Modelling Decentralised Energy Systems during capacity planning to mitigate grid congestion:
A Case Study of Business Park Uitgeest-Noord

Using linear programming optimisation modelling to optimise for costs and emission of decentralised energy system and improve local electricity security.

MSc Industrial Ecology
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By

Hidde Grootes

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Cover image: Business Park Uitgeest-Noord [1]

Preface

In the last six months, I had the opportunity to work on an innovative solution in the field of grid congestion for my thesis, with a specific focus on Decentralised Energy Systems. The thesis is part of my MSc in Industrial Ecology, a joint degree between Delft University of Technology and Leiden University. One of my main goals was to conduct my thesis at a company to gain a close-up perspective on this problem. Darel Consultancy kindly provided me with a graduation spot and the necessary resources.

With the idea of conducting a case study and performing energy modelling, I reached out to several supervisors at TU Delft. I was fortunate that my first supervisor, Francesco Lombardi, could provide the missing piece: an energy modelling tool in the form of Calliope. Together with my second supervisor, Udo Pesch, whose expertise lies more on the social side, I had the perfect supervisory team. The bi-weekly sessions with Francesco Lombardi were crucial in shaping my research, offering support with all things Calliope-related, and providing general guidance. I am especially grateful for his patience and easygoing approach, which helped me a lot. During the formal sessions, Udo Pesch helped to steer my research in the right direction and offered many useful tips on where to focus. I have a tendency to explore many interesting topics, but he reminded me that quality is more important than quantity, and made sure that the logical storyline inside my head also appeared on paper, for the reader.

This thesis would not have been possible without the resources provided by Darel Consultancy. They supplied me with a comprehensive data set on Uitgeest-Noord and related subjects. During my time at the office in Rotterdam, I immediately felt like part of the team. Over the six months, I went to the office almost every day, which helped me stay focused and allowed me and the rest of the team to get to know each other very well. In general meetings, they valued my input, and it was fascinating to see which projects were being delivered by Darel Consultancy. Special thanks to the weekly meetings with Nick Bowring, who guided me from his own experience by asking the right questions. His view strengthened the reasoning in my thesis. Thanks for always being at the office to make the days more fun and enjoyable. Rolph Spaas my second external supervisor played a crucial role in shaping the subject of this thesis and connecting me with people involved in the case study at Uitgeest-Noord. Hereby, I would like to thank the rest of the team at Darel Consultancy for all the help and genuine interest in my thesis, and my work. I enjoyed seeing and feeling the intrinsic motivation from everyone at the office, for working in the energy transition and striving to improve every day. With as highlight to do the 375 km bike route to Groningen as a team, in supporting the Climate Classic 2024.

I hope this thesis provides new insights into decentralised energy systems, and I wish you an enjoyable read.

Hidde Grootes,
Rotterdam, August 2024

Abstract

The European Union faces a significant challenge: energy use and production are responsible for over 75% of greenhouse gas emissions. To achieve carbon neutrality by 2050, there is a need for a shift towards decarbonising the energy grid, including innovative solutions. This research project focuses on the business park Uitgeest-Noord, located in the Netherlands. Uitgeest-Noord serves as a testing ground for a decentralised energy system that optimises energy components (solar and storage) to mitigate local-scale grid congestion. Therefore, the main research question is: *Can the ideal configuration of a decentralised energy system (DES) be effectively designed to avoid local grid congestion and support capacity planning during the electrification of the Business Park Uitgeest-Noord?*

To address the main research question, the thesis employs a structured methodology that includes four steps: I) theoretical context analysis, II) data collection, III) linear programming optimisation modelling, and IV) result analysis. The third step includes building a linear programming optimisation modelling setup specific to Uitgeest-Noord, with a primary objective to optimise for monetary and emissions cost classes. By running different scenarios to assess potential configurations, and analysing the results using a cview dashboard.

Key findings indicate, among other things, that integrating PV panels, EV charging infrastructure, and heat pumps without a Battery Energy Storage System (BESS) leads to significant PV curtailment and occasional grid congestion. In addition, adding BESS reduces PV curtailment and reliance on external grid supply, optimising renewable energy use. The ability to export stored electricity for revenue shows financial benefits but also highlights potential grid stress. Furthermore, battery size and PV capacity are closely linked, with cost constraints significantly impacting the system's configuration.

BESS plays a critical role in managing grid congestion and optimising renewable energy use. Flexible and scalable energy systems are essential for adapting to varying demand patterns and seasonal changes in energy generation. Therefore, accurate data collection and realistic assumptions are crucial for reliable modelling outcomes. The economic viability of different configurations is a key factor, with the model displaying that strategic use of storage and dynamic pricing can optimise financial performance.

In conclusion, this thesis project has effectively designed the ideal DES configuration for Uitgeest-Noord via a linear programming optimisation model, contributing to preventing grid congestion and supporting capacity planning. This thesis provides valuable insights into the benefits of DES and the importance of storage solutions, flexible system design, accurate data, and economic and emissions considerations. The academic value of this thesis lies in its energy modelling setup, which enables different modelling scenarios and improves performance through iterative analysis, all in a simulated environment. The reproducibility of this modelling approach makes it applicable to other case studies, advancing the understanding and practical implementation of DES in various contexts.

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List of Abbreviations

Abbreviation	*Definition*
AC	Alternating Current
BESS	Battery Energy Storage System
DC	Direct Current
DES	Decentralised Energy System
DERs	Distributed Energy Resources
EU	European Union
EMS	Energy Management System
IDES	Integral Decentralised Energy System
PV	Photovoltaic
RES	Renewable Energy Sources
LV	Low-voltage
MV	Medium-voltage

1 Introduction of research scope and case study

This thesis research was conducted during a graduation internship at Darel Consultancy in Rotterdam. This chapter introduces the thesis's research topic, focusing on the necessity and implications of decentralised energy systems (DES) in the Netherlands. First, it elaborates on the urgent need for such systems due to the current energy and environmental challenges faced by the European Union (EU). It then introduces the specific case study of Business Park Uitgeest-Noord, which is used as a practical testing ground for analysing and addressing these challenges, particularly grid congestion.

1.1 Necessity of Decentralised Energy Systems (DES)

More than three-quarters of total greenhouse gas emissions in the EU come from energy use and production. To achieve carbon neutrality by 2050, it is crucial to have a long-term plan to decarbonise the EU's energy system [2]. The European Environment Agency notes that the EU has more than doubled its use of renewable energy sources (wind power, solar power, hydroelectric, ocean energy, geothermal energy, biomass, and biofuels) since the beginning of this decade. This growth addresses climate change mitigation by reducing air pollutants and improving energy security. It aligns with the updated Renewable Energy Directive by the European Commission, which has set a binding target in 2030 to increase the total share of renewable energy sources (RES) to 42.5%.

As of 2022, the Netherlands needs to catch up with only 15% of its total energy consumption coming from renewable energy sources, below the EU average of 22% [3]. Figure 1.1 illustrates the total energy consumption in the Netherlands per energy commodity in 2022, where electricity accounts for 23%.

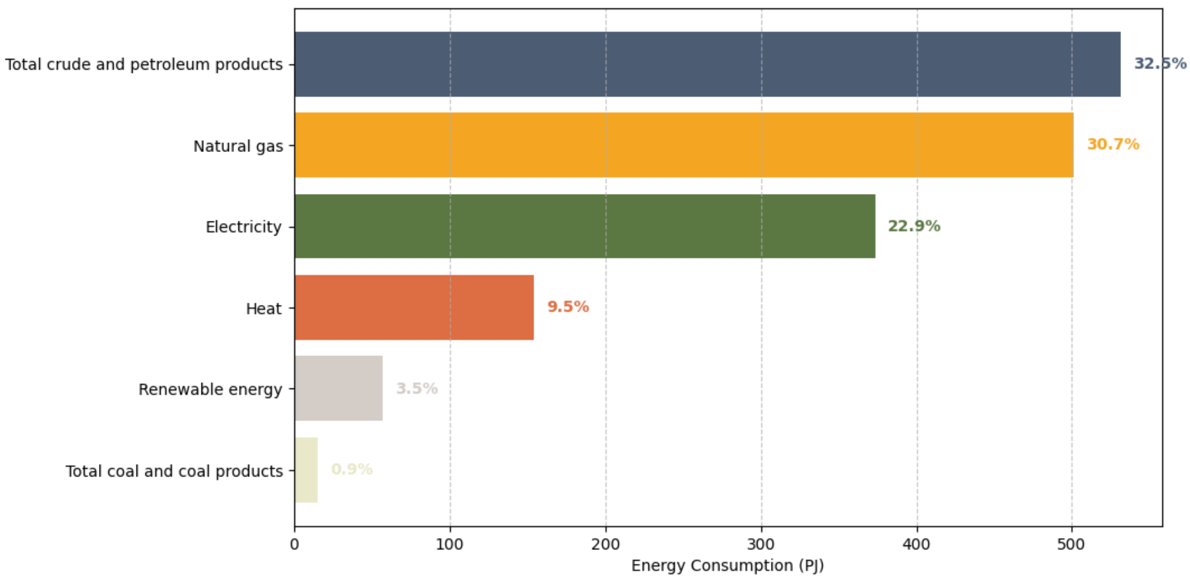

Figure 1.1: Final Energy Consumption per Energy Commodity 2022 Source [4]

There is an increasing need to transition towards a greener energy mix to comply with the EU Renewable Energy Directive. Figure 1.2 shows the percentage of energy sources to produce electricity commodity, indicating a higher share of RES (around 50%) in electricity production. Due to the widespread adoption of heat pumps and electric cars, the electrification of daily lives is leading towards substituting fossil fuels for electricity generation. With this shift towards an increase in electricity usage and thus a higher share in the Dutch energy mix, the existing energy grid experiences higher quantities of electricity, for which it originally was not designed [4]. Figure 1.2 shows a slight upward trend in total electricity volume since 2015, a trend that is expected to continue [5].

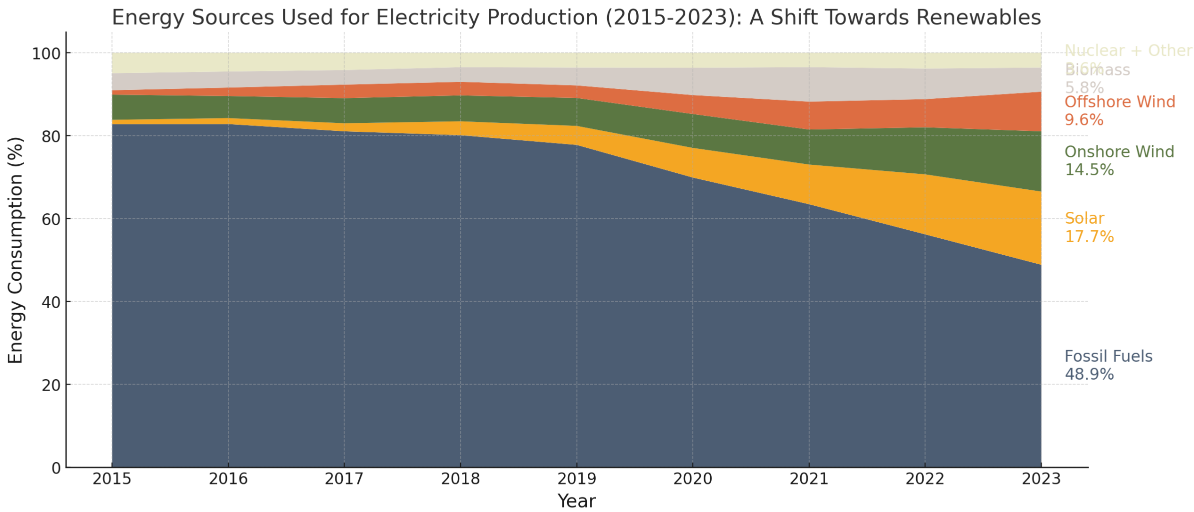

Figure 1.2; Percentage of electricity production by source (source: [5]).

The Netherlands still relies 50% on fossil fuels such as natural gas, coal, and oil to produce traditional electricity. This electricity is generated at large power plants and distributed through national and regional grid operators. As upcoming renewable energy sources like wind and solar power become more prevalent, the grid's reliance on weather conditions increases, leading to greater volatility and peak moments in electricity consumption and production. Integrating wind and solar power on different grid operator levels (see Figure 1.3) requires additional transport capacity during these peak hours, which poses new challenges for the current energy grid. These challenges were not initially anticipated by the regional grid operator level [6].

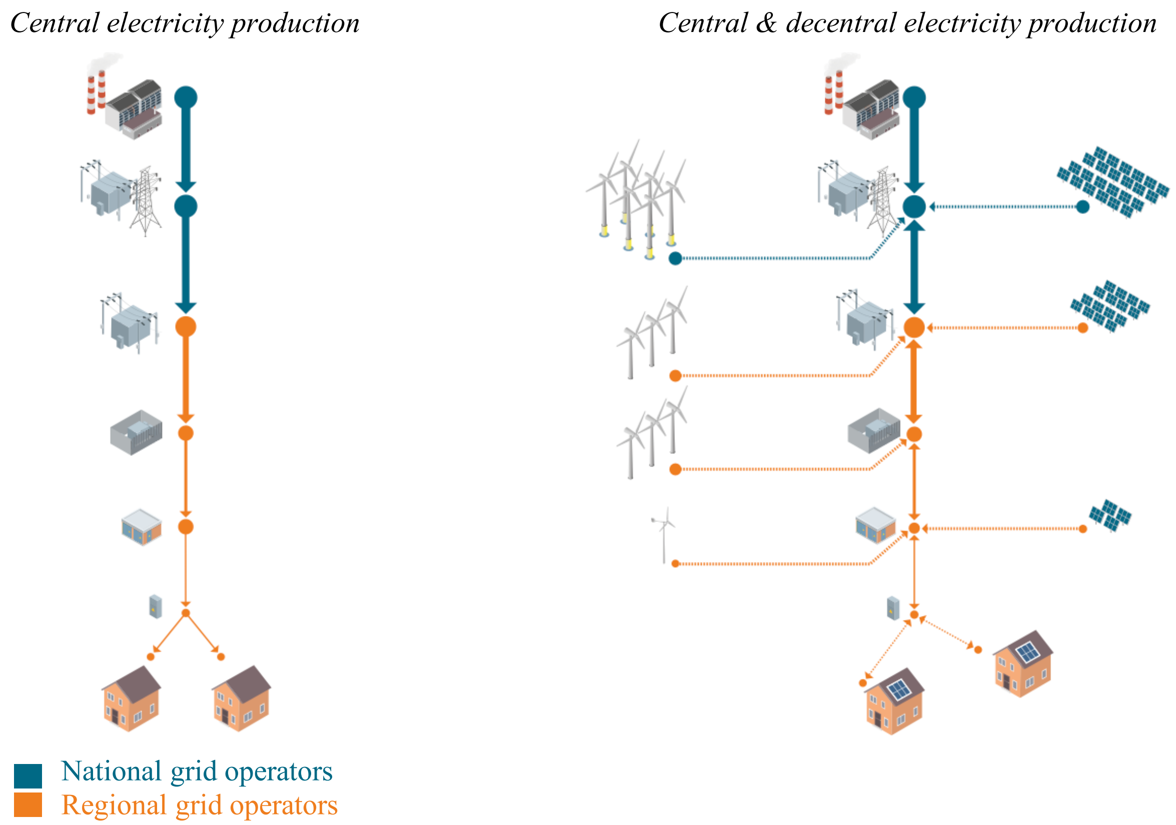

Figure 1.3: From central to decentral electricity production [7]

To keep up with an increasing demand for electricity and the growing input of RES, it is crucial to expand the capacity of the current grid system. However, this expansion process is costly and slow due to lengthy regulatory procedures, leading to grid congestion at the current capacity. As a result, no new grid connections are permitted, and the existing grids are at their maximum transport capacity [8] [9]. Therefore, adaptation measures are required to use the current transport capacity more efficiently. This includes short-term storage solutions to manage fluctuations and solve this duckcurve. A potential solution for this is decentralised electricity generation, where electricity is generated at the location of use. This approach optimises, stabilises, and makes generating RES more flexible [10]. With decentralised electricity generation, stress on the energy grid and grid congestion can be alleviated [11] by allowing for rapid implementation and construction to avoid long licensing processes [12]. However, Decentralised systems can have higher capital costs per kWh and suffer from poor technical capacity planning beforehand, leading to unstable performance [13]. A case study research is discussed in the next section to address these challenges.

1.2 Case study: Business Park Uitgeest-Noord

In transitioning to sustainable energy systems, decentralised energy systems (DES) are gaining increasing attention due to their potential to enhance energy efficiency and grid reliability at the place of installation, as discussed above. However, the current literature lacks a clear performance overview of specific locations; therefore, this thesis focuses on the case study of Business Park Uitgeest-Noord in the Netherlands, an area that experiences challenges associated with grid congestion.

Located above the Noordzeekanaal, this business park has 170 companies employing over 1500 full-time workers. The diverse range of small to medium-sized companies, including a mix of production sites and regular offices, results in varied energy consumption patterns, making Uitgeest-Noord an ideal subject for studying energy management solutions concerning grid congestion issues (see Figure 1.4).

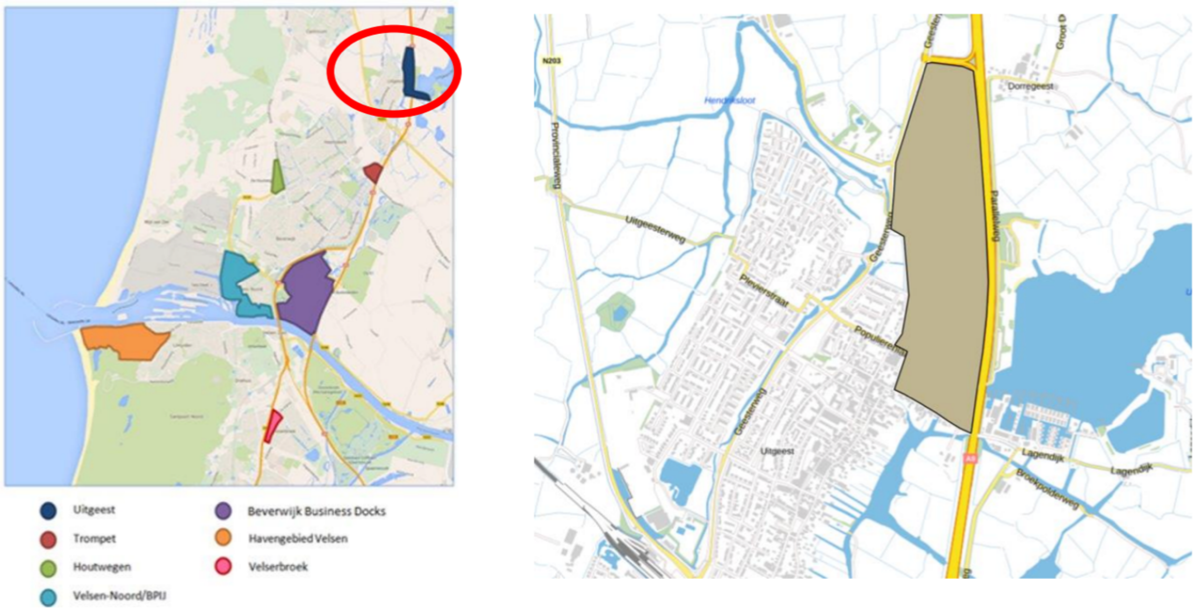

Figure 1.4: Visual map overview of Business Park Uitgeest-Noord (source: [14])

Business Park Uitgeest-Noord was chosen as the case study due to the availability of detailed energy consumption data from conducted energy scans. These scans provide diverse consumption profiles, highlighting the complexities of energy management in various business environments. By analysing this case, the study aims to expand knowledge on how DES can enhance energy efficiency and manage grid congestion in similar settings. Business Park Uitgeest-Noord, located in the IJmond region, is an ideal case study for this research.

The transition towards electrification presents several challenges, such as adopting photovoltaic (PV) panels, heat pumps, and electric vehicle (EV) charging infrastructure. The current grid connection at Uitgeest-Noord is inadequate to support the increasing demand, and obtaining a larger grid connection in the short term is unfeasible. In this case, understanding the overall dynamics of demand and supply offers significant potential to test the influence of DES using energy modelling software. Previous research and discussions with the current energy management partner at business parks have highlighted the importance of custom solutions to address unique energy consumption patterns. Compared to other business parks, Uitgeest presents complexity as a mixed-use business park. A previous study identified key areas for improvement, such as installing solar panels, building-related savings, process-related savings, and the electrification of mobility [14]. However, this study fails to adequately address a solution to the problem arising from this step towards full electrification.

1.3 Main research question

To address the critical challenges posed by the transition toward full electrification, this thesis focuses on understanding the implications for capacity planning concerning PV capacity and short-term storage solutions in a DES. Detailed insights into early-stage capacity planning for installation of DES is crucial. Therefore, this thesis explores whether an energy modelling tool can support in effectively determine the ideal configuration for a DES to support Business Park Uitgeest-Noord.

Main Research Question: *Can the ideal configuration of a decentralised energy system (DES) be effectively designed to avoid local grid congestion and support capacity planning during the electrification of the Business Park Uitgeest-Noord?*

In alignment with the main research question, the thesis will address several sub-research questions, focusing on the specific factors contributing to local-scale grid congestion within the business park, the potential for determining the ideal configuration of a DES using Calliope, and how such a modelling system can be generalised for broader applications. Additionally, the study will explore key lessons from the case study to produce practical results applicable to different types of small business parks and the socio-environmental benefits arising from the implementation of DES.

1.4 Optimising the DES of Uitgeest-Noord with the energy modelling tool Calliope

To prevent future grid congestion, Calliope, a multi-scale energy modelling system, is used to create a model of the energy system for Uitgeest-Noord. Calliope operates in Python and uses human-readable YAML files in combination with time-series CSV data to represent energy components like technologies that can mimic locations, and run multiple scenarios. The goal is to find the optimal configuration for the DES in Uitgeest-Noord, which includes PV panels and short-term storage solutions.

Section 4.2 elaborates on the concept model, emphasising the need to account for seasonal variations and unique local factors when modelling a DES. It discusses the importance of accurately providing energy generation profiles and integrating real-world data with modelled scenarios to improve grid integration and derive technical and economic benefits. Uitgeest-Noord is used as a case study to test these concepts.

Calliope's design is modular and flexible, allowing for the building and adaptation of complex energy models using a combination of linear programming and user-defined temporal and spatial resolutions. Additionally, the accuracy of the model depends heavily on the quality of input data, and the chosen modelling flow can impact the complexity and feasibility of the model. Understanding these assumptions and limitations is crucial for evaluating Calliope's accuracy and applicability in the analysis phase. This chapter also outlines some of the key benefits and drawbacks of the Calliope framework, providing a comprehensive overview of the tool's capabilities and constraints.

1.5 Societal relevance and Industrial Ecology link

In the Netherlands, grid congestion has significant societal and economic consequences. Companies are not able to innovate with sustainable ideas by expanding their electrification, the current business climate is under pressure, and new residents and companies are on a waiting list for new grid connections [15]. Within the Industrial Ecology field, we emphasise adopting systems thinking to analyse sustainability-related problems, explore innovative solutions, and, most importantly, devise strategies for implementing these solutions. This research project tackles a current issue using an energy modelling tool. The goal is to propose innovative solutions to solve grid congestion with the currently available transport capacity. With the case study at a business park in Uitgeest-Noord, a devised strategy can be advised, implemented and monitored in the future.

2 Theoretical foundation

Building upon the introduction in Chapter 1, which highlighted the urgent need for DES and introduced the case study of Business Park Uitgeest-Noord, this chapter aims to create a theoretical foundation. This theoretical foundation elaborates on four key theoretical pillars enabling a strong foundation of knowledge for further research conducted within this thesis, namely:

2.1 Grid congestion
2.2 Decentralised Energy Systems
2.3 Background information on the case study
2.4 Background information on linear programming optimisation modelling tool

At the end of this section, all theory is compared, combined and concluded into an exposed knowledge gap (section 2.5), which supports the scientific relevance of this thesis project and, therefore, forms the theoretical foundation that is sought for the research questions.

2.1 Grid congestion

The increasing integration of renewable energy sources into the electricity grid has significantly raised the demand for electricity transmission, placing considerable pressure on the existing infrastructure. Grid congestion occurs when the demand for electricity surpasses the grid's transport capacity, either during peak energy generation from sources like wind and solar (supply-side congestion) or during periods of high electricity demand (demand-side congestion). In the Netherlands, grid operators define grid congestion as a scenario where forecasted electricity usage exceeds the safety margins of the grid's transport capacity. This condition is called "theoretical grid congestion," representing a potential risk rather than an actual overload. When this theoretical peak is reached, grid operators may be unable to accommodate all requests to supply or withdraw electricity, thereby preventing actual grid overloads [9]. This thesis refers to grid congestion for both theoretical "forecasted' grid congestion and actually measured grid congestion.

Transport capacity is determined by the peak power required to maintain a stable electricity connection for each customer. However, this approach often results in significant underutilisation of grid capacity, as safety margins are calculated based on the highest potential peak demand, leading to unused capacity during lower usage periods. This inefficiency, as illustrated by the green area in Figure 2.1, underscores the need for a more optimised approach to managing the grid's transport capacity [7].

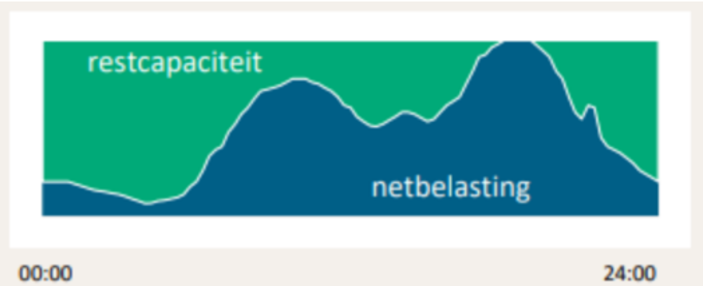

Figure 2.1: Energy profile with rest capacit and peak power at the grid (00:00 - 24:00) (Source [16])

In the Netherlands, it is expected that by 2030, one in three areas requiring network expansion will not have the necessary infrastructure. To address this challenge, section 2.1.3 discusses how integrating a battery within a DES can help utilise the otherwise unused capacity. By storing excess energy during periods of low demand and releasing it when demand is high, a DES can optimise the grid's available capacity, thereby reducing the pressure on the grid and minimising the need for further expansion [17]

2.2 Decentralised Energy System

To further explore the potential and challenges of DES within the context of Business Park Uitgeest-Noord, it is crucial to examine the specific elements that contribute to an effective DES. DES refers to an energy system characterised by the generation of electricity at or near the point of use rather than relying on large, centralised power plants. In Uitgeest-Noord, the DES consists of electricity generation through PV panels and a short-term storage solution in the form of a Battery Energy Storage System (BESS). To provide a fundamental understanding of DES at Uitgeest-Noord, three key areas have been identified from the literature review as essential theoretical contexts in understanding DES, which also supports a deeper understanding of the analysis of the results. First, a better understanding of the position of DES within the current energy transition is necessary, as it sets the stage for its relevance and impact. Following this, a theoretical context on energy generation profiles is provided, which directly influences the proposed Battery Energy Storage System. Understanding these elements is critical to ensuring the effective implementation and optimisation of the DES at Business Park Uitgeest-Noord.

2.2.1 Position of DES in the current energy transition through the Berkana Two-Loop model

In order to provide a better perspective on the position of DES within the current energy transition to underscore the necessity of researching DES via a case study is shown in Figure 2.2. Therefore, the Berkana two-loop model is utilised, and the methodology behind it is explained in more detail in section 4.1.1. Following the first loop of the model represents the dominant energy system, which is characterised by centralised electricity production and distribution through traditional grid infrastructure. This system relies heavily on fossil fuels, creating a path dependence that hinders the transition to sustainable energy solutions. Consequently, the current grid is not well-equipped to support the emergence of DES. The second loop, depicted at the bottom, illustrates the rise of a new energy system driven by innovators and early adopters who form communities with diverse and innovative practices. These pioneers must nourish and grow their influence to facilitate the development of DES. While some outliers may not succeed, they play a crucial role in the overall innovation process. As the emergent network strengthens, the dominant system gradually decays, allowing DES to flourish. With a current achievement of a 50% share of renewable electricity generation, the decline of the dominant system is evident. However, ongoing efforts are essential to continue forming, practising, nourishing and expanding new communities to support this transition. Visualising our current position in this transition with the blue line in Figure 2.2 highlights the critical importance of fostering these emergent networks with example practices to ensure the growth and stability of DES. Therefore, a case study research of the early adopters (Uitgeest-Noord) is necessary in order to form communities of practice and grow influence. By conducting this thesis, it emphasises the need for continued research and development of DES to achieve a sustainable energy future [18].

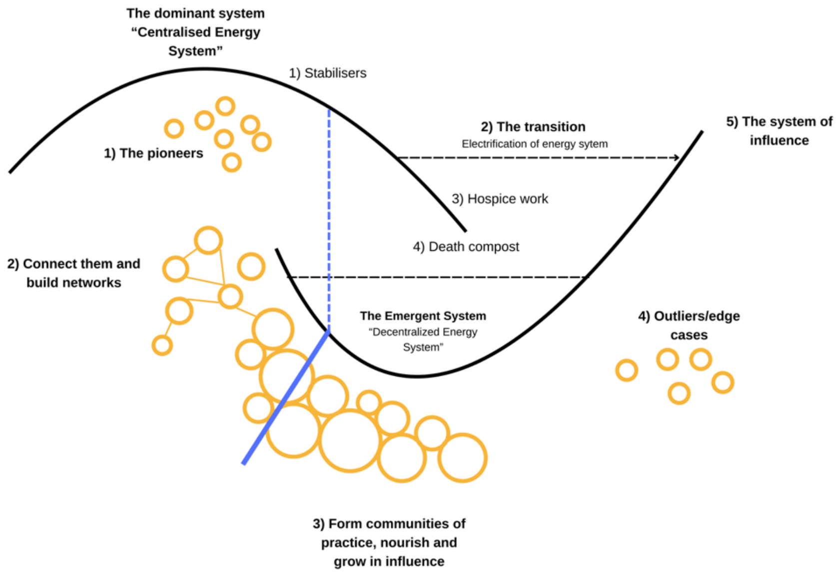

Figure 2.2: Berkana two-loop model - Transition towards electrification of the current energy system

2.1.2. Energy generation profiles

In this section, the dynamics of various energy sources and their integration into a DES are explained. Historically, as discussed in the introduction, energy generation relied heavily on fossil fuels like coal, natural gas, and oil due to their high energy density and ability to provide continuous and reliable power. However, the rise of renewable energy sources, such as solar and wind, has introduced new challenges and opportunities. Renewable energy sources generate power primarily during the day, leading to the "duck curve" phenomenon, where energy supply peaks during the day but drops significantly in the evening while demand remains high (see the orange figure in Figure 2.3) [7], [19].

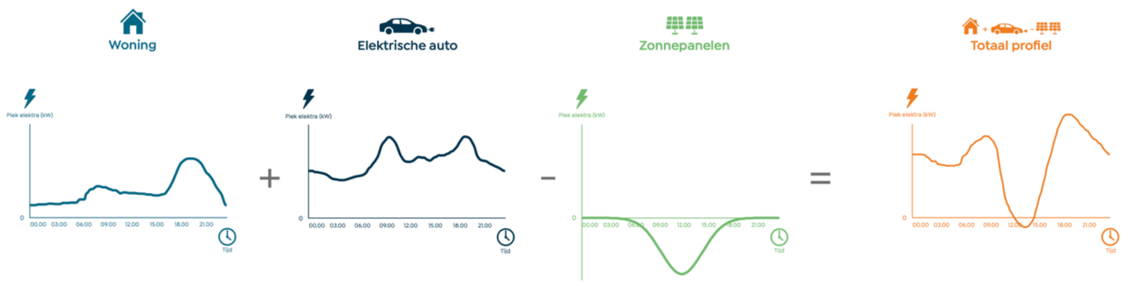

Figure 2.3: General electricity profile [7]

In the case of Uitgeest-Noord, the absence of smoothing effects that typically apply to larger, centralised systems means that demand patterns, local renewable energy generation, and weather conditions directly influence the reliability of the energy supply. The DES at Uitgeest-Noord must, therefore, carefully consider local energy generation profiles, which include factors such as the variable output of PV panels and the capabilities of the Battery Energy Storage System (BESS), to ensure an efficient and reliable energy supply. These energy generation profiles will be extensively used to create the energy model and analyse the results.

2.1.3 Battery Energy Storage Systems

Battery Energy Storage Systems (BESS) are pivotal in facilitating the integration of generated green electricity systems. Additionally, they provide numerous advantages, ranging from managing the duck curve to enhancing grid stability, overall system profits, and peak shaving. A BESS consists of batteries, converters, and energy management systems (EMS) that work together as a system.

For energy storage, lithium-iron phosphate cell technology is an excellent choice. It offers several key advantages. First, it is safer and has a lower risk of thermal runaway or fire. Second, it has a long lifespan, lasting up to 8,000 cycles, which translates to more than 15 years of use—ideal for storage applications. Lastly, this technology is more environmentally friendly, as it is easier to recycle [20].

Secondly, a connection to the electrical grid is a key component of a stationary BESS to compensate for time shifts between electricity production and demand, as well as to participate in the imbalance market to export power for revenue. To achieve a grid connection, a BESS needs to contain a converter that can be installed at the low-voltage (LV) or medium-voltage (MV) grid level. These converters in the BESS are called inverters and rectifiers. To connect a battery with Direct Current (DC) to the electrical grid, an inverter converts it to Alternating Current (AC), which is the basis of this electrical grid. Conversely, a rectifier is used to convert electrical energy from the AC grid to a DC battery. If the grid voltage differs from the AC voltage range, an extra step with a transformer is necessary to convert the voltage to the typically higher voltage levels of the electrical grid [21]. To minimise the losses of the DES at Uitgeest-Noord, it is connected to the LV grid at the same level as the locally placed electricity generation.

