
Historical Center	1391	1397	1025	1382

It is interesting to see how in Passeggiata dei Castani the difference between PVGIS and data from the weather station with the horizon height of the location included, is of only the 0.2%. As above mentioned, also PVGIS considers the horizon height but starting from a 100 m resolution map rather than 2.5m as the adopted approach. This is interesting because it suggests that while there is indeed an impact of the horizon height (see the difference with renewables.ninja and/or the data without the horizon) when the horizon is only characterized by far obstacles like the mountains in this case, high spatial resolution data such as the one used in the adopted approach is not necessary. On the contrary, if you look at the results for the Historical Center it is possible to see that the impact of the horizon, which is caused by nearby buildings, is highly relevant since it can lower the theoretical solar potential even by 36%.
These outcomes can be further proved by looking, in Figure 29, at the Pearson's correlation of the irradiance of the different data used for the two locations. The Pearson's correlation coefficient measures the linear relationship between two continuous variables, and it's based on the method of covariance. As can be seen, in Passeggiata dei Castani (29a), the correlation between data from PVGIS and data from the weather station, including the horizon height of the location, is quite high. On the contrary, in the Historical Center (29b) the correlation between PVGIS and the data of the weather station including the horizon height is one of the worst. Additionally, this also reflects on the correlation between the data obtained from renewables.ninja. In fact, in Passeggiata dei Castani this is the worst between the different cases. On the other hand, in the Historical Center renewables.ninja performs almost identically with PVGIS since probably the effects of the far horizon is neglectable.

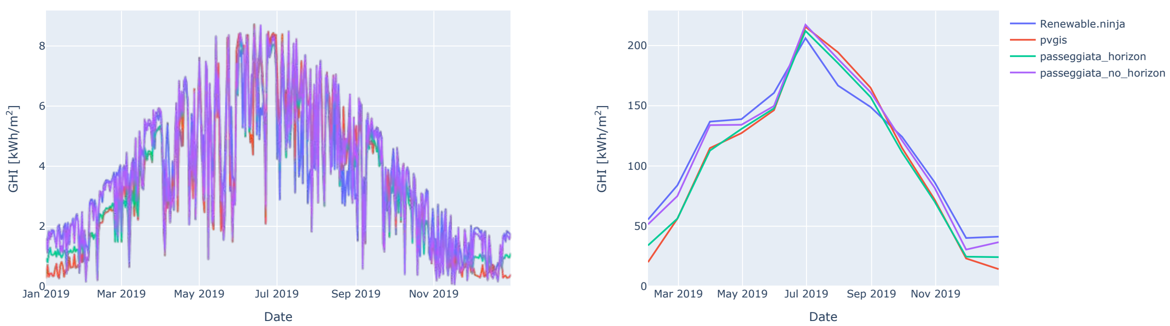


(a) Passeggiata dei Castani. (b) Historical Center.

Figure 29: Pearson Correlation of Irradiance for two of the locations under investigation.

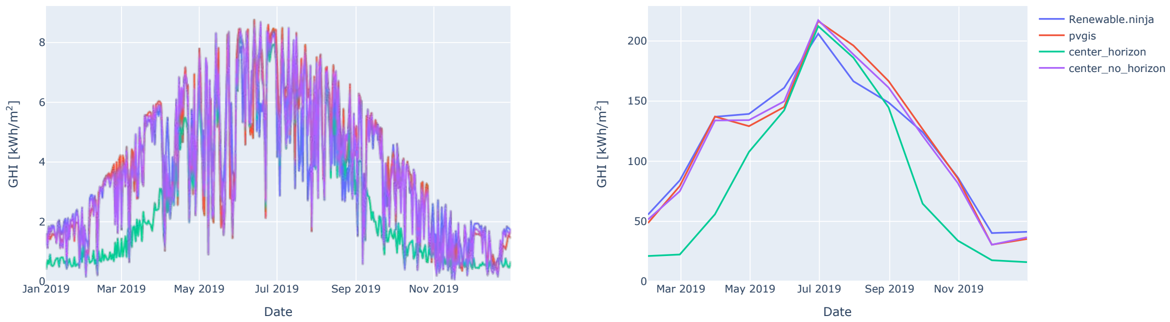
4.2.2 Analyisis of the Daily, Monthly and Hourly Radiation in two locations

In order to have a better understanding of the impact of the horizon height in evaluating the solar potential and to better evaluate the differences between various resolution of data, it is important to analyze the results not only at yearly level but also at monthly and daily. In light of this, Figure 30 shows the comparison of the irradiance both at daily (30a) and monthly (30b) resolution for Passeggiata dei Castani, while Figure 31 presents it for the Historical Center location.



(a) Daily Irradiance. (b) Monthly Irradiance.

Figure 30: Comparison of the Irradiance in Passeggiata dei Castani.

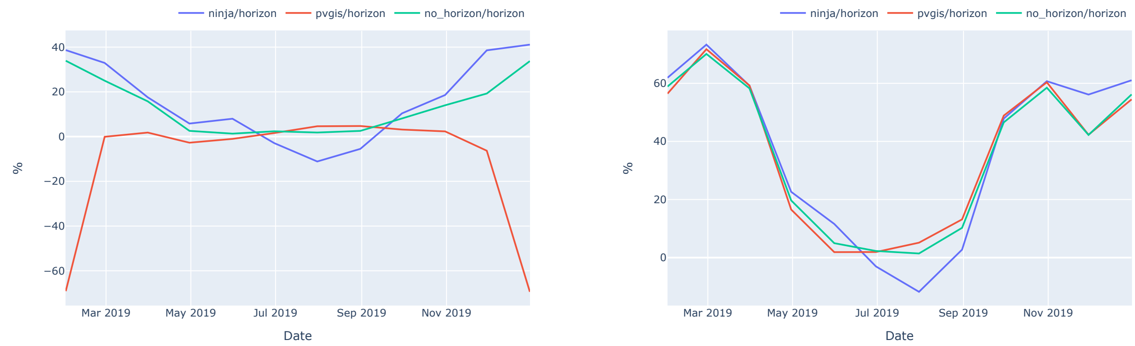


(a) Daily Irradiance.

(b) Monthly Irradiance.

Figure 31: Comparison of the Irradiance in the Historical Center.

By looking at these results it is possible to see how in Passeggiata dei Castani renewables.ninja tend to overestimate the irradiance during winter and autumn months while underestimate it during spring and summer compared with PVGIS and the data from the weather station. However, in the Historical Center, data from renewables.ninja, from PVGIS and from the weather station without the horizon are all quite similar, and they differ consistently with the data where the horizon height is included (green line) apart in summer months. This suggests that the impact of the horizon height is particularly relevant in the colder months when the irradiance is lower. However, when the horizon height is mainly the far horizon (e.g. like in Passeggiata dei Castani) the differences are only of around 9% at yearly level. On contrary, in situations like the Historical Center the impact of the nearby horizon is higher throughout the whole year.
To further investigate this, the difference between the irradiance from renewables.ninja or PVGIS and the one from weather station with horizon height included as well as the difference between the irradiance from weather station with and without horizon height was investigated for both the locations. Figure 32 shows these differences in percentage at monthly level for Passeggiata dei Castani (32a) and the Historical Center (32b) respectively.



(a) Passeggiata dei Castani.

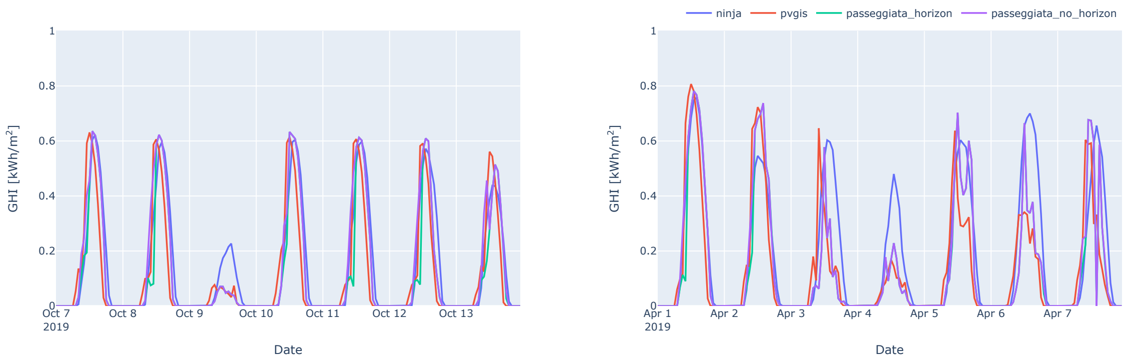
(b) Historical Center.

Figure 32: Percentage difference of irradiance at Monthly level.

On the one hand the results in Passeggiata dei Castani show that the difference between the data from PVGIS with the one of the weather station including the horizon of the location (red line in Figure 32a) is almost neglectable throughout the whole year apart in December and in January. However, this does not influence the yearly difference that, as mentioned before, is of 0.2%. Additionally, looking at difference between renewables.ninja and weather data with horizon this difference is more pronounced. In fact renewables.ninja tends to underestimate the irradiance in summer (negative values of blue line in Figure 32a) and overestimate it during winter months.

On the other hand, focusing on the Historical Center it is possible to see how the difference in the data from the weather station including the horizon with both data from PVGIS and the one of the weather station without the horizon (red and green line in Figure 32b) is almost identical. This can be explained by the fact that PVGIS does not depict the effect of the nearby horizon making the results from it very similar to the ones of the weather station with no horizon included since the effect of the mountains in the latter are neglectable.

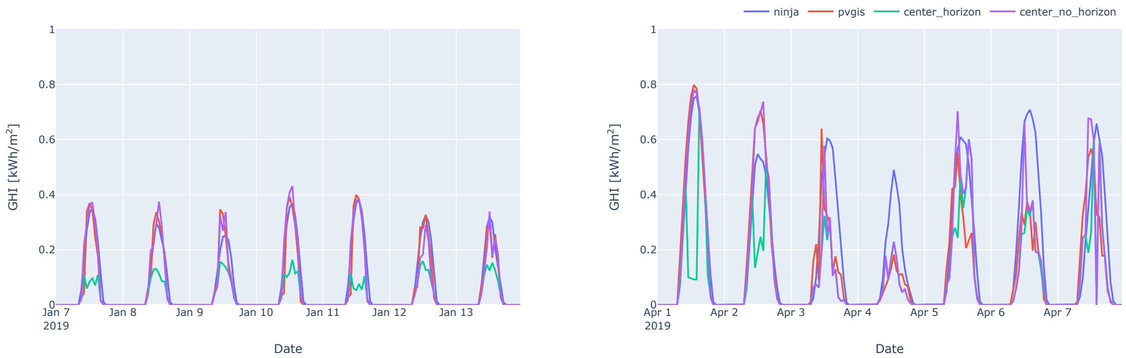
The last aspect to be investigated is how the horizon height impacts the solar potential also at an hourly level. In fact, while from an initial planning point of view knowing the difference at yearly or monthly level may be enough, properly understand the impact at hourly level allow to be aware of when the energy is available and at which hour resulting in a better modeling and deployment of technologies like PV panels coupled with electric batteries. Figure 33 and Figure 34 show the hourly behavior of irradiance during two weeks of the year for Passeggiata dei Castani and the Historical Center respectively.



(a) Autumn week.

(b) Spring week.

Figure 33: Hourly Irradiance in Passeggiata dei Castani.

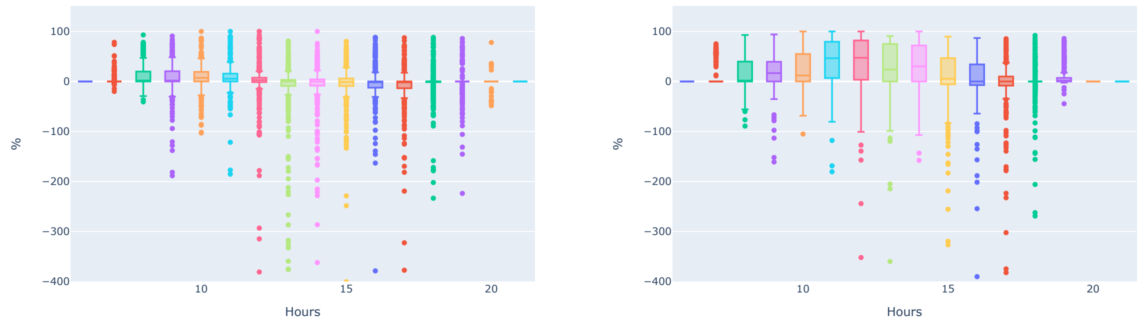


(a) Winter week.

(b) Spring week.

Figure 34: Hourly Irradiance in Historical Center.

As can be seen, in Passeggiata dei Castani the far horizon influences the hourly availability of solar energy especially in the morning and in Autumn/Winter months (red and green line in Figure 33a). On the other hand, looking at the Historical Center (Figure 34) it is possible to depict that the shading of the nearby buildings (i.e. the close horizon) strongly impact the availability of solar energy not only in the Autumn/Winter and also more constantly across the day. This can also be seen by looking at the hourly distribution of these differences between PVGIS and the data from the weather station including the horizon in the two locations (Figure 35). Indeed, looking at Passeggiata dei Castani we see a more constant and lower distribution of the differences across the hours (Figure 35a) while in the Historical Center (Figure 35b) this is more pronounced and relevant due to the large impact of the nearby buildings.



(a) Passeggiata dei Castani.

(b) Historical Center.

Figure 35: Hourly distribution of the irradiance difference between PVGIS and data of the weather station including the horizon in the two locations.

