# A systematic approach to facilitate decision-making within the heat transition in the Netherlands: A case study application to the municipality of Delft

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# Executive summary

The growing population worldwide contributes to the rising demand for energy, resulting in climate change due to increased greenhouse gas emissions. The worrying and irreversible consequences of climate change have led to various international and national targets. All targets are aimed at counteracting climate change through adaptation in different sectors. One of the most important sectors is formed by the energy sector. In the Netherlands, numerous energy transitions, including the heat transition, are currently taking place driven by national targets. The heat transition is, in addition to the desire to reduce greenhouse gas emissions, driven by the desire for international independence and the phasing out of natural gas production in Groningen. However, the heat transition is embedded in a socio-technical environment characterized by uncertain interactions between social, technical, and economic aspects leading to challenges for decision-makers. This study is designed to describe a systematic approach that decision-makers can use during the heat transition at the municipal level. The systematic approach is described using the following research question:

*How could an approach be designed to improve decision-making within the heat transition at the municipal level while considering the surrounding socio-technical environment?*

In answering the research question, the techno-economic Vesta MAIS model is central. This computational model can be used by decision-makers to determine, based on the national costs, which heat transition vision is the most appropriate for replacing natural gas-driven heat sources. The model assumes rationality and can be used by decision-makers as an exploratory, informative, and supportive tool for decision-making. Because the Vesta MAIS model is not able to integrate non-rational aspects into the model outcomes, an actor analysis is proposed in this study as a first step in the systematic approach. This actor analysis can be used to identify the different actors and perform a categorization based on the associated power and interest. In this way, the systematic approach is able to consider non-rational aspects such as willingness to participate in the heat transition and technology preferences. These non-rational aspects can then be included to identify the social feasibility of the heat transition visions before applying the Vesta MAIS model.

Next, the techno-economic Vesta MAIS model is applied to demonstrate the role of the model within the systematic approach. The Vesta MAIS model is used to provide economic and technical insights. For example, the model can be used to determine the national cost per heat transition vision at the neighborhood level. In addition, the model can determine the change in the share of each energy carrier corresponding to each heat transition vision. When applying the model to the thirteen prioritized neighborhoods within the heat transition in the municipality of Delft, it was found that the national cost for each neighborhood increases compared to 2019, regardless of the chosen heat transition vision. In addition, it was shown that the share of natural gas disappears in 2030, while the share of electricity increases. Furthermore, it was found that only two neighborhoods in the municipality of Delft will electrify their heat demand based on the national cost. This is because the national cost of the all-electric strategy is high compared to the other heat transition visions. Finally, it was found that the Vesta MAIS model is not able to determine the direct impact of the heat transition on the power grid. This is because the model is only able to calculate an annual average demand for electricity, making the results not suitable to analyse the feasibility of a heat transition vision in terms of network congestion.

The final step proposed in the systematic approach is the application of a power flow analysis. This type of analysis can enrich the technical insights provided using the Vesta MAIS model with opportunities to identify network congestion. In this study, an energy model was set up that uses the principles of a power flow analysis. The purpose of this model is to allow

decision-makers with less expertise to analyze the impact of a heat transition vision on the power grid in terms of congestion. The modeler can define his input variables, including line and bus properties, external grid configurations, hourly demand patterns, transformers, hourly load supplies, load constraints, and controllers. The model can determine the time and location of network congestion based on hourly demand patterns. This congestion is indicated by a color, leading to easily interpretable results. For example, the results showed that network congestion occurs mainly at large users, including hotels, supermarkets, and large offices. Finally, the model can be used to determine at what times of the day the electricity demand is greatest. For example, the results showed that the peak generation shifted from the evening to the morning after the electrification of the heat demand.

This study describes, using three steps, a systematic approach that can be used by decision-makers within the heat transition. The first step consists of carrying out an actor analysis to clarify the non-rational aspects, especially social aspects. In this way, the social feasibility of a heat transition vision can be determined. The second step is the application of the techno-economic Vesta MAIS model to provide economical and technical insights per heat transition vision. To enrich the technical insights with network congestion, the third step is formed by a power flow analysis. Establishing a systematic approach has a scientific contribution in that it considers the socio-technical context in which the heat transition is embedded. In this way, the systematic approach contributes to improving decision-making within the heat transition in the Netherlands.

To increase the value of the systematic approach, it is recommended to explore the possibilities of integrating an ABM into the Vesta MAIS model. In this way, the social aspects can be directly integrated into the techno-economic Vesta MAIS model. In addition, it is recommended to investigate future possibilities to improve the complementarity of the results of the Vesta MAIS model and a power flow analysis. This includes developing advanced methods to translate the annual average total electricity demand into hourly demand patterns. This will strengthen the reliability of the power flow analysis. The third future research recommendation concerns the development of an energy model that is capable of analyzing the impact of the heat transition on the gas and heat network. After all, the heat transition is also characterized by a change in demand for these energy carriers. Finally, it is recommended to perform a power flow analysis on an existing network with associated properties. In this way, the reliability of the energy model can analytically be determined.

## Acknowledgements

The complex interactions between social, economic, and technical aspects create a challenge in guiding different transitions. This is one of the main insights I have gained from the master Complex Systems Engineering and Management (CoSEM) in recent years. During the master's program, I gained a lot of experience in structuring projects that are located in a socio-technical environment. In addition, through the many group assignments, I learned to work together to see a challenge from different perspectives. The master CoSEM has taught me to combine the complexities of design projects with existing challenges in the energy transition. I applied the knowledge and experience I gained during the master's program to carry out my graduation project.

For carrying out this thesis project, I would like to thank Prof.dr.ir. Z. Lukszo, from the Energy and Industry section, as my chairperson. Prof.dr.ir. Z. Lukszo helped and supported me during the different meetings. Moreover, Prof.dr.ir. Z. Lukszo acted adequately when it appeared that the Ph.D. student who was linked to this project, stopped halfway. I would also like to thank Prof.dr. M.E. Warnier, of the Systems Engineering section, as my first supervisor. Because the Ph.D. student stopped halfway through the project, Prof.dr. M.E. Warnier, has taken over these tasks. Although Prof.dr. M.E. Warnier had indicated at the beginning of the project that he only wanted to take on the role of second supervisor due to a lack of time, I received sufficient support. The bi-weekly appointments provided me with the appropriate support. Finally, I would like to thank my two external supervisors. Dr.ir. A.A. van der Meer, working for GO-e project supported me in setting up the power flow analysis. F.v.d.Molen, working at Planbureau voor de Leefomgeving, has helped me with the collection of data following the Vesta MAIS model. I was also allowed to join PBL for a day.

Finally, I would like to thank everyone who has supported me in studying. In particular, I would like to thank my parents, sister, and girlfriend who have supported me for the past five years. Without the support from you, I would never have achieved what I have achieved now. Thank you!

## List of abbreviations

| | | | |
|---|---|---|---|
| *RIVM* | Rijksinstituut voor Volksgezondheid en Milieu (National Institute for Public Health and the Environment) | *SDG* | Sustainable development Goals |
| *GHG* | Greenhouse gas | *VAT* | Value Added Tax |
| *RES* | Regional Energy Strategy | *ISDE* | Investment Subsidy for Renewable energy and Energy Conservation |
| *WKO* | Warmte Koude Opslag (Heat Cold Storage) | *OWD* | Open Warmtenet Delft |
| *CBS* | Centraal Bureau voor de Statistiek (Central Bureau for Statistics) | *GTD* | Geothermie Delft |
| *PBL* | Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency) | *ABM* | Agent-Based model |
| *DANA* | Dynamic Actor-Network Analysis | *STS* | Sociotechnical Systems |
| *ETM* | Energy Transition Model | *CAS* | Complex Adaptive Systems |
| *RSW* | Regional Structure of Heat | *P* | Real power |
| *LT* | Low temperature | *V* | Voltage magnitude |
| *MT* | Medium temperature | *Θ* | Voltage phase |
| *Q* | Reactive power | *PV* | Photovoltaic |
| *J* | Jacobian matrix | *hv* | High voltage |
| *WD* | Wind turbine | *lv* | Low voltage |
| *mv* | Medium voltage | | |

## List of units

| | |
|---|---|
| *℃* | Degrees Celsius |
| $m^2$ | Square meter |
| *TJ* | Terajoules |
| $m^3$ | Cubic meters |
| *Kton* | Kilo tons |
| *€* | Euro |
| *KJ* | Kilojoule |
| *kWh* | Kilowatt Hour |
| *MW* | Megawatts |
| *Pu* | Per unit |
| *km* | Kilometer |

# Chapter 1 – Introduction and Problem definition

This chapter introduces the problem addressed in this study. It then describes the administrative design for the Netherlands, which functions as the context for this study. Section 1.3 describes the complexity of the heat transition. Section 1.4 presents a literature review that contributes to the identification of the knowledge gap. The identified knowledge gap functions in section 1.5 as a basis for formulating the main research question and associated sub-questions.

## 1.1 – The need for reduction of GHG emissions

The global demand for energy has increased dramatically in recent years which is a result of a growing population and improved prosperity worldwide ("The World Databank," 2022). The consequence of the rising demand for energy is the increase in anthropogenic emissions, of which $CO_2$ is the best known example, that contribute to climate change (CBS, 2022; Chang et al., 2021; Horschig & Thrän, 2017; Verhagen, van der Voet, & Sprecher, 2021). As a result, several national and international agreements have been developed, including the Paris Climate agreement and the Sustainable Development Goals (SDG) (Tolliver, Keeley, & Managi, 2019). These agreements were set up with the goal of countering the irreversible and worrying consequences of climate change, including every rising temperatures, increase in extreme weather, the melting of land and sea ice, and drastic changes in animal habitats (Dutch Emissions Authority, 2017; Tolliver et al., 2019). The Paris climate agreement is used by the undersigned countries as a policy guideline, within which national guidelines are drafted. In the Netherlands, the national climate agreement was presented in 2019. This climate agreement contains more than 600 individual goals and regulations, divided in five sectors, specifically drafted for the Netherlands (Klimaatakkoord, 2019). The five sectors are (1) the built environment, (2) mobility, (3) industry, (4) agriculture and land use, and (5) electricity (CBS, 2022). The overarching goal presented in the Dutch climate agreement is that greenhouse gas emissions must be reduced by 49% by 2030 and 95% by 2050 relative to the year 1990 (Verhagen et al., 2021). For each sector, the "Rijksinstituut voor Volksgezondheid en Milieu" (RIVM) has created a graph showing the emissions of $CO_2$ equivalents. The graph is depicted in Figure 1 and shows that the $CO_2$ equivalent emissions of all sectors are gradually decreasing in the lifespan 1990-2020.

The reduction of anthropogenic greenhouse emissions involves complex changes in each sector, requiring adjustments in existing infrastructures, technologies, and policies where the interests of all actors must be safeguarded as much as possible (Skjærseth, Andresen, Bang, & Heggelund, 2021). It is therefore important to set up specific studies for each sector. This study focuses exclusively on the heat transition in the built environment. Here, the heat transition is defined as "the process of replacing thermal energy produced by natural gas sources with sustainable alternative heat sources". Currently, most Dutch households, and utility buildings, including hospitals, businesses, schools, and other buildings are heated by natural gas which features some adverse properties including anthropogenic emissions associated with the combustion and the finite nature of the production (Jansma, Gosselt, & de Jong, 2020; Linderhof, Dekkers, & Polman, 2020). Beyond these adverse properties, the Netherlands has two other reasons for completing the heat transition, including the desire to be internationally independent and to reduce the share of natural gas produced in Groningen (Klimaatakkoord, 2019). To reduce dependence on natural gas imports and comply with the climate agreement, the Netherlands has a target of disconnecting all 7 million households and 1 million utility buildings from natural gas by 2050 (Koster, Kruit, Teng, & Hesselink, 2022). This transition will be carried out through a gradual transition, with at least 50,000 existing households being disconnected from natural gas each year until 2030. After 2030, the number of natural gas-free households should be at least 200,000 annually (Rijksoverheid, 2021).

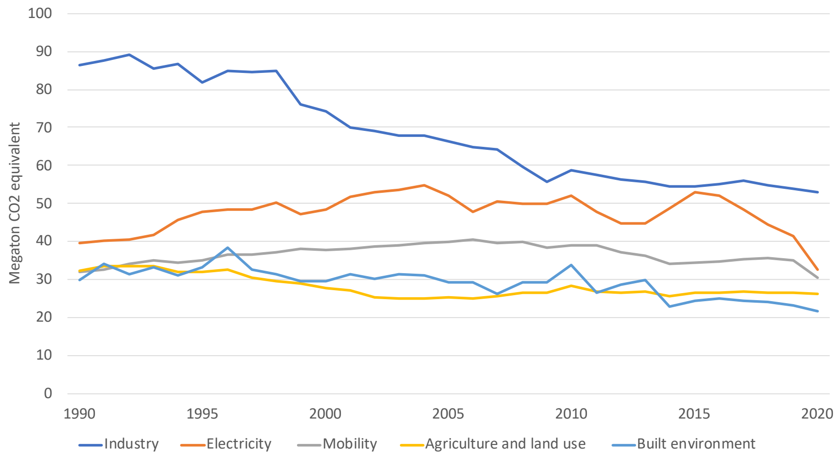

*Figure 1: A visualization of the greenhouse gas emission per sector in the Netherlands (CBS, 2022)*

### 1.2 – Administrative design in The Netherlands

The energy transition, of which the heat transition is a part, includes one of the most important aspects in the Paris climate agreement to reduce greenhouse gas (GHG) emissions (Rose, Richels, Blanford, & Rutherford, 2017; Tolliver et al., 2019). As shown, the agreements in the treaty form the basis for national regulations to ensure that each country can use its most efficient resources to replace conventional energy technologies (Rose et al., 2017). A similar approach has been adopted in the Netherlands by using the Regional Energy Strategy (RES). Indeed, within the Netherlands' climate agreement published in June 2019, it has been agreed that 30 energy regions (Appendix A1) will be established to specifically look for the most inexpensive alternative energy source on land (wind and solar) (Regionale Energie Strategie, 2022). In doing so, the energy regions will be asked to investigate whether sufficient space is available and whether the locations for alternative energy sources are acceptable and financially feasible (Bessette & Arvai, 2014; Regionale Energie Strategie, 2022). The choices made within an energy region should then be described in an RES. Within this study, the RES serves as an umbrella program set up by the government that provides the guidelines for municipality-specific initiatives to achieve the heat transition (Regionale Energie Strategie, 2022).

#### 1.2.1 – Heat transition visions

In the Netherlands it has been agreed to leave the direction of the heat transition to the municipalities. In this way, municipalities themselves can use the most appropriate resources to replace conventional natural gas technologies (Henrich, Hoppe, Diran, & Lukszo, 2021; PBL, 2022). Every municipality has signed a heat transition vision by the end of 2021 which describes a step-by-step plan to be used in the decarbonization of the built environment (PBL, 2022). This has made each municipality responsible for finding the most appropriate strategy in terms of cost and technical feasibility making the municipalaity responsible for the successful implementation of the chosen strategy (Henrich et al., 2021). This is the reason that the municipality is perceived "problem owner" within this research.

When creating the heat transition vision, a municipality has a choice of different strategies. For example, a municipality may choose to replace all heat sources from natural gas with electric heating sources. In addition, a municipality may choose to replace heat from natural gas with waste heat from industries, biomass, geothermal, aqua and sewage heat, and Heat Cold Storage (WKO). Also, a municipality may choose renewable gas, hybrid system, or a mixed strategy. The choice for a specific heat transition vision affects the existing energy infrastructure (Netbeheer Nederland, 2021). A more elaborative description of the available heat transition visions and the impact on the energy grid is described in Chapter 6.

## 1.3 – Complexity of the heat transition

The heat transition is perceived as a complex system due to the involvement of many actors (Moncada et al., 2017; Zonnenshain & Stauber, 2015). Here, a "system" is defined as an assembly of system elements which has interconnections, has a state, shows behavior, and has an external system boundary (Zonnenshain & Stauber, 2015). Because the heat transition is embedded in an environment that contains uncertain interactions between system elements such as social, technical, and economic aspects, it can be said that the transition occurs within a socio-technical environment. This type of environment features dynamism in the interactions between the system elements due to uncertain future developments of technologies and policies (Loureiro & Curran, 2007; Moncada et al., 2017). To coordinate these interactions, it is important that guidelines are set up by a regulating party that considers the surrounding system elements (Sargut & Gunther Mcgrath, 2010).

Currently, there are a few tools available to reduce the complexity of the heat transition. One of these tools is the Leidraad. This tool has been prepared to support municipalities in making the right decisions in the heat transition (Henrich et al., 2021; Netbeheer Nederland, 2021). The Leidraad was prepared by the "Expertise Centrum Warmte" (ECW) and "Planbureau voor de Leefomgeving" (PBL) (Netbeheer Nederland, 2021). The Leidraad consists of two parts. The first part consists of the "Startanalyse" where the impact of the different strategies within the heat transition vision are identified at the neighborhood level in terms of cost efficiency (Henrich et al., 2021; Netbeheer Nederland, 2021; PBL, 2022). The analysis is performed by means of a techno-economic model prepared by PBL. The data used is based on recently validated national data made available by various research organizations (PAW, 2022). In order to add the local aspects within the analysis, the Leidraad is extended with the "Handreiking voor lokale analyse" (Henrich et al., 2021). This extension provides improved action perspectives for municipalities, as the model is based on local data from local stakeholders (Henrich et al., 2021; Netbeheer Nederland, 2021). This data provides insights, for example, into planned maintenance periods of the grid operator on the energy grid and local new construction projects in the future (Netbeheer Nederland, 2021; PBL, 2022). The extension to the Startanalyse thus enables municipalities to gain a more robust understanding of the impact of the heat transition in residential areas (Henrich et al., 2021).

## 1.4 Problem identification

The previous section has shown that the heat transition is embedded in a socio-technical environment leading to complexities in guiding the transition. Furthermore, a suggestion was being provided by using an approach that considers the system elements of a socio-technical environment. In this section, using 11 literature papers, an understanding is being obtained concerning existing attempts to integrate social, technical, and economic aspects into an approach aimed to facilitate decision-making within the heat transition. The papers were found through the search queries "Facilitating decision-making in the energy transition", "Energy models to facilitate decision-making", and "The effect of social aspects on the results of quantitative models in energy transitions". The results of the literature review are described in section 1.4.1. Then, based on the findings of the available literature, a knowledge gap is formed that forms the basis for this study.

### 1.4.1 Computational models to support decision-making in the heat transition

The heat transition is, as has been shown, faced by complexities due to uncertain interactions between the system elements of a socio-technical environment. Every transition requires changes in existing policies of municipalities to cope with these dynamic interactions. In addition, municipalities must be able to determine which technological options have the most potential to replace natural gas-driven heat sources. Xavier et al. (2021) argue that these decisions are often made based on limited knowledge due to limited cooperation between decision-makers and surrounding actors resulting in uncertain decisions. This bounded rationality can be counteracted, according to Henrich et al. (2021), when evidence-based policy is integrated into existing policies. This evidence-based policymaking is characterized by fact-based knowledge to support policymaking, using data-driven policies, by policymakers (Henrich et al., 2021; Xavier & Hesselink, 2021). These data-driven policies are characterized by using data and tools, including energy models, to process and analyze data that contribute to the substantiation of policy decisions (Henrich et al., 2021). In the Netherlands, several model techniques are available that can be used as computational model to facilitate decision-making in the heat transition. These computational models are mainly formed by quantitative energy models and can be applied to discover the different possible energy transition pathways (Henrich et al., 2021; Nilsson, Dzebo, Savvidou, & Axelsson, 2020). Nilsson et al. (2020) describe two types of quantitative energy model techniques. The first technique described are the Integrated Assessment Models (IAM) which can be used to investigate the different pathways for specific energy transitions. IAMs are used by the Intergovernmental Panel on Climate Change (IPCC) and the European commission to facilitate decision-making (Nilsson et al., 2020). The second model technique described by Nilsson et al. (2020) are the energy-economic and macroeconomic models, which are mainly used by national policymakers. These models are able to integrate economic and technical components in more detail compared to the IAMs (Nilsson et al., 2020).

Besides the quantitative energy models, some socio-technical modeling approaches can be distinguished. These models approach the energy transition from a socio-technical perspective in which formal institutions play an important role in shaping the interactions between actors and technical aspects (Hansen, Liu, & Morrison, 2019; Henrich et al., 2021; Nilsson et al., 2020). Nilsson et al. (2020), Li et al. (2015), Henrich et al. (2021), and Bollinger et al. (2018) described different ways to enrich the existing quantitative models with a socio-technical approach. Nilsson et al. (2020) proposed a model that links the two models through nine components. These components consist of a systems model, socio-technical regime, local action, landscape, niche innovations, policy and governance, scenario drivers and uncertainties, scenario model, and future system view. Li et al. (2015) described an approach in which the concept of "socio-technical energy transition" is central. In his model, there is an emphasize on the mismatch between the outcomes of socio-technical models and quantitative models (Li, Trutnevyte, & Strachan, 2015). In doing so, Li et al. (2015) focus on three requirements, namely techno-economic detail, explicit actor heterogeneity, and transition pathway dynamics. Although the literature showed several attempts to implement these requirements in one single model, Li et al. (2015) argued that none of the existing models have the requirements fully integrated into the model outcomes. Finally, Bollinger et al. (2018) and Henrich et al. (2012) argue that multi-model ecologies can provide a possible solution to better link socio-technical models to quantitative models. Multi-model ecologies are characterized as systems of models that interact with each other. Bollinger et al. (2018) argued that the interaction between socio-technical models and quantitative models cannot be linked to each other in one single model. Therefore, a multi-model is required to fully integrate the social aspects with the techno-economic aspects (Bollinger, Davis, Evins, Chappin, & Nikolic, 2018).