Thirdly, in the DES in Uitgeest-Noord, the Energy Management System (EMS) is the brain of the operation. It connects the BESS with the local grid and charges the BESS with PV panels on-site or electricity from the grid. A grid connection is essential, as the system is also charged with electricity from the grid when costs are low or sells electricity when stored electricity is not necessary. This trading in an imbalanced market can further enhance the business case in Uitgeest-Noord [20]. This is also referred to as peak shaving or load shifting, as seen in Figure 2.4, where a BESS can assist by supplying power during peak times, thus elevating the maximum transport capacity (red line in Figure 2.4 [22]).

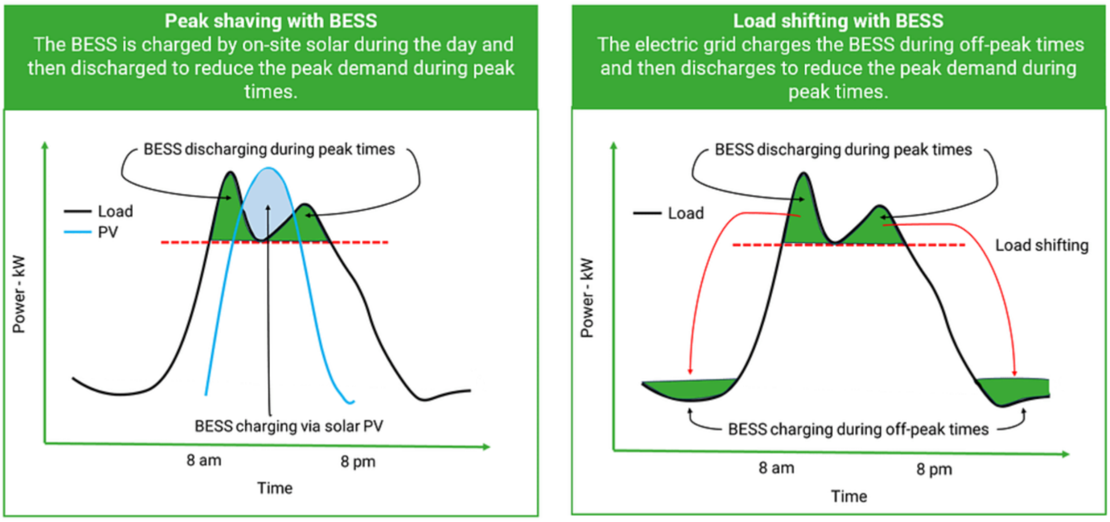

Figure 2.4: Visual display of peak shaving and load shifting with BESS Source: [22]

2.3 Background information case study: Business Park Uitgeest-Noord

This section shares some extra information on the case study of Business park Uitgeest-Noord. Firstly, it will introduce conducted energy scans, which were provided by Darel. Then, a stakeholder analysis will be conducted to understand the dynamics in business park Uitgeest-Noord.

2.3.1 Energy scans

The dataset used for this study is based on energy scans that were conducted in 2021. Out of the 170 companies approached, 65 companies cooperated, and their total energy consumption of 6 GWh accounts for 83% of the total energy consumption of 7.2 GWh at the business park in Uitgeest-Noord. This results in sufficient data to use during the modelling phase. Zooming in on the ten biggest energy consumers, it is evident that they already account for 40% of the total 6 GWh. The conclusion provided from these energy scans was laid out in a previous study by Darel [34]. It provides four main findings after analysing the data: (I) installation of solar panels on roofs, (II) building-related savings, (III) process-related savings, and (IV) electrification of mobility. In Appendix 9.4, each of these four conclusions is briefly elaborated on, followed by a visualised waterfall diagram.

In conclusion, based on the energy scans conducted, the most noteworthy development is the shift towards electrification. This shift substitutes gas for electricity and adds electricity demands from heat pumps and the implementation of EV charging (+38%). If zoomed in on the total consumption in 2040, rooftop PV panels are proposed. With this growing demand for electricity and the addition of PV panels, it is possible to calculate the percentage difference between the current grid connection and potential PV generation. Darel calculated a maximum potential capacity of 5080 kWp for PV panels [16].

The calculation in the study used for this is:

$$\textit{Potential PV Capacity (kWp)} = \textit{Usable Roof Area } (m^2) \times 0.088 \; kWp/m^2$$

This results in grid congestion if a full kWp of PV panels is generated. In Figure 2.5 per cluster is the discrepancy visualised per node cluster (> 100% results in grid congestion at max kWp of potential PV panels).

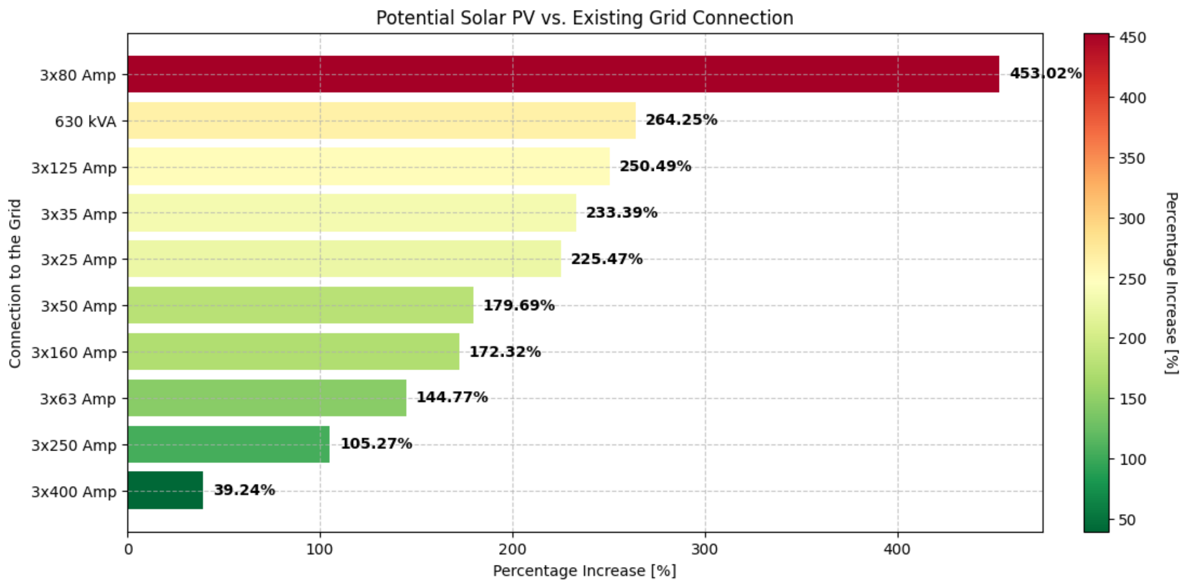

Figure 2.5: Difference in current grid capacity and potential grid capacity necessary for installation of all PV panels. If the percentage is higher than 100%, this means that the current grid connection is not sufficient enough to accommodate the kWp of the PV panels. Source[23]

For Uitgeest-Noord to proceed with electrification, expanding the current electricity grid is essential to prevent grid congestion. However, according to Liander, providing a bigger grid connection in the near future is impossible due to several challenges. The existing grid has already reached its maximum capacity, particularly in regions like Noord-Holland, where Uitgeest-Noord is located. Additionally, Liander faces significant shortages of essential materials such as cables, wires, and meters, which are necessary for grid expansion. The current infrastructure, originally designed for more stable energy sources, is also struggling to accommodate the volatility of renewable energy like solar and wind power. This means that the required overhaul of the entire system cannot happen quickly, necessitating a shorter-term solution. The next chapter explains why an energy modelling tool could provide certain benefits in mapping and solving this grid congestion issue in Uitgeest-Noord [24]

2.3.2 Stakeholder analysis plotted in power-interest grid

A stakeholder analysis of the business park Uitgeest-Noord is conducted to identify which stakeholders are relevant to include within this thesis project. Using the power-interest grid, stakeholders are effectively prioritised based on their level of power and interest in the DES at Uitgeest-Noord. They are categorised into four quadrants: I) high power-high interest, II) high power-low interest, III) low power-high interest, and IV) low power-low interest. Plotting stakeholders on this grid helps identify which stakeholders have the power to push for the shift towards DES. Later in the study, the involvement of Greenbiz, a key stakeholder, ensures that those with higher power and interest can significantly influence the project outcomes (see Figure 2.6).

Liander plays a pivotal role as the regional grid operator responsible for upgrading low- and medium-voltage cables and stations and is the distribution system operator (DSO). And thus responsible for rising demand challenges and reinforcements of the current power grid [17]. Given its right central position, Liander is both high power and high interest; however, it is not easy to collaborate with.
HVC, a company developing a heating network in the area, is willing to cooperate but currently has no expansion plans towards Uitgeest-Noord. As a high-support, low-interest stakeholder, HVC should be kept satisfied with regular communication to maintain a positive relationship. Maybe in a later stage, they will expand their current heating network and can provide valuable heating solutions.
Offices-related business in Uitgeest-Noord uses relatively low amounts of electricity. These stakeholders fall into the lower-power, high-interest quadrant.
Process-related businesses, account for 40% of energy consumption and are mostly process-related businesses. Despite their high energy consumption, they tend to focus on operational matters, and higher levels of power but varying interests.
GreenBiz IJmond is a consortium supporting business activity in Velsen, Beverwijk, Heemskerk, and Uitgeest. With its bird's-eye view, GreenBiz IJmond plays a critical role in fostering synergy among businesses and facilitating discussions across business parks. Despite having limited direct power, their supportive role and broader perspective place them in the medium-power, high-support quadrant, warranting close engagement to leverage their network and insights. This role allows them to organise events as an opportunity for different businesses, leading to more efficient solutions and using a collaborative approach for the opposed electrification.

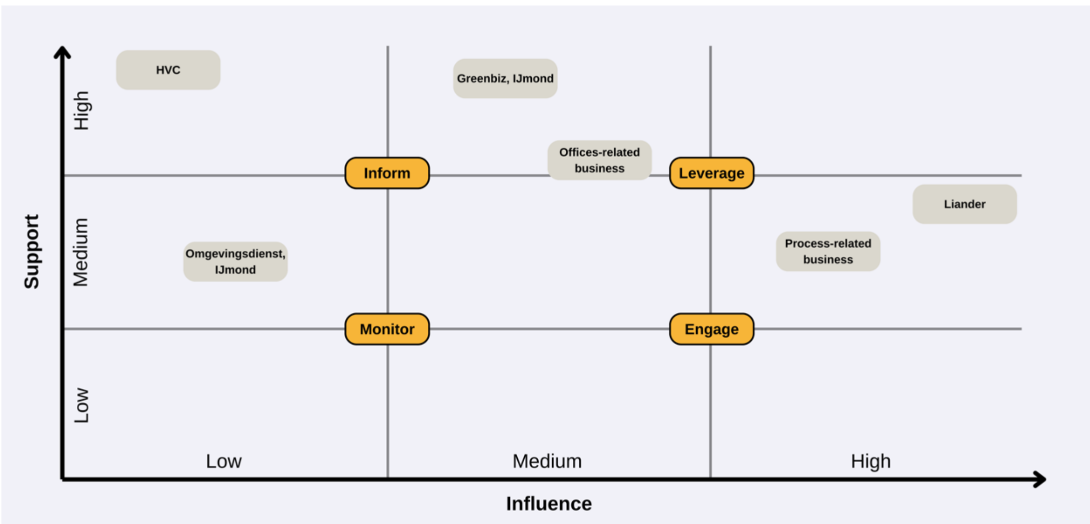

Figure 2.6: Power-interest grid of the Uitgeest-Noord region

2.4 Optimising DES with a linear programming optimisation model

2.4.1 Optimising DES via energy modelling software

During the initial phase of the energy scan at Business Park Uitgeest-Noord, it became evident that grid congestion would likely occur if all electrification plans were implemented simultaneously [14]. Various possibilities were considered, such as generating electricity with PV panels, achieving process-related savings, and implementing building-related savings. These strategies played a significant role in reducing the overall electricity usage. However, the proposed electrification, which involves installing the full capacity of solar panels on rooftops and utilising this capacity without precise measurements, necessitated a feasibility analysis. To develop a viable solution, a feasibility analysis was conducted in collaboration with stakeholders exploring smart energy storage solutions at the business park. A DES was proposed to address the different weather patterns, demand profiles, and specific locations in the energy grid. Energy modelling software was utilised to develop a DES that is reliable, efficient, and cost-effective, which is required to simulate these complex interactions between the demand profiles, cost of supply technologies, specific weather influence on PV generation, etc.

2.4.2 Reason to use linear programming optimisation model

For the Uitgeest-Noord project, a Linear Programming Optimisation Model is the most appropriate choice due to its simplicity, efficiency, and low computational demands. The problem involves linear relationships, where variables such as costs, emissions, and energy outputs are directly proportional. Linear programming is particularly well-suited to these scenarios, enabling the straightforward optimisation of a single objective and minimising total annualised without the added complexity that nonlinear problems introduce. This makes it an ideal approach for achieving cost-effective and sustainable energy solutions (see section 2.4.4) [25].

2.4.3 Calliope as chosen linear programming optimisation model

Several options were considered while selecting an appropriate energy modelling tool for addressing the grid congestion issues which included Calliope, Excel, and other available tools. After a comprehensive comparison, as summarised in Table 2.1, Calliope emerged as the most suitable choice. Its specialised functionality as a Linear Programming Optimisation Model, combined with its flexible approach with YAML files and ability to import CSV time series, besides easy access to support from TU Delft, make it particularly well-suited for the complex and dynamic nature of energy system modelling, unlike Excel, which, while widely known and easy to use, lacks the specialised features and scenario analysis capabilities required for this task. Calliope provides the necessary tools to handle the complexity of energy modelling effectively. Furthermore, its ability to handle .csv files with time data and the access support from TU Delft (1ste supervisor) solidifies Calliope as the optimal choice over other energy modelling tools or Excel for this project.

Table 2.1: Comparison of different energy modelling tools (Calliope, Excel, Others) (source: [26], [27]*)*

Criteria	Calliope	Excel	Others
Type	Linear Programming Optimisation Model	Excel	Linear Programming Optimisation Model
Functionality	Open-source energy system modeling framework, focused on flexibility and detailed optimisation of energy systems.	General-purpose tool, with basic functionality; customisable for energy modeling but not specialised.	Both open-source and licensed options available, with varying degrees of specialisation in energy modeling.
Data Handling & Storage	Ability to loading tabular data via .CSV files	More manual data handling, can struggle with large or complex datasets an no ability to load multiple .CSV files	Some tools are optimised for large datasets, others less so.
Community and Support	Easy access to support from TU Delft (1st supervisor)	Excel has a wide community and extensive resources.	Limited support; mostly available via internet or forums, depending on the tool.
Ease of Use	Requires technical expertise and coding knowledge (Python-based), but smaller learning curve due to the human readable YAML files.	User-friendly, widely known, and accessible, but complex models require manual setup.	Some tools might be intuitive, others could be complex and require specialised knowledge about python coding
Flexibility & Customisation	Highly customisable through building energy model with building blocks, allows for detailed energy system models.	Very flexible, but customisation requires creating models from scratch, which can be time-consuming.	Varies by tool, some are highly customisable, others might be more rigid or application-specific.
Scalability	Scalable for both small and large energy systems, strong in detailed optimisations.	Can become extensive with large-scale models; performance limitations.	Some tools handle large-scale models well, others might be limited in scope.
Cost	Free, open-source software, but require investment in training or development.	Low cost (part of Microsoft Office), but might need additional plugins or setup time.	Open-source options are free, commercial tools may involve significant costs.
Integration with Other Tools	Integrates well with Python-based tools and data sources.	Easily integrates with a wide range of software, but may require manual data handling.	Some tools offer extensive integration, others might be more standalone.
Simulation & Scenario Analysis	Strong capabilities for detailed scenario analysis and optimisation.	Limited by manual setup, complex simulations require significant effort.	Not specific

Calliope is an open-source tool utilised to build, replicate, and expand on Uitgeest-Noord's energy system model, which utilises linear programming optimisation modelling methods to achieve the lowest overall costs. It operates within a Python environment and consists of YAML and time-series CSV files with hourly energy data to define three separate YAML files: (I) technologies, (II) locations, and (III) scenarios [26]. YAML files are both human-readable and computer-readable, making adjustments easier to understand and conduct. The main goal during this phase is to find the ideal configuration of the DES at Uitgeest-Noord, consisting of PV panels and a short-term storage solution. The following chapters will explain why energy modelling software is used, the model concept, how to build the model, how to run the model, and how to analyse the model repetitively.

2.4.4 The primary objective of Calliope is to minimise total annualised system costs.

By employing linear programming optimisation, Calliope facilitates the analysis and determination of the optimal configuration for Uitgeest-Noord's energy system under a set of predefined constraints, including .csv files for demand and supply profiles. The model's primary objective is to optimise for the two assigned monetary and emissions cost classes and their corresponding objective weights, ensuring that the energy system is both economically viable and environmentally sustainable, using the default *min_cost_optimisation* objective below.

Min_cost_optimisation objective if costs are present and feasibility is ensured:

$$\textbf{Minimise} \sum_{costs}\Big(\sum_{nodes,techs} \big(cost_{node,tech,cost} \text{ x } objective\_cost\_weights\big) + \sum_{timesteps}\Big(\sum_{carriers,nodes} \big((unmet\_demand_{node,carrier,timestep} - unused\_supply_{node,carrier,timestep}\big) \text{ x } timestep\_weight_{timestep}\Big) \text{ x bigM}$$

This function calculates the total cost by summing the weighted costs across all nodes and technologies, ensuring that both monetary and emissions-related costs are minimised. Additionally, the function accounts for unmet demand and unused supply, penalising these by scaling with a large constant (bigM). This helps ensure that the energy system not only minimises costs but also maintains reliability by meeting energy demand effectively. The objective_cost_weightsparameter allows to assign different priorities to monetary and emissions costs, depending on your specific goals. In method section 4.2.4, more is explained on how the monetary and emissions costs classes are weighted.

As the model optimises for the assigned cost classes, the configuration of the BESS and PV capacity may vary accordingly. Key aspects to consider for future implementations include determining the correct size of the BESS to balance energy supply and demand efficiently. The model assists in identifying the appropriate storage capacity required to store excess energy generated during peak production times and to supply energy during periods of high demand or when renewable generation is low. An optimally sized BESS ensures maximum utilisation of generated renewable energy and minimises reliance on the grid, thereby enhancing energy resilience and reliability. Furthermore, the model evaluates the potential PV capacity that can be installed on available rooftop spaces within the business park. It assesses the potential for solar power generation, taking into account factors such as local weather conditions. This evaluation supports the planning of solar panel installations necessary to meet energy demands, reduce dependency on the grid, and achieve sustainability goals.

2.4.4.1 Measuring this by performance metrics

While the primary focus of the model optimisation is on minimising costs, additional performance metrics are essential for a comprehensive evaluation of the system. These metrics include the capacity of the BESS, which is assessed to ensure it is appropriately sized to meet the energy demands and storage requirements of the system. Another critical metric is the percentage of the total available PV capacity that is actually installed, as this directly influences the system's overall energy generation and efficiency. Furthermore, the overall cost of the system is measured, encompassing both the monetary cost and the cost related to CO_2 emissions. While maintaining stable monetary costs is crucial, the model aims to reduce the CO_2 emissions cost class, contributing to the sustainability goals of the business park. Additionally, system efficiency is evaluated by measuring the amount of energy transmission through power lines, with the goal of minimising losses and maximising the effectiveness of energy distribution. These metrics are analysed using real data, and the results provide insights into the system's performance across various dimensions, which are detailed in the results section.

2.4.1 Contribution to the model concept in the application of the case study Uitgeest-Noord

This paragraph presents the approach used in this thesis to enable a comparison between the modelled scenarios of our case study, Uitgeest-Noord, and real-world data. By exploring various scenarios, we aim to identify the best configuration. Subsequently, aligning the model with reality becomes crucial to extrapolating findings to similar other DES. Given the changing landscape shaped by climate policies and increased electrification, energy system modelling has gained importance as a tool for capacity planning [28]. To provide a visual representation of how the model works, the researcher's contribution is shown in where the purple area highlights the degrees of freedom to make the energy model in Calliope unique and similar to Uitgeest-Noord, whereas the part the work of the model is, and fixed without the ability to make adjustments (see Figure 2.7).

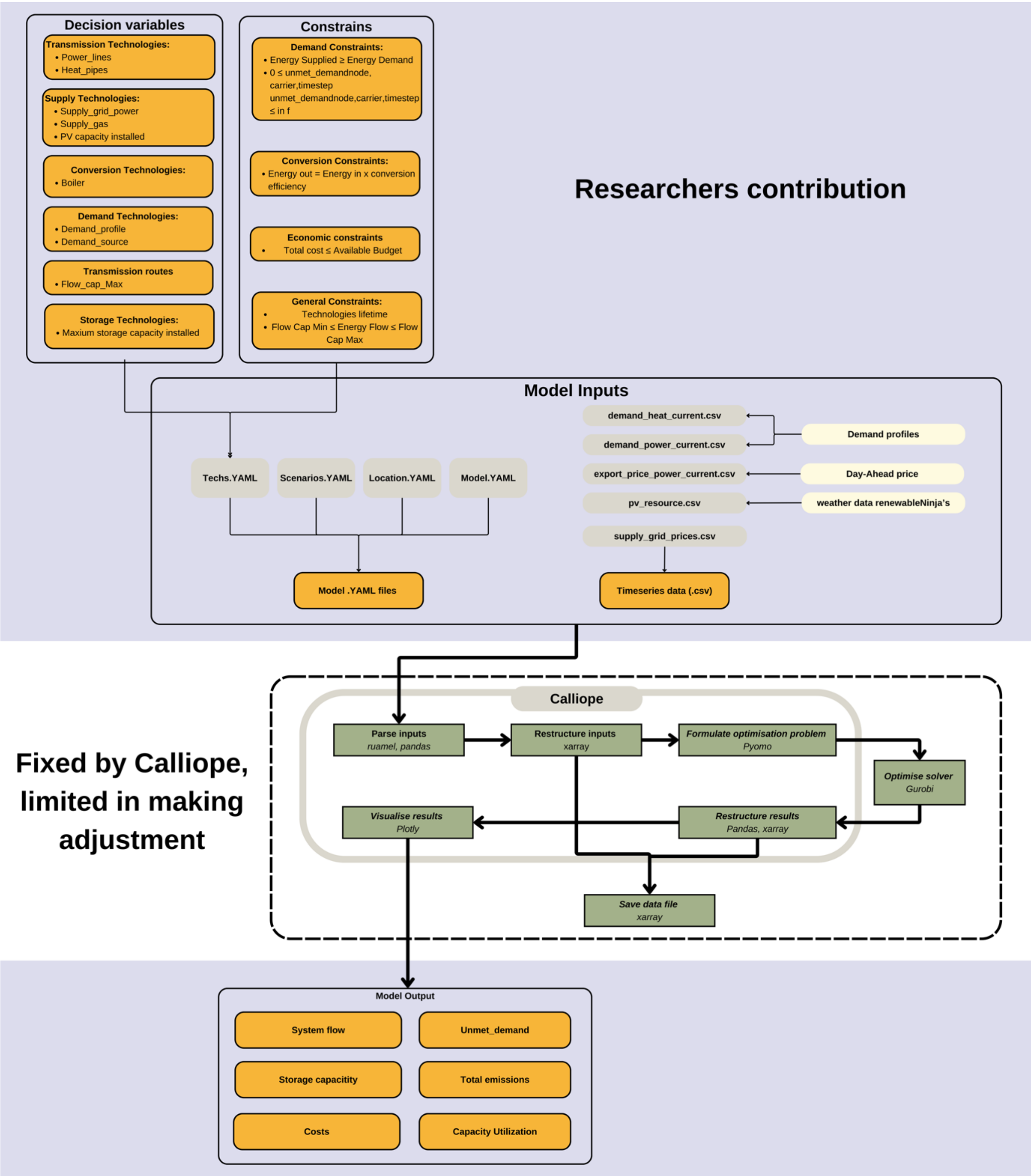

Figure 2.7: Calliope flowchart model

The figure illustrates the workflow and components of an energy modelling process; it begins by defining decision variables (such as power lines, supply technologies, and storage capacities) and constraints (like demand fulfilment, conversion efficiency, and budget limits), which guide the modelling process. Model inputs are configured using YAML files and time series data, providing crucial information on demand profiles, prices, and PV generation. Within Calliope, these inputs are restructured and used to formulate an optimisation problem, which is solved using a solver like Gurobi. The results are then restructured, saved, and visualised, showing all energy flows, unmet demand, storage capacity, total emissions, costs, and capacity utilisation. This comprehensive approach integrates various data sources and configurations to produce insightful results, demonstrating how Calliope can effectively optimise energy systems for better performance and reduced environmental impact [29].

2.4.1.1 Gurobi solver choice

Choosing the right solver to run the Calliope model involves considering both speed and ease of use. Therefore, Gurobi was selected as the solver for this project due to its superior performance and speed compared to other open-source alternatives like CBC and GLPK. With a TU Delft academic license, Gurobi is available for free, thus making it accessible for research purposes. Its significant reduction in computation time is critical during the trial-and-error phase of modelling. Additionally, Gurobi's robust optimisation capabilities and comprehensive support for various problem types ensure more reliable and efficient solutions. Therefore, Gurobi is a proven solver with the Calliope model, and it has proven to work well in the past. While it typically requires a commercial license, the availability of free academic licenses justifies its selection over other solvers (see Table 2.2).

Table 2.2: Different solver types (CBC, GLPK, Gurobi, CPLEX) (source:[29])

Solver	Type	Installation Instructions	Advantages	Disadvantages
CBC	Open-source	Easy installtion with (Linux and macOS), Manual setup required for Windows	Free and open-source, Works with Calliope, Can be installed via conda	Windows installation can be challenging, Slower compared to commercial solvers for large problems
GLPK	Open-source	Installed by default in Calliope environment, Manual installation via GLPK website if needed	Free and open-source, Works with Calliope	Can be slow and memory-intensive for larger problems
Gurobi	Commercial	Can be download and install from Gurobi website, Requires license activation key	Very fast for large problems, Commercial support available, Optimized performance, proven to work well with Calliope	Requires a license for use (free for academic purposes), Installation via conda has had issues
CPLEX	Commercial	Obtain academic license from IBM website, Installation instructions provided by IBM	Very fast for large problems, Commercial support available, Optimized performance	Requires a license for use (free for academic purposes), Installation process may be more involved

2.4.1.2 Assumptions and Limitations of Calliope

Understanding the assumptions and limitations inherent in Calliope's design is crucial for evaluating the model's accuracy during the building phase and applicability during the analysis phase. Calliope assumes that energy systems can be represented through a modular approach, comprising distinct components such as energy sources, converters, and storage units. This modular approach provides flexibility in designing complex energy systems and makes the system a unique fit for Uitgeest-Noord. Another core assumption is that linear programming is a reliable and fast-suitable optimisation technique for analysing energy systems, indicating that the relationships among system components can be effectively described using linear functions. Temporal and spatial resolution in Calliope is user-defined, allowing the size of time steps and geographic positioning to be set appropriately to fit Uitgeest-Noord. For our case study, this approach will capture the essential dynamics of the energy system of Uitgeest-Noord without making the analysis oversimplifying or overcomplicating. This means it is possible to work within the boundaries of Calliope, and this provides enough degrees of freedom to work with.

Additionally, Calliope operates under the assumption that technology constraints, resource availability, and other factors can be accurately defined and that primary objective functions—related to cost and emissions—are aligned with the overall goals of energy system optimisation, which is the case for business park Uitgeest-Noord. As we optimise for costs and emissions, an added benefit is that it also solves grid congestion, which, in the first place, is the main reason for installing a DES.

Despite its versatility, a lower resolution might lead to oversimplification, while a higher resolution could result in increased computational complexity, affecting the feasibility of larger or more detailed models. In chapter 4.2.3.1C, the input .csv files are explained, and why a 1-hour timestep is chosen for a yearly basis. The accuracy of Calliope also depends on the quality and completeness of input data. Inadequate or inaccurate data can lead to inaccurate results, undermining the reliability of the model's predictions. To mitigate this, during scenario testing, a sensitivity scenario will be performed to understand how the input data affects the results and, more importantly, how the isolation of certain functions of the model will influence the results. The sub-conclusions from this section serve as a basis for iterating on and improving the model. Moreover, the scope and complexity of linear models that can be built have practical limits; for example, computational times or building the model takes way longer due to manual input. This sometimes requires a workaround; one such workaround evolved around the modelling chose to represent 65 companies as 10 cluster nodes based on their grid connection. Chapter 4.2.1C explains why this choice is made and also elaborates on what limitations this will create.

2.5 Concluded knowledge gap

In the field of modern energy power systems, four key focus areas arise, namely: I) diversification, II) decarbonisation, III) decentralisation, and IV) digitalisation. While the first two areas have already reached the adoption phase, decentralisation and digitalisation of the electricity grid are relatively new and still in the development phase [10]. As discussed in previous sections, this thesis focuses on the growing need for DES in response to grid congestion challenges, particularly within the Dutch energy system. This emerging area of decentralisation of the energy grid requires further research and exploration for practical application. Just as mentioned when discussing the Berkana two-loop model[18]. This practical application is crucial to evolve and realise DES, where short-term energy storage is needed. However, currently, a lot of pilot projects still need to be realised due to a lack of funding and a viable business case, which often results in a higher capital cost per kWh. This leads to the urgent need for energy modelling software to provide answers to these questions when considering capacity phase planning. Business Park Uitgeest-Noord serves as a practical example of exploring these challenges in depth.

Accurately predicting energy generation profiles is essential for the successful commercialisation and cost reduction of DES. This accuracy is particularly crucial due to the inherent variability of renewable energy sources like PV generation. Unlike larger geographic areas where fluctuations in PV generation can be averaged out, each small location faces unique conditions that require precise local predictions. Effective modelling and prediction methods can significantly enhance grid integration by aligning energy supply with demand more accurately. This improved alignment reduces the need for costly backup systems and allows for more efficient use of available resources. Additionally, accurate predictions help in planning and optimising the deployment of energy storage solutions and other grid support technologies. The research underscores [13] the importance of precise predictions in achieving technical and economic benefits. By improving prediction accuracy, locations can enhance the reliability of their energy systems, reduce operational costs, and increase the overall efficiency of decentralised energy generation. This gap is also highlighted by an interview[28], where the EMS provider of Businespark Uitgeest-Noord explains the current difficulties they are experienced in capacity planning for a new case, as it is case specific what the approach is, and the correct configuration. This, in turn, facilitates a smoother transition to renewable energy and supports the broader goal of decarbonising the energy sector.

Another gap in the existing literature is the optimal size of BESS to effectively address challenges such as the 'duck curve'[19] and provide a positive effect on the surrounding energy grid [30]. Notably, existing studies often lean towards either complete decentralisation or full connection to the grid. In Uitgeest-Noord, the objective is to identify the optimal balance between these two extremes in the form of an ideal configuration in DES.

Therefore, we are using Uitgeest-Noord, especially the subsidy project of GreenBizz IJmuiden. This case study experiment can incorporate all these different stakeholders and can be used as a learning tool for other similar business parks. The theoretical foundation indicates a clear knowledge gap, where the lack of detailed, real-world examples and site-specific performance analyses for DES is pointed out, which is crucial for optimising these systems in real-world settings. This gap highlights the necessity for a more location-specific approach to DES design and implementation. This gap and challenge will be addressed in this thesis via energy modelling.

3 Research Question

Building upon the theoretical literature review, the knowledge gap, and the research objectives, this thesis addresses the critical challenges posed by the transition to full electrification, particularly in understanding the implications for capacity planning concerning PV capacity and short-term storage solutions. This is especially pertinent in the context of decentralised energy systems and poses a solution for our case study, Uitgeest-Noord, which highlights the need for detailed insights into capacity planning in the early stages. To provide a supporting role for Business Parks Uitgeest-Noord, this thesis explores whether an energy modelling tool can effectively be used to determine the ideal configuration for a decentralised energy system (DES). The aim is to provide detailed capacity planning for various components and offer insightful feedback to relevant stakeholders. Resulting in the following main research question:

Can the ideal configuration of a decentralised energy system (DES) be effectively designed to avoid local grid congestion and support capacity planning during the electrification of the Business Park Uitgeest-Noord?

The following sub-research questions were created to help answer the main research question.

Sub-research question:

1. *What specific factors currently contribute to local-scale grid congestion within the business park Uitgeest-Noord?*
2. *What is the ideal configuration of a DES according to a linear programming optimisation model?*
3. *How can an energy modelling system be generalised for broader applications to configure different DES locations?*
4. *What key lessons from the energy model exercise can be identified for the case study to produce usable conclusions for business park Uitgeest-Noord?*

4 Methodology

The thesis methodologies used to analyse and address the main research question are outlined in section 9.2, which presents the research flow diagram. This diagram provides a general overview of our research approach, consisting of four distinct phases described in chapters 4.1, 4.2, 4.3, and 4.4. Each phase focuses on answering sub-research questions that contribute to addressing the main research question.

4.1 Phase 1: Theoretical context and data collection for Uitgeest-Noord

This first chapter details the methodologies utilised in phase 1 of the research project focused on Uitgeest-Noord's business park theoretical context and how data collection is completed. It begins with why and how the Berkana two-loop model is used, followed by a stakeholder analysis employing the power-interest grid to prioritise stakeholders' influence on the adoption of DES. Structured interviews with stakeholders follow, ensuring adherence to the ethical standards of the TU Delft. Additionally, the chapter outlines the process and methodologies involved in performing energy-quick scans, which are crucial for assessing energy consumption and identifying efficiency opportunities within the business park.