4.2.3 Take out

With this work, the authors aimed to verify whether and in which context is necessary to use high- resolution data to evaluate the horizon height's impact on the solar potential in complex urban areas. These kinds of data are, in fact, not only hard to find but are also often costly. Secondly, by comparing different approaches, the aim was also to assess how the shading caused by the surroundings affects the availability of solar energy in a given location at a yearly level and hourly resolution. Going down to an hourly resolution allows investigating how the performance of an integrated system (e.g., PV + batteries) is affected at the building level. The analysis focused on comparing different tools and data sources (renewable.ninjas and PVGIS) with a more spatially explicit approach that considers the horizon height starting from a high-resolution DSM (2.5m). Additionally, the focus was on three locations in Bolzano, Italy, with different characteristics. One, the weather station, was considered as a reference for the availability of monitored data and for being in a field with no obstacles in the surrounding. The other two were chosen because they are characterized by the proximity of a mountain (Passeggiata dei Castani) and for being surrounded by different buildings (Historical Center). In particular, adopting a more spatially explicit approach is unnecessary in the presence of a clear horizon (i.e., no nearby buildings and no close-by mountains or similar obstacles). In such cases, using high-resolution data results in a neglectable difference both at the yearly and hourly levels. However, the more complex the urban context is, the higher the need for high-resolution data to properly assess the solar potential. As already mentioned, the horizon height of Passeggiata dei Castani is the far one (i.e., mountains). In these cases, there is a relevant impact not only at the yearly level (9% difference in solar irradiance, compared to when the horizon height is not explicitly considered) but mainly at the hourly level since it strongly affects when there is the availability of energy. Thus, this will affect not only the theoretical potential but also the planning of coupled solutions of PV panels and batteries, for example. However, these results also showed that in a situation similar to Passeggiata dei Castani, PVGIS - which uses data with 100m resolution - allows obtaining results that have almost no differences compared to the more spatially explicit approach presented in this work

that considers higher resolution data.
On the contrary, in complex urban situations like the Historical Center, high-resolution data is highly recommended since the shading caused by nearby buildings strongly affects the solar potential. The overall difference of 36%, in terms of solar irradiance, at the yearly level resulted in a periodic reduction of solar potential across the whole day hours. Thus, the results showed that not using high-resolution data to evaluate the horizon height will consistently impact the hourly energy availability, leading to fundamental errors in the designing phases of integrated solutions at the building level. To conclude, the work presented allowed to discuss and reveal the need for high-resolution data providing novel insights on whether and when to use them. While one could argue that it is always better to have more detailed data, the possibility of having them is critical. Thus, this work shows that in a non-complex situation, not having high-resolution data or tools like PVGIS provide enough precise results to properly design an integrated system at building levels and simulate the performance of a building. On the other hand, the more complex the urban situation is, the more high-resolution data are needed to improve the performance of integrated systems at the building level and to foster the energy transition more efficiently. Additionally, further works should focus on how the use of high-resolution data and the adoption of such approaches impact not only the coupling of PV panels with batteries but also the use of demand response solutions using PV panels and the financial and economic impacts.

4.3 Fostering Industry Symbiosis Between Districts, Industries and District Heating Operator

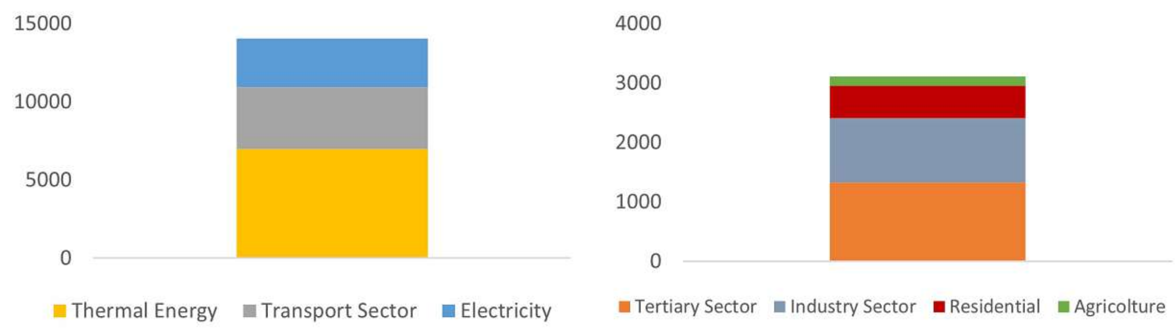
In this section, the focus is on the end goal of this work, which is to understand how decision makers can support industry symbiosis between industries, districts, and district heating operators (DHOs) in the context of waste heat utilization in district heating. This is based on *Driving Industrial Symbiosis: Evaluating Policy Intervention Effects on Waste Heat Utilization in Local District Heating Networks.* Bottecchia, Kranzl, et al. 2024, which is the third article published within this thesis.

Initially, the case study will be briefly presented. Subsequently, the effect of having district heating covering the thermal demand is evaluated against an electrified scenario where only heat pumps supply the heat. This is done to evaluate whether there are or not benefits for the district. Secondly, the analysis moves into understanding the financial feasibility of utilizing waste heat from industrial processes as a source of the district heating both from industry and DHO perspective. Finally, the impact of selected policies is evaluated.

4.3.1 Case Study and scenarios considered

The case study considered was in the industrial area of the city of Bolzano in particular focusing on three multi-apartment buildings monitored under the Sinfonia project Project 2020. Bolzano is characterized by a significant industrial presence and is also equipped with a well-established district heating network operating between 80-95 °C Project 2019. As far as the author knows, it was not possible to find the energy consumption per sector of the city of

Bolzano. Figure 36 shows the main energy data available for the province of Bolzano.



(a) Overall Energy Consumption in GWh. (b) Electricity Consumption by Sector in GWh.

Figure 36: Energy Data of the Province of Bolzano. Bolzano 2021.

Looking at the overall energy consumption of the province in 2021 this was around 14 000 GWh/yr whereas electricity consumption accounted for 22% of it and thermal energy for almost 50% and the remaining is due to the transport sector. Looking instead at the total electricity consumption the one of the industry sector of the province of Bolzano was in 2021 of 1073 GWh/yr and almost 35% of the total electricity consumption in the province.
Considering that the overall energy consumption of the industry sector is split into 60% of thermal energy and 40% of electricity, we have a total energy consumption of the industry sector of ca. 2700 GWh of which 1073 GWh of electricity consumption and the remaining of thermal energy.
Moreover, the city's relatively compact size and ongoing projects associated with SC, EC, and PEDs further enhance its suitability for this analysis. The best example of these projects is surely the Sinfonia Project Project 2020, which aims at enhancing energy efficiency and renewable in Bolzano and Innsbruck through the implementation of Smart Cities concepts. Figure 37 shows the location of the area in exam.

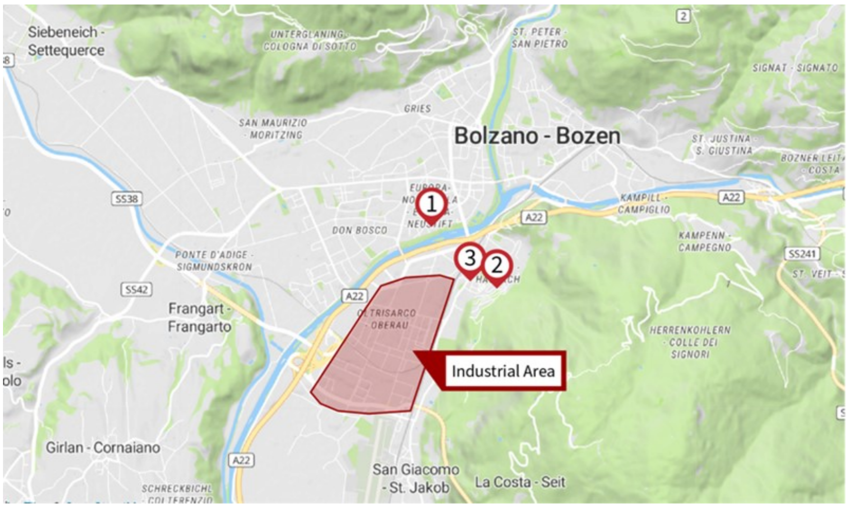


Figure 37: Locations of the area in exam. 1,2,3 are the three multi-apartment buildings considered.

Figure 38 shows the scenarios considered in the analysis.

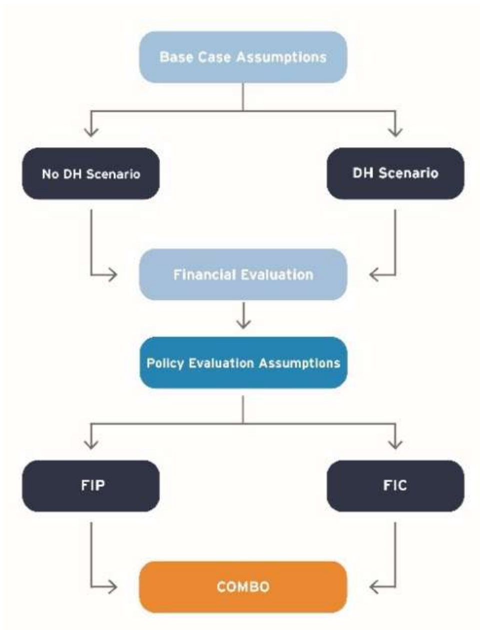


Figure 38: Scenarios considered in the analysis of industry symbiosis.

Firstly, two scenarios are investigated under the Base Case Assumptions where no policy intervention will be evaluated and simply the effect of having or not a district supplied by waste heat coming from industry will be evaluated. Both technical and economical output (i.e. Overall System Costs) will be evaluated. In particular, the two scenarios analyzed are:

1. **Base Case Assumptions:** this step assesses the effect of having or not a district heating (DH) system supplied by industrial waste heat without any policy interventions. Two

scenarios are considered:

a) **No DH Scenario:** the thermal needs of the considered district are met solely by heat pumps, representing a fully electrified case.

b) **DH Scenario:** the thermal needs of the district are met by a district heating system supplied by industrial waste heat.

The goal is to evaluate the benefit of having a district heating network from the end user's perspective, considering both technical aspects and overall system costs. This analysis is conducted using the Multi Energy System Simulator (MESS) tool

2. **Policy Evaluation Assumptions:** this step evaluates the feasibility and financial viability of the DH scenario for both industries and district heating operators. The impact of two different policy intervention is analyzed to understand the required level of policy support:

3. a) **FIP (Feed-In Premium):** evaluates the implications of introducing a Feed-In Premium tariff.

   b) **FIC (Financial Incentive for Grid Connection):** evaluates the impact of a financial incentive to cover grid costs

   c) **COMBO:** combines the two policies evaluated above.

4.3.2 Results of the Base Case Assumptions

As mentioned above, the first step in evaluating the results is to compare the base case scenario both in the only heat pump case or in the district heating case. The base case scenario is the one where no policies or interventions are implemented. Figures 39 and 40 show the overall electricity and heat supply mix in this scenario.

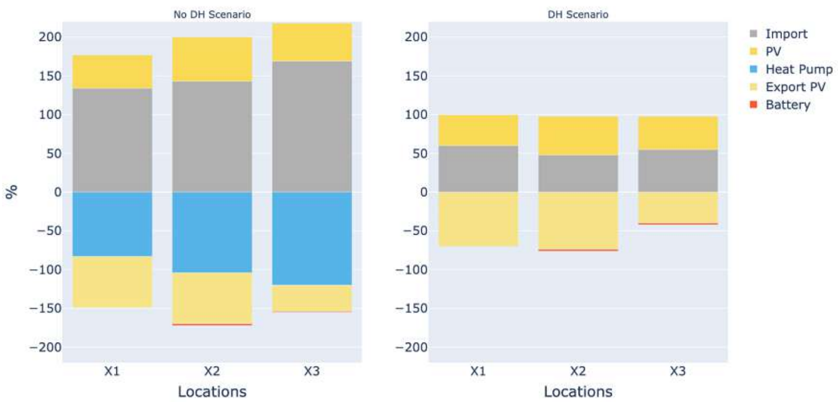


Figure 39: Overall electricity supply mix in the base case scenario.

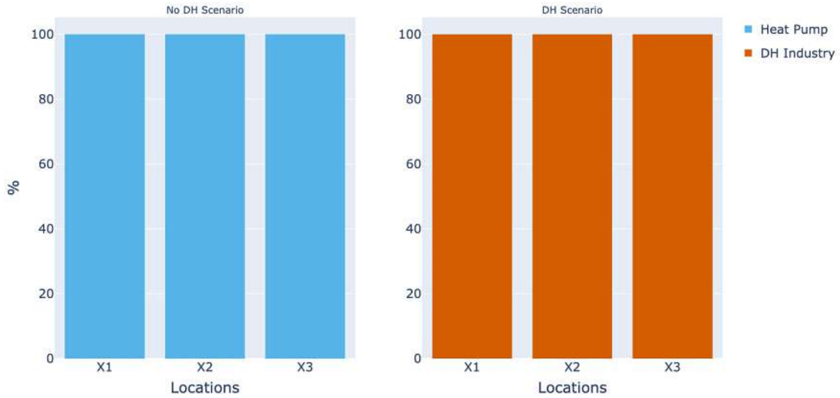


Figure 40: Overall heat supply mix in the base case scenario.

As can be seen, the main differences are related to the way the heat pumps affect the electricity demand. In the Heat Pump scenario, we have a larger electricity demand, while in the district heating one is much lower. Another aspect that can be derived from these results is that the demand is always covered by district heating. The reason behind this is that the district considered in this analysis is a rather small one. The overall heat demand of the district itself is of 310 MWh/yr and in addition to that it was considered an additional 133 MWh/yr sold to other industries. That means that if the heat is delivered thanks to the waste heat of one single industry, under the assumption that waste heat is 5% of the industry thermal demand, we are referring to an industry with an overall thermal demand of ca. 8.9 GWh/year which represents a relatively small industry.

At this point is interesting to analyze how these results affects the overall system costs. These can be derived through the economic development of the MESS model where the production of each technology is multiplied by its respective production cost.