The literature has shown that quantitative models are able to incorporate a multi-actor perspective, but that socio-technical transitions are often beyond the scope of these models. In addition, quantitative models tend to focus only on techno-economic factors. Henrich et al. (2021) analyzed different models through desk research and in-depth interviews with actors. The results showed that the impact of social and socio-economic data in the heat transition projects in the Netherlands is limited.

### 1.4.2 Knowledge gap

Henrich et al. (2021) argue that Dutch municipalities are increasingly exploring the possibilities of data-driven policymaking in the heat transition, but that a lack of guidelines, expertise, and availability of grid data plays a limiting factor in the integration of computational tools in decision-making. Decision-makers, such as municipalities, now seek advice from consultancies that use quantitative models such as CEGOIA by CE Delft, Warmte Transitie Atlas by Over Morgen, Aardgasvrije wijken by DWA, Vesta MAIS by PBL, ETM by quintel, and Caldomus by Innoforte (Henrich et al., 2021). CEGOIA can be used to calculate the costs and benefits of the heat transition. In addition, the model is seen as a bottom-up model where policymakers are able to modify the input variables ("Energiemodelleren," 2022; Henrich et al., 2021). The "Warmte transitie Atlas" and "Aardgasvrije wijken" can be used as a spatial model where the possible transition pathways are visualized. The results of these models are based on the results of other models (Delft, 2021; Netbeheer Nederland, 2021). The Vesta MAIS model is a techno-economic model that can provide insights into policymaking based on optimization and exploration using a bottom-up approach ("Energiemodelleren," 2022; Planbureau voor de Leefomgeving, 2021). ETM is a system integration model that is able to integrate different technologies to make predictions about the costs, benefits, and share of different energy carriers (electricity, heat, gas, hydrogen) (Henrich et al., 2021). Finally, Caldomus can be used to predict the costs, $CO_2$ emissions, future-proofing, and support of the possible heat transition pathways ("Energiemodelleren," 2022).

Applying the models in decision-making requires expertise because it is inevitable to run the models without assumptions (Pfenninger, Hawkes, & Keirstead, 2014). To ensure that the correct assumptions are made, the modeler must have the appropriate knowledge. If the assumptions are not applied consistently, conflicting results may arise between the models. This leads to decision-makers interpreting the results of the model differently leading to misunderstanding and a lack of credibility in the model results (Diran, Henrich, & Geerdink, 2020). Another limiting aspect that contributes to the poor implementation of data-driven policymaking is the lack of socio-technical factors in the available models (Henrich et al., 2021). For instance, the current techno-economic property of the available models does not consider non-rational aspects such as attitudes and behaviors of the public (Bollinger et al., 2018). This leads to an energy transition pathway that is feasible in terms of technical aspects and costs but non-rational aspects such as social aspects (e.g., willingness to participate in the heat transition, etc.)  leading to a stagnation of pathway implementation (Martinez, Harmsen, Menkveld, & Faaij, 2020).

In the literature used in this thesis, there is hardly any systematic approach described to apply the energy models to facilitate decision-making in the heat transition for actors without advanced grid data and expertise. This lack of a systematic approach to integrating the social, economic, and technical aspects into an energy model functions as a knowledge gap within this project, which aims to describe an easily interpretable methodology that decision-makers without access to advanced grid data can use when deciding on a heat transition vision.

## 1.5 Research questions

This study aims to describe an approach that can be applied at the municipal level to facilitate decision-making within the heat transition. The aim is to describe an approach that considers the socio-technical environment within which the heat transition is embedded. In this way, an answer to the following research question can be formed:

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*RQ: How could an approach be designed to improve decision-making within the heat transition at the municipal level while considering the surrounding socio-technical environment?*

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A generic representation of the approach is shown in Figure 2. From this figure, it becomes clear that the approach must consider the system elements of a socio-technical environment. In other words, the approach must be able to integrate social, technical, and economic aspects. In this study, each system element represents a step in the proposed approach. Based on an extensive application to an existing municipality, each step is assessed for its contribution to municipal decision-making in the heat transition. To structure the study, three sub-questions are used that are intended to describe a detailed method for integrating the aspects into the ultimate approach for facilitating decision-making in the heat transition. The following sub-questions are used:

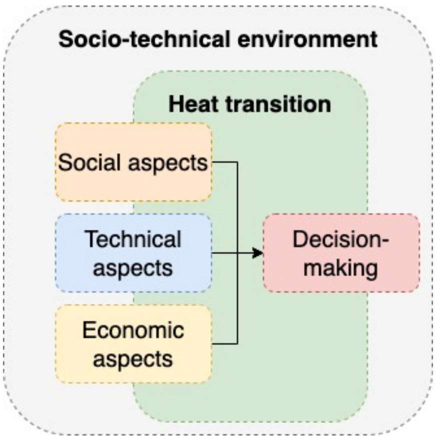


*Figure 2: A generic visualization of the composition of the approach that contributes to decision-making by considering the surrounding socio-technical environment*

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*SQ1: How could an actor analysis be integrated into an approach aimed at facilitating decision-making at the municipal level within the heat transition?*

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*SQ2: How could the techno-economic outcomes of the Vesta MAIS model be used to facilitate decision-making at the municipal level?*

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*SQ3: How could the results of the Vesta MAIS model be used to assess the feasibility of the heat transition in terms of grid congestion?*

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# Chapter 2 – Research design

This chapter describes the research objectives, research scope, research relevance, and thesis outline. The research objectives describe what the research is trying to achieve. The research scope describes what the research will cover and on what research area it is focused. The research relevance describes the importance of the research in terms of technical, institutional, and social aspects. Finally, the different chapters used in this report are described in the outline of this thesis.

## 2.1 – Research aim and objectives

This research aims to describe a systematic approach that can be used by municipalities to facilitate decision-making. It describes a way to include the social, economic, and technical aspects into the decision-making process. The aim is not to integrate the social aspects into one single techno-economic model, but to establish an approach that can be used by municipalities and other actors with less expertise and without access to advanced grid data to interpret the results of existing techno-economic models for decision-making. Therefore, in this study, two research objectives can be distinguished.

The first research objective is formed by performing an advanced actor analysis to present a way for decision-makers to integrate non-rational aspects into a systematic approach for decision-making. The literature review revealed that the current energy models are based on rational decision-making, which can lead to uncertain outcomes of the model. Here, an opportunity arises to perform an actor analysis to indicate and categorize actors based on objectives and interests. Performing an actor analysis is intended to enrich existing techno-economic models with social aspects making techno-economic models more suitable for decision-making.

The second objective is to develop a model that can analyze the impact of the heat transition on the power grid. This model should, in contrast to existing models, be able to be used by actors with less expertise and without access to advanced grid data to improve decision-making by using a systematic approach. To develop this model, use is made of the techno-economic Vesta MAIS model developed by PBL. The Vesta MAIS model is used in this research to compute the national costs and change in the share of energy carriers (heat, gas, and electricity) based on advanced input data.

## 2.2 - Research scope

In this study, two research scopes are used. The case study, actor analysis, and Vesta MAIS model application are conducted at the municipal level. This was chosen because the heat transition is led by the municipality. After all, the municipality decides which heat transition vision will be followed. In addition, the municipality also describes the importance of the interaction of actors in the "Warmteplan" (heat plan). Here, not only the actors of a specific neighborhood are described, but all actors that are influenced or have an influence on the heat transition in the municipality. A detailed description of the heat plan is described in the case study in Chapter 4. For the development and application of an energy model that helps to facilitate decision-making, a single neighborhood is used to perform a case study. This scope was chosen because the energy model that will be created in Chapter 8 describes a distribution network. These networks are located in individual neighborhoods. Therefore, to use a realistic application of the energy model, a neighborhood-level application was chosen. The visualization of the research scope with corresponding chapter indication is shown in Figure 3.

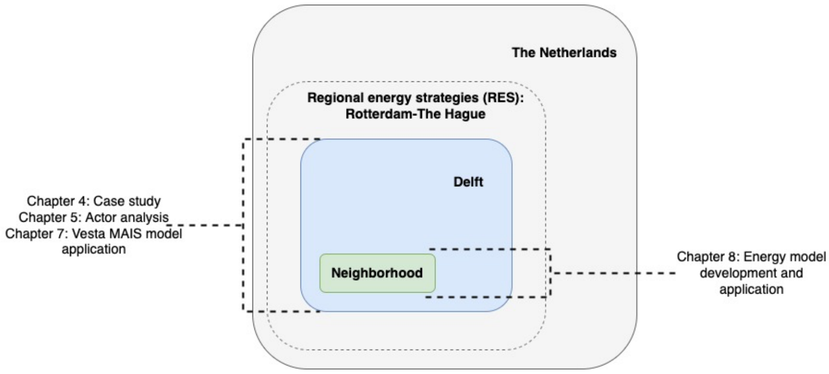



*Figure 3: A visualization of the different research scopes used in this project*

## 2.3 - Research relevance

The relevance of the study is substantiated through the information provided in the introduction chapter. Hence, four arguments contribute to the relevance of this research. The first argument is formed by the increase in GHG emissions and climate change as a result. The main goal of the Paris climate agreement is to reduce global warming to a maximum of 2°C per year and with further efforts to limit this increase to 1.5°C (Dutch Emissions Authority, 2017). Therefore, it is important to reduce GHG emissions. The built environment is responsible for more than 13% of GHG emissions in the Netherlands (Figure 1). This is mainly because most heat is supplied by burning natural gas which is a fossil fuel. The heat transition is intended to counteract the GHG emissions as it is developed to replace thermal energy produced by natural gas-driven heat sources with alternative heat sources (Henrich et al., 2021). This research contributes to the heat transition since it aims to describe a systematic approach that can be used by decision-makers. In this way, a targeted plan of action can be developed to perform the heat transition.

The second argument is formed by the fact that the Netherlands wants to reduce its international dependence on energy sources. This international dependence causes uncertain developments in the availability and price of energy. Tensions with and between exporting countries can cause energy prices to rise to such an extent that not every household or utility owner can afford to buy energy (Scholten et al., 2016). A good example are the current tensions between Ukraine and Russia, which is leading to high gas and fuel prices in the Netherlands. This research contributes to reducing international dependence by providing insights into (local) technical possibilities within the Netherlands to meet the total energy demand.

The third argument is formed by the fact that the Dutch government has decided to phase out the production of natural gas in Groningen. Large-scale public resistances underlie this (NOS, 2018). To continue to meet the total energy demand, it is therefore important to look for alternative energy sources to replace the natural gas driven heat sources in the energy mix. This research contributes to the identification of these technological possibilities and at the same time looks at the impact of these technologies on the existing energy grid. Indeed, in this way it is clear to decision-makers where potential reinforcements are necessary and where certain networks can be phased out.

The final argument is formed by the essence of social inclusion within the heat transition. The introduction showed that it is essential to listen to the different stakeholders. This is because in this way the stakeholders feel heard, and this will contribute to the success of the heat transition (Hoppe & Miedema, 2020; Ministry of Economic Affairs and Climate Policy, 2019). This research contributes to the identification of the different stakeholders and corresponding interests. Moreover, in this project the different stakeholders are categorized to distinguish between interests. In this way, this research contributes as a tool for decision-makers to implement non-rational aspects into existing techno-economic energy models.

## 2.4 – Thesis outline

In this study, ten chapters are used which together should lead to answering the formulated research question and associated (sub-)sub-questions. In Chapter 3, the research methodology is described including the research methods used to answer the individual sub-questions. Chapter 4 describes a case study of the municipality of Delft, describing the current approach used by the municipality to perform the heat transition. Then, in Chapter 5 a comprehensive actor analysis is performed identifying the different actors and corresponding roles. This chapter further investigates to what extent the techno-economic Vesta MAIS model considers social aspects. In Chapter 6, the Vesta MAIS model and the heat transition visions are introduced and in Chapter 7 the model is applied to the municipality of Delft. Based on the application of the Vesta MAIS model, Chapter 8 describes an easy-to-interpret model that can facilitate decision-making within the heat transition. The model should provide insights into possible congestions in the network after electrifying the heat demand. To show the contribution of the model, the model is applied to a single neighborhood within the municipality of Delft. A reflection on the model assumptions, the generalizability of the results, and future research recommendations are provided in Chapter 9. Finally, a conclusion is provided in Chapter 10. The outline of the study is depicted in Figure 4.

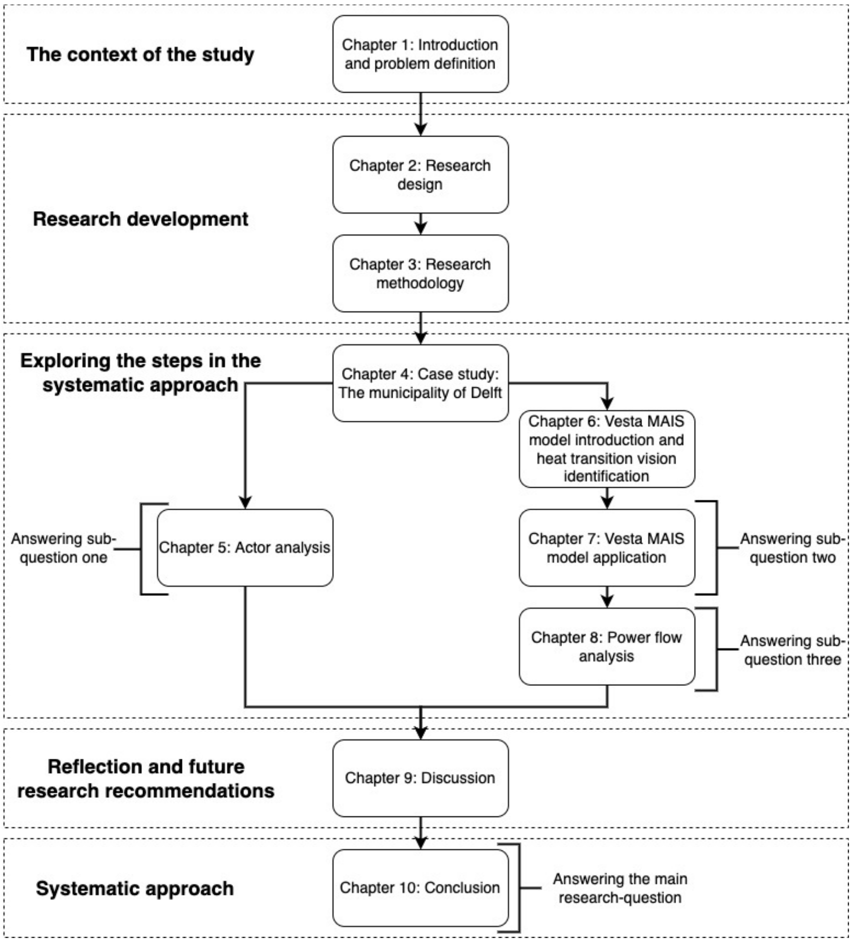



*Figure 4: A visualization of the thesis outline*

# Chapter 3 – Methodology

In this research, a case study in combination with a modelling approach is used. In section 3.1, the choice for these approaches is substantiated. Next, in section 3.2, the research method for each sub-question is described. This is required since not every sub-question can be answered using the same research method. After the description of the research methods, it is described how the results of each sub-question are presented within this study. Finally, a description regarding the validity and reliability of the results is given.

## 3.1 – Research methodology substantiation

This research is conducted using a case study approach in combination with a modeling approach. Because the heat transition is already taking place, a case study can be used to identify possible heat transition visions with associated technological opportunities. In addition, the case study can be used in identifying and categorizing actors. Nevertheless, the integration of the alternative technologies within the energy infrastructure requires new insights into the power grid (Scholten et al., 2016). Therefore, in addition to a case study, a modeling approach is required that can analyze the impact of the heat transition on the energy grid in terms of national costs, energy demand, and network congestion.

The case study approach is used in answering SQ1. This type of approach is used to get an in-depth and multifaceted understanding of the environment within which the heat transition takes place including the actors involved (Crowe et al., 2011). Crowe et al. (2011) argued that a case study approach is an important method to analyze and understand a complex problem in its real-life context. Furthermore, a case study can be used to explain and predict future challenges by being able to describe future events or phenomena within the everyday context (Crowe et al., 2011). However, the case study approach, like all research approaches, also has an important drawback. This drawback is that a case study generally lacks the ability to generalize its results, which leads to criticism (Crowe et al., 2011; Luzeaux, Ruault, & Wippler, 2011). However, there are some ways to increase the generalizability of the results including theoretical sampling and a transparent process. Theoretical sampling involves setting up specific data frameworks that are representative of a specific group of respondents. A transparent process ensures that every external actor can find out how certain choices were made (Crowe et al., 2011). By describing a transparent method used in the case study, it is expected that the method can be reproduced in other cases.

The modeling approach can identify different pathways and technical possibilities that can contribute to the heat transition. This type of approach is particularly useful because it examines the interaction between the complex environment and the embedded transformation process (Moncada et al., 2017). In this way, the modeling approach can help facilitate model-based decision-making. The disadvantage of the modeling approach is that the approach tends to generate generic results based on a limited data set. This can jeopardize the representativeness of the model results (Henrich et al., 2021). However, Henrich et al. (2021) argued that the representativeness of model results can be improved when the model contains considered scenarios as input data. In addition, Henrich et al. (2021) argued the importance of a proper model calibration technique, to be able to make statements about the model outcomes relative to the calibrated model. In this way, the model provides a handle to describe reality.

## 3.2 – Research methods

This research uses three sub-questions whose answers contribute to answering the overall research question. However, each sub-question contains a different research method to achieve the expected results. To provide insights into what results can be generated for each sub-question, ten more sub-sub-questions have been defined. For each sub-sub-question, the research method used is explained. Figure 5 provides a visualization of the integration of the research methods into the ultimate approach used for facilitating decision-making.

### 3.2.1 – Sub-question one

*How could an actor analysis be integrated into an approach aimed at facilitating decision-making at the municipal level within the heat transition?*

The answer to this sub-question will provide a clear overview of all the actors that are involved or affected by the heat transition. In addition, for each actor, the corresponding interests are identified that play a role in the heat transition. The identification of actors will be performed using an actor analysis method. In doing so, it uses the step-by-step actor analysis as described by Enserink et al. (2010). The identification of the actors is determined based on the predefined roles. For each role, it is determined by which actors it is fulfilled. Based on the identification of the relationships between actors and the visualization of the interdependencies, a categorization of actors is made using a power-interest diagram. By using this stakeholder analysis an answer is formed to the sub-sub-questions: *Which actors are affected by the heat transition in Delft?* and *What is the role of each actor within the heat transition in Delft?*

To investigate to what extent the existing techno-economic Vesta MAIS model takes the identified actors into account, a document analysis is performed. Hereby an answer is formed to the sub-sub-question: *To what extent are the identified actors currently integrated into the techno-economic Vesta MAIS model?* This document analysis is used to perform a systematic analysis of the functioning of the model. In doing so, the Functional Design Vesta MAIS 5.0 is used.

### 3.2.2 – Sub-question two

*How could the techno-economic outcomes of the Vesta MAIS model be used to facilitate decision-making at the municipal level?*

Answering this sub-question helps to identify the role of the techno-economic Vesta MAIS model within decision-making in the heat transition. For example, using an application to the municipality of Delft, it becomes clear what outcomes can be generated with the model. The Vesta MAIS model is then used to form an answer to the sub-sub-questions: *What is the most appropriate heat transition vision for the thirteen prioritized neighborhoods within the heat transition in Delft?* and *How does the identified heat transition vision affect the share of the energy carriers within the thirteen prioritized neighborhoods in Delft?* In answering these questions, use is made of a document analysis to identify the heat transition visions and a modelling approach to find for each neighbourhood the most appropriate heat transition vision. The document analysis will be performed using open-source data available by PBL.

After identifying the heat transition visions, the Vesta MAIS model can be used to answer the following sub-sub-questions: *Which neighborhood has the most potential to fully electrify the heat demand in Delft?* and *To what extent does the all-electric strategy cause changes in the share of energy carriers relative to the reference year?* The answer to the third sub-sub-question is used as a case for developing an energy model capable of analyzing the impact of electrification of the heat demand on the existing power grid.

### 3.2.3 – Sub question three

*How could the results of the Vesta MAIS model be used to assess the feasibility of the heat transition in terms of grid congestion?*

This sub-question is used to develop a model capable of analyzing the impact of electrification of the heat demand in the power grid. The input data required are based on the results of the Vesta MAIS model. A description of the added value that the energy model can bring to the existing Vesta MAIS model is described in Figure 5. The model should be able to present easily interpretable results on the impact of the electrification of the heat demand on the power grid so that the model can contribute to improving decision-making. The model will be set up based on a power flow analysis. This type of analysis is considered appropriate because it can determine for different time intervals based on formulated grid configurations whether electricity demand exceeds the capacity of the grid. Comprehensive identification of potential congestion is an important criterion for determining the feasibility of a heat transition vision. Due to a lack of advanced grid data in this study, a fictitious grid is established through a calibration technique using the following sub-sub-question: *What kind of model calibration technique can be used to create a realistic energy grid without advanced data of an existing grid?*

Next, the developed fictitious grid is used as a conventional grid to determine the role of the model in decision-making. In creating the fictitious grid, a neighborhood will be used within the municipality of Delft that has the potential in electrifying its heat demand. Based on this neighborhood, the model shows how it can contribute to improving decision-making by answering the following sub-sub-question: *Where and when can congestion be expected after an all-electric strategy is integrated as a heat transition vision?* The answer to this sub-sub-question is obtained through a modeling approach based on a power flow analysis

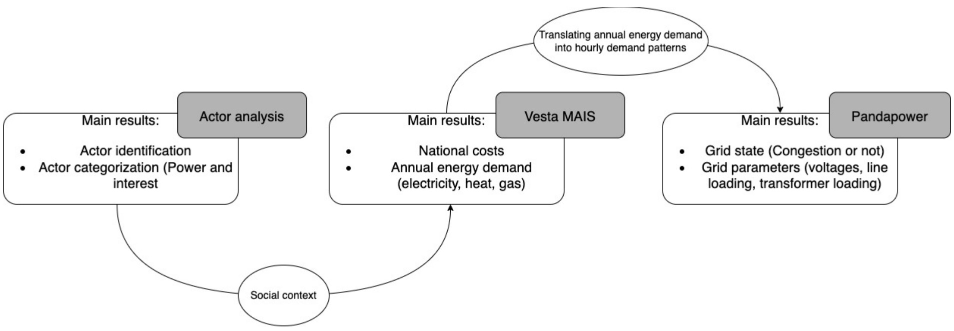



*Figure 5: A visualization of the research methods integrated into the approach for facilitating decision-making in the heat transition*

## 3.3 – Results presentation

This study uses several ways to present the results. The results of the actor analysis are classified according to the actors identified. For each actor, the corresponding role and interests are described within the heat transition. Then all results are described in a table. In this way, the interests of each actor are mapped, and a clear overview is created. Subsequently, the different interrelations between actors are described and visualized into a schematical representation. Finally, the different actors are mapped in a power-interest diagram to identify the interdependencies between the actors. This power-interest diagram helps to categorize the actors in terms of direct and indirect actors (Enserink et al., 2010). After the actor analysis, it will be examined to what extent these actors are incorporated in the Vesta MAIS model.