To address grid congestion issues and explore short-term solutions, a theoretical literature review was conducted using Google Scholar as the primary source for academic papers. This review provided insights into current challenges within the Dutch energy grid. Additionally, research papers and slide decks from Darel Consultancy and related companies were consulted to enhance understanding of recent developments in energy systems. Appendix 1 includes a glossary that assists in navigating and reviewing existing literature by providing accurate terminology. This glossary will be continually updated throughout the research project to incorporate new terms as they emerge, ensuring clarity across different aspects of energy system techniques.

4.1.1 Berkana two-loop model

The Berkana two-loop model was established following the two-loop theory of Organisational Change suggested by Wheatley and Frieze [31]. This tool is known to be used in the mapping of complex systems, e.g., food packaging, and aims to describe a nonlinear transition from the old system to the new. This model highlights both the growth and the decay sides of a transformation life cycle. The template of the Berkana two-loop model was taken from the homepage of Berkana's research institute, and the notes from the interviews were placed in each segment of Berkana's model template ([18]. The recommendations were made based on the processing and analysis of the collected data.

To provide a better understanding and visual insights into where a decentralised energy system is placed in the current energy transition, the Berkana two-loop model helps illustrate the complex, dynamic processes involved in shifting from centralised to decentralised energy systems. Thereby highlighting the interplay between emerging technologies and established infrastructures. By mapping out these transitions, the model enables the identification of critical points of growth and decay. And providing insights into how to manage and support the transition towards DES effectively. This highlights the academic relevancy of looking at a case study like Business Park Uitgeest-Noord in harvesting new connections to grow DES.

4.1.2 Power-interest grid

A stakeholder analysis of the business park Uitgeest-Noord is performed to identify which stakeholders are relevant to include in our research project. The power-interest grid is used as a tool to effectively prioritise stakeholders based on their level of power and interest in the project. Stakeholders are categorised into four quadrants: high power-high interest, high power-low interest, low power-high interest, and low power-low interest. Plotting stakeholders on this grid helps identify which stakeholders have the power to push for the shift towards decentralised energy systems.

4.1.3 Interviews

To gain more insights into the relevant stakeholders, online or on-site interviews will be conducted during the case study. This is necessary because DES is a relatively new field of research, meaning that the latest developments considering BESS as part of a DES are relevant during capacity planning. Some examples are first real-world use cases, like similar locations where BESS is supporting the energy grid and mitigating grid congestion, but also growing pains encountered during the early stages of development of a BESS manufacturer. To ensure consistency, a semi-structured interview protocol has been developed. Since this research project involves human subjects, it must adhere to the guidelines of the Human Research Ethics Committee of TU Delft. Therefore, the interviewed stakeholder will receive the consent form beforehand and have the right not to answer a question. Afterwards, interview notes are shared, and the interviewed stakeholder has the right to correct or remove information from these notes (see appendix 9.5).

4.1.4 The method used to conduct the energy-quick scans.

During this thesis, a data set created from energy scans is used. This data set is provided by the thesis partner, Darel Consultancy [16]. To provide better transparency, the methodologies that were used to perform energy-quick scans in 2021, which produced data for the data set that is used, are provided in Appendix 0. The energy quickscans focused on their role in assessing energy consumption and identifying potential savings, to guide particular businesses toward energy-efficient to provide additional space on the electricity grid to fulfil full electrification.

In the appendix section 9.3 an overview of the raw data set of Uitgeest-Noord is provided.

4.2 Phase 2: A modelling approach

4.2.1 Calliope model workflow

The model workflow below is crucial for clarity and understanding when modelling an energy system with Calliope. Each step is detailed to ensure transparency in the modelling process, building trust in the model's results and highlighting the decisions made to achieve them. A well-documented workflow enhances reproducibility, which is essential for addressing our fourth sub-research question. It enables other researchers and practitioners to replicate the study or adapt the model to their specific needs. Lastly, the workflow underscores the iterative nature of Calliope model building and analysis, starting from initial results and continuously improving the model's robustness.

Essentially, the model workflow for Calliope consists of three steps: (I) building the model, (II) running the model, and (III) analysing the model. Some sub-steps around these three main steps result in the model workflow (see Figure 4.1). The flowchart represents a structured workflow for building, running, and analysing an energy model using Calliope. The process begins with input data, which involves converting various data formats, such as hourly data in CSV files, into the same hourly format suitable for running a full year from September to August and incorporating all four seasons without splitting them. This initial step is crucial as it ensures that the data is clean and correctly formatted, providing a solid foundation for the following stages.

Next, the (I) **Building the Model** phase involves the creation and configuration of YAML files, which define the model's components, including locations, technologies, and model. These files are then connected to form a cohesive model and can be run via Python. This step can involve iterative improvements to refine the model's accuracy and reliability. Following the model building, the process moves to the (II) **Running the Model** stage. Here, the connected YAML files are used to execute the model, simulating various scenarios to evaluate different outcomes. This stage can be adjusted by configuring different scenarios, allowing for a comprehensive analysis of potential solutions and strategies. The final phase, (III) **Analysing the Model's Results**, involves examining the output generated by the model and the different scenarios. This analysis helps to interpret the results, identify trends, and make informed decisions. The entire workflow is designed to be iterative, enabling continuous improvements and refinements to enhance the model's performance and accuracy over time. Overall, this structured approach ensures a systematic and thorough exploration of energy modelling scenarios.

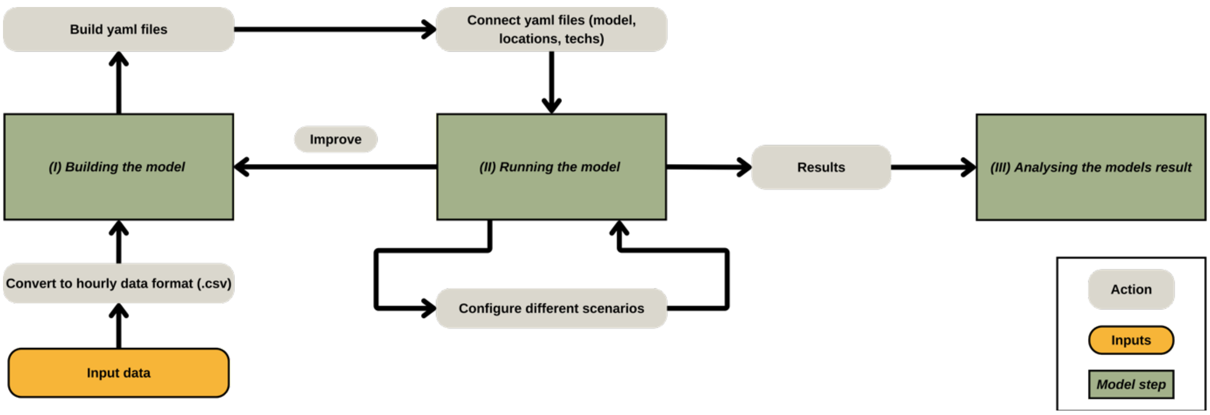

Figure 4.1: Model workflow Calliope

4.2.2 Building the model

See appendix 9.14 for the whole code inside a Github Repository

A specific directory structure must be in place to construct the model for Uitgeest-Noord. This includes four distinct YAML files - Techs, Locations, Scenarios, and Model - as well as inputted CSV files, recognisable by their .yaml and .csv extensions. You can find detailed explanations of the four YAML files in the corresponding chapters: Locations, Techs, Model, and Scenarios.

Overview of the current directory:

```
+ UitgeestNoord_model_map
    + model_config
        - locations.yaml
        - techs.yaml
    + data_sources
        - File A.csv
        - File B.csv
        - etc…
    - model. yaml
    - scenarios. yaml
    - PythonModel.py
```

4.2.2.1 Locations - file

Calliope employs a node-based structure to represent different locations within the energy system. Each node corresponds to a geographical location and serves as a hub for energy production, conversion, storage, or consumption processes. Nodes in Calliope are defined in the model configuration file under the `locations` section. Each node is assigned a unique identifier, representing a specific geographical area or site within the energy system. The configuration of each node includes several key attributes:

- Coordinates: Each node is defined with geographical coordinates (latitude and longitude), enabling spatial analysis and mapping of the energy system.
- Technologies: Nodes are assigned various technologies, which can include energy generation units, solar panels, storage solutions, conversion technologies and demand properties.
- Capacity Limits: Each technology within a node can have specific capacity limits defined, including minimum and maximum capacities. These limits are essential for modelling the physical and operational constraints of the technologies.

The node-based approach in Calliope allows for a detailed and flexible representation of the energy system's geographical and technological components. By defining nodes with specific attributes and connecting them through a network, the model can simulate complex interactions that also appear in real life and optimise the performance of the overall energy system with a linear solver. This methodology provides a robust framework for evaluating different energy system configurations and their potential impacts on energy supply, reliability, and sustainability.

Figure 4.2: Real life visualisation on powerlines at Uitgeest-Noord

Below in Figure 4.3: Simplified node-based structure Uitgeest-Noord is a corresponding representation of the real-life situation displayed, displaying the simplified node-based structure of Uitgest Noord, including the techs positioned at each node.

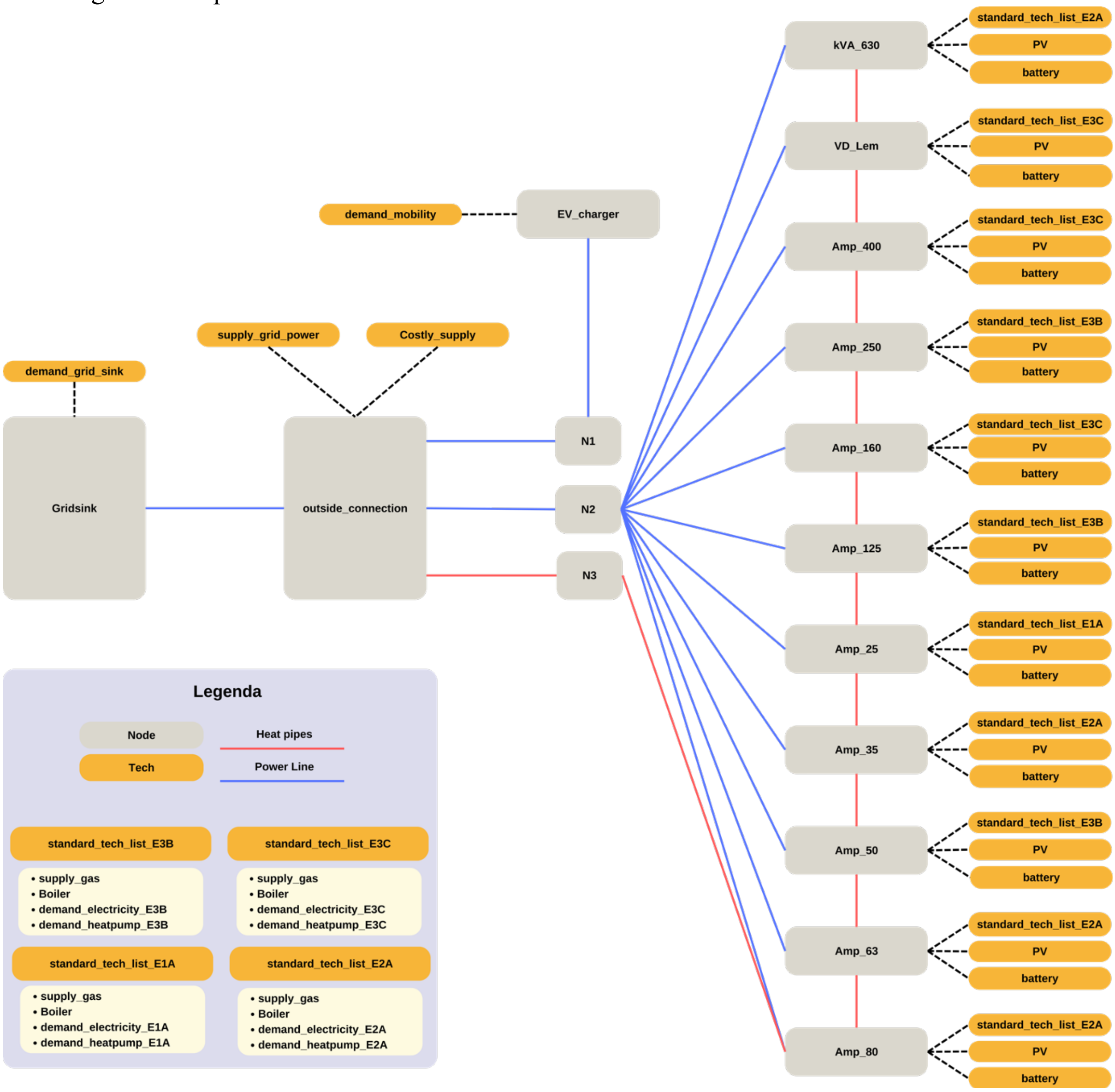

Figure 4.3: Simplified node-based structure Uitgeest-Noord

4.2.2.2 Techs - file

In the techs.yaml file Calliope enables the following standard technologies: supply, demand, storage, transmission, and conversion technologies. This specific configuration is crucial as it sets the foundation for optimisation and the defining and running results of the model. To provide a better understanding of which parameters of the system design are fixed and which can be adjusted to generate more specific model results, see the explanation below. Each technology is defined according to the following parameters:

- **Name and Color**: Optional attributes for visualisation purposes.
- **Base Technology**: The fundamental type of the technology (supply, demand, storage, transmission, conversion).
- **Carrier**: The type of energy or material being handled (e.g., electricity, heat, gas).
- **Capacity and Efficiency**: Constraints and performance metrics, such as maximum output, efficiency, and lifetime.
- **Costs**: Economic aspects, including capital costs, operational costs, and other relevant financial metrics.

See Appendix 9.8 **Error! Reference source not found.**for a detailed information table of all the techs that are installed to replicate Uitgeest-Noord.

Some interesting design choices are listed down below:

- To avoid repeating big blocks of yaml techs, a tech group can be made. Which is currently done with interest_rate_setter, power_lines and heat_pipes. These are repetitive parameters and, thus, perfect for forming a tech group.
- In our model, there are three main supply technologies: *supply_grid_power*, *supply_gas*, and *costly_supply*. As the names suggest, the first one is the supply carrier for electricity, and supply gas supplies the carrier gas. At the same time, the *costly_supply* is only used when the system is not solved and has a high price of 100 euros per kWh. This will then only be chosen when there is no other solution feasible within the model. This results in an inferior model outcome and indicates if grid congestion will occur as no constraints are evident. The above supply techs are unlimited available and need to match the demand techs. Where both PV panels and storage (battery) could act as a supply tech, this is not always the case. In theory, the model will use PV supply if there is electricity demand; when the generation of PV is higher than the demand, a storage solution will temporarily store this electricity and act as a supply source when the demand is higher than the PV generation.
- In chapter 0 is explains why and which kinds of consumption profiles are chosen, for *demand_electricity*, *demand_mobility*, *demand_heatpump* and *demand_gas*.
- In the transmission section, different nodes are connected, and electricity and heat are distributed between these nodes. In our case, it will inherit the power_lines and heat_pipe tech group. The goal of the transmission section is to mimic reality, and the reference also adds efficient parameters, which for a powerline is 0.98. As per the powerline, a certain distance is required, and the following assumption is made. The current business park, Uitgeest-Noord, is currently roughly the shape of a big rectangle of 300x900 meters. Therefore, it is assumed that every power line directly towards a node cluster is 600 meters long. As for the heat pipes, the total length in the model is 150m per heat pipeline.
- Another aspect is the boiler, which is acting both as supply and demand, which is the conversion from gas carrier into heat. This will result in a conversion loss of 15% and a conversion cost of 0.004/kWh.

4.2.2.3 Scenarios - file

In Calliope, the `scenario.yaml` file allows users to define different overrides for running the model under various conditions, such as running it for a full year or just a specific week. For instance, you can set an override to run the model from September 2019 to August 2020 or just for a summer week in 2020. Overrides are YAML blocks that specify configurations to change specific parts of the base model without the need to create multiple files. When multiple overrides are combined, they form a scenario which can be run separately to test different model configurations. This flexibility enables you to explore various scenarios, such as running the model for an entire year with a specific technology, like a disabled battery. This method streamlines the process of testing different configurations, as illustrated in Figure 4.4, where multiple scenarios are used to evaluate the Uitgeest-Noord model.

Sensitivity scenario's

To check the sensitivity of the model, five scenarios are run to provide a solid answer to sub-research question 1 and to examine which specific factors contribute to grid congestion. As explained in the model workflow, this is an iterative process. If the results do not align with the input values or if an override is not correctly implemented in a scenario, necessary adjustments are made in either the YAML or .csv files. By isolating the step towards full electrification and the proposed solution separately, specific characteristics appear more evident. Below, a visual representation of the different scenario flows is displayed. To start, the current situation without any solutions is run to showcase the function and the correct working of the model. This scenario aims to understand the current performance and costs associated with the existing energy system to establish a reference point for comparing the effects of integrating solar and storage solutions. Cross-checking the outcomes with the input values allows the system's performance to be examined and approved.

In Solution Mix 1, the integration of PV, EV charging, and heat pump installations without a battery is tested. The goal of this scenario is to cross-check the initial conclusion from the data set and the energy scans that grid congestion will arise, and therefore, solution mix 2, which analyses the benefits of adding a storage solution as a part of DES to the system, can provide the necessary solution. This addition of the storage solutions is isolated from any other external factors or parameters. It is crucial to understand the influence of storage on reducing grid dependency, improving energy self-sufficiency, and enhancing economic feasibility by reducing peak demand charges and utilising stored energy during high-cost periods. To showcase the difference in the behaviour of the calliope model when the storage solution can export power for revenue from selling excess electricity back to the grid, this function is added to solution mix 3A. In solution mix 3B, costs for both monetary and emissions classes on storage and PV panels are added as a cost per installed kWh installed capacity of storage solution is added in euro and CO2-eq in kg.

The storage system is modelled with a current cost of €400 per kWh of installed capacity in the Netherlands [20]. To simulate future scenarios, a "green premium" is added, testing price points of €400, €300, €200, €100, and €1 per installed kWh. This green premium is expected to decrease over time through subsidies and innovation, similar to the historical price reduction seen in PV technology due to increased production and market penetration [32]. To assess which price point minimally impacts the model's performance, outcomes are compared to Scenario 3B, which reflects a more realistic configuration. Additionally, storage capacity limits of 125, 500, and 1000 kWh are applied, corresponding to common BESS configurations of 125 kWh batteries connected in series. These constraints help determine the final optimal configuration, which eventually is handpicked and scaled towards 125 kWh capacity intervals. These two scenarios are also tested for similar scenarios without the ability to export for revenue due to the discontinuation of the 'solderings regeling" [33].

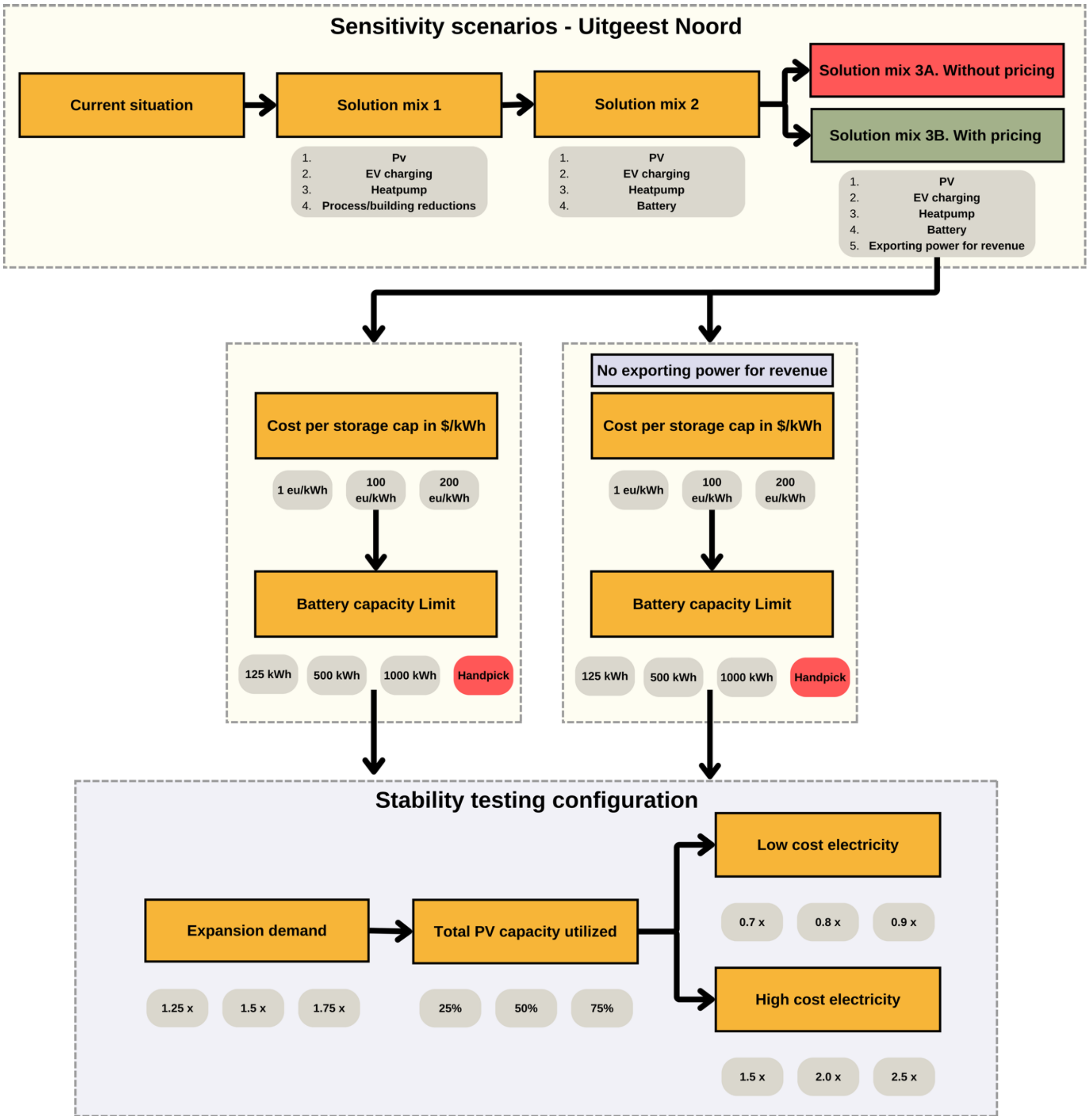

Figure 4.4: Scenario's overview moddeled in Calliope

__Stability testing configuration__

Adjustments in the timeseries.csv files are made to test the stability of the chosen configuration of the model. This is done in terms of electricity demand (1.25x, 1.5x, 1.75x), total available percentage of PV capacity(25%, 50%, 75%) and high (1.5x , 2.0x, 2.5x) and low-cost (0.5x, 0.7x, 0.9x) electricity scenarios. In Table 1 below, an overview is provided to show which override is present in which scenario. For a more extensive overview of all the overrides, see Table 4.1).

Table 4.1: Overview of which scenario is testing which overrides

Scenarios/Ovverrides	Cost per kWh	Emissions costs per kWh	PV	EV Charging	Battery Storage (BS)	Demand_Heat pump	Export for revenu	Cost per storage cap	Battery capacity limit	Expand demand	PV capacity	Low cost	High Cost
Current Scenario	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
Solution Mix 1	Off	Off	Check	Check	Off	Check	Off	Off	Off	Off	Off	Off	Off
Solution Mix 2	Off	Check	Check	Check	Check	Check	Off	Off	Off	Off	Off	Off	Off
Solution Mix 3A	Off	Check	Check	Check	Check	Check	Check	Off	Off	Off	Off	Off	Off
Solution Mix 3B	Check	Check	Check	Check	Check	Check	Check	Off	Off	Off	Off	Off	Off
Cost per storage cap in $/kWh	Check	Check	Check	Check	Check	Check	Check	Check	Off	Off	Off	Off	Off
Battery capacity limit	Check	Check	Check	Check	Check	Check	Check	Off	Check	Off	Off	Off	Off
Expansion demand	Check	Check	Check	Check	Check	Check	Check	Off	Off	Check	Off	Off	Off
PV capacity	Check	Check	Check	Check	Check	Check	Check	Off	Off	Off	Check	Off	Off
Low Cost Scenario	Check	Check	Check	Check	Check	Check	Check	Off	Off	Off	Off	Check	Off
High Cost Scenario	Check	Check	Check	Check	Check	Check	Check	Off	Off	Off	Off	Off	Check

4.2.2.4 Model – file

For Calliope to run techs, yaml, location, yaml, and scenario, the different files are important in the model.yaml file. The model.yaml file has the function to prepare the import, initialise, build and choose the right solver. A new function of calliope V0.7 dev 3 is that tabular data from the .csv files are also loaded via the model.yaml as data sources. To provide an overview, in Figure 4.5 the modelling tree of Calliope is added, whereas in the Python environment, the model file is run.

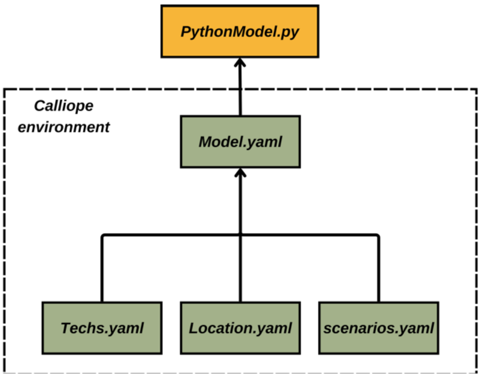

Figure 4.5: Modelling three Calliope

As seen in Figure 4.5 the Calliope *model.yaml* configuration file imports essential model components from various paths and *tech.yaml*, *locations.yaml*, and *scenarios.yaml*. It specifies initial settings, including the model name, Calliope version, and a subset of time series data. The model is built in "plan" mode with feasibility ensured as "true". As explained, Gurobi was chosen as the solver. As of the new version V0.7 dev 3, the *model.yaml* file also includes tabular data sources in the form of time-series.csv files for electricity demand, heat demand, PV resources, power export prices, and grid supply prices, defining their parameter value at a certain timestep. As mentioned, part of the model.yaml file is used to choose the right running mode. Currently, Calliope enables three different modes: (I) planning mode, (II) Operational mode and (III) SPORES mode. To choose the right mode for running the proposed scenarios, it is important to look at the intention and outcome of each of these modes. In operational mode, the system is fixed, and no capacity constraints can be determined by the system; a certain horizon, for example, 48 hours, can be chosen, and the model will do this run. For our proposed scenarios, there are always parameters which aren't fixed, and thus, this operating mode is not feasible.

On the other hand, the SPORES mode, or Spatially Explicit Practically Optimal Results, allows for the generation of alternative system configurations that differ in technology capacities and locations while staying within a specified range of optimal costs. For several reasons, the SPORES mode is not utilised in our modelling mode. Firstly, our current use of scenarios already allows us to explore diverse system configurations under varying conditions. Scenarios in our model encompass different input parameters and assumptions, enabling us to assess a range of plausible outcomes and decisions without the need for iterative exploration as in SPORES mode. Secondly, our model already incorporates a lot of fixed values, including fixed capacities and locations for technologies, which are fundamental to our analytical approach. These fixed values are integral to maintaining consistency and realism in our simulations, but they also limit the variability that the SPORES mode aims to achieve. Given these factors, the implementation of SPORES mode would not provide additional significant insights or efficiencies beyond what is already achieved through our scenario-based approach and fixed-value constraints. Therefore, while the SPORES mode offers a structured method for exploring spatially diverse alternatives, its application in our specific modelling context is unnecessary and impractical [26].

Therefore, the planning mode is used because upper and lower boundaries can be given as a constraint, and the Calliope model will decide the optimal system configuration.

4.2.3 Model file and modelling assumptions and choices

One of the biggest challenges in the context of the electrification of Uitgeest-Noord is to make precise and close-to real-life assumptions [34]. Therefore, decisions and assumptions need to be made to form an idea of how the future might change if particular decisions or parameters are changed. During the whole modelling process, assumptions are made to keep the modelling workflow close to reality and keep the model simplified enough for a decent computational time. During the data collection, certain choices and assumptions have been made; in this chapter, these assumptions are addressed to improve the transparency and reproducibility of the Calliope model.

4.2.3.1 Data collection choices and assumptions made for model Uitgeest-Noord

To achieve reliable modelling results, the quality of the model input is crucial, as the saying "garbage in, garbage out" implies. For the Uitgeest-Noord project, the model input involves selecting the right parameter values and gathering data to create hourly CSV files. These files include *demand_gas.csv*, *demand_heatpump.csv*, *demand_power.csv*, *export_price_power.csv*, and *pv_resource.csv*. Different sources, such as the energy scans mentioned earlier (see Appendix 9.3), provide the necessary data. When modelling results, it's essential to decide which parameters are fixed, which are derived from data sources, and which assumptions are made. It's also important to determine what falls within the scope of the model and what needs to be excluded. This careful selection and filtering process helps ensure the accuracy and relevance of the model's outcomes.

4.2.3.2 Electricity and gas demand profile selection

As previously discussed, the node structure in Calliope's dataset of 65 companies is split up regarding their connection to the grid. This means that ten nodes appear as company clusters, and some nodes consist, therefore, of more companies. However, this doesn't mean the electricity throughput is larger.

Data categorisation is done to determine the demand profiles for both gas gas and power, data by using grid connection points, ranging from a minimum transport capacity of 24 kW to a maximum of 536 kW (see appendix 9.7). This categorisation helps to simplify the various types of businesses. Each category has distinct and corresponding electricity and gas profiles. Currently, we use standard consumption profiles provided by MffBas [35] based on data and forecasts for the years 2025, 2026, and 2027.

This has two reasons. The first is that real-time data with the exact profile is only available for 1 or 2 companies. This kind of data is really hard to receive on time, and if received, it is only one specific moment in time. So, for example, it could be a relatively sunny year with a mild winter or a super heavy winter and relatively less sun, both impacting the specific demand profiles. Secondly, to make the model better for reproduction, generalised profiles based on the total demand of gas and power are easy to reproduce, and this also means you can easily implement less or more consumption of gas or electricity.

These consumption profiles are divided into categories for electricity (from bulk consumers to small consumers: E1A, E1B, E1C, E2A) and gas (G1A, G2C, G2A). Where for example, consumption profile E3A is a grid connection of >3 x 80 A ≤ 100kw and has an operation time of under 2000 hours per year. This time is mostly interesting for process-related companies who might have 24/7 processes, for example, and thus have fewer peak hours and more demand during the night. These corresponding profiles are then assigned per sub-cluster (see Table 4.2):

Table 4.2: Overivew of Uitgeest-Noord data collection [23]

Electricity profile	Gas profile	Connection to the grid	Value grid connection point in kW	Amount of business	SUM - electriciteit nu [kWh] - P/Y	gas nu [m3]
E3B	G2C	3x125 Amp	86	3	239197	40300
E3C	G2A	3x160 Amp	110	1	80000	5500
E1A	G2C	3x25 Amp	17	13	152914	39089
E3B	G2C	3x250 Amp	173	6	836954	111255
E2A	G1A	3x35 Amp	24	13	230135	39446
E3C	G2A	3x400 Amp	276	1	221070	5426
E2A	G1A	3x50 Amp	35	6	137817	27713
E2A	G2A	3x63 Amp	43	11	267727	55454
E2A	G2A	3x80 Amp	55	9	459471	57058
E3C	G2C	630 kVA	536	2	3415710	45760
				65	**6040995**	**427001**

In choosing the right consumption profile, it is also necessary to select the appropriate consumption type. Several standardised profiles are offered, ranging from consumption connections with feed-in to only feed-in types. For this energy model, a consumption profile without feed-in is used, focusing on consumption only, as PV feed-in is separate and, therefore, not necessary. The total profile can be seen in Figure 4.6 below. The data, divided into 15-minute intervals, needs to be converted to hourly data by summing four 15-minute intervals into one data cell to create an hourly time series .csv file. As the model covers an entire year, hourly data provides sufficient data depth.

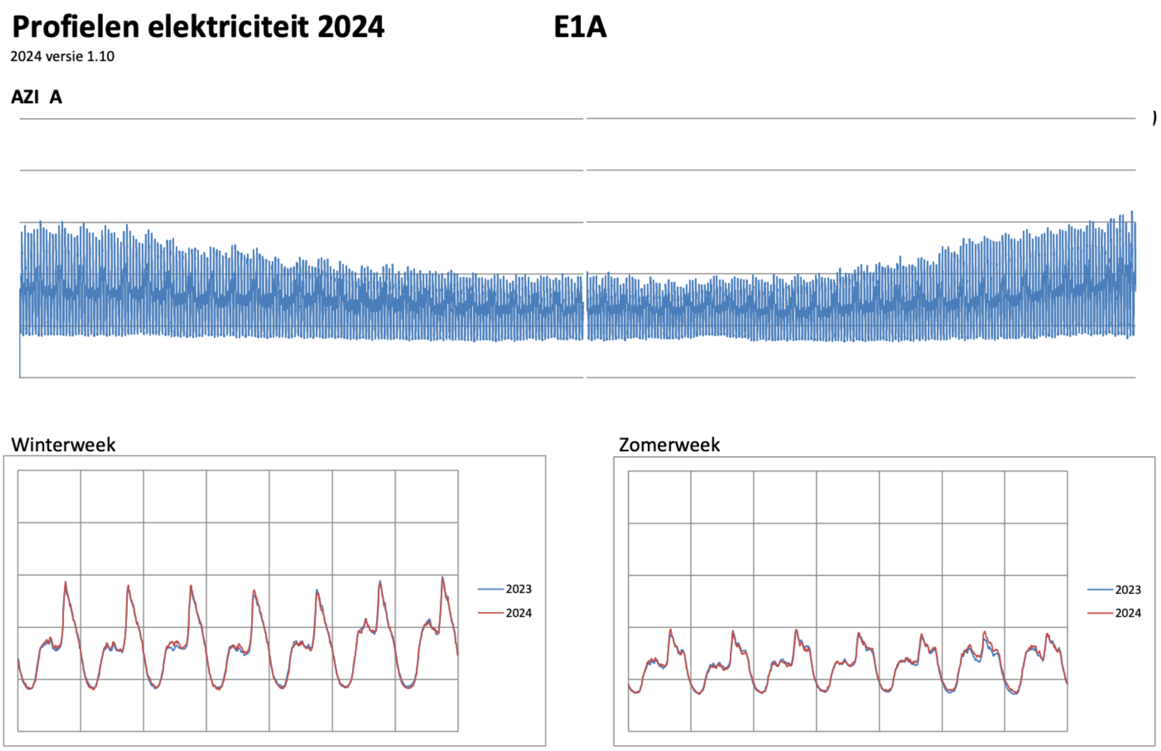

Figure 4.6: Electricity profile 2024 (screenshot from source: [34])

4.2.3.3 PV panel data collection

To rely on reproducible results, solar data for this model is retrieved from a website called Renewable Ninja. Here, with satellite data, solar capacity generation results can be calculated very accurately, in line with the total available installed capacity, by running with standard settings for the location of Uitgeest-Noord. One big assumption that is made here is that all solar panels can be fitted on mostly flat roofs in the following configuration and, therefore, also can be placed at a tilt of 35 degrees, where the typical tilt of solar panels is between 30 and 45 degrees (see Table 4.3) [29].