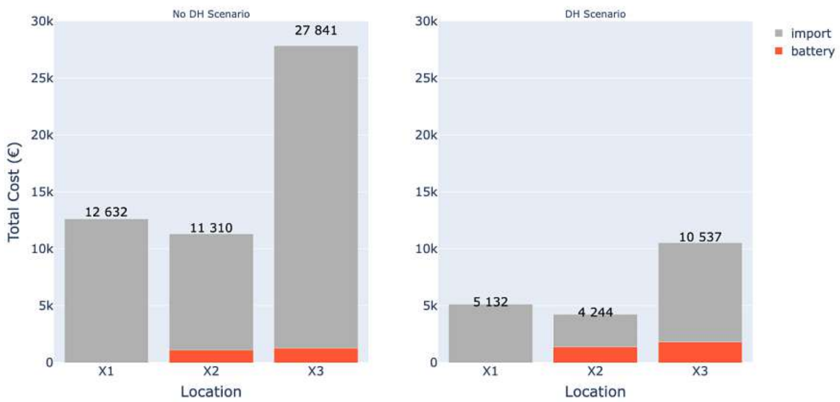


Figure 41: Overall electricity costs in the base case scenario.

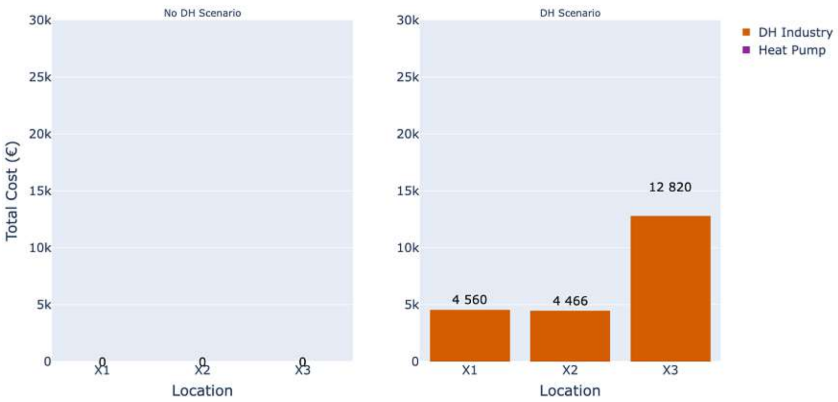


Figure 42: Overall heat costs in the base case scenario.

Table 14: Total Energy Costs in the base case scenario [k€].

Scenario	Location X1	Location X2	Location X3
No District Heating	12.6	11.3	27.8
District Heating	9.7	8.7	23.4
% Difference	-23.0%	-23.0%	-16.0%

As can be seen from Figure 41 and 42 and from Table 14, the District heating scenario is the one that, even though it experiences a higher cost for covering the thermal demand, better perform on the overall costs with an average improvement in the three locations up to 23%. This shows the potential that district heating has in supplying the thermal demand at a lower cost compared to a system based on heat pumps and reveals an opportunity to a better interplay between industries and districts and/or energy communities for the decarbonization of the energy system. It should be noted that these values only refers to three locations of the district in exam and not for the whole province of Bolzano. As mentioned above, this analysis is made to determine the energy balance of the three locations in exam and to define overall energy costs. The outcome of this analysis is used as input, in terms of heat delivered from industrial district heating, to the feasibility assessment performed to evaluate the effect of policy support in such projects.

Starting from the District Heating Scenario under the base case assumptions (no policy intervention), Table 15 shows the main results of the feasibility assessment from the industry perspective.

Table 15: Main results from the industry perspective base scenario.

	NPV [k€]	IRR	PBT
Base Scenario	0.96	9.6%	10.2

As can be seen, overall results are not positive. In fact, while the NPV (> 0) and IRR (> WACC) would suggest that the project is profitable, the PBT of more than 10 years represents an important obstacle. Usually, at industrial level, only projects with a PBT lower than 5 years can be carried out. Consequently, such projects will not be applicable in most industries.

4.3.3 Results of the Policy Evaluation Assumptions Scenarios

It is then essential to understand how these projects can become viable from the industry perspective and also from the DHO one. In fact, it is likely that DHO has no interest in letting a new player coming into their market, but they will be keener in acting together with the player to somehow sponsor such projects. In this sense, the three additional scenarios evaluated in this study help to understand exactly this aspect. Firstly, we will see the effect of implementing an FIP tariff of 15% to improve the feasibility from industry perspective (again, DHO is not involved). Then, DHO will be involved by considering that it will participate in the project following the assumption made before. Figure 43 shows the results of the various scenarios in terms of NPV, IRR, and PBT. The dotted lines in the IRR and PBT subplots represent respectively the WACC of the industry and the PBT threshold of 5 years typical in industries.

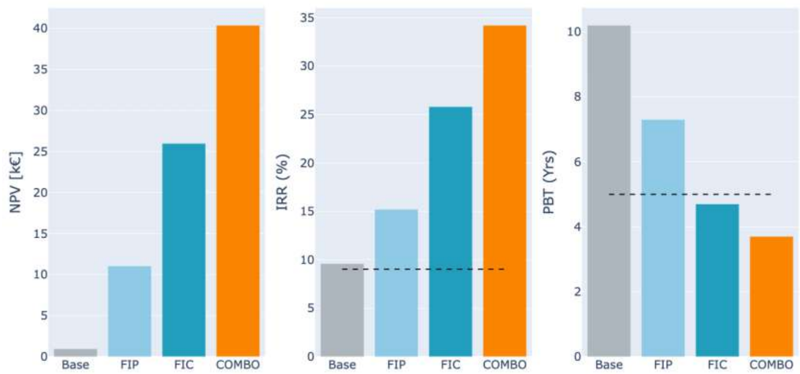


Figure 43: Main results of feasibility assessment in the various scenarios from industry perspective.

As can be seen from Figure 43 both the FIP and FIC scenarios improve sensibly the situation for the industry. However, only the FIC scenario results in a PBT below 5 years suggesting that such projects will be hard to be implemented in most of the industries. This also suggests how connection costs to the grid are one of the largest barriers. The results are more interesting when one combines the two scenarios. In this situation, the heat price at which the industry sells the heat to DHO is reduced by 35% as in the FIC scenario, but the industry sees a 15% FIP that does not affect the price at which DHO buys the heat from the industry. In this way, the industry increases its revenue streams without impacting, and thus reducing, the one of the DHO. Looking at Figure 43, it can be seen that already in the base scenario, the IRR is higher than the WACC considered for industry while PBT is two times the 5-year threshold. On the one hand, this underlines the need to utilize multiple indicators to assess the feasibility of a project. On the other hand, it shows that PBT does not follow the same dynamics of IRR and NPV.

At this point it is then interesting to see what are the results from the perspective of the DHO. In this sense we will look mainly at the yearly average DCF (in the 10 years time span).

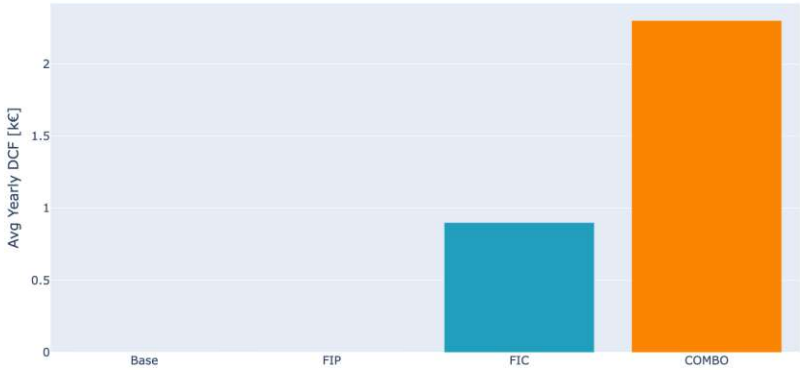


Figure 44: Main results of feasibility assessment in the various scenarios from DHO perspective.

As can be seen also in this case, the COMBO scenario is the one better performing. In particular, it shows the strong impact that heat price has on the DHO.

Figure 43 and 44 can also be used to determine the required level of policy support to make such projects viable. To do that it is also important to define what are the criteria that makes a project viable. As already mentioned, it is not only the NPV and IRR but, more importantly, from the industry perspective, the PBT since it is currently the main indicator that allows a project to be viable. From the DHO it is considered the Average Yearly DCF.

Another way to analyze the results of the COMBO scenario is to define an indicator that shows, at least from the district heating operator perspective, the average yearly DCF over the heat delivered as €/MWh that in this case is ca. 5.2 €/MWh. In this case, the analysis will focus only on the COMBO scenario. Thus, it was investigated how FIP level impacts the PBT for industry and how the FIC affects the average yearly DCF for DHO.

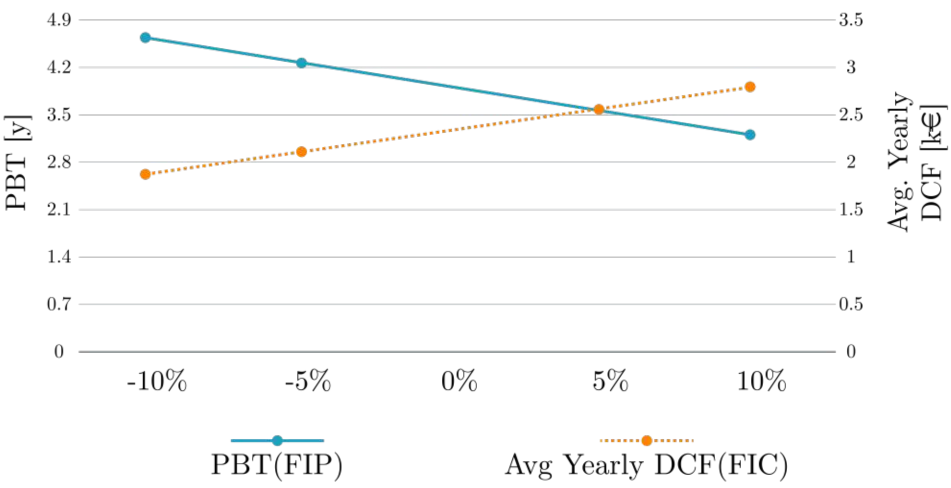


Figure 45: Evolution of PBT depending on changes of level of FIP and of Avg Yearly DCF depending on changes in level of FIC.

As can be derived from Figure 45, increasing the FIP to 25% will allow to reach a PBT of less than 4 years, while a FIP level of 5% will result in a PBT of almost 4.5, years showing thus the lower effect that the FIP itself has in this combined scenario. In fact, it should be remember though that this is still the scenario where grid connection costs are taken over by the DHO. On the other hand, from the DHO perspective, increasing the level of financial support to 70% will result in an increase of the average yearly DCF of +20% while a level of FIC of 55% will result in a -20% of average yearly DCF.

These results suggest that in this configuration, a FIP of at least 15% is necessary to guarantee a PBT safely below 5 years. However, increasing this level of support will protect the industries from price variations. In particular, the higher the heat prices at which the industry can sell the heat, the lower the level of FIP can be and vice versa. As for the DHO, probably a higher level of FIC compared to the one presented in this study of 65% will increase the possibility that DHO will engage in such projects.

While these numbers may seem anyway small, it is important to put them in the perspective of the overall local area. The amount of heat exchanged in these scenarios is ca. 444 MWh/yr, which represents ca. 0.03% of the total thermal demand of the industry sector in the province of Bolzano. Assuming that of the overall thermal demand in the industry sector there is an equivalent of 5% of waste heat it means that using all as source for the district heating will results, in the case of COMBO scenarios, as an yearly average DCF of up to 500 k€/y and a cumulated DCF at the end of the 10 year of ca. 5 M€ showing an interesting business development opportunity for DHO. In this situation we have an yearly average DCF overf heat delivered that is almost 9.6 €/MWh compared to ca. 5.2 €/MWh of the case study analyzed before (ca. +80%). This shows that the larger the waste heat involved, the higher the return of the DHO per unit of heat sold.

Given the usually tight public budgets, one last result that should be mentioned is the impact that such projects can have also from a state perspective. In particular the analysis showed that when scaling up the solution to the whole province of Bolzano 80% of the state investment in terms of financial incentive or support scheme is recovered through payable taxes generate by these projects. This is important because it shows how such initiatives can almost be self sustainable also from a public finance perspective.

5 Discussion, Limitation, and Replicability

This section aims to discuss the main results of this work, point out the limitations of the proposed work, and present replicability opportunities.
As already mentioned, this research explores, develops, and applies methods and tools to address key challenges in the energy transition across residential and industrial sectors. It integrates simulation approaches, high-resolution spatial data, and economic analysis to support decision-making processes. By providing quantitative insights, it highlights how stakeholders can design effective energy intervention, understand the right solar potential in urban areas, and foster industrial symbiosis through actions like industrial waste heat integration into local district heating networks.

5.1 Simulation vs. Optimization

Within the first part of this work, the aim was to investigate the potential of simulating energy systems rather than optimizing them. The two tools used for the analysis were Calliope (optimization tool) and the novel tool developed within this work MESS (simulator). This section is based on Bottecchia, Lubello, Zambelli, et al. 2021
The analysis of the results made it possible to observe some of the differences between MESS and Calliope. The comparison has shown how these differences derive from different principles and strategies adopted by the two models in solving the system. In Calliope, the optimization aims to minimize the whole system's costs, and this is the principle on which the functioning of each component is based. MESS, on the other hand, follows a priority order given to each technology to solve each location. This leads to the differences highlighted in the results for components such as the CHP or the battery system. Differences are not limited to how single components are solved, but are also on how Calliope solves the network with respect to MESS. Indeed, while MESS gives priority to the self sufficiency of each location, in Calliope technologies can also contribute cover the demand of other locations, always following the principle of whole system cost minimization. From the results obtained, the following considerations can be made. As seen looking at the yearly balance of energy supply and demand by energy carriers between the two models, the differences are modest. This denotes how a simplified approach like the simulation one, depending on the application considered, could provide results of a satisfactory precision. At the same time, reducing computational times are significantly reduced (10x times faster) and results might be easier to be interpret based on predefined logics possibly defined by the user. This result is relevant since suggests that in some situations a simulation approach might be the right choice. The key point is whether you would like to answer the *What is needed to achieve a certain target?* question or the *What will happen if...?* one. Optimization approach is more indicated for investment planning models and macro energy systems analysis to understand what is needed to achieve a specific target. A simulation approach might be more suitable for quick investigations of numerous scenarios on a smaller scale, making it an interesting option for a wider set of stakeholders in their decision process. Shorter execution times, together with an approach that makes it easier to understand the logic behind the model, might contribute to making the modeling process more open and inclusive. Indeed, it might be possible to include modeling process in meetings as well as workshops and information campaigns to support the design of new policies and energy strategies. In this way, it would be possible to follow a more transparent and partic-

ipatory approach. Moreover, as suggested by Pfenninger, Hawkes, et al. 2014, a model run taking seconds instead of minutes allows to perform uncertainty and sensitivity analyses on numerous parameters.