The results needed to answer sub-question two follows the Vesta MAIS model. This model makes calculations based on energy demand, energy supply, and availability of technologies that lead to an optimization of technological deployment subject to a predefined goal. Tables are used to present the heat transition visions with associated technological alternatives. These tables contain for each heat transition vision the corresponding technological alternatives and the corresponding scenario compositions. The results obtained by means of the Vesta MAIS model are displayed in graphs. For example, pie charts are used to visualize the share of each energy carrier, while bar charts are used to visualize the national costs per heat transition vision and neighborhood.

Finally, sub-question three will be answered using a modelled power grid through a power flow analysis tool. This energy model can determine based on predefined demand patterns whether congestion exists in the power grid. The model generates various results. The results regarding input external power supply, demand patterns and supply inputs are displayed in graphs. The results regarding congestion are displayed in tables. A colour indication is used to show if the model constraints, in this case the network capacity, is exceeded. Finally, the model can describe, based on the defined demand patterns, at which locations congestion can be expected. The model visualizes the used network and indicates by means of a colour indication where congestion will occur.

## 3.4 – Results validity and reliability

This study faces two main challenges that compromise the validity and reliability of the results. These include a lack of advanced data and uncertain technical developments in the future. This section describes these challenges and the impact it has on the validity and reliability of the results.

### 3.4.1- Lack of advanced data

One of the main challenges within this study is obtaining the right data. To analyze the impact of a transition vision on an existing grid through a power flow analysis, it is important to use advanced grid data as input for the analysis. However, this data is in the hands of grid operators making the data not publicly available in the Netherlands. The lack of data has an impact on the validity and reliability of the results because the described method is based on a fictitious grid. Thus, when interpreting the results of this study, it is important to recognize that the study describes a method rather than performing an actual analysis. Finally, the lack of data has meant that the systematic approach described has not been validated. Nevertheless, a few methods to validate the approach are described in section 9.3.

### 3.4.2 – Technical uncertainties

Another uncertainty affecting the results of the research arises from uncertain technical developments in the future. Future technical developments may affect the national costs which is used as a criterion within this study in determining the most appropriate heat transition vision. For example, storage options may reduce the national cost of electrifying heat demand by allowing an energy infrastructure to store excess cheap energy from renewable energy sources (Netbeheer Nederland, 2021; Planbureau voor de Leefomgeving, 2021). In interpreting the national costs, it is important to recognize that the costs were calculated based on the current situation, where energy storage is not commercially feasible. This may change in the future due to new insights and technical developments. In this study the model is used under the assumption that energy is generated based on real-time demand.

# Chapter 4 - Case study: The heat transition in Delft

This research was designed with the goal of describing a systematic approach that can be used by decision-makers to improve decision-making. To describe this approach, the municipality of Delft is used as a case. This municipality is located in the Metropolitan Region of Rotterdam-The Hague and had 104,574 inhabitants on January 1, 2022 (Gemeente Delft, 2022). The municipality of Delft has the objective of heating 20% of the buildings without the use of natural gas by 2030, and by 2050 all buildings must be off natural gas so that no fossil fuels are used in the production of heat. This ambition states that in less than 30 years, the municipality must disconnect approximately 62,000 homes and 15,500 homes equivalents other buildings from natural gas (Delft, 2021). In this context, a home equivalent is equal to one home or 130 $m^2$ of the building area of utility buildings, such as stores, schools, and offices. To carry out this heat transition, the municipality of Delft has drawn up the "Warmteplan" (heat plan), which indicates at the neighborhood level what type of adjustments must be implemented in the coming years. This heat plan contains the heat transition vision of the municipality of Delft.

This chapter begins with an introduction to the "Warmteplan", describing its relationship to international and national goals. Next, the current approach used in Delft for the heat transition is provided, describing the different aspects that contribute to decision-making in the municipality regarding the heat transition. In addition, this chapter describes the technical options available that can replace natural gas-driven heat sources. Finally, based on the selection criteria used, the neighborhoods that have priority within the heat transition in Delft are indicated. Within this research, the case study is used to contextualize the systematic approach.

## 4.1 – "Warmteplan"

The "Warmteplan" has its roots in the Climate Agreement which describes that a district-oriented approach should be used to achieve the heat transition. In this way, each district can make the best use of its local potential, so that the heat transition ultimately leads to the lowest national cost (Henrich et al., 2021). The district-oriented approach means that each municipality will examine district by district which technological alternatives have the greatest potential to replace natural gas-driven heat sources (Koster et al., 2022; Ministry of Economic Affairs and Climate Policy, 2019).

### 4.1.1 – "Warmteplan" in relation to administrative design

The "Warmteplan" drawn up by the municipality of Delft was prepared in collaboration with 22 other municipalities within the Rotterdam-The Hague region (Delft, 2021). This collaboration has led to a Regional Energy Strategy (RES) (Appendix A1). The RES 1.0 describes scenarios for the large-scale generation of renewable electricity using wind turbines and solar panels. This electricity can be used for heating houses and utility buildings that have an electric heat pump at their disposal. The RES was also used to look at the potential for supply and demand of renewable heat in the region. The findings gained were then described in a Regional Structure of Heat (RSW) (Netbeheer Nederland, 2021). The purpose of the RSW is to map municipal visions and plans at the regional level, to gain regional insights into where municipalities want to implement a heat network. In addition, it identifies where potential heat shortages may arise that can be addressed regionally (Delft, 2021).

### 4.1.2 – “Warmteplan” in relation to the SDG

The municipality of Delft has committed to the Global Goals of the Sustainable Development (SDGs) established by the United Nations. This SDG contains seventeen goals that contribute to making the world more sustainable until 2030 (Tolliver et al., 2019). The heat transition vision drawn up by the municipality contributes to SDG7 and SDG9. SDG7 relates to providing affordable and sustainable energy. SDG9 relates to protecting industry and infrastructure and encouraging innovation (Delft, 2021; Tolliver et al., 2019). In addition to the relationship between the heat transition vision and the SDG7 and SDG9, it also affects the SDG3, SDG8, SDG11, and SDG13 (Delft, 2021). The SDG3 emphasizes the importance of good health and well-being, the SDG8 is used for fair work and economic growth for all, the SDG11 emphasizes the importance of sustainable cities and communities, and the SDG13 relates to climate action (Tolliver et al., 2019).

### 4.1.3 – The principles of the “Warmteplan”

The heat transition vision used in Delft is based on eight central principles. The first principle concerns the actor involvement (Delft, 2021). In drawing up the heat transition vision, the municipality is obliged to involve all actors in the choices that are made and which are part of the heat plan (Ministry of Economic Affairs and Climate Policy, 2019). In addition, the municipality is obliged to actively publish all information so that actors can provide valuable input to the formulation of the heat plan based on the same information as is available to the municipality (Delft, 2021). In addition, a clear action perspective is necessary. The essence of “no regret” measures is emphasized here. Throughout the entire process of heat transition, the municipality will be in charge. The municipality itself has the choice of setting up an expert group to ensure that decision-makers have sufficient knowledge and experience at their disposal. This directing role must also ensure the optimal use of local opportunities. Another important principle in the heat plan is that the transition to natural gas-free technologies must not contribute to increasing wealth inequalities within residential areas (Delft, 2021). Thus, the municipality must consider the costs of the transition in the heat plan. After all, the natural gas-free desire must remain affordable for everyone (Scholten et al., 2016). Apart from the affordability of the transition, it is important that the replacement technologies have at least the same reliability and preferably even better (Delft, 2021). In addition, the technologies must contribute to the sustainability targets drawn up at the national level (Delft, 2021; Dutch Emissions Authority, 2017). Finally, any energy measures required for the heat transition must be weighed against other policy objectives (Delft, 2021).

## 4.2 – Current approach used in Delft for the energy transition

In the municipality of Delft, surveys and energy models are used to guide an energy transition. The energy models are used to assess the feasibility of a transition pathway in terms of grid congestion while the surveys are used to enrich the energy model with non-rational aspects to gain insight into the feasibility in terms of social aspects. However, since the municipality did not have sufficient knowledge and data to assess the impact of a transition pathway on the energy grid, it seeks advice from Stedin, the grid operator in Delft (Delft, 2021; Henrich et al., 2021). This corporation is important because the grid operator can provide the municipality with information regarding grid data, such as grid capacities and line coordinates. Besides, the municipality can make use of the expertise and knowledge of a grid operator. This is important since the energy models are complex to use. This complexity arises because the models must be able to simulate the complex environment in which the energy transition takes place (Pfenninger et al., 2014).

To map the social aspects, the municipality of Delft uses participation factors that contribute to the realization of the “Warmteplan”. These participation factors are an important criterion for determining the social support for the heat transition (Delft, 2021). The target group used in determining the participation factors are residents and businesses within the municipality. The participation factors used in Delft are (1) affordability and costs, (2) uncertainties about technological alternatives to natural gas, (3) importance of reliable information, (4) feasibility, and (5) integral approach (Delft, 2021). The results of the surveys are provided in Appendix B1 and showed that just under half of the surveyed residents in the municipality of Delft think that the heat transition should at least lead to the achievement of the national sustainability targets. A small proportion of this group even thinks that Delft should be a frontrunner in the heat transition. Only 8% of the inhabitants do not see the essence of the heat transition and therefore want to continue using natural gas-driven heat technologies. In addition, 30% of respondents feel that the objectives of the heat transition are unrealistic and therefore not feasible (Delft, 2021).

### 4.2.1 – Affordability and costs

The research carried out by the municipality of Delft has shown that affordability and costs are the most important factors influencing the perception of actors (Delft, 2021). For example, most respondents indicated that natural gas should continue to be used as long as no cheap alternative technologies are available. Furthermore, 32% of the respondents indicated that a natural gas-free heat portfolio is only acceptable when the monthly costs remain roughly the same. In addition, 7% of the respondents find a natural gas-free heat portfolio acceptable when loans are provided with favorable conditions, while 20% of the respondents find a heat transition only acceptable when subsidies are set up that reduce the cost of measures (Delft, 2021) (Appendix B2).

### 4.2.2 – Uncertainties about technological alternatives to natural gas

Another important aspect of improving the attitude of actors toward the heat transition is to reduce the uncertainties regarding technological alternatives to natural gas (Delft, 2021). As will be shown later in this study, several technological options can replace natural gas-driven heat sources. However, for the respondents, there are several uncertainties. For example, many respondents wonder whether hydrogen could be the alternative to natural gas and what impact this would have on the existing energy grid. Uncertainties also arise because Germany, for example, is increasing the share of natural gas in its energy portfolio, while the Netherlands wants to move away from natural gas. In addition, consumers within the municipality often indicate that they are waiting until most uncertainties have been removed before taking measures. For instance, 16% of the respondents indicated that they find a natural gas-free heat portfolio acceptable when major technological uncertainties have been reduced and only minor adjustments are needed in the homes (Delft, 2021) (Appendix B2).

### 4.2.3 - Importance of reliable information

In addition to affordability and cost, having reliable information plays an important role in improving actors' attitudes towards the heat transition (Delft, 2021). For example, 22% of respondents indicated that a natural gas-free heat portfolio would not be accepted if they get the feeling that the information is not equally distributed among the actors (Appendix B2).
When actors feel that information is not equally distributed, this will lead to a negative attitude towards the heat transition. This will, for instance, result in actors postponing insulation measures (Delft, 2021).

### 4.2.4 – Feasibility

The feasibility of the heat transition also plays an important role in actors' attitudes toward the heat transition. Various discussions between the municipality of Delft and actors have shown that mainly owners of old houses or monuments do not always see the feasibility of the heat transition in a positive light. These buildings are often poorly insulated, making many technological alternatives unsuitable for replacing natural gas. It has also emerged that, besides owners of older buildings, older inhabitants do not always see the feasibility of the heat transition in a positive light (Delft, 2021).

### 4.2.5 – Integral approach

Finally, it has been shown that an integrated approach to the heat transition can help promote social attitudes. Here, actors emphasized that the heat transition should not only lead to improving sustainability within the municipality but that the transition also improves the quality of the living environment (Ministry of Economic Affairs and Climate Policy, 2019). In addition, the municipality should not only focus on the residential neighborhoods that are first in the line for the heat transition but there should also be a focus on neighborhoods that are later in line. Consumers within these neighborhoods can already take measures in, for example, improving the insulation in the house to ensure that $CO_2$ emissions are reduced. In this way, other neighborhoods can facilitate the future heat transition and reduce energy poverty within the municipality (Delft, 2021).

## 4.3 – Available heat technologies and (future) alternatives in Delft

In Delft, the total heat demand in the built environment was 2,768 TJ in 2021. About 1,854 TJ is used to heat households, while 914 TJ is used by utility buildings (Delft, 2021). Most heat sources used in Delft are based on the combustion of natural gas (Gemeente Delft, 2022). For example, in 2019, 72,800,000 $m^3$ of natural gas was used for the total heat demand leading to 144 ktons annual $CO_2$ emissions (Delft, 2021). However, there have already been (small-scale) developments integrated into the energy grid in Delft. These developments have led to 6.9% of the buildings being connected to a district heat network (Delft, 2021). Table 2 shows per neighborhood the proportion of buildings that are currently connected to a heat grid. Although most of these heat networks are heated with natural gas, two networks are entirely heated with sustainable sources. These networks are located in Hoornse Hof and Den Hoorn and are supplied by the sewage treatment plant Harnaschpolder (Delft, 2021).

*Table 2: The current share of buildings connected to a heat network per neighborhood (Delft, 2021)*

| ***Neighborhood*** | ***Share of buildings connected to a heat network*** |
|---|---|
| *Heilige Land* | 5% |
| *Hoornse Hof* | 30% |
| *Den Hoorn* | 84% |
| *Business park Ypenburgsepoort* | 100% |
| *Poptahof-Noord* | 57% |
| *Poptahof-Zuid* | 40% |
| *Voorhof-Hoogbouw* | 41% |
| *Multatulibuurt* | 43% |
| *Juniusbuurt* | 38% |
| *TU-Noord* | 59% |
| *TU-Campus* | 39% |

### 4.3.1 – Determining technical opportunities per neighborhood

For each neighborhood within the municipality of Delft, several technological alternatives are possible to replace natural gas-driven heat sources. In neighborhoods where households and utility buildings are far apart, the construction of a heat network can become very expensive, making this option unlikely. In neighborhoods where there is still much work to be done to insulate buildings, an electric heat pump is more likely (Delft, 2021). In determining the most appropriate technological alternatives, the lowest national cost is used as the starting point. These national costs include all costs of all measures needed to switch to natural gas-free heating in a neighborhood, regardless of who pays the costs (Delft, 2021; Ministry of Economic Affairs and Climate Policy, 2019; Planbureau voor de Leefomgeving, 2021). The national cost consists of a combination of investments and annual costs, including energy and maintenance costs (Planbureau voor de Leefomgeving, 2021). Using the lowest possible national cost in identifying the most appropriate technological alternatives ensures that the cost to society as a whole is the lowest (Delft, 2021). However, the lowest national cost does not necessarily lead to the lowest cost for the end-user (Planbureau voor de Leefomgeving, 2021).

Besides the lowest national cost, some other aspects influence the suitability of technological alternatives within the municipality of Delft. These aspects include space in the subsurface, space in the building, and noise pollution (Delft, 2021). Any reinforcement in the energy grid will affect the surrounding cables and pipes. If, for example, the drinking water network heats up to more than 25℃ as a result of an electricity cable, there is a risk of legionella (Delft, 2021). To prevent this, agreements have been made about the insulation level of heat pipes and the minimum distance of a heat pipe from a water pipe. This can make a technological alternative more expensive when the insulation of pipelines needs to be improved. Furthermore, for some neighborhoods, it is not possible to integrate a heat network due to a lack of space in the subsurface. These are mainly older neighborhoods located in the inner city of Delft (Delft, 2021).

Another aspect that influences the technological alternatives is the availability of a gas network. Because buildings in new neighborhoods will not have access to a gas network after 2020, any technological alternative that uses a gas network will be discarded. It is therefore not possible for these neighborhoods to use green gas, for example (Delft, 2021).

## 4.4 – Neighborhood selection criteria

To achieve the heat transition in Delft, the most suitable technological alternatives to establish a natural gas-free heat portfolio are being examined per neighborhood. However, the municipality has decided to apply prioritization so that not every neighborhood undergoes the heat transition at the same time. The municipality uses different criteria which are then provided with a weighting. In this way, the municipality determines which neighborhoods will be the first to undergo the heat transition. The neighborhoods that receive the highest score on the criteria are considered the most likely to undergo a successful heat transition. In Delft, the criteria consist of (1) affordability, (2) $CO_2$ reduction, (3) robustness, (4) feasibility, (5) neighborhood initiatives, (6) “meekoppelkansen”, and (7) contractibility (Delft, 2021).

### 4.4.1 – Affordability

One of the aspects that play an important role in the heat plan of the municipality of Delft is, as previously shown, the affordability criteria. Neighborhoods that feature the lowest national costs for the heat transition are expected to succeed the transition in the short term (Delft, 2021). Within the affordability criteria, the municipality of Delft distinguishes between national costs and end-user costs. The national costs are described in 4.3.1. The end-user costs are all the costs paid by the end-user for the switch to a natural gas-free heat portfolio. This implies that end-user costs consist of the necessary investments, ongoing costs, and taxes associated with a specific heat transition vision (Delft, 2021). These investments consist of grid modifications, building modifications, and the implementation of heat technologies. The ongoing costs consist of energy costs gas, heat, and electricity. Taxes consist of VAT and taxes on gas and electricity prices (Zach, Kretschmer, & Stoeglehner, 2019). Part of the end-user costs can be covered by the available subsidies. These include the ISDE subsidy for heat pumps, boilers, insulation, solar panels, and wind turbines (Delft, 2021). The costs of these subsidies do not fall under the end-user costs but under the national costs. The calculation of the end-user costs assumes owner-occupiers. When it comes to rental properties, the costs are divided into the costs for housing corporations or private landlords on the one hand and the tenant on the other. The tenant pays the monthly energy bill, while the landlord bears the bulk of the investment and maintenance costs (Delft, 2021).

### 4.4.2 – $CO_2$ reduction

The municipality of Delft gives priority to neighborhoods where the most $CO_2$ can be reduced as a result of the heat transition. It looks at the cumulative $CO_2$ reduction per building in the time frame of 2030-2050. The assumption is that by 2030 a home will have completely switched to a natural gas-free heat source (Delft, 2021).

### 4.4.3 – Robustness

The robustness criteria used by the municipality of Delft in prioritizing neighborhoods for heat transition relate to reducing the uncertainty associated with future technological developments. If a neighborhood has access to an alternative heat source that clearly features the lowest national cost, this provides certainty for the choice of this alternative. The choice of this technological alternative is then seen as robust in that the certainty of the right choice is maximized (Delft, 2021).

### 4.4.4 – Feasibility

The heat plan drawn up by the municipality of Delft must be achievable in the short term. Neighborhoods, where the most favorable technological alternative involves renewable gas, cannot be addressed in the short term. This is because it is assumed that green gas and hydrogen will not be commercially and technologically available on a large scale before 2030. Moreover, the future availability and prices of these gases are highly uncertain. Neighborhoods, where renewable gases are seen as an alternative with the greatest potential, are therefore given a lower priority (Delft, 2021).

### 4.4.5 – Initiatives and neighborhood improvement

The municipality of Delft gives a higher priority to neighborhoods where local heat transition projects are already being implemented. These local projects are seen as the “flywheel” of the heat transition (Delft, 2021). There are various projects in Delft, including the Open Heat Grid Delft, geothermal energy at TU Delft, and the energy initiative Bedrijvenkring Schieoevers (Delft, 2021). In addition, some ongoing developments have a major impact on the heat plan of the municipality of Delft. These are projects of the Open Warmtenet Delft (OWD), the construction of Warmte-linQ, and the construction of the source Geothermie Delft (GTD). The OWD is being developed by Netverder in collaboration with four major Delft housing associations. This project initially focused on the high-rise buildings and corporations in the Voorhof and Buitenhof neighborhoods. However, due to reinforcements that were later applied to the heat network, all 15,000 homes in Voorhof and Buitenhof have access to this heat network (Delft, 2021). The OWD is supplied with heat by WarmtelinQ and a geothermal source. The WarmtelinQ transports residual heat from the Rotterdam harbor area to The Hague and Leiden and runs through Delft (Platform energietransitie Delft, 2022). However, this heat network is not yet in operation. Finally, for more than ten years there has been an attempt to implement a geothermal well near the TU Delft since the underground is suitable for it. The project is led by a collaboration between TU Delft, Engie, Shell, and EBN (Delft, 2021; Platform energietransitie Delft, 2022). However, obtaining the proper permits, subsidies, and financing has stalled the process (Delft, 2021).