Table 4.3: Parameters used for Renewable Ninja (source: [29]).

Parameter	Value/Details	Remarks
Latitude (Lat)	525.372	
Longitude (Lon)	47.181	
Dataset	MERRA-2 (global)	MERRA-2 (global) is chosen instead of CM-SAF SARAH (Europe), due to the timeseries available, namely 2019. Despite the higher coverage density of CM-SAF SARAH in Europe, 2019 is inline with the modelling year so MERRA-2 (globale) is chosen
Available Year	2019	
Capacity	1 kW	
System Loss Fraction	0.1	
Tracking	None	
Tilt	35 degrees	
Azimuth	180 degrees (panel is facing southwards)	

The following time series file is used and displays a daily mean (see Figure 4.7), which corresponds with the generated power per installed kWp. Due to this workflow, the only number that needs adjustments is the total installed capacity, as all the weather influence, solar system loss etc is already in the ran Renewable Ninja model.

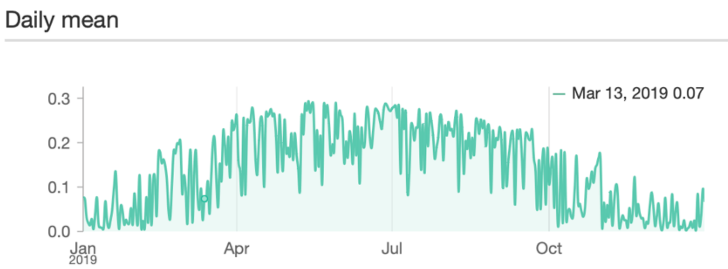

Figure 4.7: Annual PV power as daily mean for installation of 1 kW solar capacity (screenshot from [29])

4.2.3.4 Storage technology

By modelling a battery in Calliope, the pre-installed base-tech storage is utilised. This storage technology allows carriers to be stored between different time steps, enabling the inflow of electricity from both PV and the grid, storing it and releasing it later when demand rises. As discussed with a BESS manufacturer [20], the field is relatively new, and the typical lifetime of a BESS has not yet been fully realised. However, for a system rated at 1000 kWh, the manufacturer's specifications are typically used with a rated energy throughput of 3.6 GWh, resulting in about 8000 charging cycles, which is similar to around 15 years of lifetime. To simulate this multiple years by modelling just one year (from September 1, 2019, to August 31, 2020), cyclic storage is activated by default. This connects the storage parameters at the start and end of the time series, ensuring that the storage level on September 1, 2019, is the same as on August 31, 2020. If cyclic storage is deactivated, unused storage at the end of each run will accumulate year after year, leading to an unrealistic doubling of excess energy.

4.2.4 Account for monetary and emissions technology costs

In Calliope, multiple cost classes can be defined to account for different types of costs in the model. In our model, we have included both a monetary cost class and a CO2 emissions cost class. To balance these costs, we assign weights to each using the `objective_cost_weights` parameter as follows:

```
Parameters:
  objective_cost_weights:
    data: [6, 4]
    index: [monetary, co2_emissions]
    dims: costs
```

In the min_cost_optimisation function (see function below), the `objective_cost_weights` parameter is used to optimise Calliope for minimal cost through a weighted approach, where monetary costs account for 60% and CO2 emissions account for 40%:

min_cost_optimisation = *costclass [monetary] x objective_cost_weight* + *costclass [CO2_emissions] x objective_cost_weight*

This decision strikes a careful balance between economic costs and environmental responsibility. By giving slightly more emphasis to monetary costs, the model ensures that proposed solutions remain financially viable and practical, recognising that immediate economic considerations often take precedence in decision-making. At the same time, the 40% weighting for CO2 emissions reflects a strong commitment to environmental sustainability and long-term climate goals. This balanced approach ensures that the model offers solutions that are both economically sensible and environmentally sound, making it more likely to gain acceptance across a broad range of stakeholders.

Since we are dealing with two different cost classes, it is possible to assign different units per cost class and, therefore, specify monetary costs in euros per kWh (used or capacity installed) and CO2 emissions in kilograms per kWh (used or capacity installed). This approach allows us to maintain appropriate units for each cost type while accurately reflecting their impact in the optimisation process.

The cost of both cost classes can be put into all available parameters installed in Calliope. In Table 4.4 the corresponding monetary and emissions cost class is displayed for each supply tech.

Table 4.4: Monetary and emissions cost classes used in Calliope

Supply tech	Monetary	Unit	Parameter	Source
Supply gas	€ 0,025	eu/kWh	cost_flow_in	[36]
Supply grid power	Linked to the day-ahead price	eu/kWh	cost_source_cap	[37]
Battery	€ 400	eu/installed/kWh	cost_storage_cap	[20]
PV	€ 1.150	eu/installed/kWp	cost_source_cap	[38]
Costly suppy	€ 100	eu/kWh	cost_flow_out	

Supply tech	Emissions (kg CO2-eq)	Unit	Parameter	Source
Supply gas	0,18	kg CO2-eq/kWh	cost_flow_out	[39]
Supply grid power	0,37	kg CO2-eq/kWh	cost_source_cap	[39]
Battery	100	kg CO2-eq/installed/kWh	cost_storage_cap	[40]
PV	0,041	kg CO2-eq/installed/kWp	cost_source_cap	[41]

4.2.4.1 Day–Ahead prices for supply grid and export for revenue

To create a realistic representation of our model run from September 2019 – September 2020 to represent a dynamic energy contract that is used in combination with a BESS. Therefore, the electricity price is connected to the day-ahead price from that exact time frame, as prices from 2021 onwards are excluded due to significant variability caused by factors such as COVID-19 and the energy crisis related to Russia. Figure 4.8 illustrates the average day-ahead prices, with the blue line representing the scope of our research, while the red line indicates excluded data. In order to form the supply grid price, payments for bulk consumers are built up from different factors. As a business, you pay for the connection services, which include management and maintenance of the grid connections, resulting in a 0,05 euro extra per kWh (calculation based on yearly demand and average grid connection costs of around 5000 euros per connection). Besides these factors, you also pay government tax based on the total usage (see Table 9.1 in Appendix 9.9). Export electricity back to the grid (demand_grid_sink) using negative day-ahead-price electricity prices from the inputted .csv file.

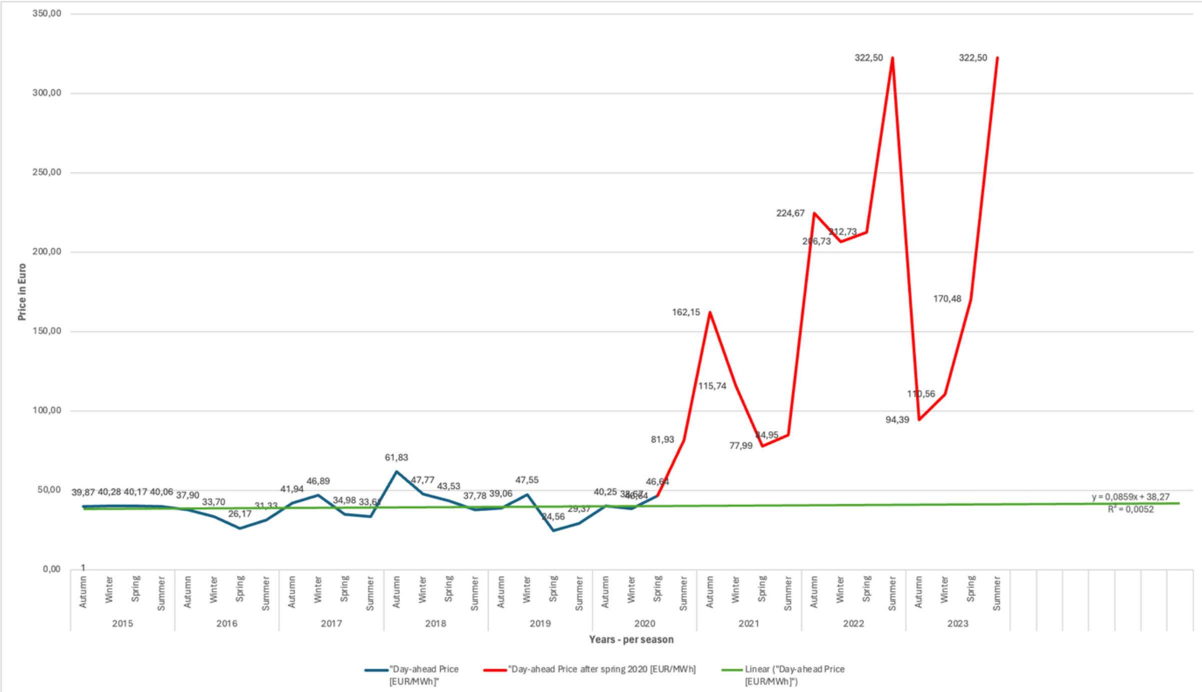

Figure 4.8: Day-ahead price displayed from 2015-2023, including cut-off data due to several factors (red line).[37]

4.2.4.2 Electric mobility demand:

The following approach is used in the Uitgeest-Noord energy scan to estimate the required grid capacity for electric vehicle (EV) charging stations in the industrial area. Due to the ongoing electrification, it is safe to assume that electric mobility will rise shortly. To determine the required grid capacity to meet this demand, an estimate of the total number of parking spaces needed is based on the total workforce. With 1,500 full-time equivalent (FTE) employees, our model assumes that 40% of them would regularly use a car. Among these, it is further assumed that half of the parking spaces should be equipped with an electric vehicle charger. This calculation leads to an estimate of 300 parking spaces with charging stations.

To determine the energy needs of electric vehicles, an average consumption of 20 kWh per 100 km and a typical daily commute of 30 km are considered. This indicates that each vehicle requires about 6 kWh of energy for the daily journey to and from work. Given that each charging station delivers 8 kW of power, the net charging time for a single vehicle is calculated to be about 45 minutes. However, considering the possibility of overlapping use and other factors, this is rounded up to 120 minutes. This allows a single charging station to service up to four vehicles per workday if charged from 09:00 to 17:00.

Based on these assumptions, a total of 75 charging stations would be needed to meet the demand. This is put in the demand .csv file where from 09:00 until 17:00, the demand is 225 kW (3 kW per hour per car, resulting in 3 * 75 = 225 kW extra grid demand (see Figure 4.9).

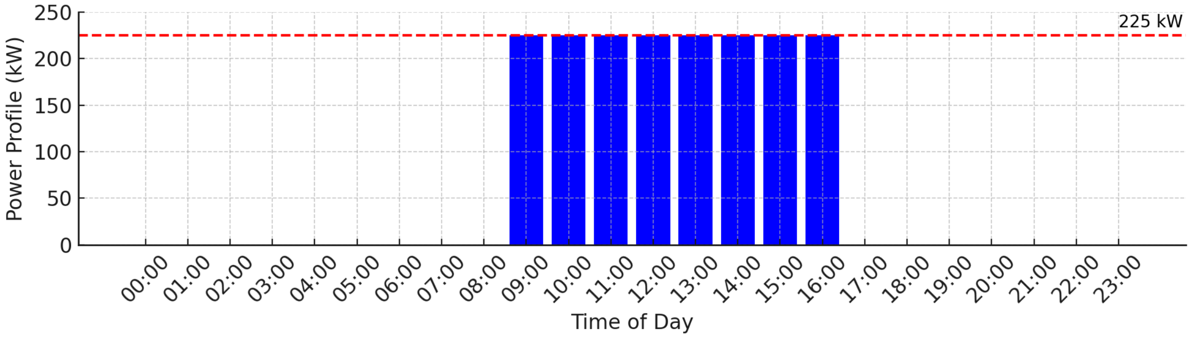

Figure 4.9: Demand mobility of EV charger points

4.2.4.3 Heat Pump:

In our case study of Uitgeest-Noord, heat pumps play a pivotal role in substituting gas used for heating. The input CSV file is constructed with one generalised heat pump profile for the entire year in the Netherlands. Due to the availability of this heat pump profile from a source similar to the gas profile, which the heat pump is meant to substitute, we have chosen to use this standard profile. Each cluster is assigned the same heat pump profile, as differentiating between clusters is challenging and falls outside the scope of this study—thus, this is an assumption[42] (see Figure 4.10).

While there are pros and cons to this choice, it is justified, given the context of the study. Although heat pump operation is weather-dependent, using a standardised profile ensures data consistency, simplifies the model, and allows for a direct comparison with the gas profile. Differentiating heat pump profiles based on detailed weather patterns would require granular data and add unnecessary complexity to the model, which is beyond the study's primary focus. Additionally, we had to rely on assumptions regarding the energy requirements for the heat pumps, as detailed and localised data were unavailable. These assumptions help maintain the model's focus on broader outcomes, acknowledging that while they introduce some uncertainty, they are necessary for practical and consistent modelling. Moreover, the generalised profile is a reasonable approximation for heat pump performance across the Netherlands, making it suitable for this regional-scale analysis.

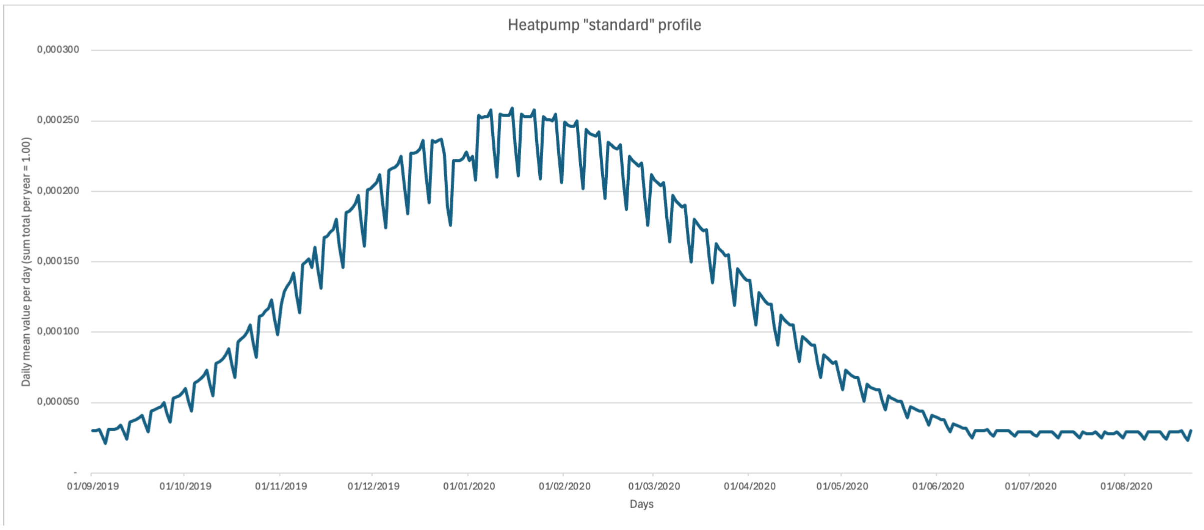

Figure 4.10: Total daily mean of heat pump standard profile

4.2.4.4 Power lines & heat pipes

In the techs.yaml, two key tech groups are defined: power_lines and heat_pipes. Power lines play a crucial role in simulating real-world electrical transmission behaviour, with flow_cap_max as the pivotal parameter. This parameter represents the maximum kW flow that the power lines can accommodate and thus plays a key role in imitating grid congestion. Calculating this flow_cap_max is done per cluster nodes in the following way. As an example, the node 3x125 Amps is translated to 28.75 kW by (125 Amps * 230 Volts / 1000). Considering three businesses per node cluster, each multiplied by three and applying a 75% safety margin ensures the power lines never exceed capacity. Thus, \`flow_cap_max\` is calculated as (28.75 * 3) * 0.75 = 64.68 kW per cluster. Summing these values across nodes gives the maximum system \`flow_cap_max\` of 1252 kW, located at the outer node (see Table 4.5).

Table 4.5: Flow_cap_max per node cluster to simulate grid congestion, which is restricted by the transport capacity

Connection to the grid	KW	Per nodes KW (75% of total available TC)	Amount of business
3x125 Amp	28,75	65	3
3x160 Amp	36,8	28	1
3x25 Amp	5,75	56	13
3x250 Amp	57,5	259	6
3x35 Amp	8,05	78	13
3x400 Amp	92	69	1
3x50 Amp	11,5	52	6
3x63 Amp	14,49	120	11
3x80 Amp	18,4	124	9
630 kVA	535,5	402	2
		1252	**65**

In contrast, heat pipes assume infinite (.inf) capacity throughput in the model, implying no maximum limit on heat transport. This assumption accommodates shifts from gas-powered boilers to heat pumps, highlighting operational scenarios without imposed capacity constraints.

4.2.5 Running the model

This methods section details running an energy system model for Uitgeest-Noord using Calliope, a modelling framework. The model is constructed based on tech data*.yaml*, *location.yaml*, and *scenario.yaml*, which are integrated into a comprehensive configuration file named *model.yaml*. In Python, the Calliope environment is set up, and the *model.yaml* file is imported. After setting up the model, it undergoes a solving process where an optimisation solver, such as Gurobi, computes the optimal configuration based on predefined goals with the following Python code:

```
import calliope
model = calliope.Model('path/to/model.yaml')
model.build()
model.solve()
```

The results presented from the Uitgeest-Noord model all run from September 2019 to September 2020. These 12 months were chosen intentionally to encapsulate an entire year, providing a comprehensive overview of all four seasons without splitting winter into separate halves. By encompassing an entire year, the results reflect four complete cycles, allowing for a thorough examination of seasonal trends and variations. To highlight or see the specific behaviour of the model, a run time of a season, month, week, or day can also be chosen. The results of this computation are then saved in a NetCDF format file named \`UitgeestNoord_results.nc\`. To facilitate interactive exploration and analysis of these results, the script launches the \`cview\` web interface, accessible via a web browser on port "number". This setup allows for a detailed examination of energy system dynamics and outcomes derived from the model's simulations. More about web browsers with Plotly visualisation is provided in the analysis in chapter 0 below.

4.3 Phase 3: Analysis

A key aspect of processing the results is conducting a consistent analysis. Analysing the results is essential for drawing meaningful conclusions from the data and different run scenarios. This analysis is performed using a dashboard created with Plotly (see screenshot in Figure 4.11), where the main conclusions are summarised by exporting CSV files and summarising different scenarios using Excel. The dashboard visualises the model's output, allowing us to export new CSV files that detail all the flows per node cluster. In the screenshot, the horizontal axis represents the entire year of the time series, which can be filtered by month, day, or hour (original resolution), while the vertical axis shows the total flow per cycle, typically measured in kWh.

The dashboard also enables immediate visualisation of specific scenarios once they have been run. Each scenario includes multiple overrides and different input parameters. On the left side of the screen, it is possible to toggle various technologies (such as supply, demand, storage, conversion, etc.) on or off. This feature allows customisation of the visualisation by hiding certain parameters without needing to re-run the scenario. However, even if a constraint is made invisible, it still exists in the model and thus impacts the result.

The primary goal during this analysis phase is to focus on the modelled storage size and its placement across different node clusters. Additionally, attention is given to potential grid congestion, unmet demand, and the overall cost of the system. Furthermore, it is important to discuss how the model has been validated to ensure its reliability and accuracy, including detailing the validation techniques used and the results obtained.

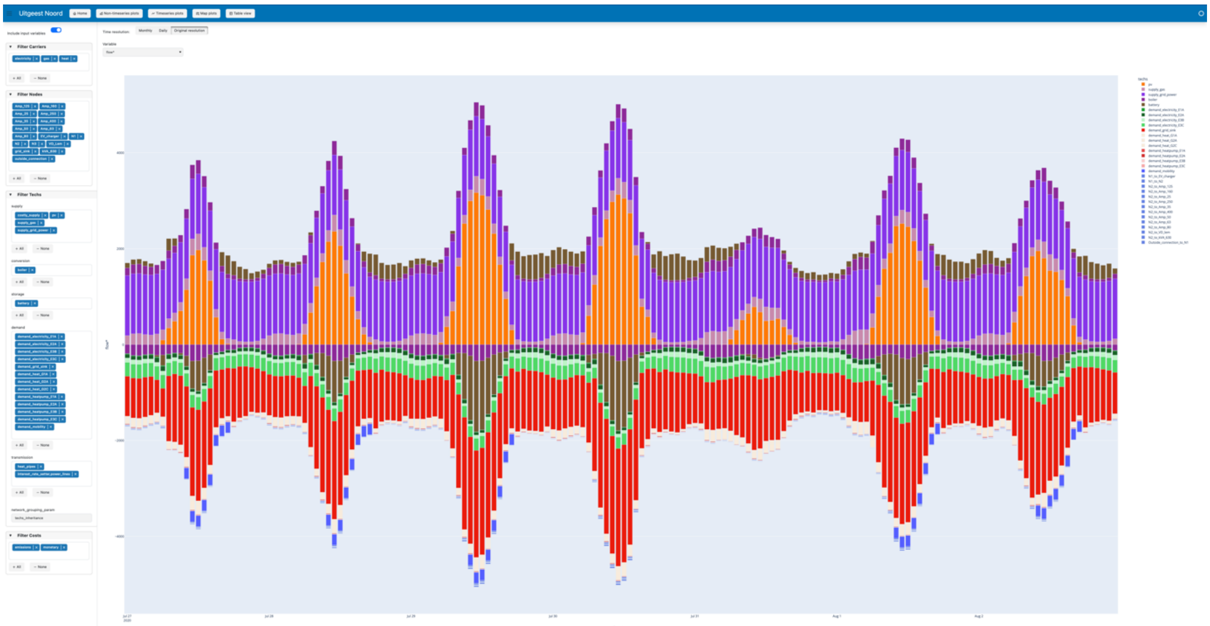

Figure 4.11: Overview of created with Cview - dashboard (source [43]

4.4 Phase 4: Recommendation

In this final phase, the key lessons that are identified from Uitgeest-Noord and the energy modelling are processed into key lessons for Uitgeest-Noord to hopefully incorporate into their subsidy plan. As of the beginning of July 2024, the subsidy has been granted, and the project can begin. Included in these key lessons are stakeholder preference, ideal IDES configuration and potential risk of application. The primary aim of providing these key lessons from the case study is to produce replicable outcomes for potential application in similar small communities. As in region IJmond, Uitgeest-Noord is the first of multiple other business parks that could phase the same issues.

5 Results

The results presented in this section stem from the Uitgeest-Noord model that was run from September 2019 to September 2020. All the results from the different scenarios will be displayed in order of the scenario flow, including sub-conclusions, some noticeable details are discussed followed by an overall conclusion of all the results.

5.1.1 Uitgeest-Noord - Current situation

Figure 5.1: Longitudunal and longitudinal spacital visualistion (created with cview [43])

In Figure 5.1, each node is displayed with its actual longitudinal and latitudinal parameters to provide a realistic representation. The model is set up with the Grid_Sink on the left, acting as a demand pool for demand_grid_sink to export electricity for revenue. The outside_grid connection acts as a supply node for both gas and supply_grid_power to fulfil the demand of all the cluster nodes on the right. To visualise it in a cleaner manner, nodes N1, N2 and N3 are added to keep the line straight; they serve no other functions or bring in limitations. All other nodes represent clusters of locations within the business park Uitgeest-Noord. This visual representation illustrates the flows within the system for each cluster node. Throughout the results, the names of the respective cluster nodes are used to explain and elaborate on the findings.

For the first graph, it's essential to clarify the axes and their significance. The y-axis represents the flow in kWh, indicating the amount of energy supplied or demanded, while the x-axis shows the time series, which can vary based on the interval selected (e.g., 1 year, one season, 1 week, or 1 day). Positive values on the y-axis represent supply, while negative values represent demand.Figure 5.2 is crucial for visualising the flows in the linear energy modelling system, helping to keep the information understandable and clear.

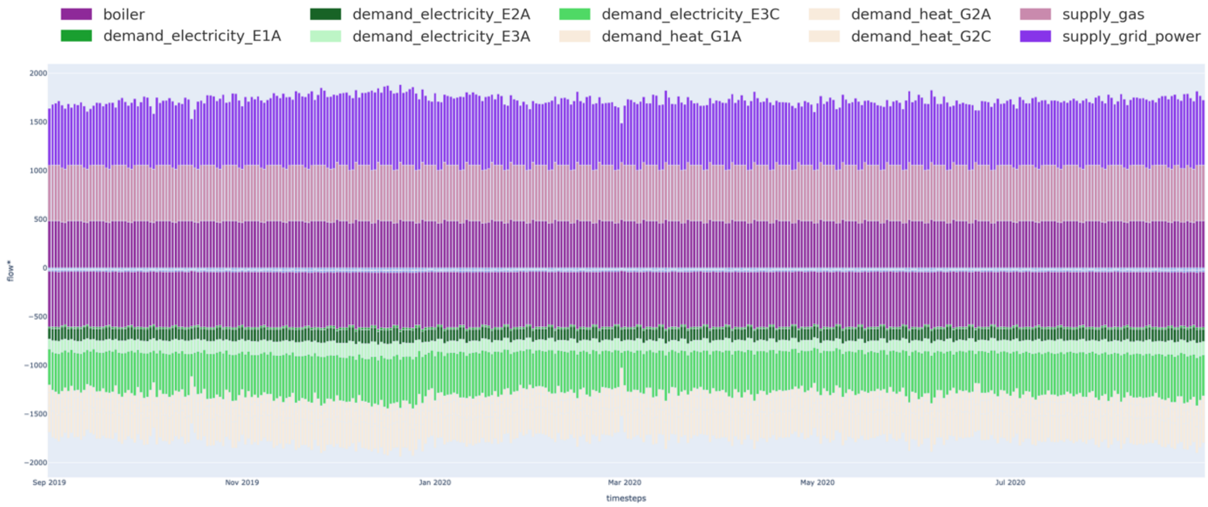

Figure 5.2: Scenario: Current situation - Uitgeest-Noord - ran from 01-09-2019 - 31-08-2020 (flow = kWh, timesteps = days) (created with cview [43])

The first result is a total overview of the current situation in Uitgeest-Noord. This is the general flow of the entire system, which helps us identify each flow using a different colour. On the horizontal axis is always the time series presented; this can have an interval of our liking. However, the intervals used in this thesis are 1 year, one season, 1 week, and 1 day. The vertical axis is represented by a value, which, in this case, is the flow in kWh. Positive values (upper part) are the supply, and negative values (lower part) are the demand side. Due to the importance of graphs outputted by the system, the first overview is put here in the result section. It provides some interesting observations. Namely, due to the way the boiler is modelled, heat is supplied both as a demand (bottom part of the graph) and where gas is needed as a supply (upper part of the graph). This current situation scenario was also used in order to cross-check the overall performance of Calliope with reality where, for example, supply_grid = 5.976.419 kWh. This is in the same order of magnitude as the inputted data. Thus, we can conclude that the model is working as intended.

5.1.2 Uitgeest Noord – Solution mix 1

In solution mix 1, every electrification step is added as described in the method section in the energy model of Uitgeest-Noord; this includes the addition of PV panels, EV-charing infrastructure and heat pumps, which replace a big portion of the traditional gas boiler. The results are displayed in Figure 5.3. These heat pumps are only used during the winter months from the end of October until May, as seen in red (demand_heatpump).

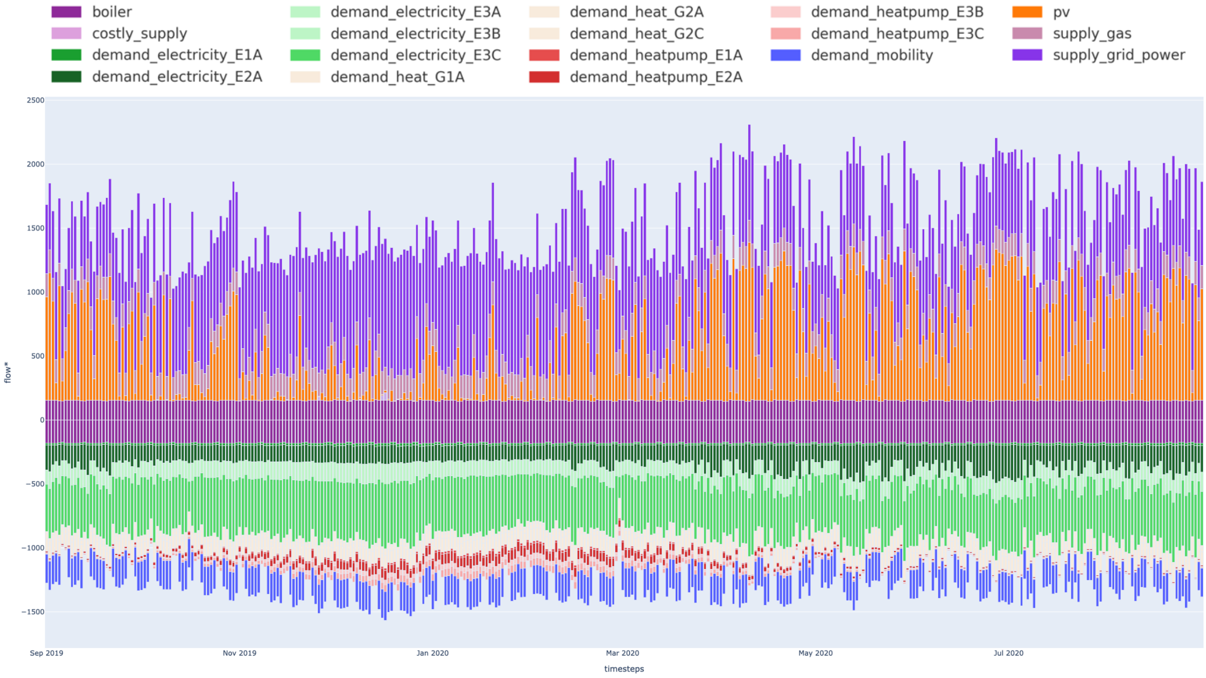

Figure 5.3: Full-year run, for solution mix 1- ran from 01-09-2019 - 31-08-2020 (flow = kWh, timesteps = days) (created with cview [42])

As this solution mix introduces the use of PV panels, it is noticeable that the model decided to curtail the PV panels on average by almost 40% (see Figure 5.4). This means that it does not use the maximum potential installed capacity (green area), which reduces the output of these solar panels. In per cluster node, the total percentage of potential capacity is displayed. The reason this is done is due to technical constraints on the transmission capacity of electricity cables, which is especially noticable in node cluster Amp_125, Amp_250 and Amp_80.

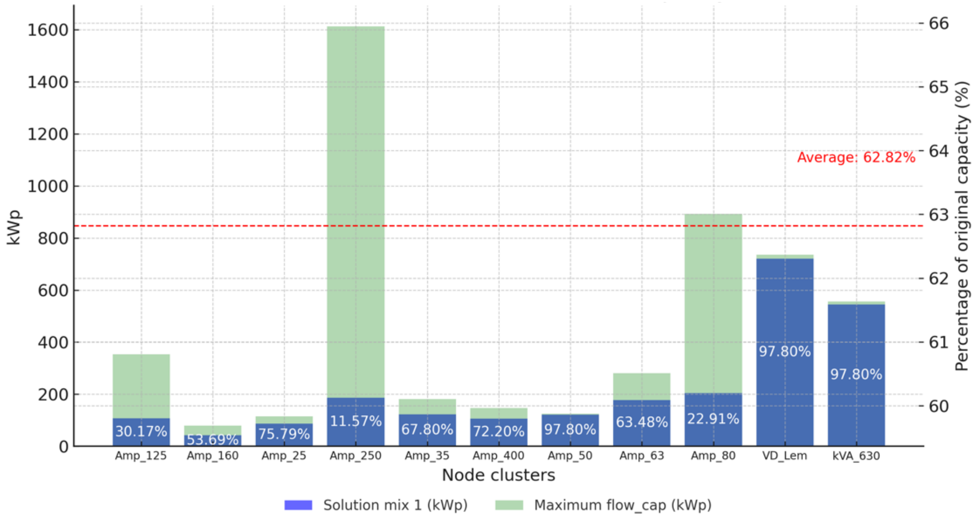

Figure 5.4: Solution mix 1 – Percentage of kWp of installed solar Capacity at each node cluster, resulting in a decreased use of all available area (generated [44])

To understand why this curtailment is evident, Figure 5.5 zooms in on December 16 and 17 to showcase that the model uses a supply tech, which is very expensive (*costly_supply*). This supply tech is designed into the model to showcase where and if grid congestion is appearing. As the model needs to ensure the feasibility, this supply tech is freely available without any constraints; however, due to the cost of 100 EU per used kWh, it is only used in unavoidable cases. On this particular day, no electricity from PV panels is generated. However, a higher demand for electricity is used, and therefore, it exceeds the technical transport capacity of 1252 kWh of supply from the grid (*supply_grid_power*). The supply from the grid (supply_grid_power) is max out to 1252 kWh. Which results in grid congestion and the use of this costly supply (*costly_supply*).