Regarding the potential of simulating energy systems, another aspect to be considered is that some of the solving principles applied in MESS, despite being simple, are particularly realistic when considering an urban context. For example, it might be more likely that in certain areas, the majority of battery owners will tend to use their batteries to store the excess production from their photovoltaic modules rather than trade energy with the grid to enhance profits. This behavior aligns with real-world observations where individual or community-based energy solutions prioritize self-sufficiency and resilience over profit maximization.

In this sense, an optimization approach is less flexible and might make it more difficult to represent behaviors that do not reflect any cost-minimization rationales. Optimization models, like Calliope, aim to find the most cost-effective solution for the entire system, which may not always reflect the local or individual priorities and constraints observed in reality. These models may fail to capture the human behavior aspects, some regulatory constraints, and other factors that lead to sub-optimal decisions in the real world. Therefore, while they provide a so-called *"optimal solution"*, these might not always be practically implemented in real scenarios.

Instead, using a simulation approach like in MESS makes it easier to implement different solving strategies that might be closer to the real-world behaviors. For instance, technologies can be dispatched following the merit order and their prices or can follow local strategies that better reflects the peculiarity of communities and districts. This kind of flexibility make it possible to model various strategies of energy consumption also following non-optimal solutions. This is feature that is essential to capture the complexity and variability of real urban energy systems.

However, predefined strategies in simulation models might also enforce faulty logic, leading to non-realistic or biased results. In fact, this characteristic can also introduce oversimplifications or assumptions that distort the outcomes.

Therefore, a combined use of optimization and simulation tools might be a way to explore non-optimal solutions using the optimal one as a reference case.

The combination of the two approaches can provide more comprehensive understanding of energy systems. In this way, it is possible to identify practical and realistic solutions to support decision-making process in the context of urban energy transition

5.2 The impact of horizon height in evaluating solar potential

In the second part of this work, I examined the impact of horizon height on evaluating solar potential and discussed the necessity of high-resolution data. This discussion is particularly relevant given the increasing demand for such data despite their limited availability and higher costs, as highlighted in Bottecchia, Dallapiccola, et al. 2023.

The use of high-resolution data is often highly suggested in assessing solar potential. The analysis focused on comparing different tools and data sources (renewable.ninjas and PVGIS) with a more spatially explicit approach that considers the horizon height starting from a high-resolution DSM (2.5 m). Moreover, the analysis focused on direct and diffuse radiation, while the reflected one was not considered. Additionally, the focus was on three locations in Bolzano, Italy, with different characteristics. One, the weather station, was considered as a reference for the availability of monitored data and for being in a field with no obstacles in the surrounding. The other two were chosen because they are characterized by the proximity of a mountain (Passeggiata dei Castani) and because surrounded by different buildings (Historical Centre). In fact, one of the aims of this work is also to evaluate the need for high-resolution data at different levels of spatial resolution to provide evidence-based guidelines on whether and when these data should be used. In particular, adopting a more spatially explicit approach is unnecessary in the presence of a clear horizon (i.e. no nearby buildings, mountains or similar obstacles). In such cases, using high-resolution data results in a neglectable difference both at the yearly and hourly levels. However, the more complex the urban context is, the higher the need for high-resolution data to properly assess the solar potential. As already mentioned, the horizon height of Passeggiata dei Castani is the far one (i.e. the one of the mountains). In these cases, there is a relevant impact not only at the yearly level (9% difference in solar irradiance, compared to when the horizon height is not explicitly considered) but mainly at the hourly level since it strongly affects when there is the availability of energy. Thus, this will affect not only the theoretical potential but also the planning of coupled solutions of PV panels and batteries, for example. However, these results also showed that in a situation similar to Passeggiata dei Castani, PVGIS – which uses data with 100 m resolution – allows obtaining results that have almost no differences compared to the more spatially explicit approach presented in this work that considers higher resolution data. On the contrary, in complex urban situations like the Historical Center, high-resolution data are highly recommended since the shading caused by nearby buildings strongly affects the solar potential. The overall difference of 36%, in terms of solar irradiance, at the yearly level resulted in a periodic reduction of solar potential across the whole day hours.

It should be also noted that when solar altitude is low on the horizon there are some additional errors that can affect the results obtained. In particular the lower the sun is the weak the radiation is making it harder for measurement devices to depict it.

While high-resolution data offer detailed insights, their necessity is context-dependent. In simpler urban environments, lower-resolution data provides accurate and cost-effective solutions. These are, for example, areas with a clear horizon and minimal obstructions, such as open fields or sparsely built neighborhoods. In this situation, the difference between high and low-resolution data in evaluating solar potential is negligible. Therefore, lower-resolution data can reliably inform the design and implementation of solar energy systems.

However, in complex urban settings, high-resolution data become essential for optimizing the correct sizing and performance of integrated systems and ensuring efficient energy transitions. Particularly, complex urban areas with dense buildings and significant shading effects present challenges that lower-resolution data cannot capture. Consequently, high-resolution spatial data allow for precise assessments of solar potential at specific locations. This level of detail is critical for designing systems that maximize energy production and efficiency.

The possibility to understand when high-resolution data are needed is essential to focus the efforts where is really necessary. Hence, decision-makers can be supported on their process to make informed decision about investment, sizing and planning.

Understanding these different aspects is crucial for developing targeted energy transition strategies. The transition to renewable energy requires not only technological advancements but also strategic planning that considers the diverse characteristics of different urban environments. By recognizing when high-resolution data are essential and when lower-resolution data suffice, stakeholders can create more effective and adaptable energy plans.

5.3 Fostering Industrial Symbiosis

In the third and final part of the work I made use of the two previous analyses to develop a model of a district and evaluate the required support level to facilitate the use of industrial waste heat as source of local district heating. This section builds on the third contribution of this thesis Bottecchia, Kranzl, et al. 2024
The comparative analysis of different scenarios revealed significant insights into the operational dynamics of districts, the symbiosis between industries, districts, and district heating operators (DHOs), and the critical role of policymakers. By examining districts equipped with heat pumps versus those utilizing district heating, the results underscored the potential benefits of district heating systems both from operative and economic perspective. Despite potentially higher thermal costs, the lower electricity demand associated with district heating leads to reduced overall system costs. This cost efficiency is particularly advantageous in urban planning and development, suggesting that integrating district heating could result in significant long-term savings and reduced energy expenses for communities.
However, energy prices play a crucial role in these analyses. Variations in the prices of heat and electricity can significantly impact the overall results, underscoring the importance of conducting tailored analyses to assess the impact of price fluctuations accurately. To address this issue in the study, considering a price evolution over the years was used as a mitigation measure. This approach increased the accuracy of the analysis and accounted for price volatility.
Another insight indicated that district heating could play a crucial role in achieving cost-effective and sustainable energy solutions, especially in industrialized regions with ample waste heat potential.
Nonetheless, the feasibility of implementing industrial symbiosis between districts, industries, and DHOs in the context of industrial waste heat depends heavily on tailored policy support. Various policy intervention scenarios, such as financial incentives and the involvement of DHOs, are crucial for overcoming economic barriers. Factors like heat price and grid connection costs can pose significant obstacles for industries, leading to high payback times (PBT) for such projects. Policy measures addressing these challenges, such as feed-in premiums (FIP) and financial incentives for grid connections, are essential for making these projects viable for both industries and DHOs. Combining these policies can ensure mutual benefits for all stakeholders, fostering a cooperative approach to energy management.
One of the assumptions made in this study was that district heating from industry serves as a baseload, operating continuously 24/7. However, this is an area of possible future investigation since, in the case of some particular industrial processes, it is possible to see slightly different processes with some seasonality aspects. Another important point is related to the conditions on which financial support is granted to the industry under the form of FIP. In fact, an important aspect that should be considered by policymakers when designing policies is the concept of security of heat delivered by industry. In this sense, in the case industry is not able to provide backup capacities and is not able to deliver waste heat, this should have an impact on the prices at which waste heat is sold by the industry to the DHO.
Moreover, understanding the dynamics of integrating renewable energy sources (RES) into these systems is essential. Achieving a positive energy balance within districts, especially those incorporating district heating, requires a higher integration of RES. This integration can facilitate better energy exchange within buildings, enhancing the overall efficiency and sustainability of the energy system. Future studies should explore the optimal mix of RES and

industrial waste heat to maximize the benefits of district heating systems.
Therefore, the integration of district heating systems, supported by targeted policy measures, offers a promising pathway for achieving cost-effective and sustainable energy solutions. The collaboration between industries, districts, and DHOs, underpinned by appropriate policy support, can lead to significant benefits, driving the energy transition forward in industrialized regions with high waste heat potential. Future studies should continue to refine these models and policies, ensuring they are adaptable to various contexts and responsive to evolving energy landscapes. By fostering such collaborations and supporting them with well-designed policies, it is possible to unlock the full potential of industrial waste heat and district heating systems, contributing to a more sustainable and resilient energy future.

5.4 Replicability

Throughout this thesis, openness and transparency have been fundamental principles guiding our research methodology. By making all datasets, energy consumption profiles, climate data, and economic parameters publicly available, I ensure the reproducibility and reliability of our findings. This transparency also encourages the expansion of the analysis to the abovementioned suggestion.
Moreover, the adoption of open-source tools such as the Multi Energy System Simulator (MESS) and optimization tool (Calliope) enhances the accessibility and applicability of our research. These tools not only facilitate the replication of the analyses presented, but also enable broader collaboration and interdisciplinary engagement. By sharing the methodologies openly, this dissertation contributes to the collective knowledge base and encourages innovation in energy modeling and policy development.
In embracing open science practices, this thesis seeks to accelerate the advancement of knowledge in sustainable energy systems. By providing unrestricted access to the models and data, this research supports evidence-based decision-making and contributes to the global effort towards resilient and sustainable energy transitions.
Through these efforts, the aim is not only to strengthen the credibility of this research but also to allow stakeholders to leverage our findings for practical applications.

6 Conclusion

This dissertation explores ways to advance the energy transition in the residential and industrial sectors. It proposes and analyzes quantitative methods and tools to enhance decision-making and facilitate progress in both sectors.
The work progresses by modeling and simulating district-level energy systems, emphasizing the importance of high-resolution spatial data to assess solar potential in these contexts. Furthermore, it examines industrial symbiosis between industries, districts, and DHOs, focusing on the role of policy interventions in fostering cooperation and driving the local energy transition. To analyze these aspects, the author developed a novel open-source simulation tool, MESS, which serves as a cornerstone of the research.

The first step is to understand how a simulation approach compares to an optimization one in modeling district-level energy systems to support decision-makers in designing effective interventions. Firstly, the limited availability of open-source simulation tools resulted in the development of MESS. As abovementioned, the MESS model is a novel modular, bottom-up, multi-node model that allows the investigation of non-optimal solutions by simulating the energy system. Through a detailed comparison of simulation and optimization approaches, the research underscores the importance of understanding the dynamic behavior of energy systems. It was found that simulation models can offer distinct advantages in this area. Particularly, the easiness of the MESS logic and behavior allowed to investigate the effects of possible non-optimal behavior of energy systems. In this way, it was possible to depict that simulation tool can lead to very similar results compared to optimization model at least at yearly level. However, they often came with an extra set of advantages. The MESS model carried out model runs ten times faster than an existing open-source optimization model (Calliope). This suggests that simulation tools can be tailored for participatory approaches with multiple stakeholders. Indeed, they allow investigating almost instantaneously multiple scenarios trying to answer the *What will happen if...?* question. Additionally, faster resolution times also means that simulation model can also be used as a cost function in optimization as in heuristic models. On the contrary, optimization models are more suited to answer the *What is needed to achieve a certain target?* question. In this sense, their utilization for investment planning and macro energy systems analysis is certainly more effective. Hence, combining optimization and simulation allows to first see the optimal solution and then investigate how non-optimal solutions deviate from it. In particular, it should be emphasized that reality is often non-optimal making the solutions obtained from the simulation tool closer to the reality.

The study further investigated the role of high-resolution spatial data in enhancing the accuracy of solar potential assessments in urban context. By integrating detailed horizon height data, the precision of solar irradiance estimates was significantly improved (up to 36%), highlighting the necessity of precise data particularly in complex urban environments. Accurate assessments are crucial for the development of effective solar energy policies and infrastructure. This may suggest that investment in high-resolution data collection and analysis is essential for maximizing the impact of solar initiatives. However, this is true only in the context of complex urban environments. For less complex environments, such investments are probably not necessary, and existing tools with medium-resolution data represent a good trade-off.

Finally, the research explored the conditions required to promote industrial symbiosis, specifically the utilization of industrial waste heat in local district heating. Such cooperation and interaction between different stakeholders (i.e. industries, districts and DHOs) are key to achieve an efficient energy transition in multiple sectors. The results indicated that while the technical feasibility of such initiatives is generally possible, their success heavily relies on the degree of policy support and stakeholder coordination. In particular, decision-makers are fundamental to overcoming key barriers in this field. On the one hand, the large paybacks faced by industries in implementing such projects. On the other hand, there is also a market competition one. In this case, DHOs will probably not be prone to accept the entrance of a new and different player (such industries) in the market. In this sense, policy interventions can address these barriers by making such projects advantageous also for DHOs ensuring that all stakeholders take part in this process. Hence, financial incentives, regulatory frameworks, and collaboration platforms are critical to ensuring that industries and district heating operators can collaborate effectively. The combination of financial incentive to support grid connection costs and support schemes on the heat price shows interesting results making the PBT for industries falling well beyond the 5 years threshold. In parallel such interventions also allows to improve the positive cash flows for DHO of a 2.5x factor. This emphasizes the need for accurate policy intervention to support such projects.