#### 4.4.6 – "Meekoppelkansen"

When prioritizing neighborhoods, the municipality also looks at "Meekoppelkansen" (co-opting opportunities). This means that the municipality gives priority to neighborhoods where large-scale maintenance is planned for the energy network. This gives room to implement any changes immediately to reduce the investment costs of a particular heat transition vision (Delft, 2021).

#### 4.4.7 – Contractibility

The contractibility of different residential neighborhoods also plays a role in prioritizing neighborhoods. When a neighborhood has many property owners, contracting heat demand becomes more complex. This is because the municipality has to deal with many different actors making it more challenging to consider all interests. When a neighborhood consists of fewer actors, this promotes contracting. Neighborhoods with a high contractibility are therefore provided with a higher prioritization because these neighborhoods have a higher chance of completing the heat transition in the short term. Similarly, a high proportion of private rent can be a barrier in the negotiations necessary to form a shared vision in the heat transition vision (Delft, 2021).

### 4.5 – Neighborhood selection

Using the above criteria, it was then determined which neighborhoods are first in starting the heat transition. The criteria are not all equally important, so each criterion is given a certain weighting. This weighting was determined by the municipality as a result of several rounds of discussions with actors and are presented in Appendix C1 (Delft, 2021). The end-user costs are attached with the highest weighting. In addition, "connecting to energy initiatives" is given a high weighting because the energy transition is already underway in these places (Delft, 2021).

Based on the criteria and weightings, the municipality of Delft then selected thirteen neighborhoods that will be the provisional first to go through the heat transition. These neighborhoods collectively have the highest score and possess 20% housing equivalents. The following neighborhoods will be the first to start the heat transition: Het Rode Dorp, Gillisbuurt, Aart van der Leeuwbuurt, Juniusbuurt, Fledderusbuurt, Buitenhof-Noord, Mythologiebuurt, TU-Noord, Roland Holstbuurt, Reinier de Graafbuurt, Kuyperwijk-Zuid, Multatulibuurt and TU Campus (Delft, 2021). The order of the neighborhoods has not yet been determined.

# Chapter 5 – Actor analysis applied to the municipality of Delft

In this chapter, an answer to sub-question one will be formed. To answer this sub-question, an analysis tool will be used to identify the different actors involved in the heat transition within the municipality of Delft. The goal of this chapter is to answer the following sub-question:

*How could an actor analysis be integrated into an approach aimed at facilitating decision-making at the municipal level within the heat transition?*

## 5.1 – Actor analysis in relation to the heat transition

To answer this sub-question a step-by-step actor analysis will be performed. This type of analysis provides a clear overview of the various actors who are affected by the heat transition (Burandt, Gralla, & John, 2015). This actor analysis is extremely valuable as it supports policymakers in developing policy guidelines (Enserink et al., 2010). Moreover, an actor analysis can contribute to the assessment of alternative transition pathways by the municipality. This is because an actor analysis maps the perceptions, motivations, and competencies of all actors with regard to a specific alternative (Brugha & Varvasovszky, 2000; Enserink et al., 2010). The heat transition is seen as a complex challenge in which various actors interact with each other, but also with the various technical aspects (Henrich et al., 2021). An advanced actor analysis can contribute to easing the heat transition process, by providing decision-makers with a clear picture of the aspects that are important when drawing up a shared vision (Henrich et al., 2021). These important aspects can, subsequently, be used to assess the feasibility of transition pathways. The case study has already shown that the municipality of Delft is aware of the importance of integrating different actors in decision-making. For instance, the municipality used different consultation rounds where different actors could share their wishes with the municipality. This has led to the weightings attached to the different criteria.

## 5.2 – An overview of actor analysis methods

Several methods can be distinguished when conducting an actor analysis. These methods are (1) network analysis, (2) stakeholder analysis, (3) game-theoretic models, (4) transactional analysis, (5) discourse analysis, (6) cognitive mapping, and (7) preference elicitation (Enserink et al., 2010). Social network analysis is an example of a network analysis, where the focus is on the structural characteristics of actor networks (Sozen, 2009). The stakeholder analysis aims to maximize the cooperative potential of stakeholders within the environment while minimizing the threat of obstruction (Enserink et al., 2010). The game-theoretical models consist of metagame analysis, which focuses on simulating actor interactions to recommend policy strategies for negotiation and coalition building, and hyper game analysis, which focuses on the role of (mis)information and strategic surprises (Enserink et al., 2010; Schlange, 1995). The transactional analysis consists of transaction process models and vote-exchange models. The first type focuses on the potential of the exchange of control between actors to contribute to the facilitation of policy procedures, while the second type focuses on the prediction of changes in positions and collective decision-making (Enserink et al., 2010). The discourse analysis consists of argumentative analysis, narrative policy analysis, and Q-methodology (Enserink et al., 2010; Jacobs, 2006). The argumentative analysis focuses on the different chains of argumentation used in policy debates, while the narrative policy analysis focuses on identifying conflicting views and possibilities for reformulating the problem. The Q-methodology focuses on actors with shared perceptions (Enserink et al., 2010). The cognitive mapping methodology consists of self-Q interviews, which focus on opportunities to address policy problems based on actor rationales, and Dynamic Actor-Network Analysis (DANA), which focuses on comparative analysis of agreement and conflict (Damart, 2010; Enserink et al., 2010). Finally, the preference elicitation method consists of an analytic hierarchy process in which the hierarchy and structure of different attributes and alternatives play an important role (Enserink et al., 2010).

## 5.4 – Actor analysis: Case study application to the municipality of Delft.

In this study, the choice was made to use a stakeholder analysis, because this type of analysis is easy to use and is capable of being applied in a wide range of situations. In addition, this method can operate in a wide range of conceptual dimensions (Enserink et al., 2010). However, in many situations, it is necessary to perform an actor analysis that goes beyond just identifying and categorizing actors. In this case, it is recommended to carry out, for example, network analysis or a method that can map the perceptions of actors (Damart, 2010; Enserink et al., 2010).

In conducting the stakeholder analysis, the method of Enserink et al. (2010) is used. This method is based on the guidelines for conducting a stakeholder analysis as described in the literature. The method describes a comprehensive analysis based on six steps including (1) formulating the problem, (2) identifying the actors, (3) visualizing the formal relationships between actors, (4) determining the interests and objectives for each actor, (5) visualizing the interdependencies between actors, and (6) interpreting the results in the context of the formulated problem (Enserink et al., 2010). The formulation of the problem, as proposed in step one of the actor analyses, is already provided in Chapter 1. Based on the problem identification in the introduction, an actor identification process will be performed. After the actor identification, the formal relationships between actors are visualized. In section 5.3.4, the different interests and objectives are identified that correspond to each type of actor. After the identification of the interests and objectives, the different interdependencies are described based on a power-interest diagram.

### 5.4.1 – Actor identification

The second step of the actor analysis described by Enserink et al. (2010) is to identify the actors that influence the formulated problem. This step can be used to answer the sub-sub-question *Which actors are affected by the heat transition in Delft?* In answering this sub-sub-question, the main focus is on actors that have a direct relationship with the decisions and outcomes of the heat transition in Delft.

Performing an actor identification is an iterative process because the identification of new actors leads to new interactions with other actors (Enserink et al., 2010). In identifying the actors, this study uses the various roles that can be distinguished within the heat transition. Then, for each role, it will be investigated by which actor it is performed. Within the actor identification, a distinction is made between direct actors and indirect actors. The direct actors have a direct relationship with the problem formulated in Chapter 1. This implies that the objective of the actor is directly related to one of the goals of the heat transition as provided in section 2.3. The indirect actors, on the other hand, are characterized by an indirect relationship with the problem as formulated in Chapter 1. This type of actor is linked to the formulated problem through interaction with direct actors. Therefore, indirect actors do not directly influence the formulated problem and, at the same time, changes within the formulated problem have no direct influence on the indirect actors (Sung & Park, 2018). In this project, the only indirect actors considered are the countries that signed the Paris climate agreement since the focus is on direct actors.

The results of the actor identification related to the municipality of Delft are shown in Figure 6. Four roles are used for identifying the actors, including regulating parties, end-users, operational parties, and energy suppliers. The municipality of Delft, the province, and the national government are the regulating parties and are responsible for setting up the policy guidelines that relate to structuring the transition process as well as structuring the interactions between actors, technologies, laws and regulations (Delft, 2021). The end-users consist of all consumers existing of both private end-users and business-related parties and are comprised of housing corporations, real estate owners (households and utility owners), and neighborhood initiatives. The investors and banks, installation companies, project developers, and research institutes are operational parties and are responsible for the operations, installations, and financial support mechanisms. Finally, the energy suppliers are responsible for the contracting, transporting, and production of energy and are comprised of grid operators, energy providers, energy cooperation's, and heat source owners. The reasoning behind the actor identification can be found in Appendix D1.

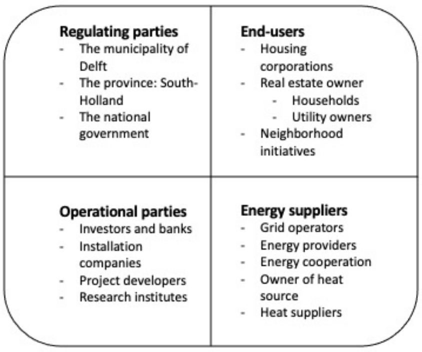



*Figure 6: A schematical representation of the different actor types involved in the heat transition*

### 5.4.2 - Visualizing the formal relationships between actors

The identified actors have different relationships with each other, as shown in Figure 7. In determining the formal relations between the identified actors, the following sub-sub-question will be answered: *What is the role of each actor within the heat transition in Delft?* In this section, each individual role is described relative to the other actors.

First of all, the municipality is assumed "problem owner". The municipality is responsible for setting up the heat transition vision. This vision is based on the national climate agreement developed by the national government which are in turn based on the Paris climate agreement (Rose et al., 2017; Skjærseth et al., 2021; Tolliver et al., 2019). The province sets several additional requirements for objectives to ensure the protection of people and the ecosystem (Tolliver et al., 2019). Furthermore, the municipality is advised by research institutes and grid operators about the availability and feasibility of technological alternatives (Diran et al., 2020). The installation companies can also provide overviews of what types of technological alternatives are possible. These companies are selected by the municipality through tendering procedures (Ministry of Economic Affairs and Climate Policy, 2019; Scholten et al., 2016). The capital required to make the necessary investments are provided by private investors or banks (Ministry of Economic Affairs and Climate Policy, 2019). From all the input streams depicted in Figure 7, the heat transition vision is drawn up. This heat transition vision is then applied to the various neighborhood initiatives, real-estate owners, and housing corporations within the municipality of Delft.

The project developers are chosen through a tendering procedure (Hoppe & Miedema, 2020). Once a project developer has been awarded the contract, they are advised by various research institutes on the technological possibilities (Diran et al., 2020). In addition, energy cooperation advises on how to increase the share of renewable energy sources in the energy mix (Hadush & Meeus, 2018). The project developer also works closely with the grid operator, who is expected to share advanced grid data. In this way, the project developer can assess the feasibility of the envisaged scenarios based on technical aspects. The project developer in turn provides clear overviews to the grid operator indicating required adjustments or reinforcements in the grid. Once the feasibility of an intended scenario has been assessed, an order is sent out to the installation companies. These are the companies that must integrate the alternative technologies with surrounding technologies (Koster et al., 2022).

To carry out the heat transition, it is important that the grid operator can make the appropriate adjustments and reinforcements to the existing network. The grid operator is responsible for balancing and maintaining the grid to ensure a stable supply (Green & Staffell, 2016; Scholten et al., 2016). Balancing is being provided by contracting different technological capacities to ensure a sufficient level of capacity output for any time (Scholten et al., 2016). In addition, the grid operator can provide permits to energy companies to set up contracts for end-users. The energy price within these contracts is based on the operational costs of the different technologies required to meet the total energy demand of end-users (Hosseini, Allahham, & Adams, 2021; Koster et al., 2022).

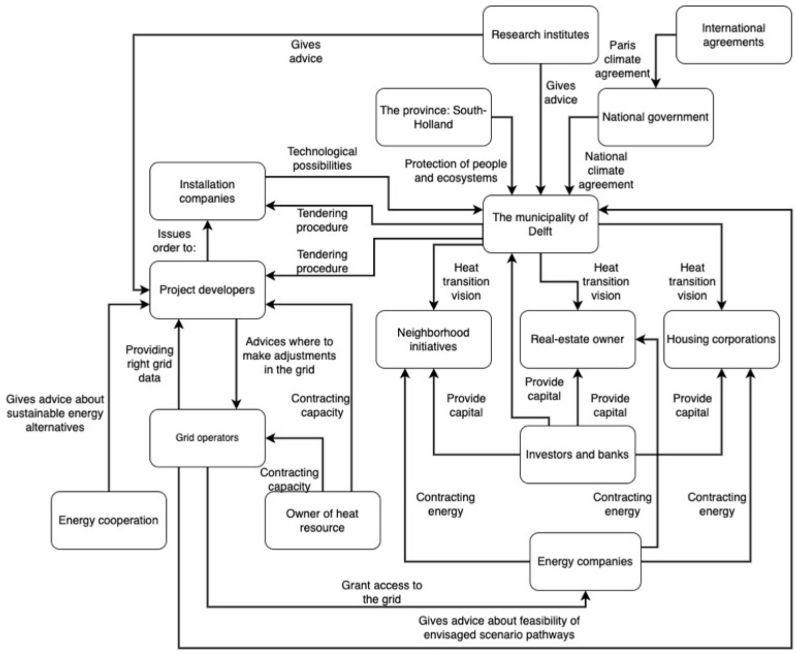



*Figure 7: A schematical representation of the formal relationships between the identified actors*

### 5.4.3 – Identifying interests and objectives

The identification of interests and objectives is intended to contribute to answering the following sub-sub-question: *What objectives can be identified that can be used to rank the actors based on the level of interest aiming to categorize the actors within decision-making in the heat transition in Delft?* This question was drafted with the underlying idea that not every actor has equal influence on decision-making. To make a ranking, the interests and objectives are first identified. Then, based on this identification, a power-interest diagram is created. This is described in section 5.3.4

The actor analysis prepared by Enserink et al. (2010) distinguishes between objectives and interests. The objectives are used to identify what a specific actor wants to achieve in a specific situation, what changes should be made, and what should remain (Enserink et al., 2010). Each actor has its objectives that must be clearly formulated to be part of the decision-making process. In this way, the objectives form a way of measuring to what extent the interests of an actor have been considered in the decision-making process (Enserink et al., 2010). An actor usually has several objectives, while not every objective is directly related to the formulated problem (Enserink et al., 2010; Scholten et al., 2016). In this study, a distinction is made between strategic objectives and problem-specific objectives. The strategic objective can be seen as the objective that an actor would have had if the problem had not existed. This type of objective is relatively stable and does not change during the project (Enserink et al., 2010). The problem-specific objective is embedded in the context of the formulated problem. These objectives often vary between actors, which can lead to contradictions (Wagner, 2016). When the problem-specific objective is directly related to the strategic objective of an actor, the interest of an actor can be assessed as "high" (Enserink et al., 2010). The interests contain all aspects that are most important to an actor and provide a clear direction. Interests are relatively stable but not directly linked to a concrete problem situation. Identifying the interests of an actor helps to assess to what extent certain objectives and solutions are acceptable for an actor involved (Enserink et al., 2010)

The identification of the objectives and interests for each individual group of actors is provided in Appendix D2. The results show that the municipality of Delft, national government, real estate owner, neighborhood initiatives, project developers, research institutes, grid operators, energy providers, energy cooperation, and the owner of the heat source have a high interest in the heat transition. This is because these actors have a strategic objective that corresponds to the problem-specific objectives (See Appendix D2). This criterion has also led to housing corporations and installation companies having a medium interest and the province, and investors and banks having a low interest in the heat transition.

### 5.4.4 - Visualizing the interdependencies between actors

Visualizing the interdependencies belong to the fifth step of the actor analysis of Enserink et al. (2010). Identifying the interdependencies between actors contribute to ranking actors and is based on the identified objectives and interests. The ranking of actors is done by means of a power-interest matrix. Enserink et al. (2010) argue that this type of matrix can provide a quick and useful illustration of important patterns of actors within the problem owner's actor environment. The matrix distinguishes between the power and interest level of a specific actor and can only be used to provide a relative classification of actors. This means that the placement of each actor within the power-interest diagram is an estimate rather than an exact classification. Within the matrix, an actor has high power when it can influence decisions within the formulated problem of the problem owner. On the other hand, an actor has low power when it is not able to (directly) influence decisions (Enserink et al., 2010). The interest levels are defined in 5.3.3 and state that an actor has a high interest when the impact of the ultimate agreement directly affects the behavior of that actor.

Furthermore, the power-interest matrix distinguishes the degree of involvement of the type of actor in the decision-making. Within the matrix a distinction is made between keep satisfied, manage closely, monitor, and keep informed (Enserink et al., 2010). When an actor is in the area of high power and low interest it is important not to involve the actor too much in the decision-making, but the general desires of the actor should be satisfied in the ultimate agreement (Enserink et al., 2010). If an actor has both low interest and low power, then the actor is not directly involved in decision-making. This does not mean that these actors can be ignored because these actors do have (in)direct influence on the formulated problem (Enserink et al., 2010). An actor that has a high interest, but low power must continue to be informed. These actors have little influence on decision-making but are directly influenced by decisions taken within the formulated problem. If an actor has both high power and high interest, then these actors must be closely involved in the decision-making process. These parties have a direct influence on decisions that are taken within the formulated problem (Enserink et al., 2010).

The power-interest matrix is provided in Figure 8 and showed that the national government, municipality of Delft, research institutes, project developers, owner of heat resource, grid operators, and energy cooperation are in the "manage closely" box. These actors have a high interest and power. The energy providers, neighborhood initiatives, real-estate owner, and owner of heat resource have less power in the decision-making in the heat transition. These actors are therefore classified in the "keep informed" box. The investors and banks and the province are classified in the "keep satisfied" box because this group does not have a (direct) interest in the heat transition. However, these actors do have a high power. Based on the results, the installation companies and housing corporations cannot be placed into one single box. The installation companies are situated between the "manage closely" box and the "keep satisfied" box, while the housing corporations are situated between the "keep informed" and "monitor" box.

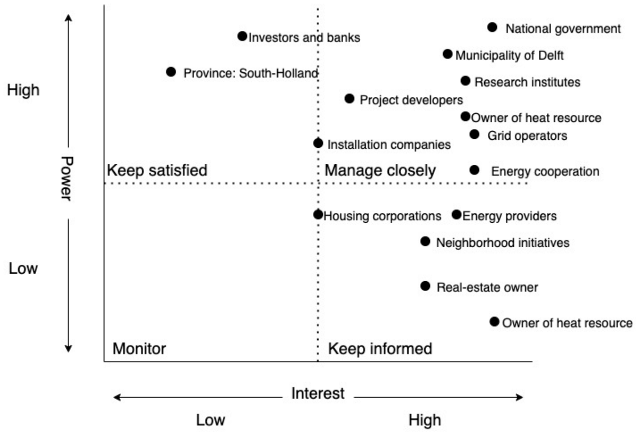



*Figure 8: A visualization of the power-interest diagram*

## 5.5 – Vesta MAIS model introduction

To explain the role of the actor analysis within the Vesta MAIS model, it is necessary to treat the model in more detail. The Vesta MAIS model is developed by PBL and can be used by municipalities to analyze the impact of the heat transition vision in terms of energy demand and national costs. There are two versions of this techno-economic Vesta MAIS model. Both models are suitable to be used to analyze the future impact of heat transition visions on the energy grid. However, the models differ in the scope of interest, assessment criteria, and some assumptions. In this section, first, a short introduction is given about both models, and then the differences are pointed out. The introduction of both models is based on the information provided in "Functioneel Ontwerp Vesta MAIS 5.0".

### 5.5.1 – Vesta MAIS default model

The Vesta MAIS default model provides a basic analysis tool that is intended to provide a spatial energy model indicating the share of each energy carrier (gas, electricity, or heat) and corresponding $CO_2$ emissions given a particular heat transition vision (Planbureau voor de Leefomgeving, 2021). In doing so, the model uses the technological alternatives that are part of a certain transition vision and assumes that a municipality will continue to follow this vision until 2050. The Vesta MAIS default model contributes to the exploration of technological alternatives for natural gas-free heating within the built environment with a focus on various environmental factors. These environmental factors already include (local) policy, the development of energy prices, and other factors (PBL, 2022). All the calculations performed in the default model are aiming at minimizing the national and individual costs (Planbureau voor de Leefomgeving, 2021).

The Vesta MAIS default model can be applied to the built environment, including houses, offices, stores, and hospitals. The model is based on three input aspects, including the year of construction, the degree of insulation, and the type of utilization of the building. In the model it is assumed that older buildings are equipped with poorer insulation compared to newer buildings. The degree of insulation is represented in scales. These “Schillables” are labeled A through G, where buildings with an A label are the best insulated and buildings with a G label the worst (Planbureau voor de Leefomgeving, 2021). Furthermore, the model assumes that office buildings have a higher consumption of energy during the day than in the morning and evening (Henrich et al., 2021). The default model also assumes that the total heat demand is fully covered by the combustion of natural gas in the conventional situation (Planbureau voor de Leefomgeving, 2021). This implies that the model does not consider the existence of a heat grid during its calculations. Finally, the results of the model are translated into a spatial energy model indicating the share of gas, heat, and electricity.