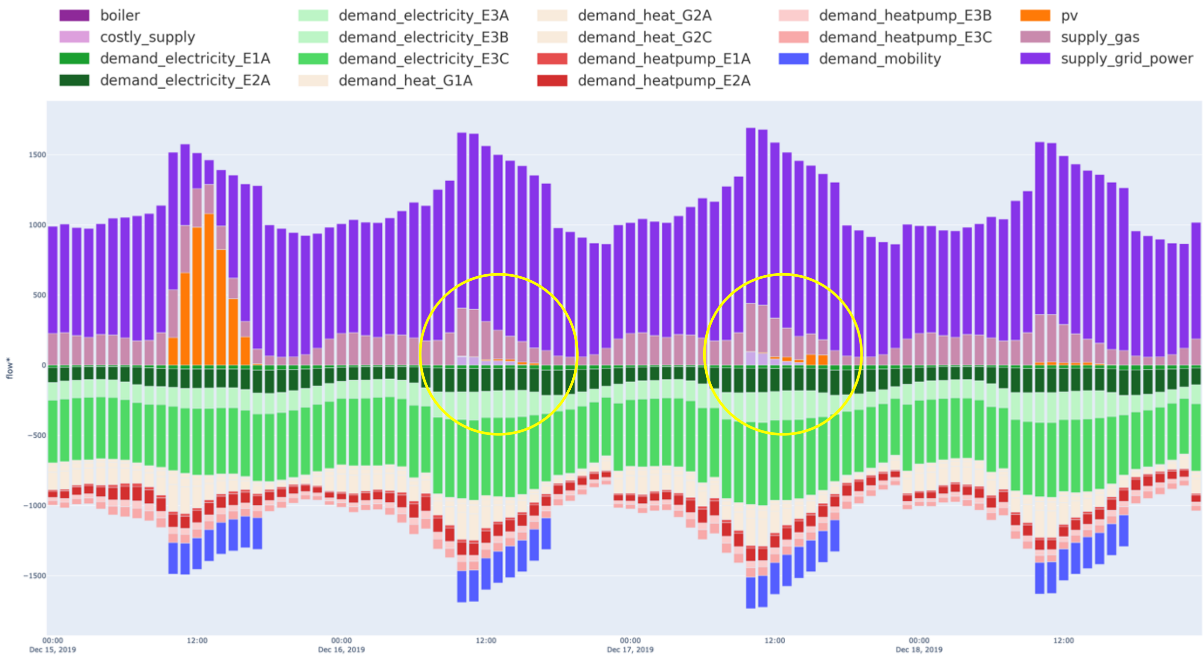

Figure 5.5: Full-year run, for solution mix 1- ran from 01-09-2019 - 31-08-2020 (flow = kWh, timesteps = hours) (created with cview [42])

Appendix 9.10 provides detailed raw data showing the exact timestamps when "costly_supply" was activated. This phenomenon is particularly evident in Figure 5.5, where the curtailment of PV panels is noticeable. On cloudy days, when PV electricity generation is minimal, and electricity demand—such as for mobility—is high, the system often exceeds the technical transport capacity of 1252 kWh allocated to the supply_grid_power tech. To maintain system feasibility under these conditions, the system is forced to rely on costly_supply, leading to grid congestion. Given the high cost of 100 euros per kWh for this supply, the system currently faces a shortfall of approximately 600 kWh annually, resulting in significant financial implications.

By examining the rest of the behaviour of the system, due to all the extra electrification a lot of extra stress is put on the system and the boundaries of transport capacity are more in reach than is anticipated after running the current scenario.

5.1.3 Uitgeest Noord – Solution mix 2

In solution mix 2, storage capabilities are added to use more of the potential installed PV capacity. This solution mix cannot sell excess stored electricity back to the grid; at times, the price is higher. To isolate the models behaviour without any cont constrains this scenario has price per kWh installed capacity of both PV panels and storage put on zero. Currently, this means that the model chooses to build the total storage capacity as high as possible to use almost all available PV panel capacity (98%). All the excess PV electricity generated is charged to the battery. In this way, all the electricity produced from the PV panels is "used" either for the demand or to charge and store this excess generated electricity. As seen in Figure 5.6, the behaviour of the storage solution in the model is to charge the battery during times of excess produce energy and use PV electricity to charge it. This results in a dip during the winter period from (December 2019 until February 2020), with a bigger available charging state during the spring and summer period. This also corresponds with the orange graph spikes representing pv generation in

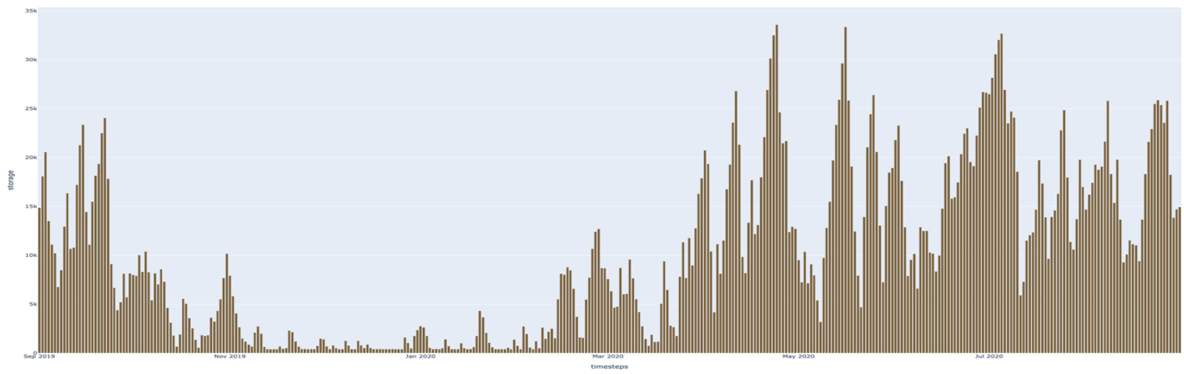

Figure 5.6: Full-year run - Solution mix 2 - Storage usages - ran from 01-09-2019 - 31-08-2020 (storage = kWh, timesteps = days) (brown = battery) (created with cview [42])

In Figure 5.7 another interesting fact is the purple lines, representing *supply_grid_power*, are mostly used to assist when there is not enough electricity usable from the storage (brown) or procude by the PV panels. As expected, the model decides to use stored electricity as much as possible and avoid using electricity from the grid (supply_grid) as much as possible; even with this infinitive amount of possible electricity storage, in the winter months, the potential installed kWp of solar power is not enough to become independent from the energy grid. This results in more electricity usages from the grid (purple) during the winter months.

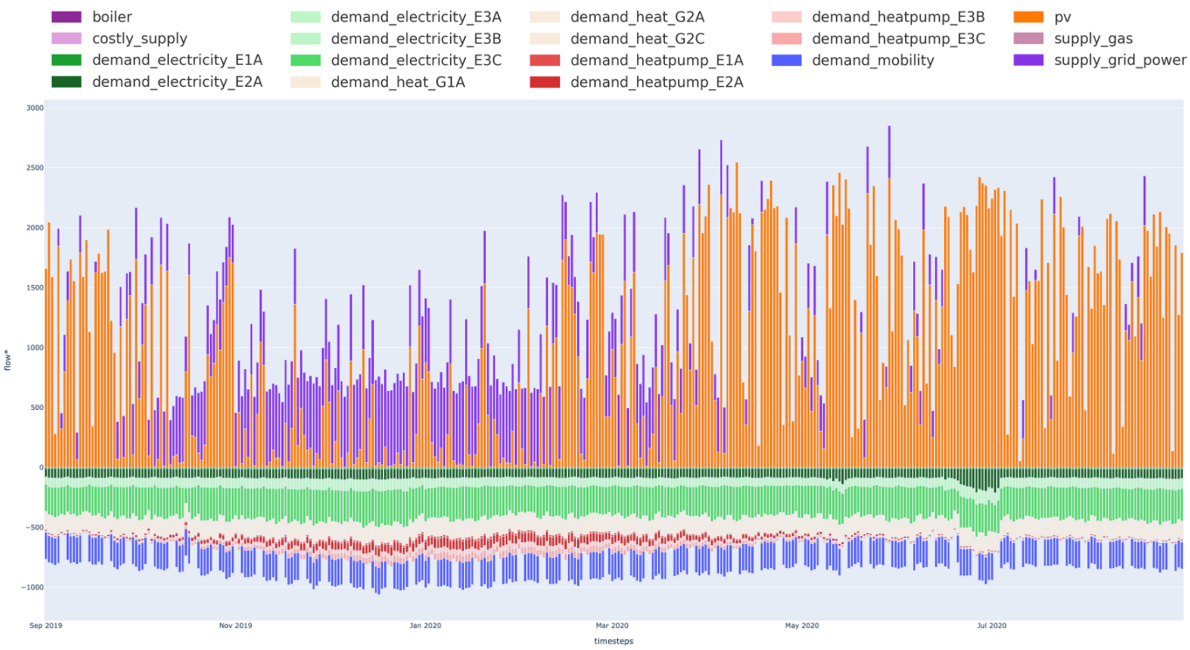

Figure 5.7: Supply from PV panels & supply grid - ran from 01-09-2019 - 31-08-2020 (flow = kWh, timesteps = hours) (created with cview [42])

5.1.4 Uitgeest Noord – Solution mix 3A – Excluding costs

In the solutions mix 3A the modelled is allowed to use *demand_grid_sink* to export electricty back to the grid for revenue. As explained in the methods sections the price of electricity supplied from the grid consist of the day-ahead price including grid operator fee. Resulting in a dynamic electricity price, to profit from when you have a storage solution installed, resulting from *demand_grid_sink*.

In our first run the the negative price received for export to *demand_grid*_sink to essentially earn money was different than the price for for supply from the grid, which poses unwanted side effecets in the modelling results, resulting in a sudden maximisation of the transport capacity of the supply_grid to sell this electricity via the storage right back to the demand_grid_sink due to a small difference in the fixed buying price of supply and the price of the model would receive by selling it as demand_grid_sink. This side affects are explaind in appendix **Error! Reference source not found., Error! Reference source not found.**the rest of the runs are executed by converting the supply_grid_power price to a negative number as explained in the method section 4.2.4.

With this change in pricing, the model's behaviour shifts, resulting in storage solution being charged during peak solar generation to charge the battery. This stored energy is then used to meet nighttime demand and to supply the demand_grid_sink (represented by red bars), generating revenue for the system. Given the assumption of an infinitely large battery, the model maximises charging during off-peak hours to maximise revenue from exporting electricity to the demand grid (red bars). Another noticeable difference is the behaviour of demand_grid_sink between summer and winter weeks. In Figure 5.8 and Figure 5.9 the outcome of a run of one week in the summer and winter is displayed. The model in the winter week charges the battery overnight by maximising supply_grid and uses the battery during the day to meet the demand. However, the excess electricity of the summer model is used for demand_grid_sink.

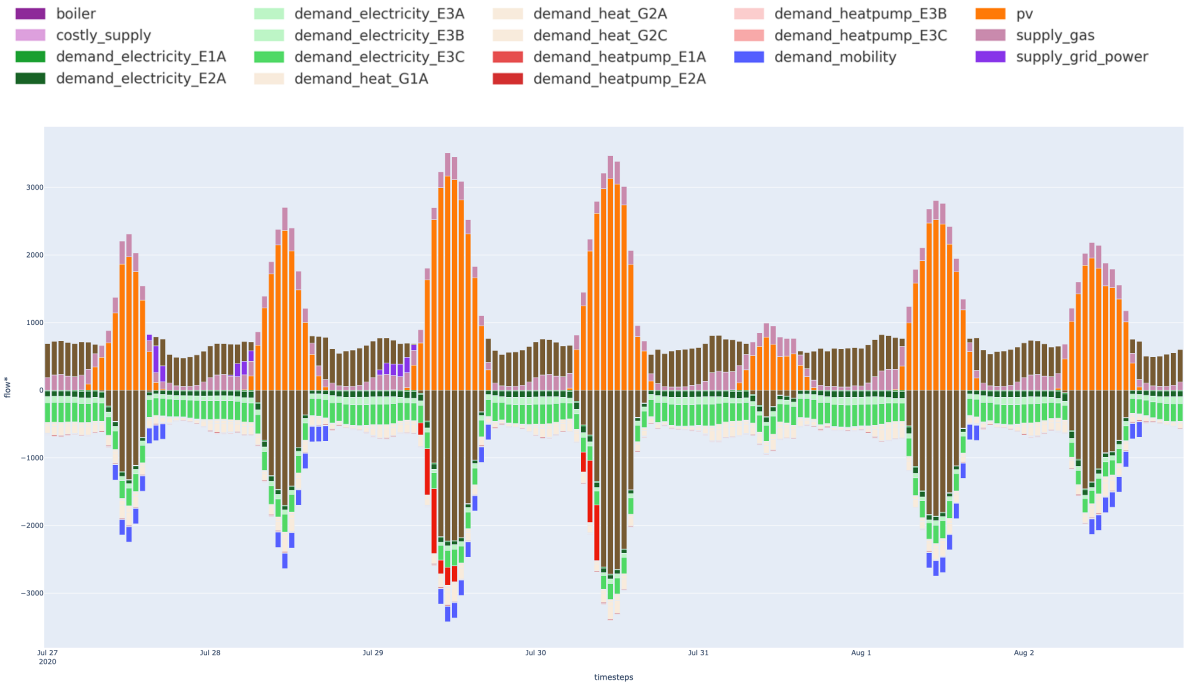

Figure 5.8: Solution mix 3A - Overview flows. Run of 1 week, summer (27-07 until 02-08) (flow = kWh, timesteps = hours) (created with cview [42])

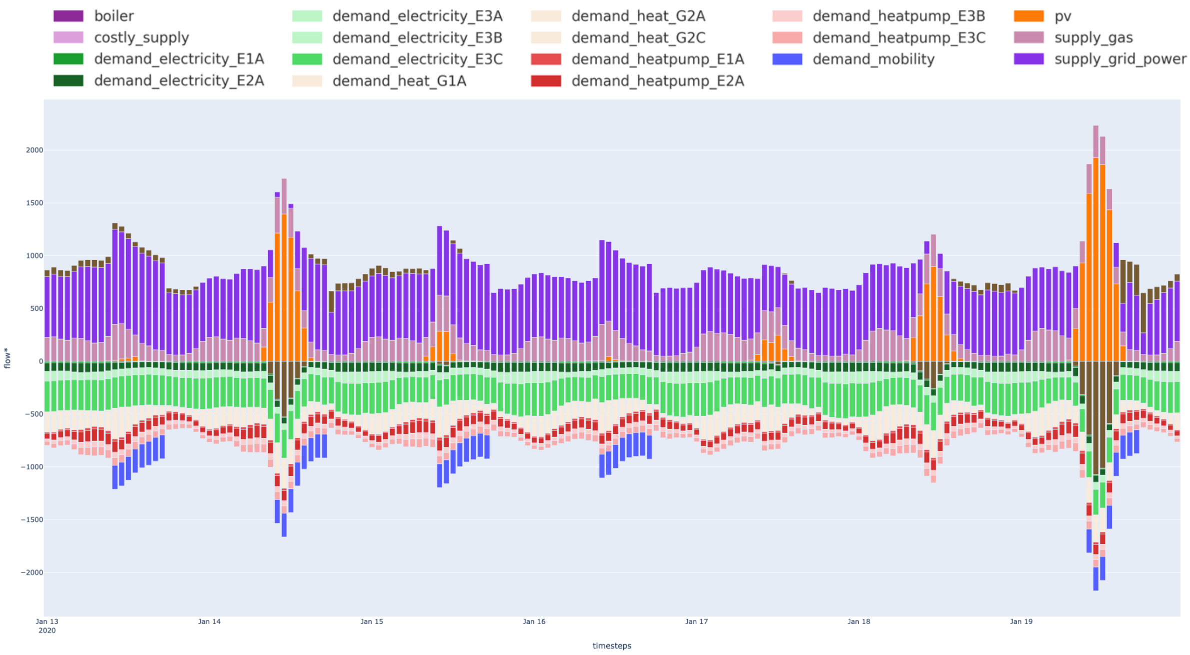

Figure 5.9: Solution mix 3A - Overview flows. Run of 1 week, winter (13-01-2020 until 20-01-2020) (flow = kWh, timesteps = hours) (created with cview [42])

5.1.5 Uitgeest Noord – Solution mix 3B – Including cost

In solution mix 3A the isolated behaviour of the model without including cost on both PV capacity and storage capacity shows that total battery capacity reduces by -50%, and total solar PV capacity installed is decreased form 98% tot 90%. Resulting in more available PV capacity to earn costs back via *demand_grid*_sink, due to the missing battery capacity (see red bars in Figure 5.10) in Solution mix 3B.

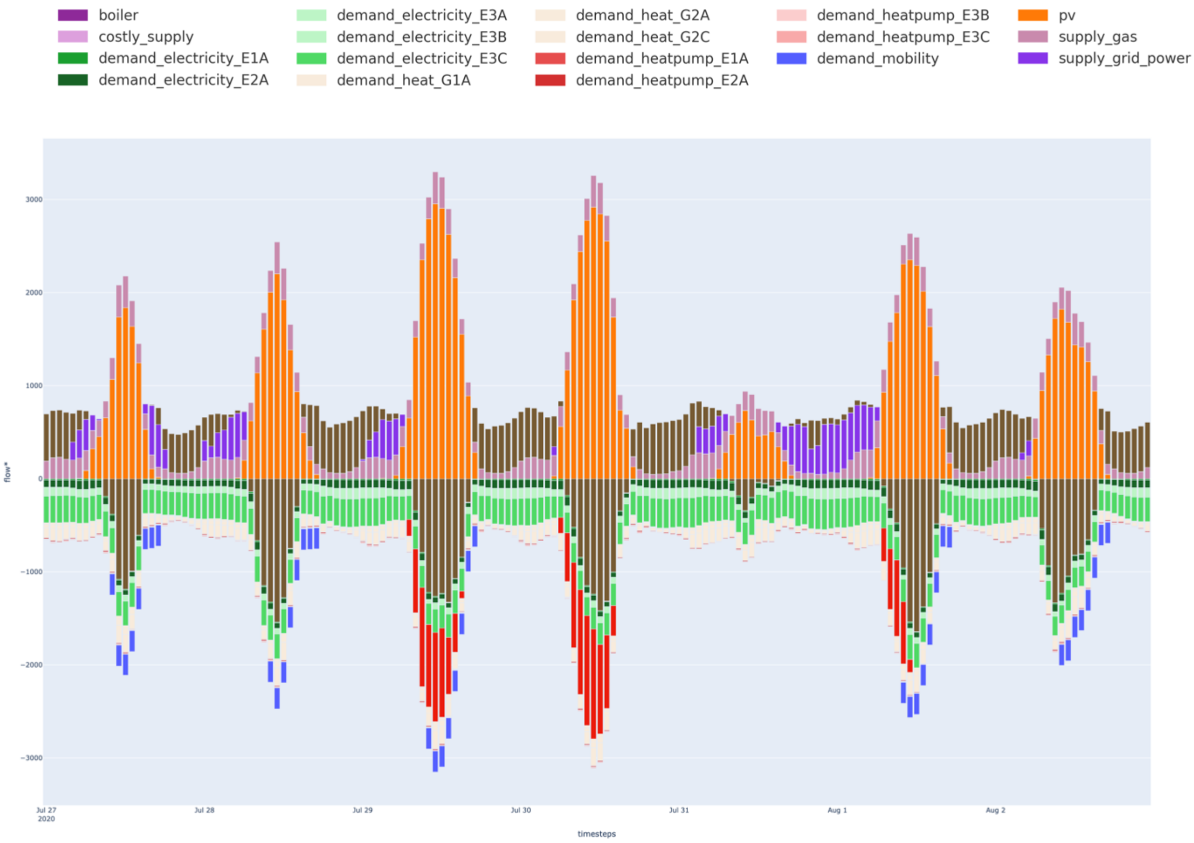

Figure 5.10: Solution mix 3B - Overview flows. Run of 1 week, summer (27-07 until 02-08) (flow = kWh, timesteps = days) (created with cview [42])

5.1.6 Comparisons of cost per storage capacity in €/kWh and including battery capacity limit scenario

By putting a cost per kWh installed storage capacity the model has no infinite amount of storage solution anymore and needs to optimise for these costs. This is done in two ways, firstly by exporting excess produced PV power back to the grid and earning costs back via demand_grid_sink as concluded in the previous paragraph. The second option is to charge up the battery, store this electricity and use it in periods as a substitution for the supply_grid price. In Figure 5.11 below, the chosen storage size per scenario is visualised in multiple bar charts. As you can see in the top row when there are no constraints in terms of costs, especially for cluster node amp_250, Amp_63 and Amp_80 the total installed capacity is higher. Intresting to node is that the biggest electricity user, KVA_630, cannot install the biggest battery. Mainly due to its flat profile and therefor it alread consumes a lot of PV capacity directly.

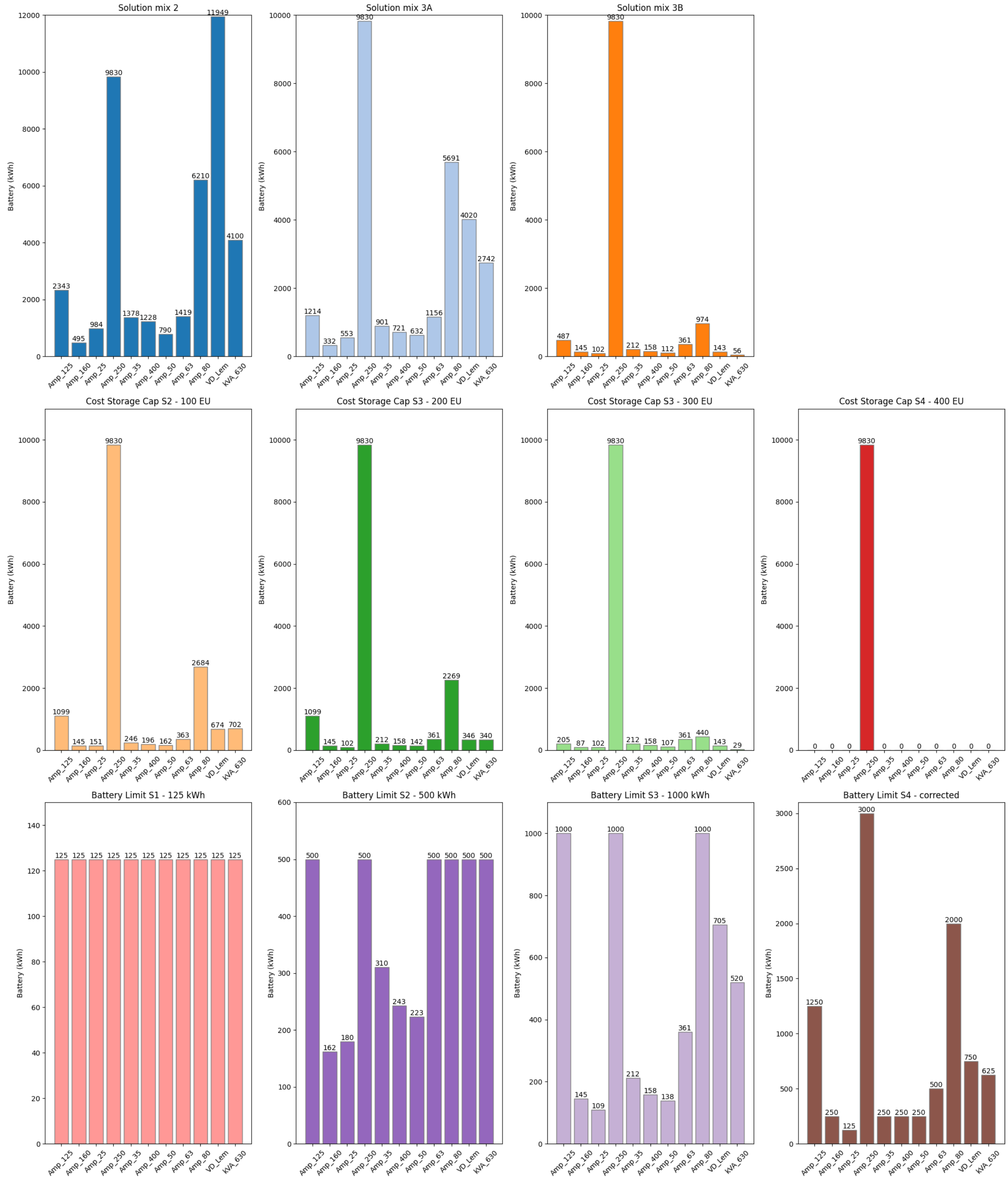

Figure 5.11: Comparison of battery size per scenario – ran from 01-09-2019 – 31-08-2020 (Because current scenario and solution mix 1 did not have a battery installed these scenario are not visible in the figure) (Generated [44]).

By adding the cost constraint of a cost per installed kWh of 1, 100, 200 or 400 euro, in the second row, it is noticeable that it directly correlates with the ability to install a high amount of PV capacity. By comparing the influence of each scenario on the utilised potential capacity of PV panels, the following three spider diagrams (see Figure 5.12) illustrate the percentage of total potential capacity used. Notably, in solution mix 1, as described earlier in the results section, there is a significant curtailment of PV panels due to the mismatch between supply and demand. In solution mixes 2 and 3, the addition of infinite storage capacity increases the potential usage to 98% on all node clusters (100% is not achievable due to efficiency factors).

As cost constraints of 1, 100, 200, 300 and 400 euros are applied, the total storage size is reduced per cluster node. The higher the cost per installed capacity, the bigger the impact on potential usage of PV capacity and the decrease in the amount of PV panels installed, as shown in the middle spider diagram. An interesting note is that by the cost increase of 100 eu per kWh to 200 eu per kWh, only cluster nodes Amp_125 and Amp_80 decreased in total PV capacity usage.

The rightmost spider diagram illustrates the decrease in usable PV generation when storage sizes are limited to 125 kWh, 500 kWh, and 1000 kWh. Node Amp_63 shows the biggest increase in PV usage when it can expand storage size capacity from 500 to 544 kWh. Conversely, Amp_250 is the only node cluster where storage size increases to 1000 kWh installed, but it has the lowest potential benefit in terms of usable installed PV panels, increasing only from 16% to 23% (113 kWp). In order to keep the battery capacity realist with 125 kWh intervals (this sizing blocks are commonly used [20]) the 1000 kWh scenario is correct to accommodate this.

The learnings from this phase indicate that the cost per installed capacity can be mitigated by fitting a larger battery to use all the electricity provided by the PV panels, thus providing enough benefit to offset the cost. However, considering the broader context and available resources, these storage sizes are not feasible in our case study of Uitgeest-Noord. Therefore, the limitation on battery capacity is the primary constraint on utilising the full potential of PV capacity.

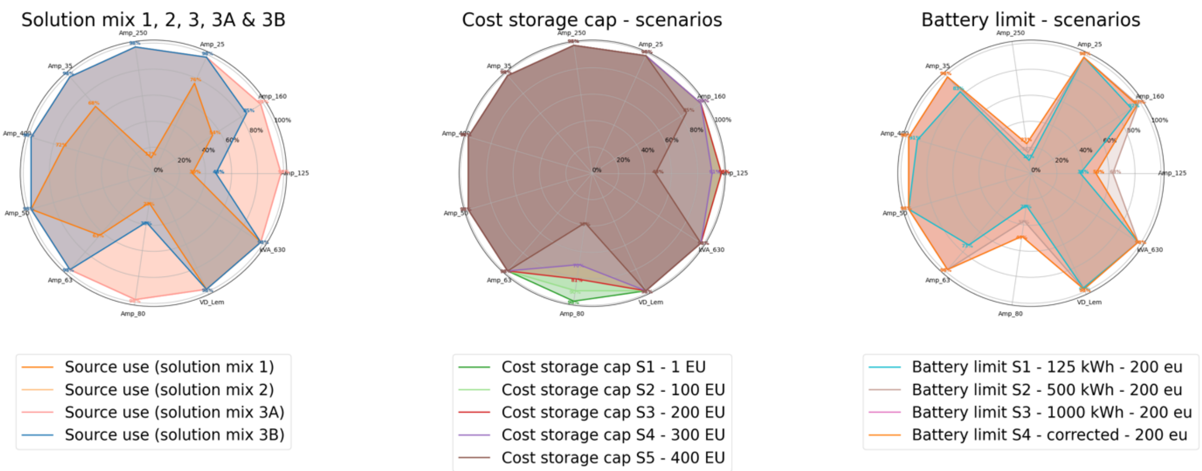

Figure 5.12: Spyder diagram visualising used PV capacity in percentages of total available capacity (Generated [43]).

5.1.7 Excluding export for revenue by comparing different costs per storage capacity in €/kWh and limiting total battery capacity.

With the discontinuation of the 'solderings regeling' [33], having a storage solution in place becomes increasingly important for energy security, as it allows you to store excess electricity generated by PV panels. Currently, the ability to sell excess power back to the grid enhances the functionality of a battery, serving multiple purposes. However, if this option is removed, the added benefits of large solar panels are diminished. This reduction leads to a decrease in average solar capacity installation from 91% to 86% when excluding export for revenue.

As a result, only two clusters—Amp 80 and Amp 125—remain where installing a battery is too expensive to justify. In these clusters, the ability to install all solar panels is compromised, with capacity utilization dropping to 62% and 49%, respectively.

Although the differences in PV capacity and storage size between scenarios are not significant, the overall system becomes more expensive, particularly with the increased demand on the grid (demand_grid_sink) that is lost. Appendices 9.12 and 9.13 present both the monetary and CO2 emissions costs for different scenarios, comparing cases with and without the option to export for revenue.

5.2 Total cost of the entire system

As explained in the method section in Calliope, two cost classes are modelled: monetary and co2_emissions in the following objective weight distribution (6:4) to optimise for:

Parameters:
objective_cost_weights:
data: [6,4]
index: [monetary, co2_emissions]
dims: costs

5.2.1 Monetary costs

The cost per scenario are displayed in Table 5.1 below. The "Current Scenario" serves as a baseline, with the highest overall cost of €784,647, primarily driven by significant reliance on grid power (€660,534) and gas supply (€124,113). The assumptions made about a green premium of 50% on battery costs per installed kWh, is active. Currently, the price per installed kWh for a BESS is around 400 eu/kWh. However, this is already decreasing, and 200 eu/kWh will be a viable price in the near future. In scenario mix 2 and 3A, no monetary costs where added.
The rest of the scenarios provide a lower overall yearly cost than the current scenario. The installed technology costly_supply is only used twice during the solution mix 1 and battery capacity limit (1) – 125, as both of the scenarios are not able to use enough to produce solar power and thus experience grid congestion.

When the ability to export for revenue is removed, the overall system cost increases across all battery capacity scenarios. This is particularly evident in the "Battery capacity limit (4) - corrected" scenario without export, where the total cost rises to €794,774, the highest in this category, highlighting the economic benefit of being able to export surplus energy.

Table 5.1: Cost per scenario (Generated [44]).

Monetary	Supply_grid_power (eu/kWh)	Supply_gas	PV	Battery (200eu/kWh/installed)	Demand_grid_sink (eu/kWh)	Costly_supply (eu)	SUM Total
Current scenario (kWh)	€ 660.534	€ 124.113	x	x	x	€ 0	**€ 784.647**
Solution mix 1	€ 587.759	€ 39.340	x	x	x	€ 63.503	**€ 690.602**
Solution mix 2*	€ 231.665	€ 39.340	€ 0	€ 0	x	€ 0	**€ 271.004**
Solution mix 3A*	€ 233.548	€ 39.340	€ 0	€ 0	-€ 26.732	€ 0	**€ 246.155**
Solution mix 3B	€ 320.918	€ 39.340	€ 347.604	€ 457.193	-€ 72.914	€ 0	**€ 1.092.141**
Battery capacity limit (1) -125	€ 360.889	€ 39.340	€ 210.667	€ 26.567	-€ 67.019	€ 0	**€ 570.444**
Battery capacity limit (2) - 500	€ 307.275	€ 39.340	€ 244.633	€ 97.354	-€ 38.802	€ 0	**€ 649.800**
Battery capacity limit (3) -1000	€ 291.960	€ 39.340	€ 271.255	€ 118.091	-€ 42.635	€ 0	**€ 678.010**
Battery capacity limit (4) - corrected	€ 266.124	€ 39.340	€ 318.431	€ 178.722	-€ 45.162	€ 0	**€ 757.454**
Without the ability to export for revenue							
Battery capacity limit (1) -125	€ 376.294	€ 39.340	€ 160.343	€ 26.567	x	€ 0	**€ 602.544**
Battery capacity limit (2) - 500	€ 303.423	€ 39.340	€ 244.633	€ 105.571	x	€ 0	**€ 692.966**
Battery capacity limit (3) -1000	€ 284.728	€ 39.340	€ 271.255	€ 135.232	x	€ 0	**€ 730.554**
Battery capacity limit (4) - corrected	€ 270.910	€ 39.340	€ 305.803	€ 178.722	x	€ 0	**€ 794.774**

** The cost of the battery is normalised for a lifetime of 15 years, taken at a price of 200 EU/kWh installed. During Solution mix 2, 3A the price was 0 EU/kWh to see how the model would handle free available storage.*

5.2.2 Emissions costs

The analysis of CO2 emissions across various energy scenarios is visualised in the bar chart in Figure 5.13. The "Current scenario" exhibits the highest emissions at 2211 tonnes CO2/kWh, which serves as the baseline for comparison. Among the alternative scenarios, the "Battery capacity limit (4) -corrected" scenario shows a significant reduction, bringing the total emissions down to 1101 tonnes CO2/kWh. This scenario incorporates a balanced approach between supply grid power, photovoltaic (PV) integration, and battery storage, resulting in the most efficient reduction in emissions. The vertical dashed line in the chart highlights this scenario, providing a reference point across all other scenarios. The "Cost per storage cap" scenarios show a progressive increase in emissions as the cost of storage increases, indicating that more affordable storage options are crucial for minimising emissions. Conversely, the "Battery capacity limit" scenarios demonstrate that higher capacity limits lead to a gradual increase in total emissions, emphasising the need for optimised battery capacity to achieve lower emissions. Overall, the results indicate that strategic adjustments in energy storage and capacity limits can lead to substantial reductions in CO2 emissions.