As a last point, this dissertation, embracing open science practices, including open access to datasets and tools like MESS, enhances the reproducibility and reliability of research findings. This transparency fosters collaboration, innovation, and evidence-based decision-making in energy policy and planning. Furthermore, as seen in Section 5, future research should explore the dynamics of integrating renewable energy sources and industrial waste heat in district heating systems across different urban contexts focusing in detail on security of supply, energy prices and district heating's temperature levels. Additionally, investigating the socio-economic impacts of policy interventions on industrial symbiosis initiatives can provide insights for designing effective and inclusive energy policies.

Overall, the findings of this research demonstrate that simulation approaches can provide a dynamic and adaptable framework for energy systems modeling at urban scale, offering enhanced support for decision-makers. High-resolution spatial data plays a pivotal role in complex urban energy planning, and the success of industrial symbiosis initiatives is contingent upon targeted policy interventions and the strong cooperation of all the stakeholders involved. These insights collectively contribute to the broader field of achieving a sustainable transition both in the industrial and residential sector, offering practical guidance and tools for the formulation of future energy policies.

Own References

Bottecchia, Luigi (2022). *PVLIB-NINJA-PVGIS · GitLab*. URL: https://gitlab.inf.unibz.it/URS/pvlib-ninja.

— (2024). *Driving Industrial Symbiosis - Data Repository*. URL: https://github.com/gigibotte/article_industry_symbiosis_repo.

Bottecchia, Luigi, Mattia Dallapiccola, et al. (Apr. 2023). "Discussing the needs of high resolution data: their impact in evaluating solar potential considering the horizon height". In: *Journal of Building Performance Simulation*. ISSN: 19401507. DOI: 10.1080/19401493.2023.2195838. URL: https://www.tandfonline.com/doi/abs/10.1080/19401493.2023.2195838.

Bottecchia, Luigi, Andrea Gabaldón, et al. (2022). "Fundamentals of Energy Modelling for Positive Energy Districts". In: Springer, Singapore, pp. 435–445. DOI: 10.1007/978-981-16-6269-0{_}37. URL: https://link.springer.com/10.1007/978-981-16-6269-0_37.

Bottecchia, Luigi, Lukas Kranzl, et al. (Dec. 2024). "Driving industrial symbiosis: Evaluating policy intervention effects on waste heat utilization in local district heating networks". In: *Energy and Buildings* 324, p. 114865. ISSN: 0378-7788. DOI: 10.1016/J.ENBUILD.2024.114865. URL: https://linkinghub.elsevier.com/retrieve/pii/S0378778824009812.

Bottecchia, Luigi, Pietro Lubello, and Pietro Zambelli (2024). *MESS - Multi Energy System Simulator*. URL: https://github.com/gigibotte/mess_model.

Bottecchia, Luigi, Pietro Lubello, Pietro Zambelli, et al. (2021). "The potential of simulating energy systems: The multi energy systems simulator model". In: *Energies* 14. Publisher: Multidisciplinary Digital Publishing Institute, p. 5724. ISSN: 19961073. DOI: 10.3390/en14185724. URL: https://www.mdpi.com/1996-1073/14/18/5724.

Casamassima Luca, Bottecchia Luigi et al. (2022). "Economic, social, and environmental aspects of Positive Energy Districts—A review". en. In: *WIREs Energy and Environment*, e452. ISSN: 2041-840X. DOI: 10.1002/wene.452. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/wene.452.

References

Abdmouleh, Zeineb et al. (May 2015). "Review of policies encouraging renewable energy integration and best practices". In: *Renewable and Sustainable Energy Reviews* 45, pp. 249–262. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2015.01.035.

Agency, Danish Energy (2023). *Technology Data | Energistyrelsen*. URL: https://ens.dk/en/our-services/projections-and-models/technology-data.

Agenzia per la Protezione Civile (2016). *Portale OpenData Bolzano*. URL: https://data.civis.bz.it/it/dataset/misure-meteo-e-idrografiche.

Ala-Juusela, Mia et al. (2016). "Defining and operationalising the concept of an energy positive neighbourhood". In: *Energy Conversion and Management* 125, pp. 133–140. ISSN: 01968904. DOI: 10.1016/j.enconman.2016.05.052.

Alhamwi, Alaa et al. (Apr. 2017). "GIS-based urban energy systems models and tools: Introducing a model for the optimisation of flexibilisation technologies in urban areas". en. In: *Applied Energy* 191, pp. 1–9. ISSN: 03062619. DOI: 10.1016/j.apenergy.2017.01.048. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261917300569 (visited on 04/28/2020).

Allwood, Julian M. et al. (2014). *Glossary*. Tech. rep. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Amaral, Ana Rita et al. (2018). "Review on performance aspects of nearly zero-energy districts". In: *Sustainable Cities and Society* 43, pp. 406–420. ISSN: 22106707. DOI: 10.1016/j.scs.2018.08.039. URL: https://doi.org/10.1016/j.scs.2018.08.039.

Bakari, Mohamed El Kamel (Jan. 2021). "Setting up the three sides of the sustainability triangle: The American blue-green-brown alliances revisited". In: *Social Sciences & Humanities Open* 3.1, p. 100134. ISSN: 25902911. DOI: 10.1016/j.ssaho.2021.100134.

Batty, M. et al. (Dec. 2012). "Smart cities of the future". In: *The European Physical Journal Special Topics 2012 214:1* 214.1. Publisher: Springer, pp. 481–518. ISSN: 1951-6401. DOI: 10.1140/EPJST/E2012-01703-3. URL: https://link.springer.com/article/10.1140/epjst/e2012-01703-3.

Bezanson, Jeff et al. (2017). "Julia: A Fresh Approach to Numerical Computing". In: *SIAM Review* 59.1, pp. 65–98. DOI: 10.1137/141000671. URL: https://doi.org/10.1137/141000671.

Bianco, Vincenzo and Paolo Michele Sonvilla (Nov. 2021). "Supporting energy efficiency measures in the residential sector. The case of on-bill schemes". In: *Energy Reports* 7, pp. 4298–4307. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2021.07.011.

Bisello, Adriano and Daniele Vettorato (Jan. 2018). "3.5 - Multiple Benefits of Smart Urban Energy Transition". en. In: *Urban Energy Transition (Second Edition)*. Ed. by Peter Droege. Elsevier, pp. 467–490. ISBN: 978-0-08-102074-6. DOI: 10.1016/B978-0-08-102074-6.00037-1. URL: https://www.sciencedirect.com/science/article/pii/B9780081020746000371 (visited on 07/30/2021).

Block, David A. and Laurent Hodges (1979). "PORTABLE PHASE CHANGE STORAGE FOR A DIRECT GAIN PASSIVE RESIDENCE." In: *IIHR Report (Iowa Institute of Hydraulic Research)*, pp. 728–730.

Bognár et al. (2021). "Calculating solar irradiance without shading geometry: a point cloud-based method". In: *Journal of Building Performance Simulation* 14 (5), pp. 480–502. ISSN: 19401507. DOI: 10.1080/19401493.2021.1971765. URL: https://www.tandfonline.com/doi/abs/10.1080/19401493.2021.1971765.

Bolzano, Provincia di (2021). *Bilancio energetico dell'Alto Adige*. URL: https://ambiente.provincia.bz.it/energia/bilancio-energetico-alto-adige.asp.

Bottecchia, Luigi (2022). *PVLIB-NINJA-PVGIS · GitLab*. URL: https://gitlab.inf.unibz.it/URS/pvlib-ninja.

— (2024). *Driving Industrial Symbiosis - Data Repository*. URL: https://github.com/gigibotte/article_industry_symbiosis_repo.

Bottecchia, Luigi, Mattia Dallapiccola, et al. (Apr. 2023). "Discussing the needs of high resolution data: their impact in evaluating solar potential considering the horizon height". In: *Journal of Building Performance Simulation*. ISSN: 19401507. DOI: 10.1080/19401493.2023.2195838. URL: https://www.tandfonline.com/doi/abs/10.1080/19401493.2023.2195838.

Bottecchia, Luigi, Andrea Gabaldón, et al. (2022). "Fundamentals of Energy Modelling for Positive Energy Districts". In: Springer, Singapore, pp. 435–445. DOI: 10.1007/978-981-16-6269-0{_}37. URL: https://link.springer.com/10.1007/978-981-16-6269-0_37.

Bottecchia, Luigi, Lukas Kranzl, et al. (Dec. 2024). "Driving industrial symbiosis: Evaluating policy intervention effects on waste heat utilization in local district heating networks". In: *Energy and Buildings* 324, p. 114865. ISSN: 0378-7788. DOI: 10.1016/J.ENBUILD.

2024.114865. URL: https://linkinghub.elsevier.com/retrieve/pii/S0378778824009812.
Bottecchia, Luigi, Pietro Lubello, and Pietro Zambelli (2024). *MESS - Multi Energy System Simulator*. URL: https://github.com/gigibotte/mess_model.
Bottecchia, Luigi, Pietro Lubello, Pietro Zambelli, et al. (2021). "The potential of simulating energy systems: The multi energy systems simulator model". In: *Energies* 14. Publisher: Multidisciplinary Digital Publishing Institute, p. 5724. ISSN: 19961073. DOI: 10.3390/en14185724. URL: https://www.mdpi.com/1996-1073/14/18/5724.
BPIE (2021). "Policy Briefing Nearly Zero: A Review of EU Member State Implementation of New Build Requirements". In: URL: https://ec.europa.eu/clima/policies/strategies/2050_en.
Brown, T. et al. (2018). "PyPSA: Python for Power System Analysis". In: *Journal of Open Research Software* 6.4 (1). DOI: 10.5334/jors.188. eprint: 1707.09913. URL: https://doi.org/10.5334/jors.188.
Caballero, Víctor et al. (Dec. 2023). "Analysis and simulation of an Urban-Industrial Sustainable Energy Community: A use case in San Juan de Mozarrifar using photovoltaic energy". In: *Energy Reports* 9, pp. 1589–1605. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2022.12.059.
Campbell, Scott (1996). "Green Cities, Growing Cities, Just Cities?: Urban planning and the contradictions of sustainable development". In: *Journal of the American Planning Association* 62.3, pp. 296–312. ISSN: 01944363. DOI: 10.1080/01944369608975696.
Carlisle, Nancy et al. (2009). *Definition of a " Zero Net Energy " Community*. Tech. rep. November. National Renewable Energy Laboratory, pp. 1–14. URL: http://www.nrel.gov/docs/fy10osti/46065.pdf.
Cartuyvels, Paul (2021). *Positive Energy Blocks | Smart Cities Marketplace*. URL: https://smart-cities-marketplace.ec.europa.eu/action-clusters-and-initiatives/action-clusters/sustainable-built-environment/positive-energy.
Casamassima Luca, Bottecchia Luigi et al. (2022). "Economic, social, and environmental aspects of Positive Energy Districts—A review". en. In: *WIREs Energy and Environment*, e452. ISSN: 2041-840X. DOI: 10.1002/wene.452. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/wene.452.
Casperson, Richard L. and Carl J. Hocevar (1979). "EXPERIMENTAL INVESTIGATION OF THE TROMBE WALL PASSIVE SOLAR ENERGY SYSTEM." In: *IIHR Report (Iowa Institute of Hydraulic Research)*, pp. 231–235.
Chang, Miguel et al. (May 2021). "Trends in tools and approaches for modelling the energy transition". en. In: *Applied Energy* 290, p. 116731. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2021.116731. URL: https://www.sciencedirect.com/science/article/pii/S0306261921002476 (visited on 05/03/2021).
Chertow, Marian R. (Nov. 2003). "INDUSTRIAL SYMBIOSIS: Literature and Taxonomy". In: *https://doi.org/10.1146/annurev.energy.25.1.313* 25, pp. 313–337. ISSN: 10563466. DOI: 10.1146/ANNUREV.ENERGY.25.1.313. URL: https://www.annualreviews.org/doi/abs/10.1146/annurev.energy.25.1.313.
Cole, Raymond J and Laura Fedoruk (2015). "Shifting from net-zero to net-positive energy buildings". In: *Building Research and Information* 43.1, pp. 111–120. ISSN: 14664321. DOI: 10.1080/09613218.2014.950452. URL: http://dx.doi.org/10.1080/09613218.2014.950452.

Commission, European (2019). *The European Green Deal*. en. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640 (visited on 06/23/2022).

— (2022). *REPowerEU: affordable, secure and sustainable energy for Europe*. en. Text. URL: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en (visited on 06/23/2022).

Cutler, Dylan et al. (2017). "REopt: A Platform for Energy System Integration and Optimization". en. In: *Renewable Energy*, p. 75.

Damodaran, Aswath (2023). *Useful Data Sets*. URL: https://pages.stern.nyu.edu/~adamodar/New_Home_Page/datacurrent.html.

Davies, G. F. et al. (Feb. 2016). "Using data centres for combined heating and cooling: An investigation for London". In: *Applied Thermal Engineering* 94, pp. 296–304. ISSN: 1359-4311. DOI: 10.1016/J.APPLTHERMALENG.2015.09.111.

Delinchant, B. et al. (2018). *OMEGAlpes / OMEGAlpes*. en. URL: https://gricad-gitlab.univ-grenoble-alpes.fr/omegalpes/omegalpes (visited on 05/03/2021).

Demartini, Melissa et al. (Mar. 2022). "An investigation into modelling approaches for industrial symbiosis: A literature review and research agenda". In: *Cleaner Logistics and Supply Chain* 3, p. 100020. ISSN: 2772-3909. DOI: 10.1016/J.CLSCN.2021.100020.