The ultimate spatial energy model created by the default model can be used to facilitate decision-making in three different ways. First, it can support owners of a heating technology to decide whether the proposed vision allows for a profitable business case. For instance, the results can be used for a cost-benefit analysis to examine whether the share of a particular technology is sufficient to cover the operational costs. Second, the results can facilitate the decision of a real-estate owner to improve the insulation of a building. The model provides the costs of an insulation improvement given a heat transition vision. When a negative business case is created, the model assumes that the real-estate owner will not invest in insulation improvements. Finally, the model can be used to support the decisions of project developers and grid operators by calculating the potential of area modifications. For example, it examines the potential of an underground heat network or heat storage opportunities (Planbureau voor de Leefomgeving, 2021).

Profitability is at the heart of all the model’s calculations. Here, the heat transition vision with the highest profitability is favored over other visions given a specific neighborhood. To calculate profitability, the model uses the payback time of the investment and the interest rate. The payback time is used to determine how long it will take for the investor to recoup its investment. To determine if an investment generates a profitable business case, the model compares the interest rate with the profitability (Planbureau voor de Leefomgeving, 2021).

### 5.5.2 – Vesta Leidraad

The Vesta Leidraad is based on the “Startanalyse” and the “Handreiking” as revealed in section 1.3.1. This model uses five different strategies consisting of different technological alternatives. The Leidraad is designed to investigate the best technological alternative to replace the conventional natural gas-driven heat sources (Netbeheer Nederland, 2021; Planbureau voor de Leefomgeving, 2021). The premise that the model uses in this regard is to minimize the national costs per neighborhood and technology alternative. The definition of national costs is given in section 4.3.1. The national costs do not provide insights into which costs are borne by which individual, but the model distinguishes different actors to relate the associated investment costs. Thus, costs are identified for the end-user, grid operator, project developer, and resource owner. Indirectly, these costs are passed on to the other identified actors. Because the model uses national costs, no insights are provided into possible taxes, subsidies, and other financial tools. This is because net cost of these financial mechanisms is zero, as the bill is paid between actors (Planbureau voor de Leefomgeving, 2021).

The Vesta Leidraad uses the heat transition visions to determine the best heat transition vision for a specific neighborhood. In doing so, the model uses the national cost. The strategy with the lowest national cost is considered by the model as the best strategy. In finding the best strategy, the model uses two steps. The first step compares all technology alternatives within a heat transition vision based on national cost. The result of this step is that each overarching strategy contains a sub-strategy with the lowest national cost for a specific neighborhood. Step two then compares the five overarching strategies with associated sub-strategies. Again, the national costs are used. The umbrella strategy with the lowest national cost is then considered the best strategy to implement the heat transition in a specific residential neighborhood. The model can represent all national costs of all strategies to provide clarity to the user on what basis certain decisions were made (Planbureau voor de Leefomgeving, 2021).

### 5.5.3 – Differences between the models

Both Vesta MAIS models were set up to analyze the impact of the heat transition vision on the energy industry. However, there are some important differences between the methodology and the results of the models. This section focuses on the differences in terms of scope of interest, assessment criteria, and the extent of insulation. These differences are explained in more detail and are shown in Table 4.

First, each model differs in terms of the scope of interest. The Vesta default model is intended to analyze the impact of the heat transition vision at the building level. This implies that the model provides the best technology alternative for each building within the area of interest (Planbureau voor de Leefomgeving, 2021). The Vesta Leidraad, on the other hand, focuses on a neighborhood level indicating which technology alternative is the best to replace the conventional natural gas-driven heating technologies. This analysis is made under the assumption that a neighborhood is homogenous meaning that every building within the neighborhood has access to the same technologies under the same regulations (Netbeheer Nederland, 2021; PBL, 2022).

Second, a difference occurs in the way how the models assess the best heat transition vision. The Vesta MAIS default model uses profitability as a presumption whereas the Vesta Leidraad model focuses on minimizing the national costs. This implies that both models can recommend different strategies to be the most suitable to replace the conventional natural gas-driven heating technologies.

The final difference relates to the assumption made about the insulation label in both models. In the Vesta MAIS default model, a building is assumed to invest in improved insulation only when it is profitable to do so. As stated earlier, the Vesta MAIS default model can support decisions, because it provides insights into the profitability of an investment. The Vesta Leidraad model, on the other hand, assumes that every building will be insulated to at least scale "B". This assumption is based on the Paris climate agreement (Rose et al., 2017).

*Table 4: The differences between the Vesta MAIS default model and the Vesta Leidraad*

| ***Aspect*** | **Vesta MAIS default model** | **Vesta Leidraad** |
|---|---|---|
| *Scope of interest* | The Vesta MAIS default model focuses on the impact of the heat transition on building-level within a predefined municipality. | The Vesta Leidraad model focuses on the impact of the heat transition on a neighborhood-level within a predefined municipality. |
| *Assessment criteria* | The Vesta MAIS default model uses the profitability as a criterion to find the best technological alternative to replace conventional heating sources. | The Vesta Leidraad model uses the national costs as a criterion to find the best technological alternative to replace conventional heating sources. |

| | | |
|---|---|---|
| *The extent of insulation* | The Vesta MAIS default model assumes that improving the insulation of buildings is only acceptable when it has a profitable business case | The Vesta Leidraad model assumes that every building has at least insulation label B as is proposed in the Paris climate agreement. |

## 5.6 – Actors in the Vesta MAIS models

Both Vesta MAIS models are intended to analyze the interaction between technical and economic aspects. The Vesta Default model aims at finding the technological alternative characterized by a favorable business case for the end-user. The Vesta Leidraad, on the other hand, determines the most favorable heat transition vision based on national costs (Planbureau voor de Leefomgeving, 2021). This techno-economic feature of both models makes it challenging to incorporate the social aspects into the outcomes of the model. This section aims to answer the following sub-sub-question: *To what extent are the identified actors currently integrated into the techno-economic Vesta MAIS model?*

Both models assume that identifying the interests and objectives of different actors plays an important role in identifying the actual national costs and profitability of heat transition visions. In addition, both models assume that the targeting of solutions can be improved when actors' desires are identified. For example, if an actor has a positive attitude towards the heat transition, then it is assumed that an actor is more willing to implement adjustments on an individual level to contribute to the heat transition (Planbureau voor de Leefomgeving, 2021). This could include, for example, improving the insulation label of individual buildings.

However, the way the results can be interpreted by the actors differs between the two models. The Vesta Default model distinguishes between specific actors. For example, the model assumes that the most appropriate heat transition vision is characterized by a positive business case for the end-user (Planbureau voor de Leefomgeving, 2021). Indeed, the model can describe a cost distribution for a specific heat transition vision in which the costs for the real-estate owner, the owner of the heat source, and the grid operator are described. In addition, this model can be used by grid operators and installation companies to implement targeted modifications to the existing energy grid. The Vesta Leidraad, on the other hand, does not distinguish between actors. The model decides on the most favorable heat transition vision in a neighborhood based on national costs. This ensures that the results cannot be interpreted at the individual actor level. A more extensive analysis is necessary to describe an advanced cost allocation. This could include, for example, a multi-actor analysis that can analyze the interactions between actors. This section further examines the Vesta default model to investigate which assumptions have been implemented in the model for specific actor groups. In addition, the limitations of the model in characterizing the actors are examined. These limitations are based on the motivations revealed by the research of the municipality of Delft (Appendix B1 & B2).

### 5.6.1 – Real estate owner in the Vesta MAIS model

The Vesta Default model, as described earlier, can be used to describe a cost distribution that describes the costs allocated to the real-estate owner, the owner of the heat source, and the grid operator. The Vesta default model uses the term "building users". In this project, only the real-estate owners are categorized as "building users" because, as shown in the actor analysis, this group of actors is considered a direct actor within the heat transition. Furthermore, the model assumes that the fixed costs of the building are borne by the corresponding "building user". For the real-estate owner, it is assumed that a one-time investment is made that is characterized by a positive business case. Here, the model does not consider the actor's attitude towards the heat transition. Thus, it is assumed that a real-estate owner invests regardless of the attitude (Planbureau voor de Leefomgeving, 2021).

### 5.6.2 – Owners of the heat source in the Vesta MAIS model

The second actor group included in the default model are the owners of the heat sources. These may be actors that directly produce heat through the combustion of biomass, for example, or through the use of a heat pump, but they may also be factories that produce residual heat (Planbureau voor de Leefomgeving, 2021). Because the model is based on rationality, it is assumed that an owner of a heat source will always make his technology available if there is a positive business case associated with it. However, the choices of the owner of a heat source are, as shown in Chapter 4, also based on the own future business plans, the moment of investment, the risk of the investment, technological preferences, and financial possibilities. These factors can cause a heat source owner to decide not to make their technology available resulting in higher national costs or unfeasible outcomes of the model.

### 5.6.3 – Grid operators in the Vesta MAIS model

Finally, the grid operators are identified in the Vesta default model. The model distinguishes between three different levels. The first level consists of the transporter. The model assumes that the transporter is responsible for transporting energy from the source to the distribution grid. In calculating the costs for the transporter, the model assumes that the transporter must make a one-time fixed investment combined with annual payments. The second level is characterized by the distributor. This type of grid operator is responsible for distributing the energy within the distribution network (Planbureau voor de Leefomgeving, 2021). The model assumes that this actor makes a one-time fixed investment consisting of the installation of heat transfer stations, pipelines, and other technical requirements necessary for fulfilling the chosen heat transition vision by the municipality. The final level of grid operators is formed by the local distributor. This actor is responsible for the distribution of energy within a building. For example, one can think of distributing energy within an apartment complex (Planbureau voor de Leefomgeving, 2021).

For every actor involved, the model assumes rational decisions based on the profitability of technological alternatives. It is assumed in this model, for instance, that a grid operator will always make investments when they are linked to a positive business case. However, investment risks, the timing of investments, technology preferences, and financial capabilities also play a role in choosing the most appropriate heat transition vision (Rose et al., 2017). For example, if a municipality has already installed a heat network, it is more likely to look at strategies characterized by the application of a heat network. Thus, in this way, the municipality has a technology preference that is not necessarily based on the results of the Vesta Default model.

## 5.7 – Conclusion to sub-question one

In this chapter, an actor analysis was performed to answer the first sub-question. This sub-question is: *How could an actor analysis be integrated into an approach aimed at facilitating decision-making at the municipal level within the heat transition?* An extensive literature study was used to describe the method that can be used to perform an actor analysis. This actor analysis was then carried out based on the municipality of Delft. A document analysis was used whereby the four formulated sub-sub-questions provided structure.

This chapter has shown that the current techno-economic models used in decision-making in the heat transition hardly consider non-rationality. Here, an opportunity arises to link non-rational aspects (e.g., technology preference, willingness to participate, etc.) to the techno-economic Vesta MAIS model using a stepwise actor analysis. To represent the role of this actor analysis, the method described by Enserink et al. (2010) is used. This method consists of six steps that ultimately lead to an advanced actor identification whereby a ranking can be set up based on objectives and interests. In Delft it turned out that fourteen actors can be identified that are somehow related to the heat transition. These actors are the municipality of Delft, the province of Zuid-Holland, the national government, housing corporations, real estate owners (Households & utility owners), neighborhood initiatives, investors and banks, installation companies, project developers, research institutes, grid operators, energy providers, energy cooperation's, owners of heat sources, and heat suppliers. All actors are characterized by specific interests and objectives. In addition, the actors have different relationships with each other. As a result, not every actor is characterized by the same power level in the heat transition. For example, one actor can directly influence the decision-making process within the heat transition, while other actors are influenced by the decisions that are made. These actors can then only operate within the framework of the decision-making process. Furthermore, it has become apparent that not every actor is characterized by the same level of interest. One actor may have a higher interest in the heat transition than another actor. In general, it was found that actors who are directly influenced by the international and national climate goals have a high interest in the heat transition. Actors that have a commercial interest in addition to the sustainability goals are generally categorized with a lower interest in the heat transition. This is because these actors, in addition to striving for sustainability, also benefit from finding a heat transition vision with a favorable business case.

In addition, this chapter described the extent to which social aspects are considered in the current Vesta MAIS models. Hereby, the Vesta default model and the Vesta Leidraad were examined. The models differ from each other based on scope of interest, assessment criteria, and insulation label assumptions. The results of the Vesta default can be interpreted at building level, while the results of the Vesta Leidraad relate to a neighborhood. The Vesta default model decides, based on profitability, which heat transition vision has the most potential. In contrast, the Vesta Leidraad makes this decision based on national cost. Finally, the Vesta default assumes that an insulation label will only be improved if this action is linked to a positive business case, while the Vesta Leidraad assumes that every building will be insulated to at least label B.

Finally, it was found that the Vesta Leidraad does not distinguish between actors. This, therefore, implies that social interactions are not included in the calculation of national costs. The Vesta Default, on the other hand, does distinguish between actors. Indeed, the model can describe a cost distribution for real-estate owners, owners of a heat source, and grid operators. However, the results showed that the model only assumes rational decisions. That is, the model assumes that a heat transition vision characterized by a positive business case is preferred over other visions. Thus, the model does not consider, for instance, the risk of the investment, social attitudes, timing of investments, capital opportunities, and technological preferences. This limitation has an impact on the outcomes of the model and shows the added value of a separate actor analysis. Indeed, only in this way can the outcomes of the techno-economic Vesta MAIS model be brought into social perspective.

## 5.8 – Recommended future enhancements for the Vesta MAIS model

This chapter has shown that the Vesta MAIS model is a techno-economic model that poorly integrates social aspects into its results. However, an opportunity arises here to add an agent-based model (ABM) to the Vesta MAIS model. An ABM is a computational model that can be used to represent complex situations in which individuals, organizations, and technologies interact in complex ways subject to rules and regulations (Nava Guerrero, Korevaar, Hansen, & Lukszo, 2019). The results of the model can be used to construct future scenario configurations based on the understanding of possible future compositions including trends and tendencies (Hansen et al., 2019; Nava Guerrero et al., 2019). Therefore, there is potential for the integration of an ABM within the Vesta MAIS model. This ABM model can be used to integrate the individual actors into the Vesta MAIS model, whereby individual interests are considered in the outcomes of the model. This could include investment risks, social attitudes, the timing of investments, and technological preferences.

In further explaining the potential of an ABM to extend the existing Vesta MAIS model, literature from Nava Guerrero et al. (2019) is used. This literature describes an ABM applied to the heat transition in the built environment. It uses the Sociotechnical Systems (STS) and Complex Adaptive Systems (CAS) perspective. In this section, the potential of an ABM is described based on these perspectives. First, the characteristics of both perspectives are described.

### 5.8.1 – Sociotechnical Systems (STS) perspective

In the STS, a distinction is made between actors, institutions, and technologies (Nava Guerrero et al., 2019). The STS perspective is characterized by interactions between networks of actors and networks of technologies in complex ways through institutions (Wu, Zhao, Shen, Madani, & Chen, 2020). Within this perspective, technologies are considered physical components of a system. The actors are characterized by individuals, organizations, and other social entities that can either make decisions or are influenced by the decisions that are made. Within this perspective, it is assumed that when actors act rationally this results in optimizing the objectives of the corresponding actor (Nava Guerrero et al., 2019). However, this rationality can be bounded. Furthermore, it is assumed that the objectives between actors can overlap, converge, or conflict (Nava Guerrero et al., 2019; Wu et al., 2020). This has the consequence that actors must adopt an objective so that participation in cooperation or competition can take place. Finally, institutions are used to shape the complex interactions between actors and technologies (Nava Guerrero et al., 2019).

### 5.8.2 – Complex Adaptive Systems (CAS) perspective

Another way to describe the heat transition in the built environment is to use the CAS. This perspective assumes that changes in the structure and behavior of the system arise from the lower-level autonomous components, known as agents (Nava Guerrero et al., 2019). The system is characterized by a large number of individual agents, which interact with each other and respond to the dynamic environment (Caprioli, Bottero, & De Angelis, 2020; Nava Guerrero et al., 2019). Furthermore, this perspective assumes that the agents are characterized by bounded rationality, can learn, and to some extent, can anticipate the future (Caprioli et al., 2020). The behavior of the CAS is determined by competition and collaborations between individual agents (Nava Guerrero et al., 2019). This ensures, according to Nava Guerrero et al. (2019), that existing mathematical methods are unable to explain the behavior.

### 5.8.3 – ABM application

An ABM can be used to analyze complex interactions between actors and technologies where the institutions provide a handle in facilitating the interactions (Caprioli et al., 2020; Nava Guerrero et al., 2019; Wu et al., 2020). Employing computational simulations, the ABM can study the complexities and nonlinear changes in a CAS. Hereby, the properties of the CAS, including emergence, adaptation, anticipation to the future, and lack of central control can be represented in the model (Nava Guerrero et al., 2019). The model is based on the actual or assumed behavior of the actor whose interaction with the environment leads to complex system structures and dynamics (Caprioli et al., 2020; Nava Guerrero et al., 2019). To achieve this, it is important to provide actors with a certain level of autonomy, where the social environment is dynamic and where social interactions take place between actors (Nava Guerrero et al., 2019).

An ABM consists of several components. The main components of an ABM are formed by the agents, the environment, and time (Nava Guerrero et al., 2019). In the context of an STS, the agents are used as software representations of the actors. Here, it is assumed that actors are problem solvers with clear boundaries and interfaces, surrounded by an environment, with objectives combined with rational behavior and the ability to influence one's behavior and the ability to anticipate future changes (Nava Guerrero et al., 2019; Wu et al., 2020). At any point in time, the agent's behavior is described as states. New states can arise due to changes in the decisions and behavior of an agent (Nava Guerrero et al., 2019). Furthermore, an ABM assumes that an agent's rationality is bounded. For example, agents do not have sufficient knowledge to determine which technological alternatives are most beneficial to replace natural gas-driven heat sources (Caprioli et al., 2020; Nava Guerrero et al., 2019). The environment consists of information structures, made up of multiple agents, and can be static or dynamic. Actors can modify the structure of the environment through actions. On the other hand, environments are also able to influence the behavior of agents (Nava Guerrero et al., 2019). Finally, an ABM uses discrete time intervals. The model assumes that changes in states occur at each time step. In addition, each step in an ABM can be influenced by the previous state of an agent and a current state can influence a future state (Nava Guerrero et al., 2019; Wu et al., 2020).

Because an ABM is a representation of reality, it is important to implement appropriate assumptions. These assumptions can be based on the actor interactions of a system in the "real" world. However, this requires a comprehensive actor identification where the different power and interest of the actors are represented. In addition, it is important to identify the different interactions between actors (Nava Guerrero et al., 2019). This can be done through an extensive literature review in combination with document analysis. The described actor analysis in section 5.3 is a good example.

### 5.8.4 – ABM integration possibilities

The research described in the literature by Nava Guerrero et al. (2019) has shown a great added value to analyze the social aspects in addition to the impact of the heat transition on the technical and economic aspects. Although no ABM model has yet been combined with the results of the Vesta MAIS, there is an opportunity to make the model more realistic. This is because an ABM matches the feasibility of the Vesta MAIS model results to social aspects. This, therefore, means that the modeler can find out at an early stage which scenarios are possible and which are not. For example, the municipality can model the social attitudes of actors to find out whether electrifying the heat demand, which would require large-scale adjustments at the individual actors, is possible. In addition, the municipality can adopt a goal-oriented approach to ensure that the heat transition is gradual without too many obstacles. This section is only intended to provide a suggestion on how to enrich the existing Vesta MAIS model. Further research is necessary to investigate the added value of an ABM to complement the Vesta MAIS model.

# Chapter 6 – Vesta MAIS model introduction

Before describing the role the Vesta MAIS model can have within the systematic approach to improve decision-making in the heat transition, the model is further introduced. Next, the pros, cons, and limitations of the model are described. Finally, the heat transition visions are described with associated technology alternatives and scenario compositions that function as model input for the Vesta MAIS model.

## 6.1 - Model introduction

The Vesta MAIS model can be used to find the heat transition vision that features the lowest national costs for a specific neighborhood or has the highest profitability for an individual end-user. Section 5.4.3 showed that two variants of the model can be distinguished. In this project, the Vesta Leidraad will be used to analyze the impact of the heat transition on the energy grid in Delft. This choice was made based on two reasons. The first reason is that this model uses the national cost as a criterium to find the best heat transition vision for a neighborhood. Within the municipality of Delft, as shown in Chapter 4, the same criterium has been used in prioritizing the neighborhoods. Here, neighborhoods with the lowest national costs resulting from the heat transition are given priority over neighborhoods with higher national costs. The second reason is formed by the fact that the Vesta Leidraad assumes a homogeneous insulation level for the built environment (Planbureau voor de Leefomgeving, 2021). This assumption affects the heat demand, as buildings with better insulation labels characterize lower heat demand (Nava Guerrero et al., 2019). Within this study, as within the Vesta Leidraad, it is assumed that each type of end-user (household and utility owners) has the same insulation label.

The result generated by the Vesta Leidraad consists of the national cost and change in share of energy carrier for each heat transition vision. These heat transition visions consist of technological alternatives that PBL considers feasible and possible for the built environment. Each heat transition vision consists of multiple technological alternatives. In addition, all technological alternatives contain different measures that affect the national costs of an alternative. The first measure that can be distinguished here are insulation measures. Improving the insulation of buildings reduces the demand for (thermal) energy by improving the efficiency of the heat supply (Damm, Köberl, Prettenthaler, Rogler, & Töglhofer, 2017; Nava Guerrero et al., 2019). The costs of insulation measures are included in the national costs unless there are subsidies attached. These subsidies are borne by the population, so the remaining costs are zero. In the Vesta Leidraad, the insulation levels are translated into insulation labels and run from A to G. The second measure that is considered in the Vesta Leidraad are the measures required in the provision of thermal energy. For example, certain technological alternatives can only be deployed if the power grid is reinforced. The cost of these reinforcements is included in determining the national cost for a specific neighborhood (Planbureau voor de Leefomgeving, 2021).