In appendix 9.13 all CO2 emissions are displayed in the form of a table.

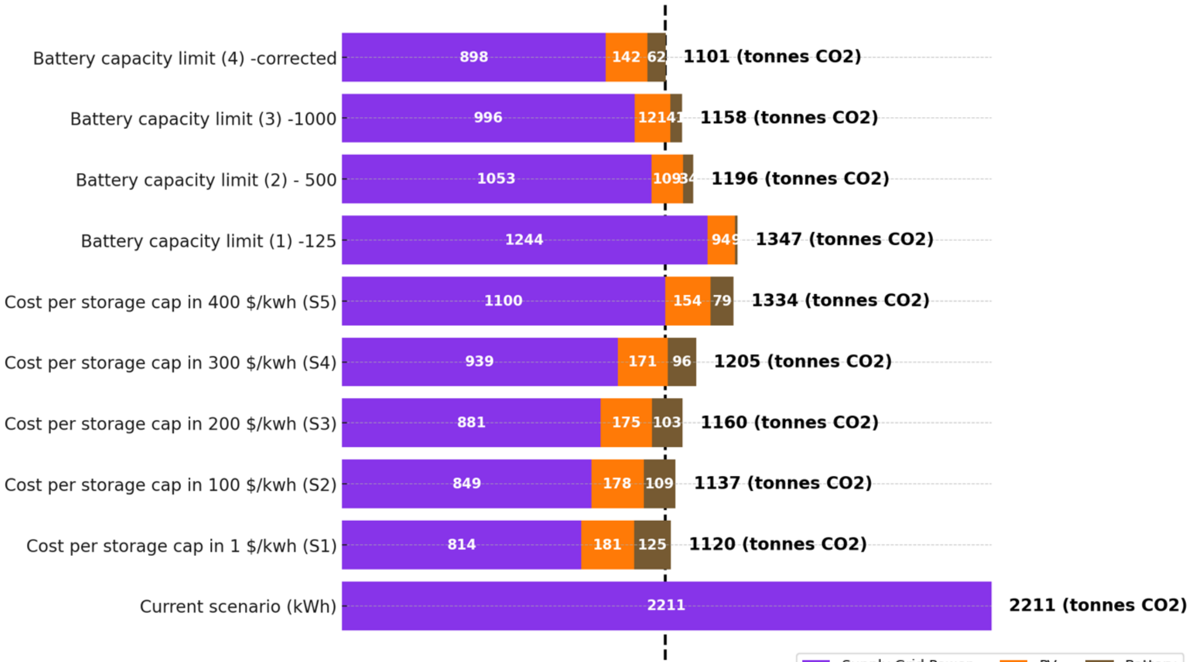

Figure 5.13: Total tonnes of CO2 per scenario (Generated [43]).

5.3 Testing robustness of final configuration.

In the following sections, the robustness of the chosen model specific is tested. Herefor, scenario *Battery capacity limit (4) – corrected* is chosen. By testing the robustness of the chosen configuration in terms of expansion of demand, limiting PV solar capacity, and incorporating low and high-cost scenarios for electricity supply prices. The impact on the configuration can be shown. In these examples, the BESS capacity sizing stays fixed. Only supply from the grid, and PV panel capacity is the same with the following capacities per node cluster:

Table 5.2: Total storage capacity per node cluster of scenario – Battery capacity limit (4) – corrected (generated [44])

Node cluster	Battery capacity limit (4) - corrected (kWh)
Amp_125	1250
Amp_160	250
Amp_25	125
Amp_250	3000
Amp_35	250
Amp_400	250
Amp_50	250
Amp_63	500
Amp_80	2000
VD_Lem	750
kVA_630	625
Sum Total	9250

5.3.1 Expansion demand scenario

By expanding the demand by 1.25x, 1.5x, and 1.75x, the total flow in the system increases, particularly in the supply_grid_power. Interestingly, when examining the PV capacity, only a slight increase of around ±1.5% per expansion scenario is noted. Specifically, the PV panel installed capacity increased from 3954 kWp in the scenario with a 1.25x demand expansion to 4022 kWp for the 1.5x expansion and further to 4084 kWp for the 1.75x demand expansion scenario, which indicates that the model can accommodate slightly more solar capacity due to the increase in demand however that the chosen battery configuration especially the limiting node cluster amp_250 is limiting factor. To still ensure feasibility, the model is increasing the supply from the grid (*supply_grid_power*).
This results in increased supply_grid_power and accommodates the increased demand for electricity, as no extra storage capacity is used to, for example, accommodate extra PV generation. Intrestinlgy due to the increased demand, the available room on the grid is reduced, and therefor the ability to export power for revenue is also reduced by almost 50%.

5.3.2 Different PV capacities utilised

By limiting the potential installed capacities of PV to 25%, 50% and 75%, we mimic a worse year in terms of solar performance and see if an expensive BESS which is already installed will influence the overall economic performance of the model. Two things occur when solar capacities are restricted. First, the model reduces the amount of exports for revenue, meaning there is less excess electricity. Secondly, the battery is way too large, and a lot of unused capacity is left on the table. This is due to the fact that charging the battery from electricity from the grid is, in terms of CO2 emissions costs inefficient.

5.3.3 Low/high-cost electricity scenario

In both the low-cost and high-cost scenarios, the cost associated with the supply grid varies as expected due to the different cost multipliers applied. In the low-cost scenarios, supply grid costs are lower, reflecting the application of multipliers of 0.5, 0.7, and 0.9. Conversely, in the high-cost scenarios, supply grid costs are significantly higher, due to the application of multipliers of 1.5, 2, and 2.5. Despite these adjustments, there is almost no increase in PV capacity, as expanding PV is not entirely feasible within the given constraints. Additionally, in the low-cost scenarios where there is no opportunity to export excess energy for revenue, the PV panels are often curtailed, limiting their output to match the reduced demand.

One expected outcome was that due to the higher difference between minimum and maximum costs in the high-cost scenario, the battery would perform better and see an increase in usage. However, this was not the case. This suggests that the model has already optimized the maximum amount of PV capacity, which continues to impose limitations on battery size, particularly for node Amp_250. The complete monetary costs for all these scenarios, including expansion demand, different PV capacities, and both low and high-cost scenarios, are displayed in Appendix 9.12.

The analysis across different scenarios reveals that the system's ability to scale and optimise PV capacity due to the fixed battery storage capacity is limited. Despite increases in demand or variations in electricity costs, the model only marginally increases PV capacity, suggesting that it is already close to its optimal capacity within the given constraints, particularly due to limitations in the battery configuration and specific nodes like Amp_250. In the low cost scenario it even decreases the PV capacity, as supply from the grid becomes much more attractive and the model takes takes the battery storagy pentalty. Additionally, the battery storage system is consistently underutilised, primarily due to the high costs associated with charging the battery from grid electricity, especially in scenarios where grid electricity is less attractive due to CO2 costs.

5.3.4 Seasonal trends

The corresponding season has a big impact on PV generation; in Figure 5.14 below, total PV generation (orange) per day is compared to total export for revenue as demand_grid_sink (red) for the four seasons. A higher PV generation will result in more excess electricity after it meets demand-supply, and therefore, it can be used as an expert for revenue. By comparing this to the storage use behaviour in Figure 5.15 during the winter period the used percentage of installed storage capacity is more than 75% lower than during the summer period. This provides us with the insight, that to make a storage solution effective, the summer period is important. Besides that the total size is also configured for this summer period, however, this is together with the fact the battery needs to be cost-effective.

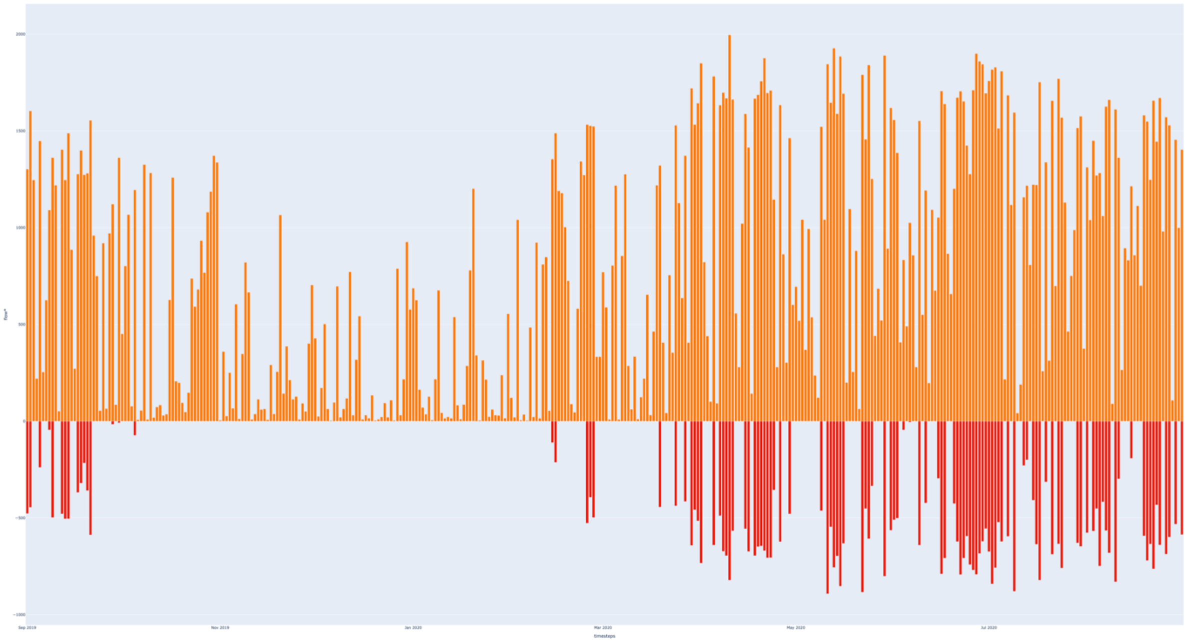

Figure 5.14: Scenario Battery limit (S4) corrected. September 2019 until Augustus 2020 (Autumn (2019-09-01 until 2019-11-30), Winter (2019-12-01 until 2020-02-29), Spring (2020-03-01 until 2020-05-31), Summer (2020-06-01 until 2020-08-31) (flow = kWh, timesteps = days) (created with cview [42])

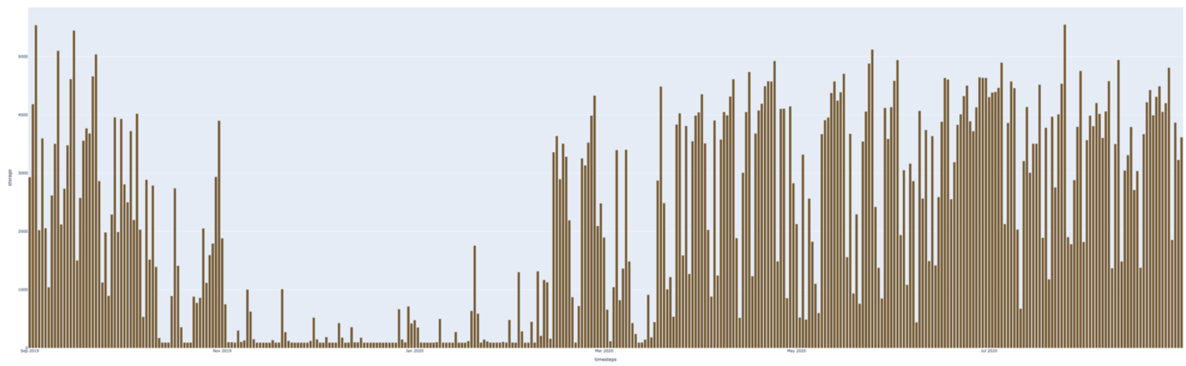

Figure 5.15: Storage used for an entire year (flow = kWh, timesteps = days) (created with cview [42])

6 Discussion

In the discussion chapter, all the technical knowledge, method approach and results analysis are gathered to discusses findings, which in chapter 7 will be concluded to anser the sub-research questions and the main research question. Firstly method approach is discussed for imperfections and potential improvements, where then limitations of results are discussed in sections 6.2, and practical and future implementations are discuessed in section 6.3.

6.1 Method used

The method developed in this thesis aimed to provide a robust technical foundation to identify and address gaps in the modelling workflow. From the outset, the focus was on understanding the rationale behind modelling each aspect and determining the specific information required for the results section. The set-up scenarios were particularly useful, as each was designed with a specific purpose for data extraction. However, this approach also had its limitations; it was somewhat narrow in scope, which meant that certain interesting parameter changes or decisions fell outside the proposed scope. For instance, while the ability for the model to export electricity to the grid for revenue was included, an initial error in pricing led to an unintended outcome: the model began to maximise supply from the grid simply to sell it back at a profit. Although this behaviour was technically correct from an optimisation standpoint, it was impractical and ultimately unusable. This issue only became apparent during the results analysis, highlighting the importance of iterative testing and validation in modelling.

6.2 Discussion limitations of results

This section discusses the limitations of the results and suggests improvements for future research, which will be covered in Section 6.5. Herefor there is looked back at the concluded knowledge gap, of accuratly modelling energy generation profiles, what the optimal size of BESS is and the lack of case study projects. Therefore validating the model's behaviour against real-life data is crucial for ensuring its accuracy and relevance. However, since the current case study involves a system that has not yet been built, it is not feasible to compare real-life demand, battery flows, and other parameters. Therefor our key findings have been cross-checked with existing studies on energy modelling for BESS [45].

One significant finding is that the model tends to prioritise cost reduction over minimising supply-grid usage. This behaviour, where the model increases supply from the grid to export electricity for revenue, is not ideal because it puts additional stress on system constraints. However, given that the linear programming optimisation model is designed to minimise annualised costs, this outcome is understandable. To mitigate this effect, additional runs were conducted without the ability to export electricity back to the grid. While this approach reduced the issue, it also made the system more expensive by eliminating potential revenue from exports.

Another observed behaviour is that limiting battery costs also limits the potential installation of PV panels. This reduction in PV capacity decreases the amount of demand-grid-sink, thereby lowering overall system costs. However, optimising battery costs can reveal external factors that, while seemingly beneficial, may also prove to be ineffective or impractical. This concurrent behaviour of a BESS model is also documented in existing literature [45].

The existing demand-grid-sink technology poses unwanted side effects, as discussed during the results phase. Currently, businesses market BESS systems with the promise of earning money based on the day-ahead price. However, this was not feasible in our model due to the unwanted side effect of maximising the demand flow from supply from the grid to then again export it for revenue. Additionally, the Netherlands already experiences an excess amount of generated green electricity during the day, making room to export for revenue not guaranteed. During the thesis period, it was agreed that from 2027 onwards, the "salderingsregeling" (where small users below 3x80 amperes are guaranteed by law to receive the same amount of money per kWh as currently modelled in the system) will be phased out [33]. Given the current high amount of green electricity generated, delivering electricity back to the grid is financially beneficial for the model's outcome. However, with ongoing developments, in hindsight, this is not the most logical modelling choice and therefor also all the scenarios are modelled where export for revenue is disabled.

As the costs in the model are normalised based on the expected lifetime of each technology, the model provides cost estimates for the duration of the modelled run (e.g., 1 year, 1 season, 1 month, 1 week). For instance, if the storage cost is €400 per kWh of installed capacity and the technology has a 15-year lifespan, the model distributes this cost over the 15 years. Therefore, if the model is run for 1 year, the annual cost for 1 kWh of installed storage capacity would be €400/15 = €26.67. This results in yearly costs that are lower than the upfront investment required for storage or PV panels. However, in reality, a business would need to pay the full €400 per kWh in the first year, rather than spreading it over 15 years as the model assumes.

The energy quickscans, which provide the input data for the model, also have certain limitations. First, their limited scope can be a constraint, as quickscans are typically preliminary assessments that do not look into detailed engineering analyses. As a result, they may overlook energy-saving opportunities that require more in-depth investigation. Additionally, quickscans rely on existing data, meaning their accuracy depends on the quality of information provided by the client and collected during the site visit. This could already be somehting as simple as total electricity demand. If this data is inaccurate or incomplete, it can undermine the reliability of the quickscan results. Another limitation is the potential for changing conditions. Energy consumption patterns and building characteristics can evolve over time, which may reduce the relevance of the quickscan recommendations, particularly if there are significant operational changes or building modifications.

The decision to summarise 65 companies into 10 node clusters based on the type of grid connection is a good step from a time-efficient modelling standpoint. This approach reduces the running time, as fewer nodes need to be constructed during the building phase, and it is not necessary to model each company separately. However, this method also presents a discussion point. Although standardised consumption profiles are used, this approach can smooth out some of the specific characteristics of individual companies. Additionally, it assumes that companies with the same grid connection type are all located in the same area, which is not the case in reality. This means that, after obtaining the results, an additional step is needed to compare them with the actual situation. Nonetheless, from a modelling perspective, this approach avoids more complications than it introduces.

Lastly, the use of 1-hour data intervals instead of 15-minute intervals improves computational times and reduces the length of CSV files. However it also limits the overall analysis, as 1-hour data provides a broad overview, it fails to capture finer temporal variations, potentially underestimating peak loads and thus grid congestion. This smoothing effect can mask short-term spikes in energy demand and generation, leading to less precise modelling outcomes. The rapid fluctuations in renewable energy sources and the dynamic response of storage systems are better represented with 15-minute data, offering a more accurate simulation of system behaviour. Therefore, using 1-hour data limits the detailed analysis needed for optimising energy systems and accurately assessing grid stress.

6.3 Practical implementation & future research

The implementation of Calliope V0.7 dev 3 required significant debugging efforts. While the model runs smoothly for shorter periods, such as a week, extending the run to an entire year sometimes causes failures. These issues are often due to integration problems between Calliope and Python or errors in the YAML file and the .csv files. As a result, there is a steep learning curve when starting with Calliope, but it becomes more manageable for users with prior Python knowledge.

In terms of practical implementation, Calliope can be highly effective in the early stages of mapping out a case study. It offers deep insights into specific energy systems and can be expanded to include additional technologies. During the research phase, Calliope is particularly useful for evaluating the potential benefits of DES in specific scenarios. One of the biggest challenges companies face today is dealing with the consequences of the energy transition, such as grid congestion, which can limit their ability to expand. Effective communication between Energy Management System (EMS) providers and these companies is crucial. EMS providers must offer clear incentives for investment, such as demonstrating a return on investment (ROI) or highlighting that planned expansions may not be viable due to current grid capacity limitations.

This is also a role for Darel Consultancy to visulaise such a energy system before hand, therefor the made energy model in this thesis could be used as a starting point for future other business parks. In this context, Calliope can be invaluable for creating a shared visual understanding at the start of such discussions. An EMS provider using Calliope can demonstrate, with a certain margin of error, the potential benefits of a DES tailored to a company's consumption profile. This might also include providing negative advice if the system is not beneficial. In this way, the Calliope energy model can play a pivotal role in identifying key issues and highlighting potential challenges early in the process.
Looking to the future, significant developments in grid infrastructure are on the horizon. Grid operator TenneT plans to invest around 8 billion euros annually from 2025 onwards to expand the current grid. However, until 2030, one in three areas where grid expansion is necessary will not see improvements until after that year. This delays businesses' growth plans and, consequently, economic growth. In this context, near-term solutions like BESS combined with Calliope could play a crucial role in bridging the gap.

For future research, several opportunities for energy model optimisation can be explored. One area of improvement is cost optimisation, as the current model balance between monatary and emissions cost is 6:4, change this ratio could impact the optimastion results. Additionally, Uitgeest-Noord is part of the IJmond region, which includes other business parks facing similar grid congestion challenges during electrification. Adjusting the model to serve as a tool for analysing these other business parks could be an interesting road for further research. Moreover, future research could explore integrating Vehicle-to-Grid (V2G) technologies, which allow electric vehicles to feed energy back into the grid, thus providing additional flexibility and extra storage capacity.

7 Conclusions

This conclusion chapter formulate answers to the sub-research question to build answering the main reser question in section 7.3. By firstly summerising a general conclusion on the main research question and the key findings of this thesis in section 7.1. In section 7.2, each the academic value provided by this study will be discussed.

7.1 General conclusion

In conclusion, this thesis presents key findings from a linear programming optimisation modelling analysis of the business park Uitgeest-Noord, where multiple businesses are facing electrification challenges due to grid congestion. Through various modelling scenarios, this study demonstrates the effectiveness of using linear programming to configure an optimal Distributed Energy System (DES) with the primary objective of minimising total annualised costs.

The ideal battery size within a DES is directly linked to the total installed PV capacity—the more PV electricity generated, the larger the required battery capacity. In addition to PV generation, the cost per kWh of installed storage capacity plays a crucial role in determining the optimal battery size. The model, which optimises costs and emissions in a 6:4 ratio, highlights the significant impact of battery installation costs. For example, in scenario Solution Mix 3A, where battery storage costs were set to zero, the model suggested an unrealistically large battery size, leading to excessively high system costs. To achieve meaningful improvements in system efficiency, a price of €200/kWh per installed storage capacity is necessary.

The analysis also emphasises the influence of seasonal trends on system performance. PV generation peaks during the summer, resulting in excess electricity that can be exported for revenue or charge the storage solution, while winter sees a significant drop in the utilisation of installed storage capacity—more than 75% lower than in summer. This seasonal variation highlights the importance of designing cost-effective storage solutions that can handle the increased demand and generation during the summer months. But also highlights the still dependency on supply from the ordinary grid.

By desiging a linear programming optimisation modelling tool which is modular and could easly be converted to different values or newly inputted .cvs files for location specific paramaters, this thesis provides a extra step towards desentralisation of the energy grid, by supporting capacity planning.

7.2 Sub-Research questions

7.2.1 What specific factors currently contribute to local-scale grid congestion within the business park Uitgeest-Noord?

The results indicate several key factors contributing to local-scale grid congestion within Uitgeest-Noord, which is tested in solution mix 1. In this scenario, all electrification solutions were applied at once to highlight potential issues. Firstly, the curtailment of PV panels, which reaches around 40%, highlights a significant mismatch between supply and demand. This curtailment is primarily due to no storage capacity and the lack of demand during peak PV generation periods, particularly on sunny days. Secondly, the technical transport capacity of the grid in Uitgeest-Noord set at 1252 kWh, is frequently exceeded during high-demand periods. This is particularly evident on cloudy days when PV generation is minimal, and electricity demand, is needed from supply spikes due to scheduled mobility and other electrification items, like heat pumps. The model shows that on days like December 16-17, the system relies on costly loss of load to meet demand, indicating the use of costly emergency generators which are modelled in, and thus indicatin grid congestion. Thirdly, the increased electrification within the business park, which includes the addition of EV charging infrastructure and the replacement of traditional gas boilers with heat pumps, adds significantly stresses the grid. These steps, while beneficial for reducing carbon emissions, increase the overall electricity demand, pushing the grid closer to its capacity limits more frequently.

Additionally, the role of the ability to export power for revenue, indirectly contributes to grid stress. While it doesn't directly cause grid congestion, this extra demand for export power can create fluctuations in grid load. During periods when the system exports excess electricity, it must draw more power from the supply grid during low-cost times. This additional draw and input can stress the grid, especially when combined with other high-demand activities. The increased complexity of managing supply and demand to optimise revenue while preventing congestion adds another layer of stress to the grid infrastructure. In expansion 1.75x scenario it also indecated that the export for revenue was almost reduced by 50%, due to the lack of available transport capacity. In order to prevent grid congestoin from appari this reduction is necessary and therefore it can be concluded that the system configuration currently chosen is on the conservative side.

In summary, grid congestion within Uitgeest-Noord is primarily driven by the mismatch between supply and demand, resulting in an increase use of supply from the grid during low PV generation periods. Both the increased electrification steps and the operational dynamics of export power for revenue are factors that collectively push the grid closer to its capacity limits and necessitate careful management and storage solutions to optimise and mitigate congestion.

7.2.2 What is the ideal configuration of a DES according to a linear programming optimisation model?

According to the linear programming optimisation model, the ideal configuration of a Distributed Energy System (DES) is primarily optimised for cost efficiency. In our model, two cost classes were considered: monetary costs and CO2-emission costs. These were weighted in a 6:4 ratio, focusing mainly on reducing monetary costs while still accounting for CO2 emissions.
The model suggests that with a storage capacity cost of €200 per kWh, the optimal configuration includes a total system storage capacity of 9,250 kWh, combined with a PV capacity that covers 91% of energy needs (equivalent to 4,000 kWp). This configuration effectively balances the system’s ability to store excess solar energy and minimise reliance on grid power, while also maintaining overall cost efficiency. During the modelling this was scenario for battery limit (S4) – corrected.

7.2.3 How can an energy modelling system be generalised for broader applications to configure different DES locations?

Generalising the designed linear programming optimisation model for broader applications involves several key aspects. The model must be flexible, modular, and scalable to accommodate various energy sources, storage technologies, and demand profiles. During the building phase of the model, specific assumptions were made to take advantage of Calliope's modular structure (Calliope is the linear programming optimisation model used in this research [26]), allowing for easy integration and adaptation of different components, making it applicable to a wide range of case studies beyond Uitgeest-Noord.

One example of this is the node cluster layout based on grid connection, which improves the usability of the model by simplifying the representation of companies. Instead of using 65+ different nodes to represent individual companies, the model uses aggregated node clusters. While this approach simplifies the model, it also has limitations, as discussed in section 6.2.

Another example is the configuration of PV technology. By placing the changeable parameters in the location.yaml file instead of baked into the .csv file, the model allows for easy adjustments to PV capacities, making it straightforward to run different scenarios. The model includes a differentiation of parameters built into the overrides, enabling flexibility. In the standard model, all technologies are active, simulating a complete electrification scenario. This flexibility allows for easy testing of supply and demand curves with the addition or exclusion of PV panels, battery storage, heat pumps, etc., by simply adjusting the overrides and running different scenario’s.

Additionally, the construction of the time series (.csv) files makes it easy to substitute certain values with custom data. The use of generalised consumption profiles and standardised demand profiles ensures the model's reusability for other case studies. Furthermore, since each data source is a separate .csv file, the model can operate with different input values. To enhance the substitution of input data, the model components—such as techs, locations, overrides, and time-series CSV files—are named as generically as possible during the building phase. This approach significantly improves the model's transferability to other similar case studies.

7.2.4 *What key lessons from the energy model exercise can be identified for the case study to produce usable conclusions for business park Uitgeest-Noord?*

Uitgeest-Noord is part of multiple business parks in the IJmond region, and they are the first ones that granted a subsidy to invested possibilities to mitigate grid congestion that several businesses already experience [28]. Several key lessons emerge from the Uitgeest-Noord case study that can be directly applied in the first stage of this subsidy trajectory. By incorporating these lessons, the ideal configuration for a DES can be determined, and the findings can be applied to optimise energy systems in other small business parks, enhancing their sustainability and efficiency.

Firstly, the critical role of storage in mitigating grid congestion and optimising the use of renewable energy is evident. Adequate storage capacity allows for better management of supply and demand, reducing curtailment and reliance on external supply, it also directly provides the possibility to install 91% of the proposed capacity of solar panels, instead of 60%. And most importantly removes the resulting grid congestion from the proposed electrification steps.

Secondly, the need for flexible and scalable energy systems is highlighted. DES must be able to adapt to varying demand patterns and seasonal changes in energy generation. This adaptability ensures that the system remains efficient and effective under different conditions. This means that the storage size is configured on summer peak demands from PV, the higher the PV generation, the higher the excess energy which cannot be used if there is no ability to store it. By running multiple scenarios, the model provides comprehensive insights into the system's performance under different configurations, helping to identify the most effective solutions in terms of costs and CO2-emissions. As tested with the stability scenarios of lower PV capacity, expansion of demand, and low and high-cost scenarios it changes the outcome of the model, and it is not desirable that small input mistakes influence the model's outcome too much.

Also, accurate data collection and realistic assumptions are crucial for reliable modelling outcomes. It became clear that it is important to continuously update and refine data inputs to reflect actual conditions and emerging trends in the energy consumption and generation industry. The use of the generalised consumption and demand profiles improves the model reproducibility, and due to specific data sets can be misleading also improves accuracy.

Thirdly, it becomes evident economic viability of different configurations plays a crucial factor. The model shows that strategic use of storage and dynamic pricing can optimise the system's financial performance, making the energy system more cost-effective. However, due to the optimisation for costs and CO2-emissions, the model can solely focus on optimising for these cost classes and neglect other goals. For example using extra supply from the grid in order to export this for revenue and make it the storage capacity primary function, while putting extra stress on the electricity grid.

7.3 Main research question

Can the ideal configuration of a decentralised energy system (DES) be effectively designed to avoid local grid congestion and support capacity planning during the electrification of the Business Park Uitgeest-Noord?

In answering the main research question, it is evident that an ideal DES configuration can be effectively modelled using a linear programming optimisation approach. This model is to be found crucial in capacity planning and in identifying and mitigating potential localised grid congestion, thereby supporting the full electrification of the Business Park Uitgeest-Noord. The results provide a robust framework for balancing energy supply and demand, incorporating renewable energy sources such as PV panels, and integrating storage solutions, as stated in the answering sub-research question 2, for the exact configuration.

The model's flexibility allows for the adjustment of various parameters, enabling the simulation of multiple scenarios that reflect different configurations and external conditions. This capability allows for pinpointing areas of grid congestion and testing the effectiveness of potential solutions. Moreover, for future capacity planning, the model offers detailed analyses of energy profiles, encompassing both the current state and projected future demands. This information is vital for making informed decisions about infrastructure investments and upgrades, as well as for supporting subsidy programmes by providing a comprehensive understanding of the energy system's limitations and opportunities.

In summary, the modelling of the Business Park Uitgeest-Noord demonstrates that a DES configuration can be effectively designed to prevent localised grid congestion while also supporting strategic capacity planning. The model's detailed simulations and analyses are critical in aiding the transition to a fully electrified and sustainable energy system within the business park, ensuring that both current and future energy needs are met efficiently.

7.4 Academic value from an Industrial Ecology standpoint

As explained in the introduction, there is an increasing need for solutions to mitigate grid congestion resulting from electrification. While Decentralised Energy Systems (DES) offer promising solutions, they are still emerging and need to prove their value. Due to a lack of funding, many real-life projects are cancelled, limiting insights into DES performance and thereby hindering the advancement of their installation. By modelling DES beforehand, it is possible to thoroughly examine their performance and visualise energy flows, providing valuable estimates. This energy modelling step can add real value in kick-starting similar projects and utilising DES where needed.

In order to look to the added academic value from an Industrial Ecology point of view, the learning objectives from the rubric are used to answer this question. Firstly the innovative modelling setup, enables the exploration of different scenarios and enhances performance through iterative scenario analysis. This approach is significant in the context of Industrial Ecology, where understanding the interaction between technological systems and environmental impacts is crucial. The broad framework allows for the testing of multiple use cases, providing new insights that can be directly applied to the design and implementation of sustainable energy systems.

Furthermore, this thesis demonstrates the ability to independently conduct research that contributes to Industrial Ecology by addressing specific sustainability challenges related to grid congestion and energy systems. The application of research methodologies and analytical tools to investigate complex industrial and urban systems aligns with the core objectives of the Thesis Research Project. By synthesizing and critically evaluating existing literature, identifying research gaps, and employing quantitative methods to analyze data, this research advances knowledge in the field.

Additionally, the integration of perspectives from various disciplines to develop and test innovative solutions is a key academic contribution of this work. The reproducibility of the modelling setup ensures that it can be adapted and applied to various contexts, making it a versatile tool for both academic research and practical applications. Lastly, this work reflects on the ethical implications of research in Industrial Ecology, by demonstrating the potential environmental, social, and economic consequences of the DES.

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9 Appendix

9.1 Appendix - Glossary

Term	Definition
Battery Energy Storage System (BESS)	An Energy storage system equipt with a battery to alleviate the transmission grid congestion [19]
Decentralised Energy System (DES)	Local scale system that distribute energy that is generated close to where it will be used, rather than at an industrial plant and sent through the national grid
Distributed Energy Resource (DERs)	A small-scale energy resources usually situated near sites of eletricity use, such as rooftop solar panels and battery storage[46].
Energy Management System (EMS)	System to operate, monitor control and optimse performance of an energy grid espicially used aside of an decentralised energy system.
Grid connection value	The value in kW a party has towards the electricity grid.
Grid congestion	Grid congestion is evident if the demand for electricity (on the supply, consumer or both) is bigger than the available transportcapacity of the grid.
Integraal Decentralised Energy System (IDES)	Integraal adds all the relevent RES that a relevant at the specific locations
Renewable Energy Sources (RES)	Include wind power, solar power, hydroelectric, ocean energy, geothermal energy, biomass and biofuels and substitute fossil fuels alternatives, to cut greenhouse gas emission, diversify the energy supply and reduce dependence on unreliable and volatile fossil fuel markets, in particularly oil and gas [5].