Development Team, pvlib python (2021). *pvlib.solarposition.get solarposition — pvlib*. URL: https://pvlib-python.readthedocs.io/en/stable/reference/generated/pvlib.solarposition.get_solarposition.html?highlight=get_solarposition.

Dorfner, Johannes et al. (July 2019). *tum-ens/urbs: urbs v1.0.1*. https://doi.org/10.5281/zenodo.3265960. Version 1.0.1. DOI: 10.5281/zenodo.3265960.

Dou, Yi et al. (Jan. 2018). "Innovative planning and evaluation system for district heating using waste heat considering spatial configuration: A case in Fukushima, Japan". In: *Resources, Conservation and Recycling* 128, pp. 406–416. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2016.03.006.

Erbs, D. G. et al. (Jan. 1982). "Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation". In: *Solar Energy* 28.4. Publisher: Pergamon, pp. 293–302. ISSN: 0038-092X. DOI: 10.1016/0038-092X(82)90302-4.

Europe, JPI Urban (2020). *White paper on PED Reference Framework White Paper on Reference Framework for Positive Energy Districts and Neighbourhoods*. Tech. rep. URL: https://jpi-urbaneurope.eu/ped/.

European Innovation Partnership on Smart Cities and Communities (2013). *Strategic Implementation Plan*. Tech. rep.

European Parliament (2018). *Directive 2018/2002/EU*. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2002&from=EN.

European Union (2010). *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*. Tech. rep.

Eurostat (2018a). *Glossary:Degree of urbanisation - Statistics Explained*. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Degree_of_urbanisation (visited on 08/06/2020).

— (2018b). *Glossary:Urban area - Statistics Explained*. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Urban_area (visited on 08/06/2020).

— (2022). *Energy statistics - an overview*. en. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview (visited on 06/23/2022).

Exchange, Intercontinental (2023). *Dutch TTF Natural Gas Futures*. URL: https://www.ice.com/products/27996665/Dutch-TTF-Natural-Gas-Futures/expiry.

Fierro, José J. et al. (2020). "Evaluation of waste heat recovery technologies for the cement industry". In: *International Journal of Thermofluids* 7-8, p. 100040. ISSN: 2666-2027. DOI: https://doi.org/10.1016/j.ijft.2020.100040. URL: https://www.sciencedirect.com/science/article/pii/S2666202720300276.

Fonseca, Jimeno A. et al. (Feb. 2016). "City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts". en. In: *Energy and Buildings* 113, pp. 202–226. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2015.11.055. URL: https://www.sciencedirect.com/science/article/pii/S0378778815304199 (visited on 05/03/2021).

Fraccascia, Luca et al. (June 2020). "Energy-based industrial symbiosis: a literature review for circular energy transition". In: *Environment, Development and Sustainability 2020 23:4* 23 (4), pp. 4791–4825. ISSN: 1573-2975. DOI: 10.1007/S10668-020-00840-9. URL: https://link.springer.com/article/10.1007/s10668-020-00840-9.

Freitas, S. et al. (Jan. 2015). "Modelling solar potential in the urban environment: State-of-the-art review". In: *Renewable and Sustainable Energy Reviews* 41. Publisher: Pergamon, pp. 915–931. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2014.08.060.

GME - Download - - EXCEL HISTORICAL DATA (n.d.). URL: https://www.mercatoelettrico.org/En/download/DatiStorici.aspx.

Good, N. et al. (Sept. 2017). "Barriers, Challenges, and Recommendations Related to Development of Energy Positive Neighborhoods and Smart Energy Districts". In: *Energy Positive Neighborhoods and Smart Energy Districts: Methods, Tools, and Experiences from the Field*. Elsevier Inc., pp. 251–274. ISBN: 9780128103982. DOI: 10.1016/B978-0-12-809951-3.00008-9. URL: https://www.research.manchester.ac.uk/portal/en/publications/barriers-challenges-and-recommendations-related-to-development-of-energy-positive-neighborhoods-and-smart-energy-districts(ae86b6db-9c3d-4a14-aca2-b388ebccc57f)/export.html.

Hedman, Åsa et al. (Mar. 2021a). "IEA EBC Annex83 positive energy districts". In: *Buildings* 11.3. Publisher: MDPI AG, p. 130. ISSN: 20755309. DOI: 10.3390/buildings11030130. URL: https://www.mdpi.com/2075-5309/11/3/130.

— (Mar. 2021b). "IEA EBC Annex83 positive energy districts". In: *Buildings* 11.3, p. 130. ISSN: 20755309. DOI: 10.3390/buildings11030130. URL: https://www.mdpi.com/2075-5309/11/3/130.

Helistö, Niina et al. (Jan. 2019). "Backbone—An Adaptable Energy Systems Modelling Framework". en. In: *Energies* 12.17. Number: 17 Publisher: Multidisciplinary Digital Publishing Institute, p. 3388. DOI: 10.3390/en12173388. URL: https://www.mdpi.com/1996-1073/12/17/3388 (visited on 05/04/2021).

Hermelink, Andreas et al. (2013). *Towards nearly zero-energy buildings Definition of common principles under the EPBD Final report Panel of international experts*. Tech. rep. URL: www.ecofys.com.

Hilpert, Simon et al. (Nov. 2018). "The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling". In: *Energy Strategy Reviews*

22. arXiv: 1808.08070, pp. 16–25. ISSN: 2211467X. DOI: 10.1016/j.esr.2018.07.001. URL: http://arxiv.org/abs/1808.08070 (visited on 05/03/2021).

Holmgren, William F. et al. (Sept. 2018). "pvlib python: a python package for modeling solar energy systems". In: *Journal of Open Source Software* 3.29. Publisher: The Open Journal, p. 884. ISSN: 2475-9066. DOI: 10.21105/JOSS.00884. URL: https://joss.theoj.org/papers/10.21105/joss.00884.

HOMER Energy LLC (2021). *HOMER - Hybrid Renewable and Distributed Generation System Design Software*. https://www.homerenergy.com/index.html. (Visited on 06/29/2021).

Hoppe, Thomas and Ellen van Bueren (June 2015). "Guest editorial: governing the challenges of climate change and energy transition in cities". In: *Energy, Sustainability and Society 2015 5:1* 5.1. Publisher: BioMed Central, pp. 1–9. ISSN: 2192-0567. DOI: 10.1186/S13705-015-0047-7. URL: https://link.springer.com/articles/10.1186/s13705-015-0047-7%20https://link.springer.com/article/10.1186/s13705-015-0047-7.

Huld, Thomas et al. (June 2012). "A new solar radiation database for estimating PV performance in Europe and Africa". In: *Solar Energy* 86.6, pp. 1803–1815. ISSN: 0038092X. DOI: 10.1016/j.solener.2012.03.006.

Ineichen, Pierre et al. (1992). "Dynamic global-to-direct irradiance conversion models | Archive ouverte UNIGE". In: *ASHRAE Transaction* 98.1, pp. 354–369. URL: https://archive-ouverte.unige.ch/unige:38583.

"Innovation Fund (InnovFund) Call for proposals Annex B: Methodology for Relevant Costs calculation Innovation Fund Large-scale Projects InnovFund-LSC-2021 Annex B: Methodology for Relevant Costs calculation Contents" (n.d.). In: ().

IPCC, Working Group II - (2022). *AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability — IPCC*. Tech. rep. URL: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_FullReport.pdf (visited on 06/23/2022).

Jaccard, Mark (Jan. 2006). *Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy*. en. ISBN: 9780521861793 9780521679794 9780511754104 Library Catalog: www.cambridge.org Publisher: Cambridge University Press. DOI: 10.1017/CBO9780511754104. URL: /core/books/sustainable-fossil-fuels/B86C073510E622256812244BBE9F7914 (visited on 04/30/2020).

Jiao, Wenting and Frank Boons (Mar. 2014). "Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review". In: *Journal of Cleaner Production* 67, pp. 14–25. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2013.12.050.

JPI Urban Europe (2020). *White paper on PED Reference Framework White Paper on Reference Framework for Positive Energy Districts and Neighbourhoods*. Tech. rep. URL: https://jpi-urbaneurope.eu/ped/.

JRC (2012). *JRC Photovoltaic Geographical Information System (PVGIS) - European Commission*. URL: https://re.jrc.ec.europa.eu/pvg_tools/en/.

JuliaPlots/PlotlyJS.jl (June 2021). original-date: 2015-11-21T06:06:46Z. URL: https://github.com/JuliaPlots/PlotlyJS.jl (visited on 06/14/2021).

Kabir, Ehsanul et al. (Feb. 2018). "Solar energy: Potential and future prospects". In: *Renewable and Sustainable Energy Reviews* 82. Publisher: Pergamon, pp. 894–900. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2017.09.094.

Keirstead, James et al. (Aug. 2012). "A review of urban energy system models: Approaches, challenges and opportunities". en. In: *Renewable and Sustainable Energy Reviews* 16.6, pp. 3847–3866. ISSN: 1364-0321. DOI: 10.1016/j.rser.2012.02.047. URL: https://www.sciencedirect.com/science/article/pii/S1364032112001414 (visited on 02/18/2021).

Kheloufi, S. et al. (Oct. 2021). "Multi-energy planning of a city neighbourhood and improved stakeholders' engagement—Application to a Swiss test-case". In: *Energy Reports* 7, pp. 343–350. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2021.08.097.

Kieffer, Bruce David (1979). "LOWER COST PASSIVE SOLAR HOMES." In: *IIHR Report (Iowa Institute of Hydraulic Research)*, pp. 367–372.

Koch, Andreas et al. (2012). "Towards a neighbourhood scale for low- or zero-carbon building projects". In: *Building Research {\&} Information* 40.4, pp. 527–537. ISSN: 0961-3218. DOI: 10.1080/09613218.2012.683241. URL: http://www.tandfonline.com/doi/abs/10.1080/09613218.2012.683241.

Koutra, Sesil et al. (2017). "A Simplified methodological approach towards the net zero energy district". In: *Communications in Computer and Information Science*. Vol. 738. Springer Verlag, pp. 207–224. ISBN: 9783319637112. DOI: 10.1007/978-3-319-63712-9{\{}{\textbackslash}{_}{\}}12. URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?.

Lee, Shen C (1979). "ENERGY CONSERVATION BY PASSIVE SOLAR HEATING." In: *Alternative Energy Sources: Proceedings of the Miami International Congress on Energy and the Environment* 9, pp. 3667–3681.

Li, Jiaxin et al. (Nov. 2022). "Driving factors analysis of residential electricity expenditure using a multi-scale spatial regression analysis: A case study". In: *Energy Reports* 8, pp. 7127–7142. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2022.05.026.

Lindholm, Oscar et al. (2021). "Positioning Positive Energy Districts in European Cities". In: *Buildings* 11.1, p. 19. ISSN: 2075-5309. DOI: 10.3390/buildings11010019. URL: https://www.mdpi.com/2075-5309/11/1/19.

Lou, Siwei et al. (Nov. 2020). "Solar energy and daylight on tilt planes under CIE standard skies". In: *Energy Reports* 6, pp. 895–905. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2020.04.014.

Lund, Henrik, Finn Arler, et al. (June 2017). "Simulation versus Optimisation: Theoretical Positions in Energy System Modelling". en. In: *Energies* 10.7, p. 840. ISSN: 1996-1073. DOI: 10.3390/en10070840. URL: http://www.mdpi.com/1996-1073/10/7/840 (visited on 10/17/2019).

Lund, Henrik, Jakob Zinck Thellufsen, et al. (Feb. 2021). "EnergyPLAN – Advanced analysis of smart energy systems". en. In: *Smart Energy* 1, p. 100007. ISSN: 2666-9552. DOI: 10.1016/j.segy.2021.100007. URL: https://www.sciencedirect.com/science/article/pii/S2666955221000071 (visited on 05/03/2021).

Lybæk, Rikke et al. (Jan. 2021). "Enhancing policies for deployment of Industrial symbiosis - What are the obstacles, drivers and future way forward?" In: *Journal of Cleaner Production* 280, p. 124351. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2020.124351.

Maes, Tom et al. (May 2011). "Energy management on industrial parks in Flanders". In: *Renewable and Sustainable Energy Reviews* 15 (4), pp. 1988–2005. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2010.11.053.

Magrini, Anna et al. (2020). "From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example". In: *Developments in the Built Environment* 3, p. 100019. ISSN: 26661659. DOI: 10.1016/j.dibe.2020.100019. URL: https://doi.org/10.1016/j.dibe.2020.100019.

Manso-Burgos et al. (Nov. 2022). "Local energy communities modelling and optimisation considering storage, demand configuration and sharing strategies: A case study in Valencia (Spain)". In: *Energy Reports* 8, pp. 10395–10408. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2022.08.181.

Marique, Anne-Françoise and Sigrid Reiter (Oct. 2014). "A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale". In: *Energy and Buildings* 82, pp. 114–122. ISSN: 03787788. DOI: 10.1016/j.enbuild.2014.07.006. URL: https://linkinghub.elsevier.com/retrieve/pii/S0378778814005404.

Martínez-Gordón, R. et al. (May 2021). "A review of the role of spatial resolution in energy systems modelling: Lessons learned and applicability to the North Sea region". en. In: *Renewable and Sustainable Energy Reviews* 141, p. 110857. ISSN: 1364-0321. DOI: 10.1016/j.rser.2021.110857. URL: https://www.sciencedirect.com/science/article/pii/S1364032121001519 (visited on 06/23/2022).

Maturo, Anthony et al. (Nov. 2021). "Design and environmental sustainability assessment of energy-independent communities: The case study of a livestock farm in the North of Italy". In: *Energy Reports* 7, pp. 8091–8107. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2021.05.080.