Finally, the model uses a reference year, allowing the impact of the heat transition vision to be analyzed relative to a base year. In this way, it becomes clear how the share of the energy carrier changes with a specific heat transition vision compared to the energy mix in the base year. The base year contains a situation where no measures have been taken yet to meet the agreements made within the Paris Climate Agreement (Planbureau voor de Leefomgeving, 2021).

## 6.2 – Advantages and disadvantages of the Vesta Leidraad

The Vesta Leidraad is characterized by a few advantages and disadvantages. This section describes the three biggest advantages and the two biggest disadvantages of the model when using the model to find the most appropriate heat transition vision. It is important to consider these advantages and disadvantages while interpreting the results in Chapter 7.

The first advantage of the Vesta Leidraad is that the model can provide an overview of the national costs associated with all technological alternatives. This implies that the model generates twenty-four results. The Vesta default model, on the other hand, stops computing when the model objective is satisfied. This means that the model stops when a heat transition vision is found that generates a favorable business case for the real estate owner. The Vesta Leidraad can, therefore, be better used in facilitating decision-making, because it can present an overview of the different possibilities that a municipality has (Diran et al., 2020; Henrich et al., 2021). After all, PBL itself has indicated that municipalities do not always let the choice for a heat transition vision depend on the lowest national cost. A second advantage of the Vesta Leidraad is that the model can be used to calculate the most appropriate technological alternative for individual neighborhoods within a municipality. This capability is important because the targets in the national climate agreement also focus on addressing individual neighborhoods so that at the local level the most appropriate resources can be deployed to replace natural gas-driven heat sources. In addition, the national climate agreement states that a heat transition vision must be prepared on a neighborhood level (Ministry of Economic Affairs and Climate Policy, 2019). By using the Vesta Leidraad, the choice for this heat transition vision can be substantiated by the municipality. The third advantage is that the results of the Vesta Leidraad allow for easy comparison between different neighborhoods within a municipality. The model assumes that all building types (households or utility buildings) have the same insulation label. This is also reflected in the scenario composition as shown in Figure 8. In addition, it is assumed that each building within a specified neighborhood has access to the same heat sources.

Furthermore, the Vesta Leidraad possesses some drawbacks. The first drawback relates to the cost allocation assumed in the model. The national costs are allocated to a single neighborhood. For example, when a heat grid must be installed, it is assumed that these investment costs are borne by an individual neighborhood. However, because these heat grids are often used by multiple neighborhoods, these costs will rather be borne by multiple neighborhoods. The consequence of this assumption is that the calculated national costs by the model for an individual neighborhood are often higher than the actual costs that characterize this heat transition vision. Another drawback of the Vesta Leidraad is that its neighborhood-level results do not distinguish between differences in energy demand by building. In other words, no significant distinction is made between the energy demand of utility buildings and households. This drawback can be countered when using data on the building level, indicating per building the expected demand for heat, electricity, and gas after the heat transition.

## 6.3 – Limitations of the Vesta Leidraad

Besides the described advantages and disadvantages of the Vesta Leidraad, the model also features some limitations. Chapter 5 has already shown that the model does not consider the relationship between the different actors that influence the heat transition within the municipality. In addition to the lack of actor integration, the model has other limitations.

The first limitation of the model is a lack of detailed local data. There are many uncertainties in the model about the potential of geothermal energy, for example, due to a lack of data. There is also much uncertainty in the level of investment costs, for example, for the construction of a heat grid. Much of this spatial data is considered sensitive and is therefore in the hands of specific actors making this data poorly accessible. If a modeler has access to this data, then the model can be supplemented, which improves the reliability of the results. For example, data related to the type of land and the cost of implementing a heat grid in a specific neighborhood.

The second limitation is formed by the uncertainty that new construction projects bring. For example, it is often not clear where new construction projects are planned and what the impact will be on the national costs of a specific heat transition vision. After all, if a neighborhood electrifies its heat demand, then it is necessary to calculate investment costs at the individual level to find out the total national cost. New residential neighborhoods can then have a significant impact on the calculated national costs.

In addition, the Vesta Leidraad uses specific aspects in determining energy demand by building type. These factors are insulation label, building type, and year of construction (Planbureau voor de Leefomgeving, 2021). Based on these factors, the model then calculates at the neighborhood level per heat transition vision what the "average" total energy demand will be in 2030. When the model is set at the building level, the model calculates per household and utility building what the predicted energy demand will be during a year. However, no demand patterns are described that provide detailed insights into the demand for heat, electricity, and gas for 24 hours every day of the year. As a result, the model does not distinguish between, for example, winter and summer demand for energy. This, therefore, means that the results of the Vesta Leidraad cannot be used directly to analyze the impact of the heat transition vision on, for example, the power grid. To translate the total demand per energy carrier into demand patterns, complex methods are required that are characterized by high uncertainty.

The final limitation of the Vesta Leidraad is formed by the complexity of the model. PBL has developed a model which should provide a realistic representation of reality. As a result, complex interactions between aspects that influence the heat transition led to an increase in the complexity of the model. This ensures that the model can only be used by experts. For many municipalities, it is, therefore, a challenge to use the model for decision-making.

## 6.4 – Heat transition vision identification

Based on the heat transition visions, the Vesta Leidraad calculates for each technological alternative its corresponding national costs. The main strategies used include an all-electric strategy, a collective heating strategy with medium-temperature (MT) heat sources, a collective heating strategy with low-temperature (LT) heat sources, renewable gas strategy, and a hydrogen strategy. A detailed overview of the different heat transition visions including the corresponding technological alternatives and scenario compositions is provided in Figure 9. In Appendix E, a detailed description about the heat transition visions can be found discussing the heat source, supply temperature, working principle, installation, insulation label, and heat temperature for each heat transition vision. All the information is obtained from the "Functioneel Ontwerp Vesta MAIS 5.0."

It is clear from Figure 9 that two technological options can be distinguished in electrifying the heat demand, namely the air source heat pump and bottom-heat pump. The all-electric strategy is further characterized by an insulation label B+ for both households and utility buildings and a space heating temperature of 50°C. For the collective heating strategy, a distinction is made between MT heat sources and LT heat sources. In the collective heating strategy with MT heat sources, three technological alternatives can be distinguished, namely MT waste heat, MT geothermal energy on an individual basis, and MT geothermal energy on a collective basis. This strategy is characterized by an insulation label of B+ or D+ for households, an insulation label of B+ for utility buildings and a space heating temperature of 70°C. For the collective heating strategy with LT heat sources, three technological alternatives can be distinguished. These alternatives are LT heat sources, thermal storage, and thermal energy from surface water and thermal storage. The scenario composition of this strategy is characterized by an insulation label of B+ or D+ for households, an insulation label B+ for utility buildings, and a space heating temperature of 50℃ or 70℃. The next heat transition vision used by the Vesta Leidraad is the renewable gas strategy, which is characterized by the application of green gas with hybird heat pump or green gas with a boiler. Here households have insulation label B+ or D+, utility buildings have insulation label B+, and a space heating temperature of 70°C. Finally, the hydrogen strategy can be distinguished. This strategy can be implemented using hydrogen in combination with a heat pump or hydrogen in combination with a boiler. Households have insulation label B+ or D+ and utility buildings have insultation label B+. The space heating temperature characteristic for the hydrogen strategy is 70℃.

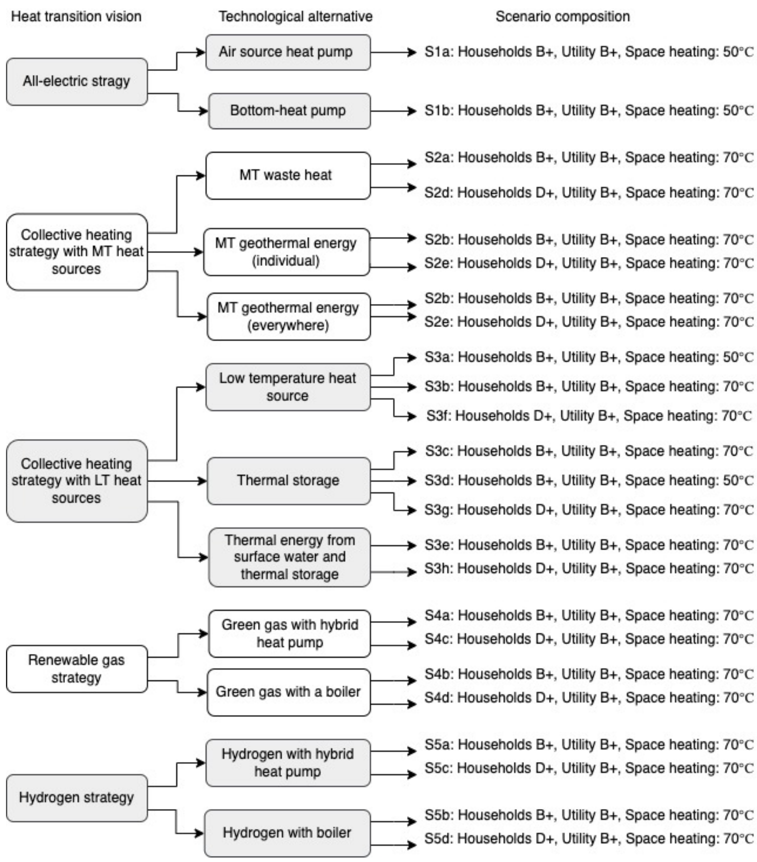



*Figure 9: An overview of the different technological alternatives and scenario compositions used in the Vesta Leidraad to calculate the national costs for each heat transition vision*

# Chapter 7 – Vesta MAIS model application to the municipality of Delft

In this chapter, the techno-economic Vesta MAIS model is applied to a real-life case to investigate the contribution of the model within a systematic approach to improve decision-making in the heat transition. Therefore, in this chapter an answer is formed to the following sub-question:

*How could the techno-economic outcomes of the Vesta MAIS model be used to facilitate decision-making at the municipal level?*

In answering this sub-question, the municipality of Delft is used as a real-life case. This chapter begins with identifying the required input variables. Based on these input variables, the Vesta MAIS model is used to investigate the impact of the heat transition visions in terms of national costs and share of energy carrier in the municipality of Delft. Finally, the Vesta MAIS model is used to examine which neighborhood within the municipality of Delft has the most potential to electrify its total heat demand. This neighborhood is used in Chapter 8 as a case for the preparation of a power flow analysis.

## 7.1 – Vesta Leidraad input variables

The Vesta Leidraad uses several input variables when analyzing the impact of different heat transition visions on national costs. In this study, only the insulation label, building type, and year of construction are addressed. This is because default settings were chosen when running the model, so the model uses specified default parameters in the calculations. These default settings can be found in the Functional Design Vesta MAIS 5.0. Table 10 shows the thirteen neighborhoods that have priority in the heat transition in Delft. All households and utility buildings are categorized. In addition, for each building, the insulation label has been examined. Finally, the year of construction is indicated. All the data is based on the situation in 2022 and was obtained from the "Basisregistratie Adressen en Gebouwen" (BAG).

*Table 10: A representation of the input data required to run the model for the thirteen prioritized neighborhoods in Delft*

| Neighborhood | Households | Utility buildings | Label A(+) | Label B | Label C | Label D/E/F | Year of construction |
|---|---|---|---|---|---|---|---|
| *Het Rode Dorp* | 488 | 4 | 0 | 0 | 271 | 217 | 1965 - 1991 |
| *Gillisbuurt* | 655 | 2 | 0 | 0 | 27 | 628 | 1965 - 1991 |
| *Aart van der Leeuwbuurt* | 564 | 13 | 12 | 29 | 23 | 513 | 1965 - 2005 |
| *Juniusbuurt* | 371 | 8 | 144 | 0 | 72 | 163 | 1975 - 2022 |
| *Fledderusbuurt* | 494 | 15 | 5 | 36 | 260 | 208 | 1965 - 2005 |
| *Buitenhof-Noord* | 1825 | 73 | 57 | 95 | 627 | 1119 | 1965 - 2022 |
| *Mythologiebuurt* | 1129 | 137 | 633 | 26 | 114 | 493 | 1965 - 2022 |
| *TU-Noord* | 556 | 51 | 371 | 31 | 67 | 138 | 1930 - 2022 |
| *Roland Holstbuurt* | 1755 | 32 | 54 | 0 | 161 | 1572 | 1965 - 2022 |
| *Reinier De Graafbuurt* | 317 | 10 | 0 | 0 | 0 | 327 | 1975 - 1991 |
| *Kuyperwijk-Zuid* | 853 | 74 | 47 | 56 | 47 | 777 | 1946 - 2022 |
| *Multatulibuurt* | 659 | 72 | 0 | 8 | 190 | 533 | 1965 - 1974 |
| *TU Campus* | 1918 | 107 | 1175 | 345 | 142 | 363 | 1930 - 2022 |

## 7.2 – The share of each energy carrier in the heat demand in 2019

Based on the input data shown in Table 10, the Vesta Leidraad can be used to calculate for each heat transition vision the associated national cost and share of each energy carrier. To investigate this, the model uses a reference year. In this study, the year 2019 was used as the reference year. Figure 9 shows the results in a pie chart presenting for each energy carrier (gas, electricity, and heat) the share in the supply of heat for the thirteen neighborhoods.

The diagram shows that the proportion of natural gas in the heat supply is the highest in the thirteen neighborhoods. In fact, 67% of the total heat demand in 2019 in these neighborhoods is provided by the combustion of natural gas. In addition, 28% of the heat is produced by electric heat pumps. Furthermore, 5% of the heat demand in 2019 is provided by MT-heat sources. The results further show that renewable gas, LT-heat sources, and waste heat were not used in 2019 in the prioritized neighborhoods.

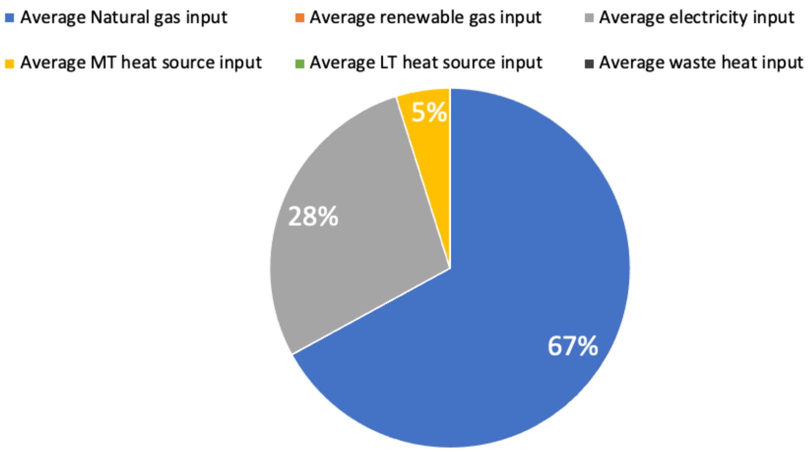



*Figure 10: A visualization of the share of each energy carrier in the total heat supply in the thirteen neighborhoods in Delft in 2019*

## 7.3 – The calculated national costs of the thirteen neighborhoods in 2030

The Vesta Leidraad is used to calculate the national cost of a specific heat transition vision for each neighborhood. In this way, the Vesta Leidraad contributes to answering the following sub-sub-question: *What is the most appropriate heat transition vision for the thirteen prioritized neighborhoods within the heat transition in Delft?* The model assumes that a municipality chooses the heat transition vision characterized by the lowest national cost. In the Vesta Leidraad, the national cost consists of several aspects. These aspects are; (1) reinforcing the electricity grid, (2) phasing out the existing gas grid, (3) modifying the gas grid, (4) transporting the heat grid, (5) implementing a heat grid, (6) improving the insulation level of buildings, (7) installations at individual buildings, (8) purchase of gas, (8) purchase of electricity, (9) purchase of heat, and (10) maintenance costs of the energy network (Planbureau voor de Leefomgeving, 2021). For each neighborhood, the heat transition vision that had the lowest national cost is indicated in parentheses. Furthermore, Figure 11 visualizes the difference between the national costs in 2019 and 2030.

Figure 11 shows that all heat transition visions generate higher national costs compared to the reference year. It further shows that eight neighborhoods have the lowest national cost in strategy 2d, three neighborhoods have the lowest national cost in strategy 4d, one neighborhood has the lowest national cost in 2e, and one neighborhood has the lowest national cost in strategy 3h. The neighborhood "TU Campus" has the highest national cost, while "Het Rode Dorp" has the lowest national cost. All the results are provided in Appendix F2.

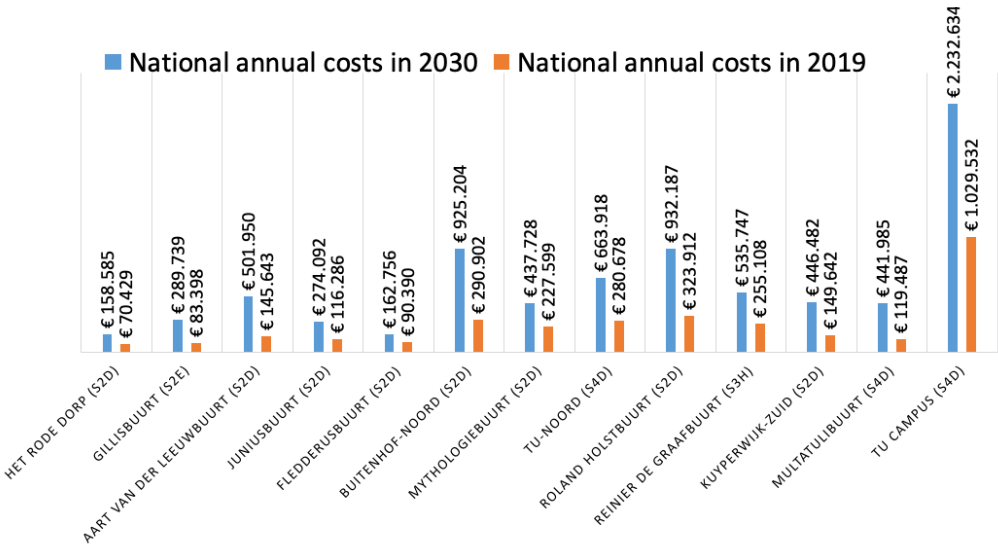



*Figure 11: A representation of the heat transition visions associated with the lowest national costs for specific neighborhoods compared to the national costs in 2019*

### 7.4 – The share of each energy carrier in the heat demand in 2030

In addition to identifying the most appropriate heat transition vision, the Vesta Leidraad can also be used to identify the share of each energy carrier in 2030. Therefore, the model can be used to answer the following sub-sub-question: *How does the identified heat transition vision affect the share of the energy carriers within the thirteen prioritized neighborhoods in Delft?* The calculation is performed using the previously mentioned input data provided in the Functional Design Vesta MAIS 5.0 and the information described in Table 10. In identifying the share of each type of energy carrier, the thirteen neighborhoods that have priority within Delft were used as a starting point. These neighborhoods are considered to describe a clear situation that will take place after the heat transition because these neighborhoods must be completely off natural gas by 2030 (Delft, 2021). This selection of neighborhoods, therefore, provides a clear indication for other neighborhoods of how the share of each type of energy carrier will change as a result of the heat transition. The results of the Vesta Leidraad are visualized in a pie chart in Figure 12.

The results showed that the share of natural gas in the heat supply is disappearing. This is in line with the targets used for these neighborhoods. The results also show that the share of electricity within the heat supply will increase from 28% to 34% by 2030. This means that electricity will not only play a more vital role as an energy carrier in an all-electric strategy compared to the reference year but also in other strategies. Moreover, the results show that renewable gas will play an important role in the heat transition. After all, in 2019 renewable gas did not yet have a share in the heat supply while in 2030 this share will increase to 21% for these neighborhoods in Delft. Finally, it appears that the role of LT-heat sources remains limited. In 2019, LT-heat sources did not yet account for a share of the heat supply. This share increases to 1% in 2030.

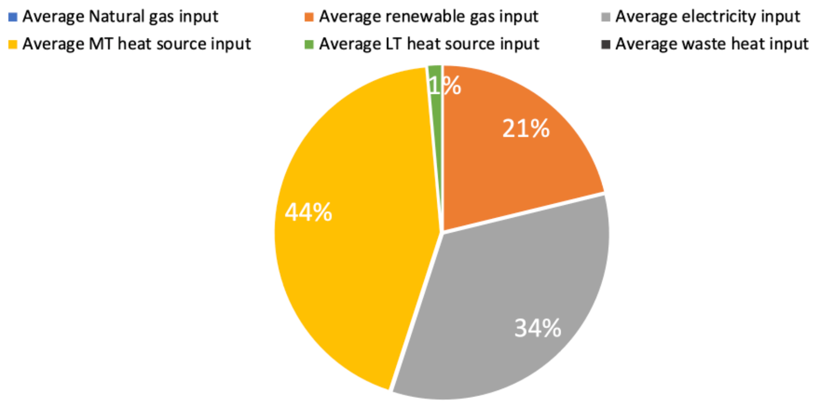



*Figure 12: A visualization of the share of each energy carrier in the total heat supply in the thirteen neighborhoods in Delft in 2030*

## 7.5 – Neighborhood selection for power flow analysis

The Vesta Leidraad, as shown in the limitations of the model, is hardly able to analyze the impact on the power grid due to a lack of advanced data regarding (hourly) demand patterns. To analyze the impact of the heat transition on the power grid, an opportunity arises to translate the results of the model into suitable input data for a power flow analysis. Here, a neighborhood is used where the all-electric strategy is characterized by the lowest national cost. After all, an all-electric strategy is characterized by electrifying the entire heat demand leading to a significant increase in electricity demand. The description of the power flow analysis and the associated model is given in Chapter 8. In this section, the Vesta Leidraad is used to find a neighborhood that will adopt an all-electric strategy based on national costs. Therefore, this model can be used to answer the following sub-sub-question: *Which neighborhood has the most potential to fully electrify the heat demand in Delft?* In doing so, all strategies are applied to all neighborhoods within Delft. The municipality of Delft consists of 91 neighborhoods. This means that there are a total of 2,184 outcomes. The data is collected in CSV files and can be obtained separately.