9.2 Appendix - Reseach flow diagram

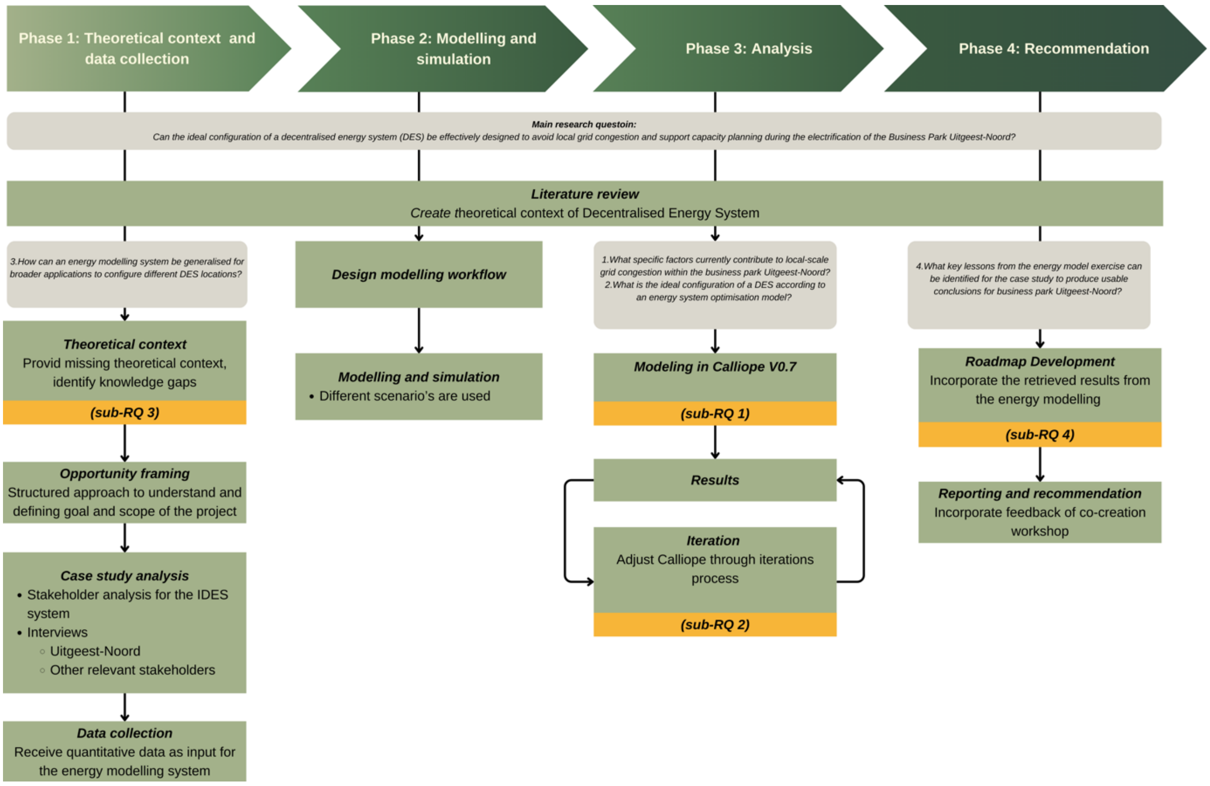

Figure 9.1: Research flow diagram

9.3 Appendix – Dataset Uitgeest Noord

Detaildata Uitgeest

Data GreenBiz 2022 voor netbeheerders
Darel, Kasper Ligtenberg, 22 november 2022

rapport	klant	project	adres	postcode	stad	CO2 uitstoot PV	bedrijfstijd [uren/wk]	oppervlakte [m2]	aansluitwaarde elektra
https://quickscan.klimaatroute.nl/report/adminis	Administratiekantoor BASO	ODIJ - Uitgeest 2020- 2021	Middelweg 62	1911 EH	Uitgeest		60	189	3x25 Amp
https://quickscan.klimaatroute.nl/report/adviest	Adviesbureau van Wees	ODIJ - Uitgeest 2020- 2021	Molenwerf 21L	1911 DB	Uitgeest		40	436	3x25 Amp
https://quickscan.klimaatroute.nl/report/assumt	Assumburg Koeltechniek BV	ODIJ - Uitgeest 2020- 2021	Oosterwerf 1	1911 JB	Uitgeest		50	1.100	3x63 Amp
https://quickscan.klimaatroute.nl/report/bakkun	Bakkum & Krook Tegels en Sanitair	ODIJ - Uitgeest 2020- 2021	Geesterweg 10	1911 NB	Uitgeest		60	1.250	3x50 Amp
https://quickscan.klimaatroute.nl/report/bandtra	Bandtransport Europe BV	ODIJ - Uitgeest 2020- 2021	Molenwerf 12	1911DB	Uitgeest		60	3.095	3x250 Amp
https://quickscan.klimaatroute.nl/report/beentje	Beentjes Bouwgroep	ODIJ - Uitgeest 2020- 2021	Geesterweg 6	1911NB	Uitgeest		60	417	3x35 Amp
https://quickscan.klimaatroute.nl/report/berko-b	Berko Bloemenexport B.V.	ODIJ - Uitgeest 2020- 2021	Geesterweg 14	1911 NB	Uitgeest		45	2.028	3x63 Amp
https://quickscan.klimaatroute.nl/report/bezo-8	Bezo	ODIJ - Uitgeest 2020- 2021	Molenwerf 5	1911 DB	Uitgeest		45	1.537	3x80 Amp
https://quickscan.klimaatroute.nl/report/bistro-t-	Bistro 't Schippersrijk	ODIJ - Uitgeest 2020- 2021	Lagendijk 3	1911 MT	Uitgeest		65	327	3x80 Amp
https://quickscan.klimaatroute.nl/report/bosch-	Bosch Car Service Van Velzen	ODIJ - Uitgeest 2020- 2021	Populierenlaan 55	1911BK	Uitgeest		60	361	3x35 Amp
https://quickscan.klimaatroute.nl/report/brameh	Brameho B.V.	ODIJ - Uitgeest 2020- 2021	Populierenlaan 49	1911 BK	Uitgeest		60	1.513	3x80 Amp
https://quickscan.klimaatroute.nl/report/cor-jon	Cor Jongejans Beheer B.V. Oosterwerf 5	ODIJ - Uitgeest 2020- 2021	Oosterwerf 5	1911JB	Uitgeest		40	1.147	3x50 Amp
https://quickscan.klimaatroute.nl/report/cor-jon	Cor Jongejans Beheer B.V. Populierenlaan 41	ODIJ - Uitgeest 2020- 2021	Populierenlaan 41	1911 BK	Uitgeest		40	568	3x35 Amp
https://quickscan.klimaatroute.nl/report/cor-jon	Cor Jongejans Beheer B.V. Populierenlaan 41a	ODIJ - Uitgeest 2020- 2021	Populierenlaan 41a	1911 BK	Uitgeest		60	214	3x35 Amp
https://quickscan.klimaatroute.nl/report/cor-jon	Cor Jongejans Beheer B.V. Westerwerf 5B	ODIJ - Uitgeest 2020- 2021	Westerwerf 5B	1911 JA	Uitgeest		40	450	3x25 Amp
https://quickscan.klimaatroute.nl/report/cor-jon	Cor Jongejans Beheer B.V. Westerwerf 5C	ODIJ - Uitgeest 2020- 2021	Westerwerf 5C	1911 JA	Uitgeest		40	570	3x25 Amp
https://quickscan.klimaatroute.nl/report/de-boe	De Boer Staal	ODIJ - Uitgeest 2020- 2021	Molenstraat 28	1911 DA	Uitgeest		55	22.000	630 kVA
https://quickscan.klimaatroute.nl/report/destem	Destemi Pomptechniek	ODIJ - Uitgeest 2020- 2021	Hoorne 15	1911 BD	Uitgeest		50	263	3x25 Amp
https://quickscan.klimaatroute.nl/report/dmf-die	DMF Dietvorst Machinefabriek BV	ODIJ - Uitgeest 2020- 2021	Molenstraat 32	1911 DA	Uitgeest		50	2.000	3x250 Amp
https://quickscan.klimaatroute.nl/report/enk-sof	ENK Software - verhuurde unit (34C)	ODIJ - Uitgeest 2020- 2021	Molenwerf 34 C	1911 DB	Uitgeest		40	323	3x25 Amp
https://quickscan.klimaatroute.nl/report/enk-sof	ENK Software BV - Kantoor	ODIJ - Uitgeest 2020- 2021	Molenwerf 32	1911 BP	Uitgeest		60	800	3x50 Amp
https://quickscan.klimaatroute.nl/report/enk-sof	ENK Software BV (34E)	ODIJ - Uitgeest 2020- 2021	Molenwerf 34E	1911 DB	Uitgeest		40	323	3x25 Amp
https://quickscan.klimaatroute.nl/report/enk-sof	ENK Software BV (34F)	ODIJ - Uitgeest 2020- 2021	Molenwerf 34 G	1911 DB	Uitgeest		40	323	3x25 Amp
https://quickscan.klimaatroute.nl/report/enk-sof	ENK Software BV (34G)	ODIJ - Uitgeest 2020- 2021	Molenwerf 34G	1911DB	Uitgeest		40	323	3x25 Amp
https://quickscan.klimaatroute.nl/report/fac	Facta Aandrijftechniek	ODIJ - Uitgeest 2020- 2021	Westerwerf 11	1911 JA	Uitgeest		55	2.318	3x250 Amp
https://quickscan.klimaatroute.nl/report/facta-2-	Facta aandrijftechniek locatie 2	ODIJ - Uitgeest 2020- 2021	Westerwerf 20	1911JA	Uitgeest		50	2.200	3x125 Amp
https://quickscan.klimaatroute.nl/report/fami-79	Fami	ODIJ - Uitgeest 2020- 2021	Westerwef 28	1911 JA	Uitgeest		40	790	3x35 Amp
https://quickscan.klimaatroute.nl/report/golfdisc	Golfdiscountstore	ODIJ - Uitgeest 2020- 2021	Westerwerf 5a	1911 JA	Uitgeest		48	700	3x25 Amp
https://quickscan.klimaatroute.nl/report/haarlen	Haarlemse Akademie	ODIJ - Uitgeest 2020- 2021	Westerwerf 9C	1911 JA	Uitgeest		43	325	3x25 Amp
https://quickscan.klimaatroute.nl/report/jachtha	Jachthaven Uitgeest	ODIJ - Uitgeest 2020- 2021	Lagendijk 7	1911 MT	Uitgeest		50	4.300	3x80 Amp
https://quickscan.klimaatroute.nl/report/kischo-	Kischo B.V. / Ton Scholten B.V.	ODIJ - Uitgeest 2020- 2021	Westerwerf 2	1911 JA	Uitgeest		65	6.000	3x80 Amp
https://quickscan.klimaatroute.nl/report/konijn-b	Konijn Bouwmachines B.V.	ODIJ - Uitgeest 2020- 2021	Molenwerf 15	1911 DB	Uitgeest		50	1.120	3x35 Amp
https://quickscan.klimaatroute.nl/report/landbo	Landbouwmechanisatie Smit & Alles	ODIJ - Uitgeest 2020- 2021	Molenwerf 3	1911 DB	Uitgeest		60	707	3x35 Amp
https://quickscan.klimaatroute.nl/report/liefting-	Liefting Fit	ODIJ - Uitgeest 2020- 2021	Molenwerf 36 B	1911 DB	Uitgeest		70	835	3x25 Amp
https://quickscan.klimaatroute.nl/report/medisc	Medisch Centrum Molenstraat	ODIJ - Uitgeest 2020- 2021	Molenstraat 1	1911 BR	Uitgeest		60	1.600	3x125 Amp
https://quickscan.klimaatroute.nl/report/monkey	Monkey Town Uitgeest	ODIJ - Uitgeest 2020- 2021	Molenwerf 20	1912 DB	Uitgeest		61	2.367	3x80 Amp
https://quickscan.klimaatroute.nl/report/more-th	More Than Gifts B.V.	ODIJ - Uitgeest 2020- 2021	Populierenlaan 80	1911 BM	Uitgeest		45	1.244	3x35 Amp
https://quickscan.klimaatroute.nl/report/noord-h	Noord-Holland Totaal Beveiliging	ODIJ - Uitgeest 2020- 2021	Westerwerf 36	1911 JA	Uitgeest		30	400	3x25 Amp
https://quickscan.klimaatroute.nl/report/noppes	Noppes Kringloopwinkel Uitgeest	ODIJ - Uitgeest 2020- 2021	Kleis 67	1911 MD	Uitgeest		55	930	3x63 Amp
https://quickscan.klimaatroute.nl/report/paul-go	Paul Goeman Autoservice	ODIJ - Uitgeest 2020- 2021	Molenwerf 19	1911 DB	Uitgeest		60	772	3x35 Amp
https://quickscan.klimaatroute.nl/report/putter-e	Putter en Zn	ODIJ - Uitgeest 2020- 2021	Molenwerf 40	1911 DB	Uitgeest		55	486	3x50 Amp
https://quickscan.klimaatroute.nl/report/qlift-44	Qlift	ODIJ - Uitgeest 2020- 2021	Hoorne 7	1911 BD	Uitgeest		50	150	3x35 Amp
https://quickscan.klimaatroute.nl/report/remonc	REMONDIS Rioolservice West B.V.	ODIJ - Uitgeest 2020- 2021	Molenwerf 23	1911 DB	Uitgeest		50	3.525	3x125 Amp
https://quickscan.klimaatroute.nl/report/restaur	Restaurant Havenrijk Uitgeest	ODIJ - Uitgeest 2020- 2021	Lagendijk 41	1911 MT	Uitgeest		88	500	3x250 Amp
https://quickscan.klimaatroute.nl/report/s-de-gr	S. de Groot Uitgeest B.V	ODIJ - Uitgeest 2020- 2021	Molenwerf 38	1911 DB	Uitgeest		55	704	3x80 Amp
https://quickscan.klimaatroute.nl/report/schoon	Schoone Vloeren	ODIJ - Uitgeest 2020- 2021	Molenwerf 21K	1911DB	Uitgeest		60	191	3x63 Amp
https://quickscan.klimaatroute.nl/report/schoon	Schoonmaakbedrijf Breedweer	ODIJ - Uitgeest 2020- 2021	Molenwerf 58	1911 DB	Uitgeest		60	400	3x63 Amp
https://quickscan.klimaatroute.nl/report/skywor	Skyworks B.V.	ODIJ - Uitgeest 2020- 2021	Westerwerf 30	1911 JA	Uitgeest		50	790	3x35 Amp
https://quickscan.klimaatroute.nl/report/facta-5	Stambouw B.V.	ODIJ - Uitgeest 2020- 2021	Geesterweg 4	1911JA	Uitgeest		45	1.800	3x250 Amp
https://quickscan.klimaatroute.nl/report/stichtin	Stichting Jachthaven Zwaansmeerpolder	ODIJ - Uitgeest 2020- 2021	Lagendijk 41	1911 MT	Uitgeest		40	2.600	3x250 Amp
https://quickscan.klimaatroute.nl/report/technic	Technical Lubricants Int. B.V. (TecLub)	ODIJ - Uitgeest 2020- 2021	Molenwerf 56	1911 DB	Uitgeest		50	661	3x63 Amp
https://quickscan.klimaatroute.nl/report/uitgees	Uitgeest Mechanische Industrie B.V. (pand 1)	ODIJ - Uitgeest 2020- 2021	Westerwef 14	1911 JA	Uitgeest		60	1.224	3x400 Amp
https://quickscan.klimaatroute.nl/report/uitgees	Uitgeest Mechanische Industrie B.V. (pand 2)	ODIJ - Uitgeest 2020- 2021	Westerwef 18	1911 JA	Uitgeest		60	600	3x63 Amp
https://quickscan.klimaatroute.nl/report/valkerir	Valkering Accountants	ODIJ - Uitgeest 2020- 2021	Westerwerf 7B	1911 JA	Uitgeest		45	169	3x63 Amp
https://quickscan.klimaatroute.nl/report/van-de	Van der Horst pand 1	ODIJ - Uitgeest 2020- 2021	Oosterwerf 6	1911 JB	Uitgeest		60	2.150	3x160 Amp
https://quickscan.klimaatroute.nl/report/van-de	Van der Horst pand 2	ODIJ - Uitgeest 2020- 2021	Oosterwerf 7	1911 JB	Uitgeest		60	2.155	3x63 Amp
https://quickscan.klimaatroute.nl/report/van-de	Van der Horst pand 3	ODIJ - Uitgeest 2020- 2021	Westerwerf 24	1911 JA	Uitgeest		60	480	3x63 Amp
https://quickscan.klimaatroute.nl/report/van-de	Van der Horst pand 4	ODIJ - Uitgeest 2020- 2021	Molenwerf 9	1911 DB	Uitgeest		60	815	3x63 Amp
https://quickscan.klimaatroute.nl/report/van-de	Van der Horst pand 5	ODIJ - Uitgeest 2020- 2021	Westerwerf 1	1911 JA	Uitgeest		60	6.762	3x80 Amp
https://quickscan.klimaatroute.nl/report/van-de	Van der Horst pand 7	ODIJ - Uitgeest 2020- 2021	Molenwerf 8	1911 DB	Uitgeest		60	770	3x35 Amp
https://quickscan.klimaatroute.nl/report/van-de	Van der Horst pand 8	ODIJ - Uitgeest 2020- 2021	Molenwerf 17	1911 DB	Uitgeest		60	636	3x80 Amp
https://quickscan.klimaatroute.nl/report/van-de	Van der Lem Groothandel B.V.	ODIJ - Uitgeest 2020- 2021	Molenwerf 26	1911 DB	Uitgeest		88	9.984	630 kVA
https://quickscan.klimaatroute.nl/report/wp-lanc	W.P. Langendijk	ODIJ - Uitgeest 2020- 2021	Populierenlaan 57	1911 BK	Uitgeest		50	449	3x50 Amp
https://quickscan.klimaatroute.nl/report/wijnbee	Wijnbeek Sanitair BV	ODIJ - Uitgeest 2020- 2021	Molenwerf 1	1911 BK	Uitgeest		40	378	3x35 Amp
https://quickscan.klimaatroute.nl/report/wri-tech	Wri-tech Industrial Services Holland BV	ODIJ - Uitgeest 2020- 2021	Molenwerf 23A	1911 DB	Uitgeest		45	621	3x50 Amp
	Totaal								

klant	electriciteit nu [kWh]	electriciteit na [kWh]	electriciteits reductie [kWh]	gas nu [m3]	gas na [m3]	gasreductie [m3]	Warmtepomp elektrisch [kWh]	Aantal laadpalen #	EV laden w-w [kW]	EV laden [kWh]	Aantal FastCharging	E-truck opportunity charging [kW]	FastCharging [kWh]
	84.462				Geel is handmatig aangepast nav onderverdeling proces en gebouw								
			Reductie incl PV		Top 10 bekeken in vgl tot dakopp methode		Berekend uit gas na, met COP van 4	75 laadpalen voor heel gebied. Verdeling nog te verfijnen	gemid 8 kW charger op 75% vermogen = 6 kW	Per laadcyclus 2 uur laden per werkdag, 52 weken	20 fast charging. Verdeling nog te verfijnen	Gemid. 450 kW per laadcyclus	Per laadcyclus van 20 min 2uur lang per werkdag, 52 weken
							Top 10 nagaan			Spikes van 60 kW			Spikes van 900 kW
Administratiekantoor BASO	4.760	0	4.760	2.394	918	1.476	2.243						
Adviesbureau van Wees	20.000	-30	20.030	7.412	7.024	388	17.156						
Assumburg Koeltechniek BV	23.941	0	23.941	2.715	1.409	1.306	3.441						
Bakkum & Krook Tegels en Sanitair	34.000	0	34.000	6.700	5.718	982	13.966						
Bandtransport Europe BV	161.552	-226.015	387.567	36.931	3.921	8.411	9.577						
Beentjes Bouwgroep	42.435	0	42.435	5.437	5.328	109	13.014						
Berko Bloemenexport B.V.	41.223	-230.736	271.959	1.187	1.163	24	2.841						
Bezo	40.000	0	40.000	8.000	10.750	-2.750	26.257						
Bistro 't Schippersrijk	92.000	63.728	28.272	15.144	11.658	3.486	28.475	10	6	31.200	2	450	468.000
Bosch Car Service Van Velzen	26.159	0	26.159	1.542	1.491	51	3.642						
Brameho B.V.	13.044	0	13.044	5.322	3.816	1.506	9.320	10	6	31.200	2	450	468.000
Cor Jongejans Beheer B.V. Oosterwerf 5	20.000	0	20.000	5.000	4.960	40	12.115						
Cor Jongejans Beheer B.V. Populierenlaan 41	16.000	-6.524	22.524	2.000	560	1.440	1.368						
Cor Jongejans Beheer B.V. Populierenlaan 41a	7.000	0	7.000	0	0	0	0						
Cor Jongejans Beheer B.V. Westerwerf 5B	10.000	0	10.000	2.200	2.140	60	5.227						
Cor Jongejans Beheer B.V. Westerwerf 5C	9.373	0	9.373	1.841	1.721	120	4.204						
De Boer Staal	1.100.000	505.590	594.410	38.000	34.580	3.420	84.462	10	6	31.200	2	450	468.000
Destemi Pomptechniek	5.203	0	5.203	5.352	2.780	2.572	6.791						
DMF Dietvorst Machinefabriek BV	180.000	66.513	113.487	10.000	7.850	2.150	19.174						
ENK Software - verhuurde unit (34C)	15.000	-239	15.239	3.500	3.096	404	7.562						
ENK Software BV - Kantoor	30.868	-297	31.165	3.700	3.404	296	8.314						
ENK Software BV (34E)	15.000	-239	15.239	3.500	3.096	404	7.562						
ENK Software BV (34F)	15.000	-239	15.239	3.500	3.096	404	7.562						
ENK Software BV (34G)	15.000	-239	15.239	3.500	3.096	404	7.562						
Facta Aandrijftechniek	279.387	19.666	259.721	27.389	5.284	3.952	12.907						
Facta aandrijftechniek locatie 2	35.000	-100.491	135.491	8.000	6.876	1.124	16.795						
Fami	10.932	0	10.932	7.000	5.200	1.800	12.701						
Golfdiscountstore	11.174	0	11.174	1.145	-23	1.168	-56						
Haarlemse Akademie	5.229	0	5.229	3.471	436	3.070	1.064						
Jachthaven Uitgeest	60.262	-209.956	270.218	4.735	-95	4.830	-232	10	6	31.200	2	450	468.000
Kischo B.V. / Ton Scholten B.V.	71.415	26.754	44.661	2.107	1.605	502	3.920						
Konijn Bouwmachines B.V.	15.771	0	15.771	4.696	3.452	1.244	8.430						
Landbouwmechanisatie Smit & Alles	11.333	0	11.333	3.300	3.234	66	7.899						
Liefting Fit	23.753	0	23.753	750	499	251	1.219						
Medisch Centrum Molenstraat	78.197	41.719	36.478	18.000	1.763	4.612	4.307						
Monkey Town Uitgeest	100.000	-23.404	123.404	9.800	2.894	6.906	7.069	10	6	31.200	2	450	468.000
More Than Gifts B.V.	20.351	0	20.351	1.191	806	385	1.969						
Noord-Holland Totaal Beveiliging	3.422	0	3.422	524	296	228	723						
Noppes Kringloopwinkel Uitgeest	21.111	1.111	20.000	16.152	9.252	6.900	22.598						
Paul Goeman Autoservice	29.000	-3.745	32.745	2.380	1.106	1.274	2.702						
Putter en Zn	22.001	0	22.001	0	0	0	0						
Qlift	4.654	3.491	1.163	3.100	1.385	1.715	3.383						
REMONDIS Rioolservice West B.V.	126.000	-103.179	229.179	14.300	10.785	3.516	26.341						
Restaurant Havenrijk Uitgeest	78.400	-258.442	336.842	18.500	12.133	6.367	29.635						
S. de Groot Uitgeest B.V	22.750	-11.719	34.469	1.950	1.911	39	4.668						
Schoone Vloeren	14.866	2.850	12.016	1.604	1.572	32	3.839						
Schoonmaakbedrijf Breedweer	15.000	0	15.000	8.000	3.200	4.800	7.816						
Skyworks B.V.	12.000	0	12.000	4.000	3.112	888	7.601						
Stambouw B.V.	45.000	-112.502	157.502	15.000	13.374	1.626	32.666						
Stichting Jachthaven Zwaansmeerpolder	92.615	-235.597	328.212	3.435	3.206	229	7.830						
Technical Lubricants Int. B.V. (TecLub)	23.264	0	23.264	3.594	467	3.127	1.141						
Uitgeest Mechanische Industrie B.V. (pand 1)	221.070	58.414	162.656	5.426	5.189	237	12.675						
Uitgeest Mechanische Industrie B.V. (pand 2)	12.322	0	12.322	5.959	5.712	247	13.951						
Valkering Accountants	6.000	-700	6.700	750	535	215	1.307						
Van der Horst pand 1	80.000	-13.887	93.887	5.500	5.358	142	13.087						
Van der Horst pand 2	58.000	0	58.000	5.500	5.290	210	12.921						
Van der Horst pand 3	35.000	0	35.000	4.000	1.085	2.915	2.650						
Van der Horst pand 4	17.000	0	17.000	5.993	5.623	370	13.735						
Van der Horst pand 5	20.000	-321.354	341.354	4.000	3.920	80	9.575	10	6	31.200	2	450	468.000
Van der Horst pand 7	20.000	0	20.000	3.000	2.940	60	7.181						
Van der Horst pand 8	40.000	-1	40.000	6.000	5.476	524	13.375	10	6	31.200	2	450	468.000
Van der Lem Groothandel B.V.	2.315.710	1.549.142	766.568	7.760	6.665	1.095	16.279	10	6	31.200	2	450	468.000
W.P. Langendijk	13.000	0	13.000	7.090	5.241	1.849	12.801						
Wijnbeek Sanitair BV	14.500	0	14.500	1.800	1.542	258	3.766						
Wri-tech Industrial Services Holland BV	17.948	0	17.948	5.223	3.891	1.332	9.504						
Totaal	6.040.995	479.439	5.561.555	427.001	275.772	96.886	673.573			249.600			3.744.000
										kWh			kWh
							569.023		832.000				
							via waterval						

klant	Aansluitwaarde nu [kW]	PV genoemd in Escan [kWh]	PV vermogen uit Escan [kWp]	E nu - E red. + E PV uit scan	Energiescan zon PV [kWp]	Verschil energiescan PV met bestaande aansluiting [%]	benodigde aansluitwaarde energiescan PV [kWp]	Potentieel zon PV [kWp]	Verschil potentieel PV met bestaande aansluiting [%]	benodigde aansluitwaarde potentieel PV [kWp]	Electriciteit nu MWh	Gas nu MWh	Elect + Gas MWh	Elect + Gas Cumulatief MWh
				Verifieren										
	Berekend uit aansluitwaarde	In quickscan opgezocht	Berekend uit quickscan waarde	Berekend: E nu - E red + PV in Escan										
				E-verbruik na										
Administratiekantoor BASO	17	3.266	4	3.266	11	62%	17	17	97%	17	5	23	28	#VALUE!
Adviesbureau van Wees	17	19.550	22	19.520	25	143%	25	39	224%	39	20	72	92	#VALUE!
Assumburg Koeltechniek BV	43	7.940	9	7.940	62	143%	62	97	224%	97	24	27	50	#VALUE!
Bakkum & Krook Tegels en Sanitair	35	32.994	37	32.994	71	205%	71	111	321%	111	34	65	99	#VALUE!
Bandtransport Europe BV	173	382.720	425	156.705	175	102%	175	274	159%	274	162	361	522	#VALUE!
Beentjes Bouwgroep	24	22.498	25	22.498	24	98%	24	37	153%	37	42	53	96	#VALUE!
Berko Bloemenexport B.V.	43	15.732	17	(215.004)	115	264%	115	179	413%	179	41	12	53	#VALUE!
Bezo	55	11.371	13	11.371	87	158%	87	136	246%	136	40	78	118	#VALUE!
Bistro 't Schippersrijk	55	17.385	19	81.113	19	34%	55	29	52%	55	92	148	240	#VALUE!
Bosch Car Service Van Velzen	24	24.892	28	24.892	20	85%	24	32	132%	32	26	15	41	#VALUE!
Brameho B.V.	55	15.578	17	15.578	86	155%	86	134	243%	134	13	52	65	#VALUE!
Cor Jongejans Beheer B.V. Oosterwerf 5	35	19.286	21	19.286	65	188%	65	101	294%	101	20	49	69	#VALUE!
Cor Jongejans Beheer B.V. Populierenlaan 41	24	8.615	10	2.091	32	133%	32	50	208%	50	16	20	36	#VALUE!
Cor Jongejans Beheer B.V. Populierenlaan 41a	24	6.530	7	6.530	12	50%	24	19	78%	24	7	0	7	#VALUE!
Cor Jongejans Beheer B.V. Westerwerf 5B	17	6.266	7	6.266	25	148%	25	40	231%	40	10	21	31	#VALUE!
Cor Jongejans Beheer B.V. Westerwerf 5C	17	8.380	9	8.380	32	187%	32	50	292%	50	9	18	27	#VALUE!
De Boer Staal	536	500.160	556	1.005.750	1246	233%	1.246	1.947	364%	1.947	1.100	371	1.471	1.471
Destemi Pomptechniek	17	3.599	4	3.599	15	86%	17	23	135%	23	5	52	57	1.529
DMF Dietvorst Machinefabriek BV	173	83.904	93	150.417	113	66%	173	177	103%	177	180	98	278	1.806
ENK Software - verhuurde unit (34C)	17	9.657	11	9.418	18	106%	18	29	166%	29	15	34	49	1.856
ENK Software BV - Kantoor	35	23.643	26	23.346	45	131%	45	71	205%	71	31	36	67	1.923
ENK Software BV (34E)	17	9.657	11	9.418	18	106%	18	29	166%	29	15	34	49	1.972
ENK Software BV (34F)	17	9.657	11	9.418	18	106%	18	29	166%	29	15	34	49	2.021
ENK Software BV (34G)	17	9.657	11	9.418	18	106%	18	29	166%	29	15	34	49	2.070
Facta Aandrijftechniek	173	191.360	213	211.026	131	76%	173	205	119%	205	279	268	547	2.617
Facta aandrijftechniek locatie 2	86	119.040	132	18.549	125	144%	125	195	226%	195	35	78	113	2.730
Fami	24	5.588	6	5.588	45	185%	45	70	289%	70	11	68	79	2.810
Golfdiscountstore	17	8.585	10	8.585	40	230%	40	62	359%	62	11	11	22	2.832
Haarlemse Akademie	17	984	1	984	18	107%	18	29	167%	29	5	34	39	2.871
Jachthaven Uitgeest	55	270.000	300	60.044	244	441%	244	380	689%	380	60	46	107	2.978
Kischo B.V. / Ton Scholten B.V.	55	7.000	8	33.754	340	616%	340	531	962%	531	71	21	92	3.070
Konijn Bouwmachines B.V.	24	3.410	4	3.410	63	263%	63	99	410%	99	16	46	62	3.131
Landbouwmechanisatie Smit & Alles	24	10.993	12	10.993	40	166%	40	63	259%	63	11	32	44	3.175
Liefting Fit	17	10.952	12	10.952	47	274%	47	74	428%	74	24	7	31	3.206
Medisch Centrum Molenstraat	86	32.190	36	73.909	91	105%	91	142	164%	142	78	176	254	3.460
Monkey Town Uitgeest	55	117.760	131	94.356	134	243%	134	209	379%	209	100	96	196	3.656
More Than Gifts B.V.	24	17.446	19	17.446	70	292%	70	110	456%	110	20	12	32	3.688
Noord-Holland Totaal Beveiliging	17	3.295	4	3.295	23	131%	23	35	205%	35	3	5	9	3.696
Noppes Kringloopwinkel Uitgeest	43	16.873	19	17.984	53	121%	53	82	189%	82	21	158	179	3.875
Paul Goeman Autoservice	24	25.000	28	21.255	44	181%	44	68	283%	68	29	23	52	3.928
Putter en Zn	35	14.256	16	14.256	28	80%	35	43	125%	43	22	0	22	3.950
Qlift	24	-	-	3.491	8	35%	24	13	55%	24	5	30	35	3.984
REMONDIS Rioolservice West B.V.	86	167.808	186	64.629	200	231%	200	312	362%	312	126	140	266	4.250
Restaurant Havenrijk Uitgeest	173	323.000	359	64.558	28	16%	173	44	26%	173	78	181	259	4.509
S. de Groot Uitgeest B.V	55	-	-	(11.719)	40	72%	55	62	113%	62	23	19	42	4.551
Schoone Vloeren	43	9.016	10	11.866	11	25%	43	17	39%	43	15	16	31	4.582
Schoonmaakbedrijf Breedweer	43	52.565	58	52.565	23	52%	43	35	81%	43	15	78	93	4.675
Skyworks B.V.	24	10.254	11	10.254	45	185%	45	70	289%	70	12	39	51	4.726
Stambouw B.V.	173	147.200	164	34.698	102	59%	173	159	92%	173	45	147	192	4.917
Stichting Jachthaven Zwaansmeerpolder	173	323.000	359	87.403	147	85%	173	230	133%	230	93	34	126	5.044
Technical Lubricants Int. B.V. (TecLub)	43	27.286	30	27.286	37	86%	43	58	135%	58	23	35	58	5.102
Uitgeest Mechanische Industrie B.V. (pand 1)	276	132.480	147	190.894	69	25%	276	108	39%	276	221	53	274	5.376
Uitgeest Mechanische Industrie B.V. (pand 2)	43	5.895	7	5.895	34	78%	43	53	122%	53	12	58	71	5.447
Valkering Accountants	43	4.764	5	4.064	10	22%	43	15	34%	43	6	7	13	5.460
Van der Horst pand 1	110	72.128	80	58.241	122	110%	122	190	172%	190	80	54	134	5.594
Van der Horst pand 2	43	58.000	64	58.000	122	281%	122	191	439%	191	58	54	112	5.705
Van der Horst pand 3	43	40.229	45	40.229	27	63%	43	42	98%	43	35	39	74	5.780
Van der Horst pand 4	43	14.619	16	14.619	46	106%	46	72	166%	72	17	59	76	5.855
Van der Horst pand 5	55	331.200	368	9.846	383	694%	383	598	1084%	598	20	39	59	5.914
Van der Horst pand 7	24	11.024	12	11.024	44	181%	44	68	282%	68	20	29	49	5.963
Van der Horst pand 8	55	32.693	36	32.693	36	65%	55	56	102%	56	40	59	99	6.062
Van der Lem Groothandel B.V.	536	662.400	736	2.211.542	565	106%	565	883	165%	883	2.316	76	2.392	8.454
W.P. Langendijk	35	11.188	12	11.188	25	74%	35	40	115%	40	13	69	82	8.536
Wijnbeek Sanitair BV	24	16.259	18	16.259	21	89%	24	33	138%	33	15	18	32	8.568
Wri-tech Industrial Services Holland BV	35	11.121	12	11.121	35	102%	35	55	159%	55	18	51	69	8.637
Totaal			5.080		6.069									
			Redelijk veel spreiding											

9.4 Appendix Theoretical Background Energy scans: Business Park Uitgeest-Noord

The dataset used for this study is based on energy scans that were conducted in 2021. Out of the 170 companies approached, 65 companies cooperated, and their total energy consumption of 6 GWh accounts for 83% of the total energy consumption of 7.2 GWh at the business park in Uitgeest-Noord. Resulting in sufficient data to use during the modelling phase. Zooming in at the 10 biggest energy consumers, it is evident that they already account for 40% of the total 6 GWh. The conclusion provided from these energy scans was laid out in a previous study by Darel [34]. It provides four main conclusions after analysing the data: (I) installation of solar panels on roofs, (II) building-related savings, (III) process-related savings, and (IV) electrification of mobility. In the following subsection, each of these four conclusions is briefly elaborated on, followed by a visualised waterfall diagram in Figure 9.2.