Moser, Simon and Gabriela Jauschnik (July 2023). "Using Industrial Waste Heat in District Heating: Insights on Effective Project Initiation and Business Models". In: *Sustainability* 15 (13), pp. 10559–10559. ISSN: 2071-1050. DOI: 10.3390/SU151310559. URL: https://typeset.io/papers/using-industrial-waste-heat-in-district-heating-insights-on-33ohlqa0.

Munday, Dick (1979). "INCLINED MASS TROMBE WALL." In: *IIHR Report (Iowa Institute of Hydraulic Research)*, pp. 762–766.

Nations, United (2015). *The Paris Agreement*. Tech. rep. United Nations. URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (visited on 06/22/2022).

Neteler, Markus et al. (May 2012). "GRASS GIS: A multi-purpose open source GIS". In: *Environmental Modelling & Software* 31. Publisher: Elsevier, pp. 124–130. ISSN: 1364-8152. DOI: 10.1016/J.ENVSOFT.2011.11.014.

Neves, Angela et al. (Dec. 2019). "The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation". In: *Sustainability 2019, Vol. 11, Page 7095* 11 (24), p. 7095. ISSN: 2071-1050. DOI: 10.3390/SU11247095. URL: https://www.mdpi.com/2071-1050/11/24/7095/htm%20https://www.mdpi.com/2071-1050/11/24/7095.

Nichols, Susan and Wayne Nichols (1979). "ISSUES AND OPPORTUNITIES IN PASSIVE SOLAR DEVELOPMENT." In: *Preprints - Division of Petroleum Chemistry, American Chemical Society*, pp. 509–518.

Noll, Scott A. et al. (1979). "TROMBE WALLS AND DIRECT GAIN: PATTERNS OF NATIONWIDE APPLICABILITY." In: *IIHR Report (Iowa Institute of Hydraulic Research)*, pp. 199–206.

Nzengue, Yvann et al. (2018). "Planning city refurbishment: An exploratory study at district scale how to move towards positive energy districts - Approach of the SINFONIA project". In: *2017 International Conference on Engineering, Technology and Innovation: Engineering, Tech-*

nology and Innovation Management Beyond 2020: New Challenges, New Approaches, ICE/ITMC 2017 - Proceedings 2018-Janua.609019, pp. 1394–1400. DOI: 10.1109/ICE.2017.8280045.

openmod (2020). *Open Models - wiki.openmod-initiative.org*. URL: https://wiki.openmod-initiative.org/wiki/Open_Models (visited on 04/15/2021).

Paatero, Jukka (2009). *COMPUTATIONAL STUDIES ON VARIABLE COMPUTATIONAL STUDIES ON VARIABLE*.

Pachauri, Rajendra K and Andy Reisinger (2008). *Climate change 2007: Synthesis Report*. Tech. rep., p. 104.

Pärssinen, Matti et al. (Jan. 2019). "Waste heat from data centers: An investment analysis". In: *Sustainable Cities and Society* 44, pp. 428–444. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2018.10.023.

Petcu, Cristian et al. (Oct. 2017). "Materials from Renewable Sources as Thermal Insulation for Nearly Zero Energy Buildings (nZEB)". In: pp. 159–167. DOI: 10.1007/978-3-319-63215-5{_}12. URL: https://link.springer.com/chapter/10.1007/978-3-319-63215-5_12.

Pfeifroth, Uwe et al. (2017). *Surface Radiation Data Set - Heliostat (SARAH) - Edition 2No Title*. Tech. rep. Satellite Application Facility on Climate Monitoring. DOI: https://doi.org/10.5676/EUM_SAF_CM/SARAH/V002..

Pfenninger, Stefan, Adam Hawkes, et al. (May 2014). "Energy systems modeling for twenty-first century energy challenges". en. In: *Renewable and Sustainable Energy Reviews* 33, pp. 74–86. ISSN: 13640321. DOI: 10.1016/j.rser.2014.02.003. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364032114000872 (visited on 04/28/2020).

Pfenninger, Stefan and Bryn Pickering (Sept. 2018). "Calliope: a multi-scale energy systems modelling framework". en. In: *Journal of Open Source Software* 3.29, p. 825. ISSN: 2475-9066. DOI: 10.21105/joss.00825. URL: https://joss.theoj.org/papers/10.21105/joss.00825 (visited on 04/30/2020).

Pfenninger, Stefan and Iain Staffell (Nov. 2016a). "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data". In: *Energy* 114. Publisher: Pergamon, pp. 1251–1265. ISSN: 0360-5442. DOI: 10.1016/J.ENERGY.2016.08.060. URL: www.renewables.ninja.

— (2016b). *Renewables.ninja*. URL: https://www.renewables.ninja/.

Plumb, James (1979). "SUNCATCHER HOUSE." In: *Preprints - Division of Petroleum Chemistry, American Chemical Society*, pp. 495–498.

Project, Sinfonia (2019). *Sinfonia Smartcities - District Heating Bolzano*. URL: http://www.sinfonia-smartcities.eu/en/demo-site/district-heating-bolzano.

— (2020). *Sinfonia Smartcities - Project*. URL: http://www.sinfonia-smartcities.eu/en/project.

Purvis, Ben et al. (2019). "Three pillars of sustainability: in search of conceptual origins". In: *Sustainability Science* 14.3, pp. 681–695. ISSN: 18624057. DOI: 10.1007/s11625-018-0627-5. URL: https://doi.org/10.1007/s11625-018-0627-5.

Ramaswami, Anu et al. (May 2011). "Two Approaches to Greenhouse Gas Emissions Foot-Printing at the City Scale". en. In: *Environmental Science & Technology* 45.10, pp. 4205–4206. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/es201166n. URL: https://pubs.acs.org/doi/10.1021/es201166n (visited on 05/06/2020).

Rienecker, Michele M. et al. (July 2011). "MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications". In: *Journal of Climate* 24.14. Publisher: American Meteorological Society, pp. 3624–3648. ISSN: 0894-8755. DOI: 10.1175/JCLI-D-11-00015.1. URL: https://journals.ametsoc.org/view/journals/clim/24/14/jcli-d-11-00015.1.xml.

Rosen, Robert (1991). *Life Itself. A Comprehensive Inquiry Into the Nature, Origin, and Fabrication of Life.* 1st ed. Columbia University Press. ISBN: 978-0-231-07564-0.

Saini, Puneet et al. (Oct. 2023). "Techno-economic analysis of a 5th generation district heating system using thermo-hydraulic model: A multi-objective analysis for a case study in heating dominated climate". In: *Energy and Buildings* 296, p. 113347. ISSN: 0378-7788. DOI: 10.1016/J.ENBUILD.2023.113347.

Schnieders, Jürgen et al. (2015). "Passive Houses for different climate zones". In: *Energy and Buildings* 105, pp. 71–87. ISSN: 03787788. DOI: 10.1016/j.enbuild.2015.07.032.

Selvakkumaran, Sujeetha et al. (Oct. 2021). "How do business models for prosumers in the district energy sector capture flexibility?" In: *Energy Reports* 7, pp. 203–212. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2021.08.154.

SINFONIA (2020). *Sinfonia Project*. URL: http://www.sinfonia-smartcities.eu/ (visited on 06/30/2021).

Song, Ziye et al. (2022). "Multi-objective optimization strategy for home energy management system including PV and battery energy storage". In: *Energy Reports* 8. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2022.04.023.

Sørnes, Kari (2017). *Improvement proposals for replication actions*. Tech. rep. URL: http://hdl.handle.net/11250/2502084.

Strategic Energy Transition Plan 3.2 (2018). *Europe to become a global role model in integrated, innovative solutions for the planning, deployment, and replication of Positive Energy Districts*. en. URL: https://setis.ec.europa.eu/implementing-actions/set-plan-documents_en (visited on 06/23/2022).

Sun, Yuming et al. (July 2014). "Quantification of model form uncertainty in the calculation of solar diffuse irradiation on inclined surfaces for building energy simulation". In: *Journal of Building Performance Simulation* 8 (4), pp. 253–265. ISSN: 19401507. DOI: 10.1080/19401493.2014.914247. URL: https://www.tandfonline.com/doi/abs/10.1080/19401493.2014.914247.

Termovalorizzatore Bolzano (2023). URL: https://www.eco-center.it/it/attivita-servizi/ambiente/impianti/impianto-di-termovalorizzazione-897.html.

The National Institute of Building Sciences (2015). *A Common Definition for Zero Energy Buildings*. URL: https://www.energy.gov/eere/buildings/downloads/common-definition-zero-energy-buildings.

Tymura, Edward J. (1979). "SOLUTIONS TO ENERGY CONSERVATION IN NORTHERN CLIMATES." In: *IIHR Report (Iowa Institute of Hydraulic Research)*, pp. 708–712.

Vaquero, P. et al. (Dec. 2020). "Portugal 2020: Improving energy efficiency of public infrastructures and the municipalities' triple bottom line". In: *Energy Reports* 6, pp. 423–429. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2020.11.195.

Wahlroos, Mikko et al. (Feb. 2018). "Future views on waste heat utilization – Case of data centers in Northern Europe". In: *Renewable and Sustainable Energy Reviews* 82, pp. 1749–1764. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2017.10.058.

Wenninger, Simon et al. (Nov. 2022). "Evidence for residential building retrofitting practices using explainable AI and socio-demographic data". In: *Energy Reports* 8, pp. 13514–13528. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2022.10.060.

Wessling Jr., F.C. (1974). "THERMAL ENERGY STORAGE IN ADOBE AND IN STONE STRUCTURES." In: *American Society of Mechanical Engineers (Paper)* 74 -WA/HT-.

Wiese, Catharina et al. (Apr. 2018). "Interaction effects of energy efficiency policies: a review". In: *Energy Efficiency 2018 11:8* 11 (8), pp. 2137–2156. ISSN: 1570-6478. DOI: 10.1007/S12053-018-9659-Z. URL: https://link.springer.com/article/10.1007/s12053-018-9659-z.

Wurbs, Ralph A. (July 1993). "Reservoir-System Simulation and Optimization Models". en. In: *Journal of Water Resources Planning and Management* 119.4, pp. 455–472. ISSN: 0733-9496, 1943-5452. DOI: 10.1061/(ASCE)0733-9496(1993)119:4(455). URL: http://ascelibrary.org/doi/10.1061/%28ASCE%290733-9496%281993%29119%3A4%28455%29 (visited on 04/23/2020).

Zhang, Lingwei et al. (Apr. 2021). "A Framework for Design and Operation Optimization for Utilizing Low-Grade Industrial Waste Heat in District Heating and Cooling". In: *Energies* 14 (8), p. 2190. ISSN: 1996-1073. DOI: 10.3390/EN14082190. URL: https://typeset.io/papers/a-framework-for-design-and-operation-optimization-for-2dadjafhw0.

Appendix A

Monthly Results MESS vs. Calliope

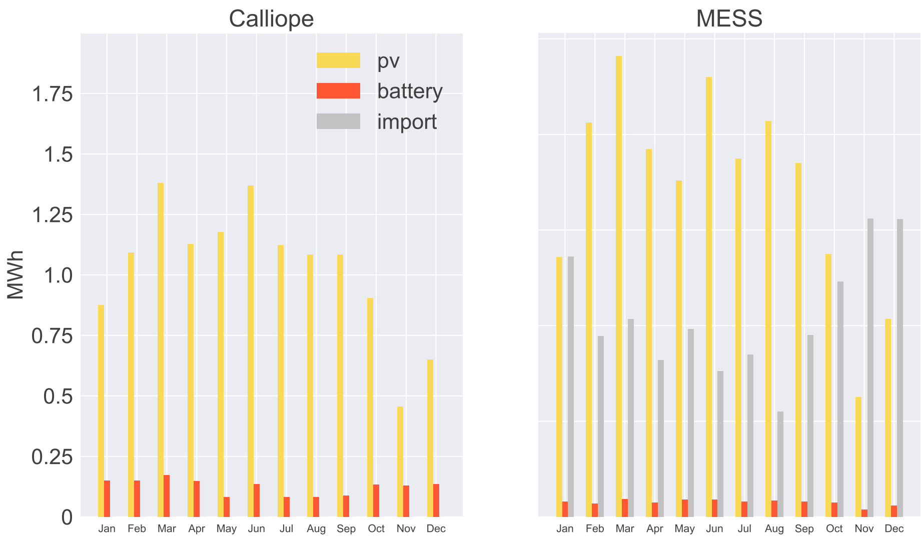


Figure 46: Monthly electricity generation per technology: Location X2 - Calliope and MESS comparison

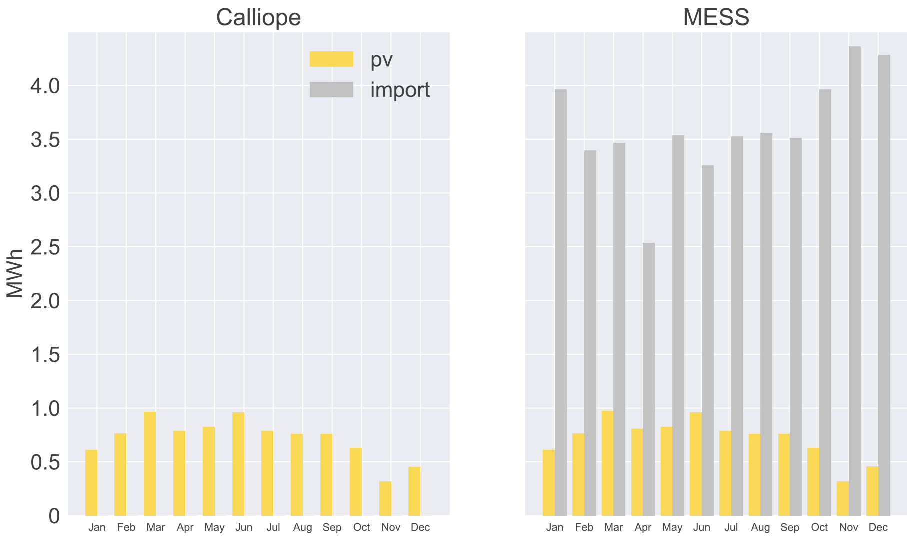


Figure 47: Monthly electricity generation per technology: Location X3 - Calliope and MESS comparison