The Vesta Leidraad has shown that there are two neighborhoods in Delft where the all-electric strategy characterizes the lowest national cost. These neighborhoods are “Business Park Technopolis” and “Stationsbuurt”. Both neighborhoods have the lowest national costs at S1b. The total national costs for Technopolis are €1,006,732, while the national costs for the “Stationsbuurt” are €75,572. The input data that is used for the Vesta Leidraad to find the lowest national costs for both neighborhoods are described in Table 12 and are based on information provided in the BAG. The results regarding national costs are visualized in Figure 13. However, there is no reliable data available for the “Stationsbuurt” regarding insulation labels making the data uncertain. Therefore, the Business Park Technopolis will be used for the power flow analysis in Chapter 8.

*Table 12: A representation of the input data required to run the model for Business Park Technopolis and “Stationsbuurt*

| Neighborhood | Households | Utility buildings | Label A(+) | Label B | Label C | Label D/E/F | Year of construction |
|---|---|---|---|---|---|---|---|
| *Business Park Technopolis* | 2 | 55 | 0 | 0 | 0 | 57 | 1946-1974 |
| *Stationsbuurt* | 0 | ±22 | 0 | ±3 | ±19 | 0 | 1992-2005 |

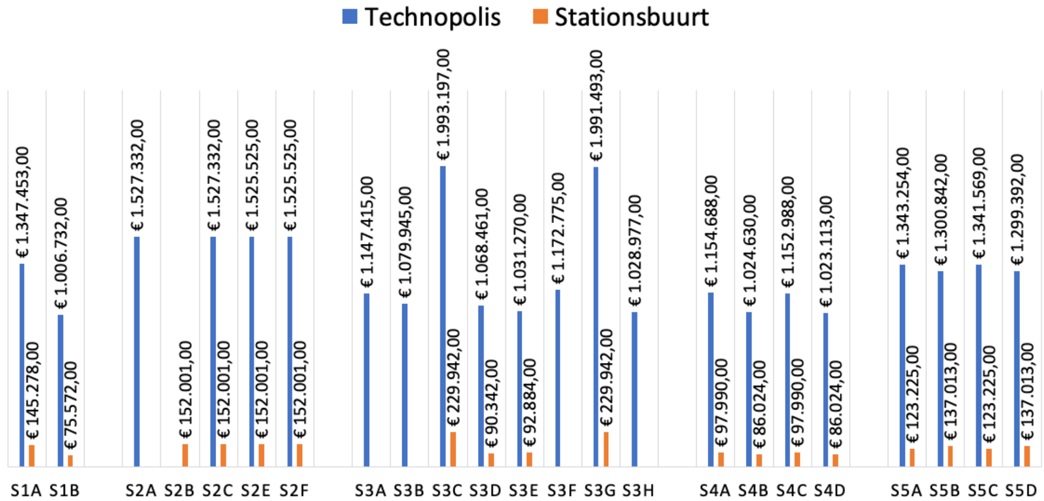



*Figure 13: A visualization of the national costs of the different heat transition visions belonging to "Business Park Technopolis" and "Stationsbuurt"*

## 7.6 – The share of energy carriers in the heat demand in Business Park Technopolis

After identifying the national costs of the different heat transition visions in the Business Park Technopolis, the Vesta Leidraad can be used to calculate the different shares of energy carriers. Therefore, the model can be used to answer the following sub-sub-question: *To what extent does the all-electric strategy cause changes in the share of energy carriers relative to the reference year?* From Figure 13, it was found that strategy S1b characterizes the lowest national cost for the Business Park Technopolis. To use the Vesta Leidraad to calculate the share of each energy carrier within the total heat demand in this neighborhood, the model uses the data described in Table 12. This data is obtained from the BAG and contains information about the situation in 2022.

The Vesta Leidraad first breaks down the share of each energy carrier for the reference year. In this way, the modeler can analyze the difference in the share of each energy carrier by making a comparison with a situation in which natural gas plays a significant role in the total heat demand in the Business Park Technopolis. These results can be found in Figure 14a. Because the Vesta Leidraad is instructed to calculate a situation in which natural gas no longer contributes to the heat demand, the results for the Business Park Technopolis do not relate to the 2030 situation. After all, this neighborhood has no priority from the municipality of Delft (See section 4.5). This means that the municipality does not expect this neighborhood to be completely off natural gas by 2030. Within this study, however, it is assumed that the natural gas-free situation generates the best results for analyzing the impact on the power grid. Indeed, this situation is characterized by the largest increase in electricity demand as natural gas-driven heat sources are entirely replaced by electric heat pumps and other sustainable alternatives. The results are described in Figure 14b.

Figure 14b shows that natural gas will no longer have a share in the total heat demand in the Business Park Technopolis in 2050. In addition, it appears that the share of electricity is increasing significantly. For example, the share of electricity in 2019 was 48% and this increases to 66% in 2050. This result can be explained by the fact that this neighborhood will focus on electrifying its heat demand. Finally, Figure 14 shows that the share of waste heat increases from 6% in 2019, to 34% in 2050. This, therefore, implies that two types of energy carriers are expected in the Business Park Technopolis in 2050.

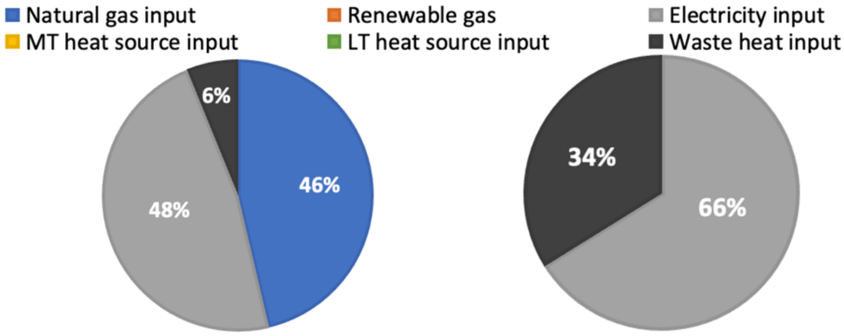



Figure 14a: A visualization of the share of each energy carrier in the total heat demand in the Business Park Technpolis in 2019

Figure 14b: A visualization of the share of each energy carrier in the total heat demand in the Business Park Technpolis in 2050

## 7.7 – Conclusion to sub-question two

In this chapter, using a real-life case, it has been shown what role the Vesta Leidraad can have within the systematic approach to improve decision-making within the heat transition. In this way, an answer was formed to the sub-question: *How could the techno-economic outcomes of the Vesta MAIS model be used to facilitate decision-making at the municipal level?*

The results showed that the Vesta Leidraad can be used as an explorative, informative, and supportive tool to determine which heat transition vision has the most potential for an individual neighborhood. In doing so, the model calculates the national cost for each heat transition vision and then examine the change in the share of each energy carrier relative to a reference year. This reference year can be described by a situation where no measures have yet been implemented to meet the (national) climate targets. Applying the Vesta Leidraad to the municipality of Delft, it was found that eight neighborhoods have the most potential with strategy 2d, three neighborhoods with 4d, one with 2e, and one with 3h. Furthermore, the model showed that the share of natural gas as an energy carrier in the total heat demand of 67% in 2019, disappears in 2030. It was also found that the share of electricity increases from 28% in 2019 to 34% in 2030. This, therefore, implies that increasing demand for electricity does not only occur with the all-electric strategy, but also with other strategies.

Because the Vesta Leidraad can be used to determine the most appropriate heat transition vision, in this study the model is also used to find a neighborhood where electrifying the total heat demand has the most potential. After all, this neighborhood has the greatest impact on the power grid due to an increased demand for electricity. This is the reason why this neighborhood is perceived as a suitable case for performing a power flow analysis. The results showed that there are two neighborhoods where the all-electric strategy has the most potential. However, due to a lack of reliable data, the power flow analysis will be set up based on the Business Park Technopolis. The results of the Vesta Leidraad showed that the share of electricity as an energy carrier within the Business Park Technopolis in the total heat demand increases from 48% in 2019, to 66% in 2050. Finally, it was found that the Vesta Leidraad is hardly able to analyze the direct impact of a heat transition vision on the power grid. This is because the model is only able to calculate an average annual demand for electricity. Thus, the model says nothing about the hourly demand patterns which is an important factor to investigate the impact of the heat transition on the power grid in terms of congestion. To determine whether the power grid is capable of operating after a chosen heat transition vision, it is important to map out the daily peak demands. In this way, a power flow analysis can be used to analyze the impact of a heat transition vision on the power grid.

# Chapter 8 – Power flow analysis applied to a neighborhood in Delft

In this chapter, an energy model is developed that can be used to enrich the Vesta MAIS model with expanded technical aspects. The goal is to design a model whose outcomes can be easily interpreted by decision-makers so that even actors with less expertise can use the model in facilitating decision-making. The proposed method should contribute to decision-making by identifying potential congestion locations in the power grid. This chapter describes an approach to developing such a model, forming an answer to the following sub-question:

*How could the results of the Vesta MAIS model be used to assess the feasibility of the heat transition in terms of grid congestion?*

This chapter begins by introducing a power flow analysis, the underlying mechanism of the model being developed. Next, Pandapower is introduced. Pandapower is used as the Python environment within which the model is developed. After that, the necessary input variables required for running the model are described. In section 8.4, the hourly demand patterns used for the model are described and in section 8.5 the model is applied to a real-life case. Here, first, a method to calibrate the model is provided. Then, based on the results, it will be examined at what times and at what locations congestion will occur as a result of electrifying the heat demand. Finally, section 8.6 describes the validity and interpretability of the results while a conclusion is provided in section 8.7.

## 8.1 – Introduction in power flow analysis

To develop an energy model, a power flow analysis is used as underlying mechanism. This type of analysis can calculate the corresponding grid state and grid parameters based on the defined electricity demand. The grid state can be used to determine whether congestion occurs in the power grid (Low, 2013). In this study, it is assumed that congestion occurs when the generation capacity exceeds the grid capacity in a time interval of 24 hours. In addition, a power flow analysis provides insight into grid parameters, including voltages, line loadings, and transformer loadings (Aien, Hajebrahimi, & Fotuhi-Firuzabad, 2016; Petridis et al., 2021). Furthermore, a power flow analysis represents a simplified notation such as a one-line diagram and per-unit systems based on a power system operating in a normal steady-state (Aien et al., 2016). A power flow analysis can be used to identify adjustments and reinforcements in the power grid but also to determine the best operation of an existing system (Aien et al., 2016; Low, 2013). The results of the analysis are the magnitude and phase angle of the voltage associated with each bus, and the real and reactive power flowing in the defined lines (Aien et al., 2016; Petridis et al., 2021). The real power is used in the power grid and is defined as $P = V \cdot I \cdot \cos(\Theta)$ while the reactive power is defined as the power that flows between load and source and is defined as $Q = V \cdot I \cdot \sin(\Theta)$ (Aien et al., 2016). A bus contributes to the power distribution within a power grid and is also used to connect high voltage equipment to power plants (Petridis et al., 2021).

The purpose of a power flow analysis is to obtain complete voltage angles and magnitude information for each defined bus in the power grid for specific loads and real power and voltage conditions of the generator (Petridis et al., 2021). Once this information is known, the real and reactive power in each line can be determined analytically (Petridis et al., 2021). The preparation of a power flow analysis begins with the identification of the known and unknown parameters. These parameters relate to the defined buses in the power grid. A bus that is not directly connected to a generator is defined as a "Load bus", while a bus that is directly connected to a generator is defined as a "Generator bus". Furthermore, within the power flow analysis, a “Slack bus” is defined. This slack bus is used to balance the reactive power |Q| and real power |P| within the network (Petridis et al., 2021).

In a power flow analysis, it is assumed that the real power $P_d$ and reactive power $Q_d$ are known for each Load bus. For the generator buses, it is assumed that the real power generated $P_g$ and the voltage magnitude |V| are known. Furthermore, for the Slack bus, the voltage magnitude |V| and voltages phases Θ are assumed to be known. This implies that the voltage magnitude and angle are unknown for the Load bus, while the voltage angle is an unknown parameter for the Generator bus. For the Slack bus, there are no unknown parameters. In a system consisting of N buses and R generators, the number of unknown parameters can be calculated through *2(N-1) - (R-1)* (Petridis et al., 2021). To solve this equation, a power balance is used. This power balance is described for both the real and reactive power for each bus. The power balance belonging to the real power can be written as follows:

$$0 = -P_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik} \cos \Theta_{ik} + B_{ik} \sin \Theta_{ik}) \tag{1}$$

Here $P_i$ is the net injected real power at Bus i, $G_{ik}$ characterizes the $i^{th}$ and $k^{th}$ portion of the bus matrix used to compute the nonlinearity of the power flow analysis, $B_{ik}$ denotes the imaginary portion of the $i^{th}$ and $k^{th}$ buses, and $\Theta_{ik}$ denotes the difference between the voltage angles of the $i^{th}$ and $k^{th}$ buses (Petridis et al., 2021). Here, $\Theta_{ik}$ is defined as $\Theta_{ik}=\Theta_i- \Theta_k$. The reactive power balance is written as follows:

$$0 = -Q_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik} \sin \Theta_{ik} + B_{ik} \cos \Theta_{ik}) \tag{2}$$

Here $Q_i$ is defined as the net reactive power injected at bus i. The power flow analysis is thus based on the power balances for the real and reactive power for each load bus and the real power balance for the Generator Bus. For the Generator Bus, the analysis does not use the reactive power balance, because it is assumed that the net power injected at the Generator Bus is unknown. Furthermore, no power balances are established for the Slack bus because this bus has no unknown parameters.

## 8.2 – Model introduction

Due to the complexity caused by the nonlinearities of the power flow analysis, Pandapower is used in this study. This computer model is used in Python and uses data analysis library pandas and the power system analyses toolbox PYPOWER. Both data sources are used to create a simplified representation of a power grid to be able to implement optimizations within a network (Thurner et al., 2018). Pandapower was developed to provide a simple tool that is accessible to everyone. In doing so, it does not have the disadvantages of existing commercial tools (e.g., Sincal, PowerFactory, NEPLAN) and open-source tools (e.g., MATPOWER, PYPOWER). For example, commercial tools are restricted and only accessible to a specific group of users, while open-source tools are characterized by high complexity that allows the tools to be used only by experts (Milano & Vanfretti, 2009; Thurner et al., 2018). Pandapower, on the other hand, is characterized by an easy-to-understand interface accessible to any user.

The results that can be generated using Pandapower are voltage magnitudes for the buses and the real and reactive power in the line and generators (Thurner et al., 2018). The results are displayed in tabular data structures characterized by a table for each element within the defined power grid that describes all parameters of that element. This data structure is based on the Python library pandas. Furthermore, Pandapower contains a standard type of library that allows the modeler to implement lines and transformers in the power grid using standard type parameters with predefined values (e.g., line capacities, bus capacities). These parameters can also be modified by the modeler. For example, if the modeler has access to advanced grid data, then the model can be applied to that specific grid.

Pandapower can be used for various power system analyses, including Power Flow, Optimal Power Flow, State estimation, Short-circuit calculation, and Topological graph searches. To perform a power flow analysis, Pandapower uses the Newton-Raphson method. This method is based on initial estimates of the unknown variables, including voltage magnitudes, angles at Load buses, and voltage angles at Generator buses (Thurner et al., 2018). Then Taylor series are described, ignoring the higher-order terms. These Taylor series contain all the power balances that affect the defined power grid. Here, Pandapower uses expression (3) (Pandapower, 2022).

$$\begin{bmatrix} \Delta\Theta \\ \Delta|V| \end{bmatrix} = -J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3}$$

Here, ΔP and ΔQ are considered as the mismatch equations, as described in (4) and (5).

$$\Delta P_i = -P_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik} \cos\Theta_{ik} + B_{ik} \sin\Theta_{ik}) \tag{4}$$

$$\Delta Q_i = -Q_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik} \sin\Theta_{ik} + B_{ik} \cos\Theta_{ik}) \tag{5}$$

In addition, J describes a matrix of partial derivatives known by the term Jacobian. The matrix is described in equation (6).

$$J = \begin{bmatrix} \frac{\partial \Delta P}{\partial \Theta} & \frac{\partial \Delta P}{\partial |V|} \\ \frac{\partial \Delta Q}{\partial \Theta} & \frac{\partial \Delta Q}{\partial |V|} \end{bmatrix} \tag{6}$$

Based on equation (4) and (5), the next estimate is then determined with respect to the voltage magnitude and angles. This calculation is done using equation (7) and (8)

$$\Theta^{m+1} = \Theta^m + \Delta\Theta \tag{7}$$

$$|V|^{m+1} = |V|^m + \Delta|V| \tag{8}$$

The Newton-Raphson method is performed by the model until the value of the estimate falls outside the tolerance area (Thurner et al., 2018). It is, therefore, important to define a tolerance area in advance. In Pandapower, a default tolerance area can be used which is included in the data analysis library pandas (Pandapower, 2022).

## 8.3 – Pandapower input variables

When running the model using Pandapower, several variables are required. The codes used for the model can be found in Table 13 and Appendix G2. This is also where all the input variables are listed. The codes are derived from the open-source manual of Pandapower.

The first input variables are formed by the hourly demand profiles. These demand profiles describe the demand for electricity for 24 hours. Section 8.4 describes how the demand profiles were created. Subsequently, all demand profiles were described in CSV files that serve as input for the power flow analysis. The demand profiles used can be found in Appendix G1. Furthermore, the modeler can choose to add some local energy sources. This could include solar panels or wind turbines connected to the medium or low voltage grid. In this project, for illustration purposes, eight solar panels and one wind turbine have been integrated into the model. These are designated as "PV" and "WD".

Next, the network is set up. When setting up the network, the modeler can add line properties, including the line capacitance in nano Farad per km (c_nf_per_km), the line resistance in ohms per km (r_ohm_per_km), maximum thermal current (max_i_ka), and the type of line (overhead line or underground cable system) (Pandapower, 2022). Finally, the modeler can enter the type of network. In this study, CIGRE networks are used. This choice was made due to a lack of advanced grid data and because these types of networks are based on comprehensive reference systems that contribute to a suitable analysis for high voltages (hv), medium voltage (mv), and low voltage (lv) grids (Pandapower, 2022; Thurner et al., 2018). Next, the modeler can define buses within the network. Here, a name can be given to the bus. In addition, the modeler can define the rated voltage of the bus (vn_kv), the type of bus (node (n), busbar (b), or muff (m)), and the zone (Pandapower, 2022). The zone can be used to group buses based on local coordinates. After defining the buses, the lines can be integrated into the network. Here, the modeler can define lines between specific buses. If the modeler has access to advanced grid data, then an existing network can be simulated. Furthermore, the modeler indicates what type of line can be found at a specific location. This line specification is entered at std_type. Next, the modeler can define the external network. Here, the modeler can determine which bus within the established network is directly connected to the external network. This bus is called the Slack bus and the modeler can define the voltage at the slack node per unit (vm_pu), the voltage angle at the slack node (va_degree), the maximum and minimum apparent short circuit formation to calculate the internal impedance of the external grid for short circuit calculations (s_sc_max_mva and s_sc_min_mva), and the maximum and minimum R/X ratio to calculate the internal impedance of the external grid for short circuit calculations (rx_max and RX_min) (Pandapower, 2022). Furthermore, the modeler integrates the transformers. Here, the rated apparent power of the transformer (sn_mva), rated voltage at low and high voltage bus (vn_hv_kv and vn_lv_kv), real component of short circuit voltage (vkr_percent), short circuit voltage (vk_percent), iron losses (pfe_kw), open-loop losses (i0_percent), and transformer phase shift angle (shift_degree) are defined (Pandapower, 2022). Finally, the modeler defines which demand profiles are connected to which buses. Here, the model uses the CSV files described in section 8.4 as input data. In addition, the modeler defines for each demand profile the rated power of the load (sn_mva) and the power factor (cos_phi) (Pandapower, 2022).

After identifying the lines and buses, the modeler can define the constraints. These constraints depend on the loading constraints of the lines and the voltage constraints in the buses (Pandapower, 2022). When the modeler has acces to advanced grid data, a realistic model can be created. The modeler can define the load limit (load_limit) and the maximum and minimum load per unit (vm_max_pu and vm_min_pu).

Next, the modeler can implement controllers in the network. These controllers are used as control modules for simulated elements that are controlled based on current flows

(Pandapower, 2022). This can include, for example, droop controllers in PV plants that adjust reactive power according to bus voltages. To integrate controllers, the modeler must define the network in which the controller operates, the element (e.g., sgen, load, etc), variable (e.g., p_mw, q_mv, vm_pu, etc), the data source, and the profile name.

Finally, the modeler must define an initial load flow to perform a power flow analysis using Pandapower. In doing so, the modeler defines the number of time steps (n_timesteps). This number of time steps cannot be larger than the data frame used for the analysis. To collect the results, the modeler can define an output direction. In this way, for example, the results can be collected in CSV files.