PV panels: the potential installed capacity of solar panels in Uitgeest-Noord, according to the energy scans, is calculated by using the potentially available roof surface and multiplying it with a reference value of 0.0088 kW/m2 (365 Wp per panel of 1m x 1.65m, and 40% of the total roof surface in total). Of the nine companies who have already planned to place solar-PV on their roof, the current transport capacity is too small, and they are, for example, not able to deliver back to the grid. This results in a 2.8 MW peak power needed, with only 1.75 MW available. If this is extrapolate to 2040 and uses all of the 40% available roof surface even a bigger discretion of 5.6 MW peak power is needed vs 2.7 MW transport capacity available.

Building-related savings: These savings are mainly focused on increasing efficiency and can be installed by business owners themselves. For example, a time switch, energy monitoring, isolation or LED lighting. This leads to the substitution of gas for heating with heat pumps, and a net reduction of 1.707,068 kWh (see building related savings).

Process-related savings: In processes around 34% of total electricity is used and 23% of total gas is used is process-related. As energy quickscan only provides suggestions no individual processes are investigated, but an average reduction of 2% per year is deemed logical, in this way a total of 20% is achieved between the period of 2030 – 2040.

Electrification of mobility: In business park Uitgeest-Noord numerous companies have opted to electrify their car fleet. This will result in a reduction of both CO2 and particulate matter of nitrogen with the substitution of fossil fuel-powered cars. However, this also means an expansion of a calculated grid capacity of 420 Kw is necessary for this charging infrastructure, resulting in a total increased electricity usage of 832 MWh.

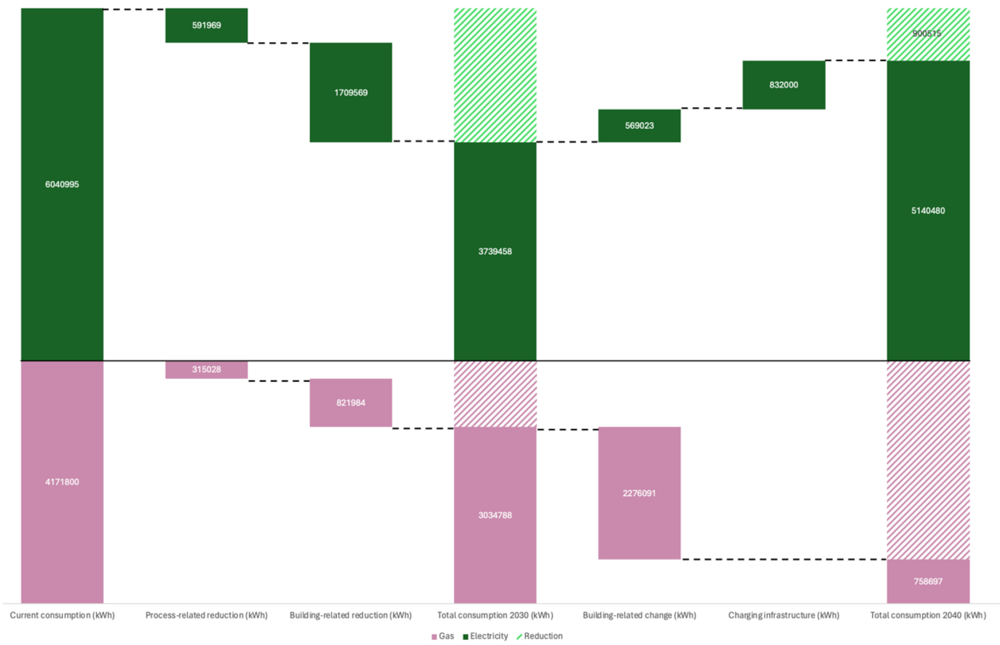

Figure 9.2: Visualised waterfall diagram of electricity and gas consumption currently, in 2030 and 2040 from the energyscans conducted in 2020 [23]

9.4.1 Method energy scans:

The produced energy quick scan relies on a combination of field inspections, data collection, energy consumption analysis, and energy efficiency recommendations. It involves the following key elements:
Site Inspection: From the 65 energy quickscans different energy consultant visits the site to assess its current energy infrastructure, including lighting, heating, cooling, insulation, and other energy-consuming systems.
Data collection: The consultant collects data on several factors such as energy consumption, operational hours, equipment efficiency, and building characteristics such as age, size, and layout. This data is typically gathered from utility bills, equipment specifications, and interviews with facility managers.
Energy Consumption Analysis: In the report of the energy quickscan the collected data is analyzed to understand patterns of energy use, peak consumption times, and overall energy efficiency. This analysis often involves benchmarking against industry standards.
Identification of Energy-Saving Opportunities: Based on the analysis, the concerned consultant identifies areas for potential energy savings. This includes recommendations for both processes and building-related savings, for energy-efficient lighting, heating and cooling system improvements, insulation upgrades, and renewable energy options.
Quality Control: Quality control measures ensure the accuracy of the collected data and the reliability of the recommendations. This includes cross-checking utility data, validating equipment specifications, and conducting additional assessments as needed. This quality control is essential for ensuring the accuracy and reliability of the energy-quick scan. It involves several key measures. First, data verification is crucial, requiring double-checking of utility bills and equipment specifications to ensure that the information is accurate. Next, cross-validation comes into play by comparing the quick scan findings with industry benchmarks and standards, particularly against other business parks in the IJmond region, to confirm the validity of the results. Finally, client feedback is gathered to identify any discrepancies or additional areas of concern, allowing for adjustments and a more comprehensive understanding of the client's needs and observations.

9.5 Semi structered interview – consent form

Delft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT TEMPLATES AND GUIDE
(English Version: January 2022)

Title: Decarbonization Strategies for the Dutch Energy Grid

You are being invited to participate in a research study titled "Decarbonization Strategies for the Dutch Energy Grid". This study is being conducted by Hidde Grootes and Darel Consultancy, in collaboration with the TU Delft.

The purpose of this research study is to investigate effective strategies for decarbonizing the Dutch energy grid by implementing a decentralized energy system. Your participation will involve completing a semi structure interview, which will take approximately 60 minutes to complete. The data collected will be used for research purposes, including publication, application in real-world scenarios, and teaching future generations about sustainable energy practices.

During this study, we will be asking you to provide information about your perspectives, experiences, and opinions related to energy transition, renewable energy sources, and potential barriers to decarbonization efforts.

As with any offline/online activity, there is a risk of data breach. However, we assure you that your answers will remain confidential to the best of our ability. We will minimize risks by storing data securely, anonymizing responses, and adhering to data protection regulations. Your IP address or other personal data will not be collected unless explicitly stated otherwise.

Your participation in this study is entirely voluntary, and you have the right to withdraw at any time. You are free to skip any questions you do not wish to answer. Please note that once data is anonymized, it may not be possible to remove it from the study.

If you have any questions or concerns about the study, please contact the corresponding researcher, Hidde Grootes. Additionally, if you encounter any issues or wish to make a complaint about the study, please follow the provided procedure for making complaints.

By proceeding with the semi-structured interview, you are indicating your voluntary consent to participate in this research study.

Signatures

____________________________ ___________________________ ________
Name of participant [printed] Signature Date

I, as legal representative, have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

____________________________ ___________________________ ________
Name of witness [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Hidde Grootes ___________________________ ________
Researcher name [printed] Signature Date

9.6 Appendix - Battery Energy Management System

An energy storage solutions provider, herein referred to as "ES Provider," anticipates significant growth in the coming years, particularly with its offerings of 500 and 1000 kWh storage solutions. The growth trajectory primarily revolves around three key areas, ranked by priority:

- Rental Services:

One of the primary growth areas for ES providers lies in offering rental services, both for short and long-term durations. These services cater to various sectors, including events like festivals and fairs, as well as construction projects requiring emission-free energy solutions. These projects often demand temporary boosts in energy transport capacity to prevent downtime. By providing rental solutions, ES Provider addresses these needs efficiently, substituting diesel generators with sustainable energy solutions during peak demand periods.

- Addressing Network Congestion:

Another significant growth avenue for ES Providers is in alleviating network congestion. Currently a lot of inquiries from businesses looking to expand or struggling with their existing transport capacity (TC) on the grid. With increasing electrification industries experience peak periods that can be managed effectively through peak shaving techniques. For example, the electrification of vehicles presents opportunities. Charging the battery storage during the day with green energy and utilising the stored energy to charge vehicles overnight within business premises is becoming a common practice.

- Participation in the Imbalance Market:

A further area of growth for ES providers involves participating in the imbalanced market, as exemplified by initiatives like Eddy Grid.

9.7 Appendix - Consumption Profiles 2023

De profielcategorieen

E1A	-	≤3 x 25	niet op afstand uitleesbare kleinverbruikmeetinrichting onbemeten aansluiting (met uitzondering van gedimensioneerde profielen)
E1B	-	≤3 x 25	op afstand uitleesbare kleinverbruikmeetinrichting nachttariefregime
E1C	-	≤3 x 25	op afstand uitleesbare kleinverbruikmeetinrichting avondtariefregime
E2A	>3 x 25 A	≤3 x 80	niet op afstand uitleesbare kleinverbruikmeetinrichting
E2B	>3 x 25 A	≤3 x 80	op afstand uitleesbare kleinverbruikmeetinrichting
E3A	>3 x 80 A	≤ 100kw	Bedrijfstijd ≤ 2000 uur
E3B	>3 x 80 A	≤ 100kw	Bedrijfstijd > 2000 uur, Bedrijfstijd <=3000 uur
E3C	>3 x 80 A	≤ 100kw	Bedrijfstijd > 3000 uur, Bedrijfstijd < 5000 uur
E3D	>3 x 80 A	≤ 100kw	Bedrijfstijd >= 5000 uur
E4A	alle gemeten aansluitingen geschakeld op het stuursignaal openbare verlichting met een aangesloten vermogen van minder dan 100 kW		

Figure 9.3: Different consumption profiles 2023 in Dutch

9.8 Appendix – Node structure

This node structure provides an extra explantion on how every node is connected, for more information look inside the github repository

Technology		Name	Parameter	Value	Unit	Type	Description	Source
Tech groups		interest_rate_setter	cost_interest_rate	0,05		picked		
		power_lines	flow_out_eff	0,98		picked		
			lifetime	25	years	Fixed		Urban model example
			cost_flow_cap_per_distance	0,01	monetary	picked		
		heat_pipes	flow_cap_max	2000		selected		
			flow_out_eff_per_distance	0,975		picked		Urban model example
			lifetime	25	years	Fixed		
			cost_flow_cap_per_distance	0,3	monetary	picked		Urban model example
Techs	Supply	supply_grid_power	source_use_max	∞		selected		
			flow_cap_max	1252		picked		
			lifetime	25	years	picked		
			cost_emissions	0,37	kg CO2/kW	picked		
		supply_gas	source_use_max	∞		selected		
			flow_cap_max	2000	kW	picked		
			lifetime	25	years	Fixed		
			cost_flow_out	0,025	monetary	picked		
			cost_emissions	1,78	kg CO2/kW	picked		
		costly_supply	flow_cap_max	∞		picked		
			cost_flow_out	100	monetary	picked		
	Renewble supply	pv	flow_out_parasitic_eff	0,85		picked		
			flow_cap_max_systemwide	5080		picked		
			lifetime	25	years	Fixed		
			cost_om_annual	1000	monetary	picked		
			cost_emissions	0,41	kg CO2/kW	picked		
	storage	battery	storage_discharge_depth	0,01		picked		
			lifetime	15	years	Fixed		
			flow_cap_per_storage_cap_max	0,25		picked		
			flow_out_eff	0,95		picked		
			flow_in_eff	0,95		picked		
			storage_loss	0,01		picked		
			cost_storage_cap	400	$/kWh	picked		
			cost_emissions	80	kg CO2/kW	picked		
	conversion	boiler	flow_cap_max	∞		picked		
			flow_out_eff	0,85		picked		
			lifetime	25	years	Fixed		
	Demand	demand_electricity_E3B, E3C, E1A, E2A	base_tech	demand		selected		
			carrier_in	electricity		selected		
		demand_mobility	base_tech	demand		selected		
			carrier_in	electricity		selected		
		demand_heatpump_E3B, E3C, E1A, E2A	base_tech	demand		selected		
			carrier_in	electricity		selected		
		demand_heat_G1A, G2A, G2C	base_tech	demand		selected		
			carrier_in	heat		selected		
		demand_grid_sink	base_tech	demand		selected		
			carrier_in	electricity		selected		
	Transmission	Grid_sink_to_Outside_connection	from	grid_sink		Chosen		
			to	outside_connection		Chosen		
			inherit	power_lines		Chosen		
			distance	20		Chosen		
		Outside_connection_to_N1	from	outside_connection		Chosen		
			to	N1		Chosen		
			inherit	power_lines		Chosen		
			distance	20		Chosen		
		N1_to_BS	from	N1		Chosen		
			to	BS		Chosen		
			inherit	power_lines		Chosen		
			distance	20		Chosen		
		N1_to_EV_charger	from	N1		Chosen		
			to	EV_charger		Chosen		
			inherit	power_lines		Chosen		
			distance	10		Chosen		
		N1_to_N2	from	N1		Chosen		
			to	N2		Chosen		
			inherit	power_lines		Chosen		
			distance	10		Chosen		
		N2_to_Amp_125	from	N2		Chosen		
			to	Amp_125		Chosen		
			flow_cap_max	65		Assumed		
			inherit	power_lines		Chosen		
			distance	10		Chosen		
		N2_to_Amp_160	from	N2		Chosen		
			to	Amp_160		Chosen		
			flow_cap_max	28		Assumed		
			inherit	power_lines		Chosen		
			distance	10		Chosen		
		N2_to_Amp_250	from	N2		Chosen		
			to	Amp_250		Chosen		
			flow_cap_max	28		Assumed		
			inherit	power_lines		Chosen		
			distance	10		Chosen		
		N2_to_Amp_400	from	N2		Chosen		
			to	Amp_400		Chosen		
			flow_cap_max	69		Assumed		
			inherit	power_lines		Chosen		
			distance	10		Chosen		
		N2_to_VD_lem	from	N2		Chosen		
			to	VD_Lem		Chosen		
			flow_cap_max	402		Assumed		
			inherit	power_lines		Chosen		
			distance	10		Chosen		
		N2_to_kVA_630	from	N2		Chosen		
			to	kVA_630		Chosen		
			flow_cap_max	402		Assumed		
			inherit	power_lines		Chosen		
			distance	10		Chosen		
		N2_to_Amp_25	from	N2		Chosen		
			to	Amp_25		Chosen		
			inherit	power_lines		Chosen		
			flow_cap_max	56		Assumed		
			distance	10		Chosen		
		N2_to_Amp_35	from	N2		Chosen		
			to	Amp_35		Chosen		
			inherit	power_lines		Chosen		
			flow_cap_max	78		Assumed		
			distance	10		Chosen		
		N2_to_Amp_50	from	N2		Chosen		
			to	Amp_50		Chosen		
			inherit	power_lines		Chosen		
			flow_cap_max	52		Assumed		
			distance	10		Chosen		
		N2_to_Amp_63	from	N2		Chosen		
			to	Amp_63		Chosen		
			inherit	power_lines		Chosen		
			flow_cap_max	120		Assumed		
			distance	10		Chosen		
		N2_to_Amp_80	from	N2		Chosen		
			to	Amp_80		Chosen		
			inherit	power_lines		Chosen		
			flow_cap_max	124		Assumed		
			distance	10		Chosen		
		N3_to_Amp_80	from	N2		Chosen		
			to	Amp_80		Chosen		
			inherit	heat_pipes		Chosen		
			distance	10		Chosen		
		Amp_80_to_Amp_63	from	Amp_80		Chosen		
			to	Amp_63		Chosen		
			inherit	heat_pipes		Chosen		
			distance	10		Chosen		
		Amp_63_to_Amp_50	from	Amp_63		Chosen		
			to	Amp_50		Chosen		
			inherit	heat_pipes		Chosen		
			distance	10		Chosen		

9.9 Appendix - Government tax per kWh

Table 9.1: Government tax per kWh + average since 2017 [47]

Jaar	Jaar	0 t/m 2.900 kWh	2.901 t/m 10.000 kWh	10.001 t/m 50.000 kWh	50.001 t/m 10 miljoen kWh	meer dan 10 miljoen kWh particulier
2017	0,1013	0,1013	0,04901	0,01305	0,00107	0,00053
2018	0,10458	0,10458	0,05274	0,01404	0,00116	0,00057
2019	0,09863	0,09863	0,05337	0,01421	0,00117	0,00058
2020	0,0977	0,0977	0,05083	0,01353	0,00111	0,00055
2021	0,09428	0,09428	0,05164	0,01375	0,00113	0,00056
2022	0,03679	0,03679	0,04361	0,01189	0,00114	0,00057
2023	0,12599	0,12599	0,10046	0,03942	0,00175	0,00115
2024	0,1088	0,1088	0,09037	0,03943	0,00254	0,00188
	€ 0,09600875	€ 0,09600875	€ 0,06150375	€ 0,01991500	€ 0,00138375	€ 0,00079875

9.10 Appendix – Costly_supply appereance in solution mix 2

index	nodes	techs	timesteps	source_use
2578	outside_connection	costly_supply	17/12/2019 10:00	96,884
2579	outside_connection	costly_supply	17/12/2019 11:00	86,135
2554	outside_connection	costly_supply	16/12/2019 10:00	62,290
2555	outside_connection	costly_supply	16/12/2019 11:00	59,642
2580	outside_connection	costly_supply	17/12/2019 12:00	49,187
2074	outside_connection	costly_supply	26/11/2019 10:00	40,185
2075	outside_connection	costly_supply	26/11/2019 11:00	38,758
2581	outside_connection	costly_supply	17/12/2019 13:00	36,454
2557	outside_connection	costly_supply	16/12/2019 13:00	35,868
2556	outside_connection	costly_supply	16/12/2019 12:00	34,020
2558	outside_connection	costly_supply	16/12/2019 14:00	32,055
2582	outside_connection	costly_supply	17/12/2019 14:00	25,140
2386	outside_connection	costly_supply	09/12/2019 10:00	18,663
2559	outside_connection	costly_supply	16/12/2019 15:00	9,387
2076	outside_connection	costly_supply	26/11/2019 12:00	4,839
2218	outside_connection	costly_supply	02/12/2019 10:00	3,037
2387	outside_connection	costly_supply	09/12/2019 11:00	2,482
				635,027

9.11 Appendix – Low-cost/high-cost scenario (battery and PV size)

Table 9.2: Size of installed storage capacity in kWh and installed PV capacity in kWp for low and high-cost scenario

	Battery size						
	Battery_limit_S2_500	**Low_cost_0_5x (kWh)**	**Low_cost_0_7x (kWh)**	**Low_cost_0_9x (kWh)**	**High_cost_1_25x (kWh)**	**High_cost_1_5x (kWh)**	**High_cost_1_75x (kWh)**
	9250	**9250**	**9250**	**9250**	**9250**	**9250**	**9250**
Amp_125	1250	1250	1250	1250	1250	1250	1250
Amp_160	250	250	250	250	250	250	250
Amp_25	125	125	125	125	125	125	125
Amp_250	3000	3000	3000	3000	3000	3000	3000
Amp_35	250	250	250	250	250	250	250
Amp_400	250	250	250	250	250	250	250
Amp_50	250	250	250	250	250	250	250
Amp_63	500	500	500	500	500	500	500
Amp_80	2000	2000	2000	2000	2000	2000	2000
VD_Lem	750	750	750	750	750	750	750
kVA_630	625	625	625	625	625	625	625
	PV capacity installed						
	Battery_limit_S2_500	**Low_cost_0_5x (kWp)**	**Low_cost_0_7x (kWp)**	**Low_cost_0_9x (kWp)**	**High_cost_1_25x (kWp)**	**High_cost_1_5x (kWp)**	**High_cost_1_75x (kWp)**
	3892	**3402**	**3419**	**3419**	**3419**	**3419**	**3419**
Amp_125	346	316	326	326	326	326	326
Amp_160	78	78	78	78	78	78	78
Amp_25	112	112	112	112	112	112	112
Amp_250	725	480	480	480	480	480	480
Amp_35	177	177	177	177	177	177	177
Amp_400	144	144	144	144	144	144	144
Amp_50	122	122	122	122	122	122	122
Amp_63	275	275	275	275	275	275	275
Amp_80	648	434	441	441	441	441	441
VD_Lem	720	720	720	720	720	720	720
kVA_630	544	544	544	544	544	544	544

9.12 Appendix – Monetary costs Table

Table 9.3: Total monetary cost of energy system in Calliope, with export for revenue

Scenario	Supply_grid_power	Supply_gas	PV	battery	demand_grid_sink	Costly_supply	SUM Total
Current scenario (kWh)	€ 660.534	€ 124.113		€ 0	€ 0	€ 0	**€ 784.647**
Solution mix 1	€ 587.759	€ 39.340	€ 0	€ 0	€ 0	€ 63.503	**€ 690.602**
Solution mix 2	€ 231.665	€ 39.340	€ 0	€ 0	€ 0	€ 0	**€ 271.004**
Solution mix 3A	€ 233.548	€ 39.340	€ 0	€ 0	-€ 26.732	€ 0	**€ 246.155**
Solution mix 3B	€ 320.918	€ 39.340	€ 347.604	€ 457.193	-€ 72.914	€ 0	**€ 1.092.141**
Cost per storage cap in 1 $/kwh (S1)	€ 243.346	€ 39.340	€ 406.416	€ 1.802	-€ 45.126	€ 0	**€ 645.777**
Cost per storage cap in 100 $/kwh (S2)	€ 252.750	€ 39.340	€ 400.917	€ 158.146	-€ 51.662	€ 0	**€ 799.491**
Cost per storage cap in 200 $/kwh (S3)	€ 261.297	€ 39.340	€ 394.413	€ 297.580	-€ 55.285	€ 0	**€ 937.345**
Cost per storage cap in 300 $/kwh (S4)	€ 276.470	€ 39.340	€ 384.140	€ 414.110	-€ 62.146	€ 0	**€ 1.051.914**
Cost per storage cap in 400 $/kwh (S5)	€ 320.918	€ 39.340	€ 347.604	€ 457.193	-€ 72.914	€ 0	**€ 1.092.141**
Battery capacity limit (1) -125	€ 360.889	€ 39.340	€ 210.667	€ 26.567	-€ 67.019	€ 0	**€ 570.444**
Battery capacity limit (2) - 500	€ 307.275	€ 39.340	€ 244.633	€ 97.354	-€ 38.802	€ 0	**€ 649.800**
Battery capacity limit (3) -1000	€ 291.960	€ 39.340	€ 271.255	€ 118.091	-€ 42.635	€ 0	**€ 678.010**
Battery capacity limit (3) -handpick	€ 266.124	€ 39.340	€ 318.431	€ 178.722	-€ 45.162	€ 0	**€ 757.454**
Expasion demand (1)	€ 352.034	€ 39.340	€ 323.530	€ 178.722	-€ 32.248	€ 0	**€ 861.377**
Expansion demand (2)	€ 442.941	€ 39.340	€ 329.068	€ 178.722	-€ 24.255	€ 0	**€ 965.814**
Expasion demand (3)	€ 535.959	€ 39.340	€ 334.171	€ 178.722	-€ 17.626	€ 0	**€ 1.070.565**
PV capacities (1)	€ 425.039	€ 39.340	€ 101.604	€ 178.722	€ 0	€ 0	**€ 744.704**
PV capacities (2)	€ 339.422	€ 39.340	€ 198.068	€ 178.722	-€ 69	€ 0	**€ 755.481**
PV capacities (3)	€ 288.607	€ 39.340	€ 266.919	€ 178.722	-€ 16.656	€ 0	**€ 756.931**
Low-cost scenario (1)	€ 133.373	€ 39.340	€ 318.403	€ 178.722	-€ 22.562	€ 0	**€ 647.275**
Low-cost scenario (2)	€ 186.496	€ 39.340	€ 318.431	€ 178.722	-€ 31.613	€ 0	**€ 691.375**
Low-cost scenario (3)	€ 239.531	€ 39.340	€ 318.431	€ 178.722	-€ 40.646	€ 0	**€ 735.377**
High-cost scenario (1)	€ 398.510	€ 39.340	€ 318.431	€ 178.722	-€ 67.743	€ 0	**€ 867.260**
High-cost scenario (2)	€ 530.876	€ 39.340	€ 318.431	€ 178.722	-€ 90.336	€ 0	**€ 977.032**
High-cost scenario (3)	€ 662.964	€ 39.340	€ 318.431	€ 178.722	-€ 116.480	€ 0	**€ 1.082.975**

Table 9.4: Table 9.4: Total monetary cost of energy system in Calliope, without export for revenue

No Demand GridSink							
Scenario	**Supply_grid_power**	**Supply_gas**	**PV**	**battery**	**demand_grid_sink**	**Costly_supply**	
Cost per storage cap in 1 $/kwh (S1)	€ 239.507	€ 39.340	€ 404.462	€ 2.068	x	€ 0	**€ 685.377**
Cost per storage cap in 100 $/kwh (S2)	€ 261.004	€ 39.340	€ 374.116	€ 159.959	x	€ 0	**€ 834.418**
Cost per storage cap in 200 $/kwh (S3)	€ 271.505	€ 39.340	€ 360.682	€ 299.575	x	€ 0	**€ 971.101**
Cost per storage cap in 300 $/kwh (S4)	€ 283.856	€ 39.340	€ 348.985	€ 421.631	x	€ 0	**€ 1.093.812**
Cost per storage cap in 400 $/kwh (S5)	€ 336.171	€ 39.340	€ 289.790	€ 460.340	x	€ 0	**€ 1.125.641**
Battery capacity limit (1) -125	€ 376.294	€ 39.340	€ 160.343	€ 26.567	x	€ 0	**€ 602.544**
Battery capacity limit (2) - 500	€ 303.423	€ 39.340	€ 244.633	€ 105.571	x	€ 0	**€ 692.966**
Battery capacity limit (3) -1000	€ 284.728	€ 39.340	€ 271.255	€ 135.232	x	€ 0	**€ 730.554**
Battery capacity limit (3) -handpick	€ 270.910	€ 39.340	€ 305.803	€ 178.722	x	€ 0	**€ 794.774**
Expasion demand (1)	€ 347.288	€ 39.340	€ 323.530	€ 191.002	x	€ 0	**€ 901.159**
Expansion demand (2)	€ 438.422	€ 39.340	€ 329.068	€ 190.931	x	€ 0	**€ 997.761**
Expasion demand (3)	€ 534.048	€ 39.340	€ 334.171	€ 184.002	x	€ 0	**€ 1.091.560**
PV capacities (1)	€ 425.039	€ 39.340	€ 101.604	€ 178.722	x	€ 0	**€ 744.704**
PV capacities (2)	€ 339.422	€ 39.340	€ 198.068	€ 178.722	x	€ 0	**€ 755.550**
PV capacities (3)	€ 288.626	€ 39.340	€ 266.919	€ 178.722	x	€ 0	**€ 773.606**
Low-cost scenario (1)	€ 140.036	€ 39.340	€ 285.596	€ 178.722	x	€ 0	**€ 643.693**
Low-cost scenario (2)	€ 192.769	€ 39.340	€ 295.386	€ 178.722	x	€ 0	**€ 706.216**
Low-cost scenario (3)	€ 245.600	€ 39.340	€ 300.900	€ 178.722	x	€ 0	**€ 764.562**
High-cost scenario (1)	€ 398.593	€ 39.340	€ 318.431	€ 178.722	x	€ 0	**€ 935.085**
High-cost scenario (2)	€ 530.083	€ 39.340	€ 318.431	€ 180.163	x	€ 0	**€ 1.068.017**
High-cost scenario (3)	€ 659.423	€ 39.340	€ 318.431	€ 184.068	x	€ 0	**€ 1.201.262**

9.13 Appendix – CO2 emission costs (tonnes CO2-eq)

Table 9.5: Total CO2 emission in Tonnes CO2-eq of energy system in Calliope, with export for revenue

Scenario	Supply_grid_power (tonnes CO2/kWh)	Supply_gas (Tonnes CO2/kWh)	PV (tonnes CO2/kWh)	battery (tonnes CO2/kWh)	SUM Total (tonnes CO2/kWh)
Current scenario (kWh)	2211	893	x	x	**3104**
Solution mix 1	2029	283	x	x	**2312**
Solution mix 2	769	283	0	x	**1052**
Solution mix 3A	777	283	181	x	**1241**
Solution mix 3B	1100	283	154	79	**1617**
Cost per storage cap in 1 $/kwh (S1)	814	283	181	125	**1403**
Cost per storage cap in 100 $/kwh (S2)	849	283	178	109	**1420**
Cost per storage cap in 200 $/kwh (S3)	881	283	175	103	**1443**
Cost per storage cap in 300 $/kwh (S4)	939	283	171	96	**1488**
Cost per storage cap in 400 $/kwh (S5)	1100	283	154	79	**1617**
Battery capacity limit (1) -125	1244	283	94	9	**1630**
Battery capacity limit (2) - 500	1053	283	109	34	**1479**
Battery capacity limit (3) -1000	996	283	121	41	**1441**
Battery capacity limit (3) -handpick	898	283	142	62	**1385**
Expasion demand (1)	1200	283	144	62	**1689**
Expansion demand (2)	1520	283	146	62	**2011**
Expasion demand (3)	1847	283	148	62	**2341**
PV capacities (1)	1475	283	45	62	**1865**
PV capacities (2)	1162	283	88	62	**1595**
PV capacities (3)	978	283	119	62	**1441**
Low-cost scenario (1)	897	283	141	62	**1384**
Low-cost scenario (2)	898	283	142	62	**1384**
Low-cost scenario (3)	898	283	142	62	**1384**
High-cost scenario (1)	899	283	142	62	**1385**
High-cost scenario (2)	899	283	142	62	**1386**
High-cost scenario (3)	905	283	142	62	**1391**

Table 9.6: Total CO2 emission in Tonnes CO2-eq of energy system in Calliope, without export for revenue

No Demand GridSink					
Scenario	**Supply_grid_power (tonnes CO2/kWh)**	**Supply_gas (Tonnes CO2/kWh)**	**PV (tonnes CO2/kWh)**	**battery (tonnes CO2/kWh)**	**SUM Total (tonnes CO2/kWh)**
Cost per storage cap in 1 $/kwh (S1)	800	283	180	143	1405
Cost per storage cap in 100 $/kwh (S2)	878	283	166	111	1438
Cost per storage cap in 200 $/kwh (S3)	917	283	160	104	1464
Cost per storage cap in 300 $/kwh (S4)	964	283	155	97	1499
Cost per storage cap in 400 $/kwh (S5)	1153	283	129	80	1644
Battery capacity limit (1) -125	1298	283	71	9	1662
Battery capacity limit (2) - 500	1039	283	109	37	1467
Battery capacity limit (3) -1000	968	283	121	47	1418
Battery capacity limit (3) -handpick	915	283	136	62	1396
Expasion demand (1)	1182	283	144	66	1675
Expansion demand (2)	1503	283	146	66	1998
Expasion demand (3)	1840	283	148	64	2335
PV capacities (1)	1475	283	45	62	1865
PV capacities (2)	1162	283	88	62	1595
PV capacities (3)	978	283	119	62	1441
Low-cost scenario (1)	944	283	127	62	1416
Low-cost scenario (2)	929	283	131	62	1405
Low-cost scenario (3)	922	283	134	62	1400
High-cost scenario (1)	899	283	142	62	1385
High-cost scenario (2)	898	283	142	62	1385
High-cost scenario (3)	895	283	142	64	1383

9.14 Appendix – Github repository

The complete codebase and documentation for the decentralised Energy System Model for the Business Park can be accessed through the following GitHub repository.

Link: https://github.com/hiddegrootes/decentralised-Energy-System-Model_Business-Park.git.

This repository contains all the scripts, data, and models used in the analysis, along with README file instructions for replicating the results. It serves as a comprehensive resource for anyone interested in exploring the model further or applying it to similar projects.