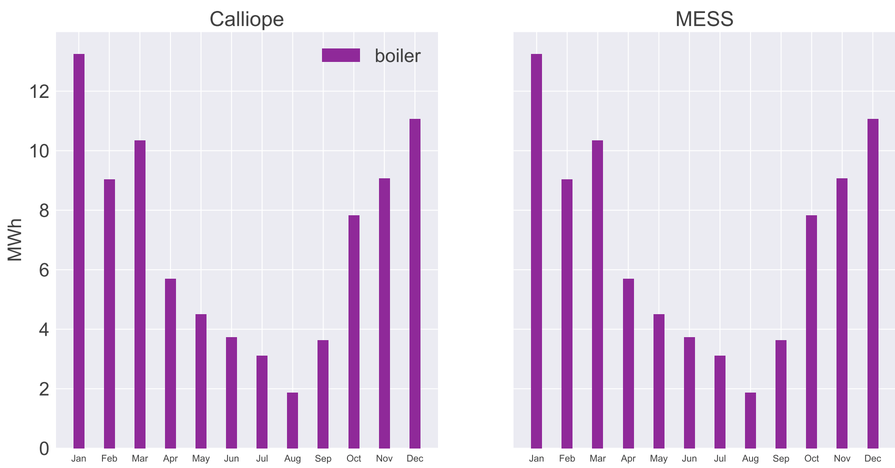


Figure 48: Monthly heating generation per technology: Location X2 - Calliope and MESS comparison

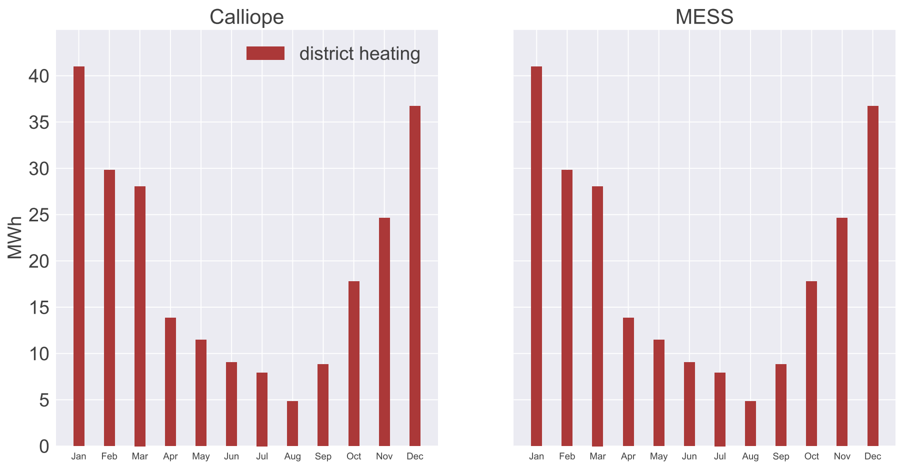


Figure 49: Monthly heating generation per technology: Location X3 - Calliope and MESS comparison

Weekly Results MESS vs. Calliope

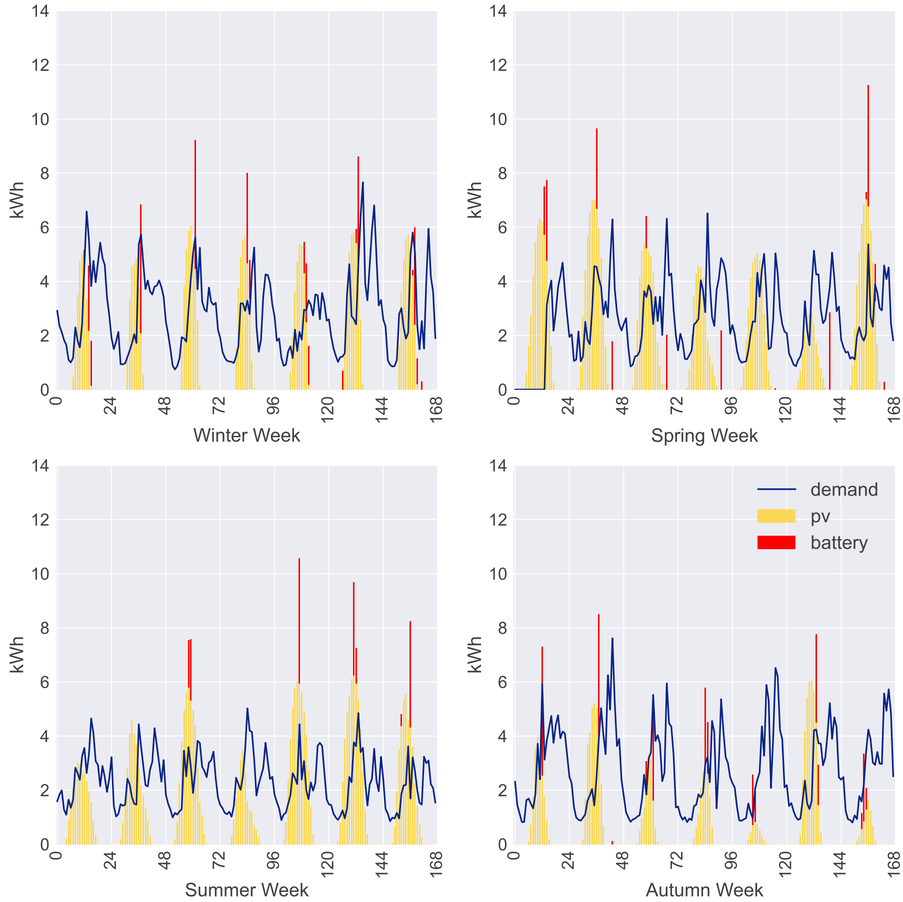


Figure 50: Weekly electricity generation per technology: Location X2 - Calliope

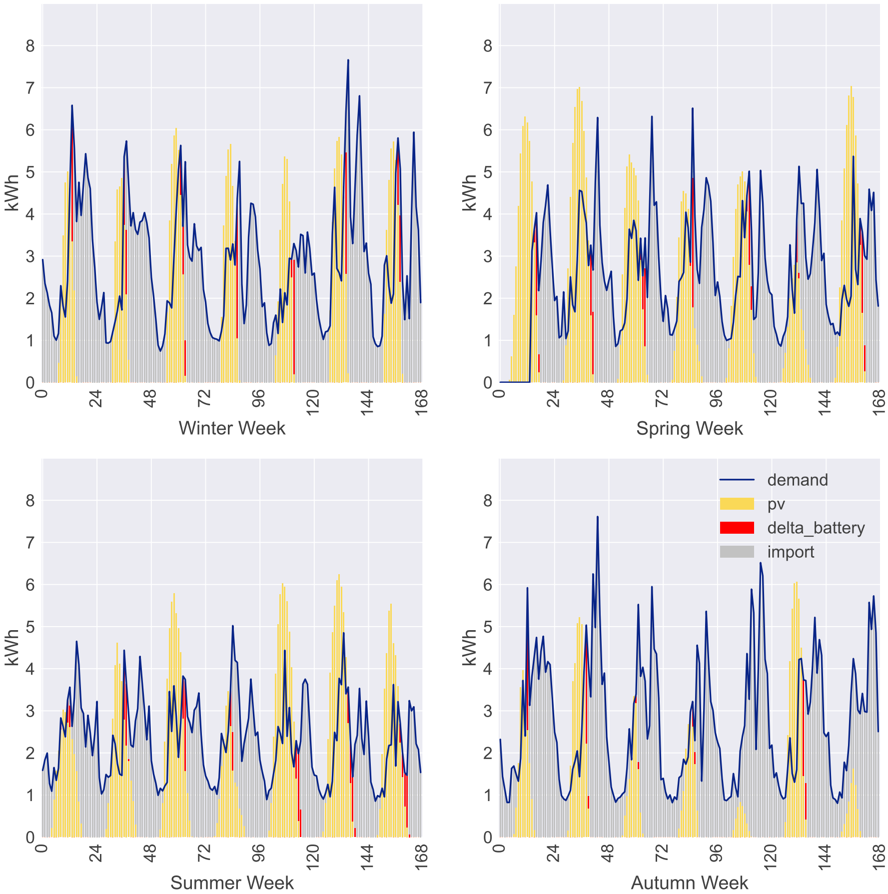


Figure 51: Weekly electricity generation per technology: Location X2 - MESS

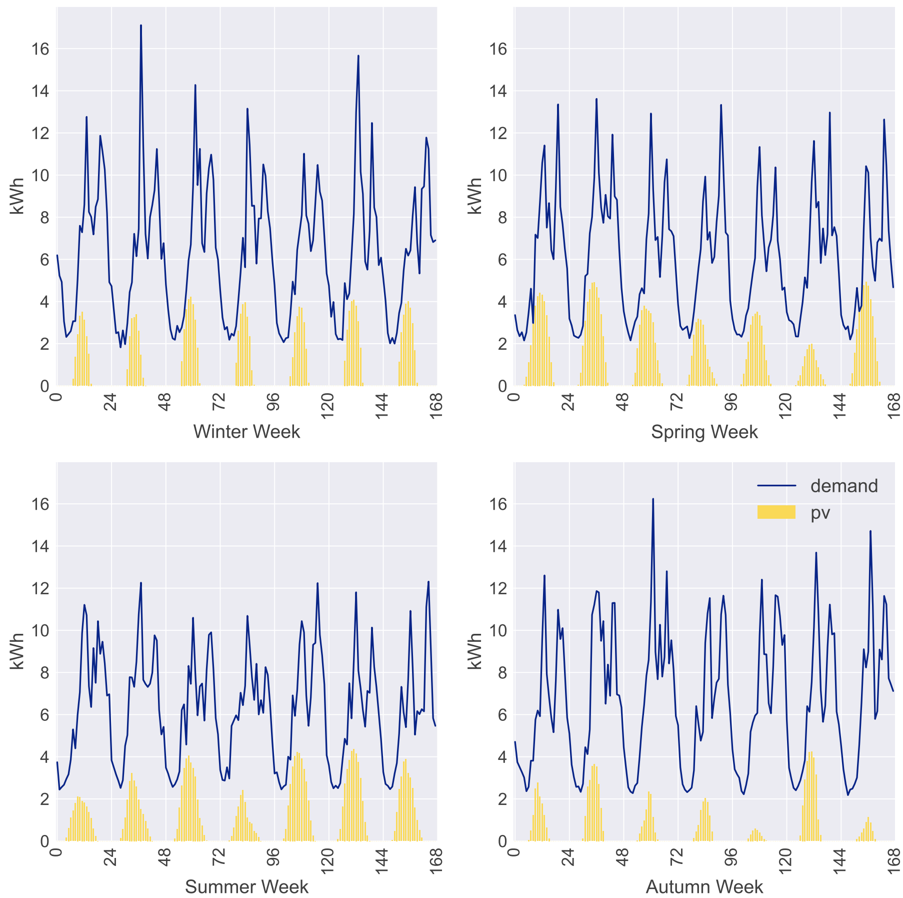


Figure 52: Weekly electricity generation per technology: Location X3 - Calliope

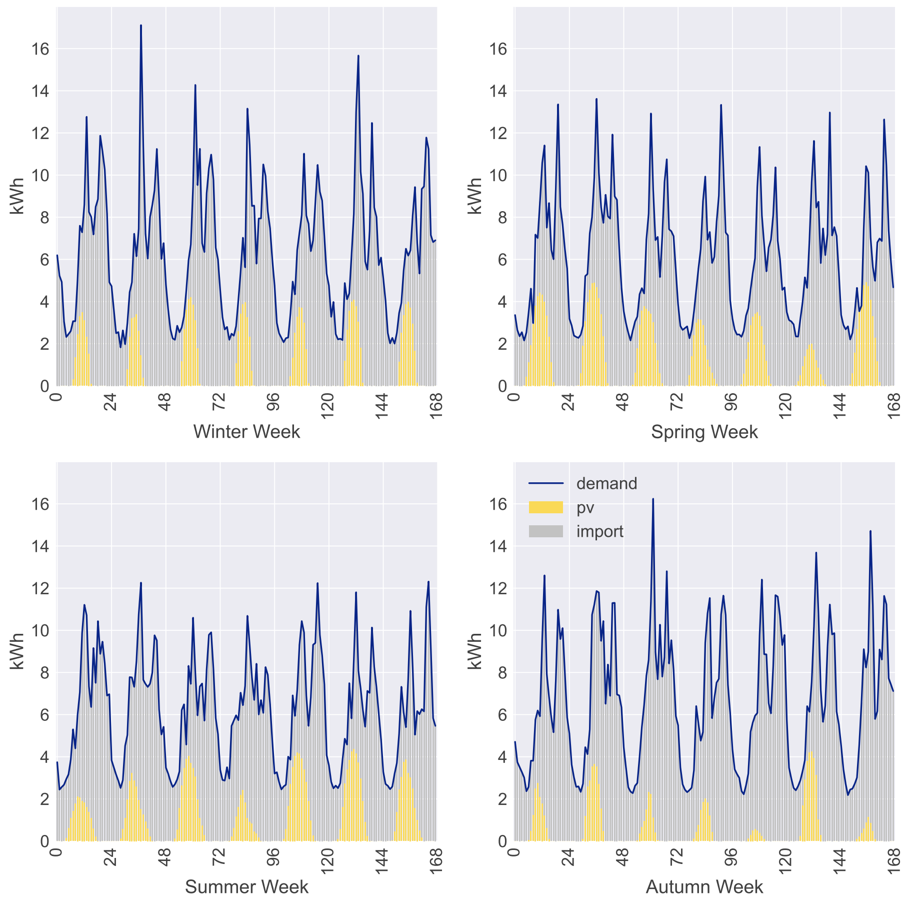


Figure 53: Weekly electricity generation per technology: Location X3 - MESS