*Table 13: An overview of the pandapower codes used to fulfill a specific function*

| **Function** | **Pandapower code** |
|---|---|
| *Line definition* | line_data = {'c_nf_per_km': …, 'r_ohm_per_km': …, 'x_ohm_per_km': …, 'max_i_ka': …,'type': '…'} |
| *Line creation* | pp.create_std_type(network_type,line_data, name='…', element='line') |
| *Bus definition* | bus=pp.create_bus(net_cigre_mv, name='Bus …', vn_kv=…, type='…', zone='…') |
| *Lines between buses* | pp.create_line(net_cigre_mv, buses[…], buses[…], length_km=…, std_type='…', name='Line …') |
| *External grid definition* | pp.create_ext_grid(net_cigre_mv, bus…, vm_pu=…, va_degree=…., s_sc_max_mva=…, s_sc_min_mva=…, rx_max=…, rx_min=…) |
| *Transformer definition* | Trafo… = pp.create_transformer_from_parameters(net_cigre_mv, bus…, buses[…], sn_mva=…,vn_hv_kv=…, vn_lv_kv=…, vkr_percent=…,vk_percent=…, pfe_kw=…, i0_percent=…, |
| *Load demand definition* | pp.create_load_from_cosphi(net_cigre_mv, buses[…], sn_mva, cos_phi, "underexcited", name='Load …', index = 0) |
| *Load supply definition* | pp.create_sgen(net_cigre_mv, buses[…], q_mvar=0, sn_mva=0.02, name='PV …', type='PV', index = 0) |
| *Load constraints definition* | Load_limit = …, vm_max_pu=…,vm_min_pu=… |
| *Controller definition* | ConstControl(net, "element", "variable", element_index=net.load.index[…], profile_name=["Load …"], data_source=ds, order=0, level =0, recycle = False) |

## 8.4 – Demand patterns

As shown in section 6.3 the results of the Vesta Leidraad cannot be used directly to analyze the impact on the power grid, because the model says nothing about the hourly demand distribution. Complex methods are necessary to translate the total demand for energy carriers into hourly demand patterns. However, these methods are subject to uncertain future developments (e.g., technological improvements and developments).

In this study, use is made of the data from Voulis (2019) to construct the demand patterns. Voulis (2019) developed a method to harness heterogeneity in demand patterns from 2014 and distinguishes between different type of end-users including hospitals, households, hotels, offices, schools, and stores. Within this study, a further distinction is made between the demand for electricity and the demand for natural gas for heating buildings and heating water (Voulis, 2019).

Based on the individual demand patterns described by Voulis (2019), hourly demand patterns can be developed after electrifying the heat demand. To do this, the coldest day in 2014 was used which was the 28th of December. After all, on this day it can be expected that the demand for natural gas for space heating was the highest. Next, the demand for natural gas was translated into an equivalent in terms of electricity. In doing so, the fact that 1 $m^3$ of natural gas contains approximately 36,000KJ of energy was used. It was further assumed that 1 $m^3$ of natural gas contains 10.2 kWh (Karavalakis et al., 2013). Thus, within this study, it has been assumed that the total demand for natural gas has been completely replaced by electricity. When this assumption is taken, the demand for electricity in megawatts (MW) can be added to the demand for natural gas in MW. Figure 15 shows the results of this method and describes per building type the individual hourly demand profiles before and after the electrification of the heat demand. In doing so, it was assumed that each building within an end-user category features the same demand profile.

Figure 15 shows that supermarkets have the highest electricity demand on a cold day followed by large offices. The demand for electricity for supermarkets increases after 6:00 a.m.. This can be explained by the fact that supermarkets usually open around this time. Furthermore, this demand decreases after 10:00 p.m., the time when the supermarket closes. For large offices, the peak demand for electricity is slightly later than for supermarkets. Further, large offices have peak demand in the morning and the evening. Figure 15 also shows that a small hotel has a small demand for electricity compared to large offices and supermarkets. The peak demand for electricity is at 9:00 a.m.. Finally, it shows that medium offices, primary schools, and households contribute only a small amount of electricity demand compared to large offices and supermarkets.

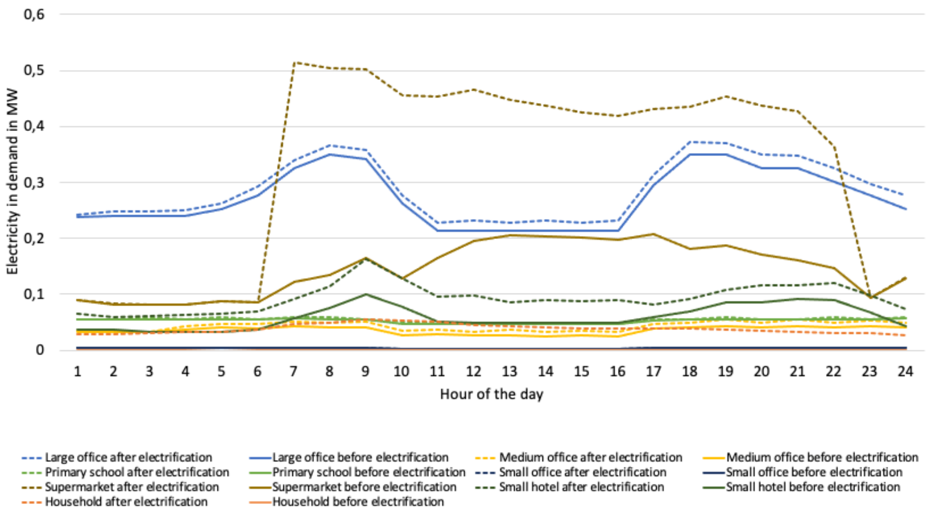



*Figure 15: A visualization of the different individual hourly demand patterns before and after the electrification of the heat demand in Business Park Technopolis*

## 8.5 – Power flow analysis: Case application to Business Park Technopolis

In this section, Business Park Technopolis is used as a case to demonstrate how the Pandapower model can be used to analyze the impact of the all-electric strategy on the existing power grid. Here, the end-user categorization as proposed by Voulis (2019) is used. The identified end-users were then translated to the situation of the Business Park technopolis. The results are shown in Table 14.

In Table 14, a distinction is made between large, medium, and small offices. This distinction is made based on the surface area of the office. Hereby, offices with a surface area greater than 10,000 $m^2$ are considered "large offices", while offices with a surface area of 5,000 $m^2$ to 10,000 $m^2$ are considered "medium offices". All offices with an area of fewer than 5,000 $m^2$ are considered "small offices". The same criterium was used to distinguish between large, medium, and small hotels.

*Table 14: A representation of the building categorization in the Business Park Technopolis used to run the Pandapower model.*

| **Type of building** | **Representative building categorisation from Voulis (2019)** | **Number of buildings** |
|---|---|---|
| *Household* | Household | 2 |
| *Office* | Large office | 2 |
| *Office* | Medium office | 9 |
| *School* | Primary school | 10 |
| *Meeting rooms* | Small office | 4 |
| *Shop* | Supermarket | 17 |
| *Holiday* | Small hotel | 2 |
| *Others* | Small office | 9 |

Due to a lack of data regarding power grid configurations in the Business Park Technopolis, a calibration technique was used to establish a conventional grid that allows for comparison with new grid configurations. In calibrating the model, the hourly demand patterns for electrification as described by Voulis (2019) were used (Figure 15). In this project, these demand patterns were assumed to be representative of the Business Park Technopolis. Furthermore, it is assumed that there are 15 buses in the neighborhood's power grid. In addition, the model assumes that each bus is connected to an approximately equal number of end-users. In other words, there are about four end-users connected to a bus. However, due to a lack of advanced grid data for the Business Park Technopolis, the classification of the connections between the buses and end-users is based on a "logical positioning", assuming that end-users within the same category are closely located to each other. In this way, for example, households are connected to the same bus. A detailed description of the connections between buses and end-users can be found in the code provided in Appendix G2.

### 8.5.1 – Model calibration method

Pandapower is a tool that can be used to model the impact of changing demand patterns on the power grid in terms of congestion. To investigate the impact, a conventional fictious grid is developed using a calibration method. In this section, an answer is formed to the following sub-sub-question: *What kind of model calibration technique can be used to create a realistic energy grid without advanced data of an existing grid?* It is first important to recognize that Pandapower is not designed as a time-varying tool for simulations. Moreover, by default, Pandapower is not explicitly capable of generating values during the domain of calculations of the defined load flow. However, by using the controllers and time series, these values can still be generated. The method used to calibrate the Pandapower model is visualized in Figure 16.

To calibrate the model, the modeler first needs to implement a first guess of geographical coordinates, grid capacities, cable lengths, and the number of buses with corresponding voltage capacities. Next, the modeler needs to define hourly demand patterns as data frames that serve as model input. After setting up the time steps, demand patterns, and initial grid configurations, the modeler must define the grid controllers. The modeler can use the default controller settings defined in Pandapower, or the modeler can design new controllers. The different types of controllers allow the modeler to use different control strategies. In this way, for example, the grid state can be modeled in which storage options for excess electricity are included. There is, for instance, a controller available that can update the active power of load $P_{load}(t)$ and solar panels or optimize the power of a battery depending on the rated energy capacity and rated power of the storage limitations. During the time series, the controllers are iterated, while the power flow is repeatedly remodeled.

After defining the controllers, the modeler defines the initial power flow. Based on this initial power flow, the model is run for the first time. When running the model, two problems may occur. The first problem that can be faced is that the model does not converge. When the model is not converged the modeler should adjust the controllers or initial load flow. The second problem that can take place is congestion in the lines or buses. The model assumes that a line is operational when the line loading percentage is between 20% and 80%. In addition, the model assumes that a bus is operational when the bus voltage per unit (pu) is between 0.95 and 1.05. If the model converged and no congestion features, then the modeler can define the next time step. If the model does not converge then the modeler can make further adjustments to the controllers and initial load flow until the model converges. If the established model leads to a solution without congestion and the model fully converges for the desired time steps, the calibration has been successfully performed.

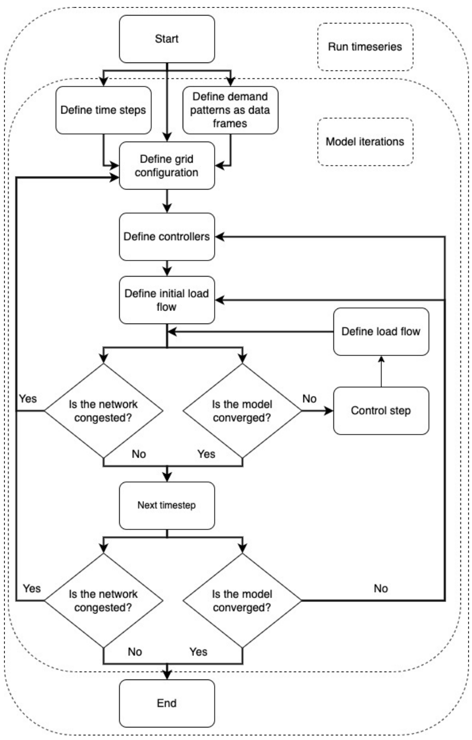



*Figure 16: A visualization of the method used to calibrate the model*

### 8.5.2 – Power flow analysis results

After performing the calibration, the same grid configuration can be used to analyze the impact of electrifying the heat demand on the power grid in Business Park Technopolis. For modeling the impact on the power grid, the grid configurations and controllers have been kept the same. Thus, this model assumes that the model as established through a calibration method will not be adjusted or reinforced until the total heat demand is electrified in Business Park Technopolis. The network that follows from the calibration is visualized in Figure 17. This figure shows the network created projected onto a map of Business Park Technopolis. Because the network is based on a calibration method, Figure 17 does not show the actual power grid of the Business Park Technopolis. The demand patterns used for the power flow analysis are provided in Appendix G1. In this section an answer is formed to the sub-sub-question: *Where and when can congestion be expected after an all-electric strategy is integrated as a heat transition vision?*

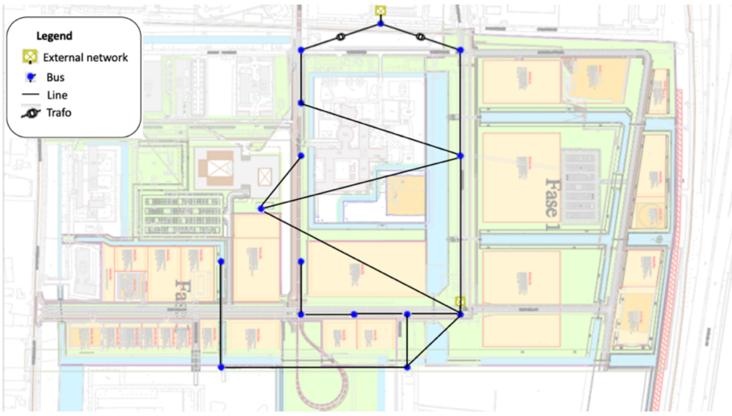



*Figure 17: A visualization of the power grid that follows from the calibration projected onto a map of Business Park Technoopolis*

### *8.5.2.1 – Power supply and demand profiles*

The first result generated by the model are the total generation capacities for each hour during a day. Figure 18 visualizes the total generation capacity before and after the electrification of the heat demand. The result shows that the maximum generation capacity before the electrification of the heat demand increases from ~5 MW to ~11 MW after electrification. This is because the grid configurations remained the same (e.g., number of end-users, network configuration, and local power supply) while the electricity demand increased, as shown in Figure 15. The results further show that in the sixth hour the generation demand after the electrification of the heat demand increases from ~3MW to ~11MW, while the situation before electrification features an increase from ~3MW to ~4MW. Finally, it becomes clear that after the electrification of heat demand, the largest peak generation capacity is located between the sixth and ninth hour of the day, while in the situation before the electrification the peak was around the seventeenth and nineteenth hour. In other words, the peak generation capacity shifted from the evening to the morning according to the outcomes of the model.

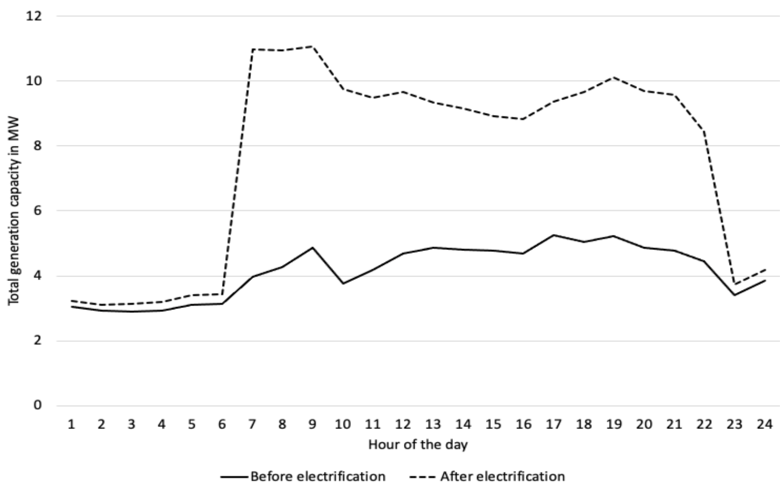
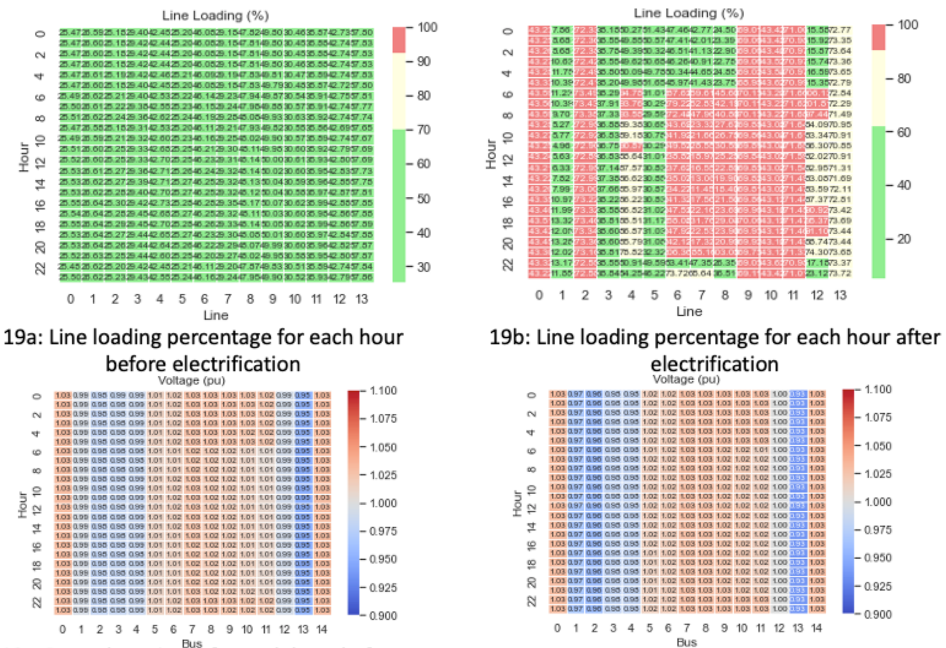



*Figure 18: An overview of the total electricity generation before and after the electrification of the heat demand*

### 8.5.2.2 – Line and bus constraints

After identifying the power supply and demand profiles in the conventional situation and in the situation where the total heat demand is electrified, the model can also be used to discover potential locations for congestion. The model can determine for each bus and line whether congestion will occur after electrification of the heat demand. The model uses the constraints described in section 8.5.1. The results are shown in Figure 19.

The results showed the impact of the electrification of the heat demand on the power grid. For example, it was found that the increasing demand for electricity due to the electrification of the heat demand leads to congestion in the calibrated model. The congestion is shown in Figure 18b with boxes highlighted in red. From the figure, it becomes clear that congestion occurs throughout the day in lines 0, 2, 9,10, and 11. In lines 6, 7, and 8 congestion occurs mainly between 6:00 a.m. and 9:00 p.m. Also, in lines 4 and 12 the capacity exceeds the line loading percentage of 80%. In addition, the results show that the electrification of the heat demand also impacts the bus voltages. However, the results show that most buses do not face challenges related to congestion. All voltages per unit are within the range of 0.95-1.05 except bus 13 which features a per unit voltage of 0.93.



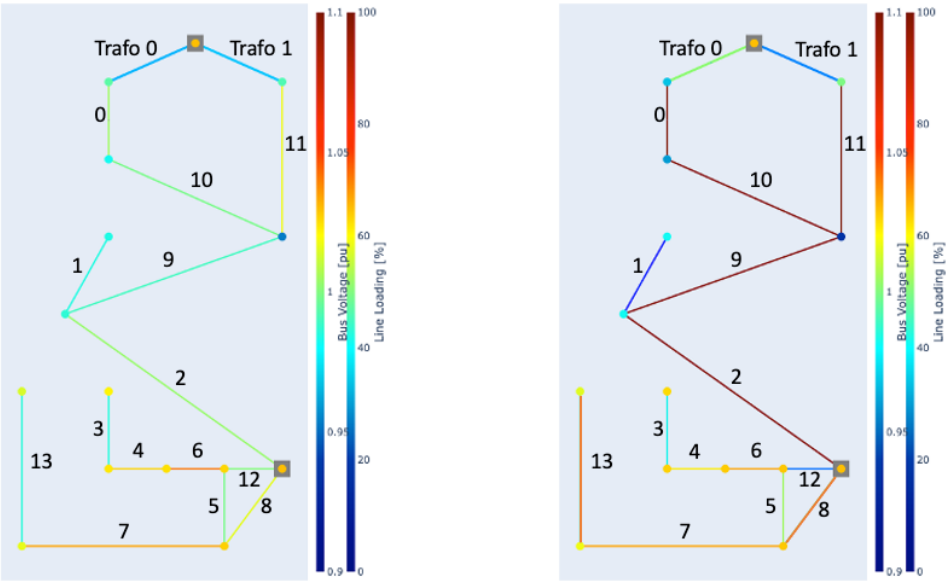
19a: Line loading percentage for each hour before electrification
19b: Line loading percentage for each hour after electrification
19c: Bus voltage in pu for each hour before electrification
19d: Bus voltage in pu for each hour before electrification

*Figure 19: An overview of the bus voltages and line loadings before and after the electrification of the heat demand in Business Park Technopolis calculated with Pandapower*

### 8.5.2.3 – Network visualization

Finally, using Pandapower, it is possible to visualize the power grid after the electrification of the heat demand. Here, again, the calibrated network as shown in Figure 20a was used. This calibrated model is characterized by a network that features no congestion based on the hourly demand patterns for the electrification of the heat demand. The results are shown in Figure 20.

The results showed that the increasing demand due to the electrification of the heat demand leads to congestion in the fictious power grid of Business Park Technopolis. Lines 0, 2, 9, 10, and 11 are congested following the increasing electricity demand. The results showed that the line loading percentages of these lines are exceeding the upper limit capacity. All the lines that exceed the upper capacity limit are marked in red in Figure 20b while the lines that exceed the lower limit capacity are marked in blue. Furthermore, it becomes clear that, based on the location of the end-users within the power grid, most congestion occurs among large consumers. Thus, the results show that congestion occurs mainly at the location where supermarkets, large offices, and hotels are located. These types of end-users are located at the ends of lines 2, 9, and 10 (see Appendix G2). As a result of these congested lines, insufficient electricity can flow to line 1 resulting in a line loading percentage that is below the lower limit capacity. Furthermore, the results show that the capacity of none of the buses is exceeded. Buses that are connected with lines that are not congested characterize an increase in electricity input. However, this does not lead to capacity overruns. At locations where the line capacity is exceeded, it also becomes clear that the buses characterize a decrease in electricity input. This is because, according to the model results, not enough electricity can flow to these buses.




20a: Network before electrification

20b: Network after electrification

*Figure 20: A visualization of the power grid in Business Park Technopolis before and after the electrification of the heat demand calculated with Pandapower*

## 8.7 – Results validity and interpretation of the case study

In this chapter, Pandapower was used as a power flow analysis tool to analyze the impact of the all-electric strategy on the existing power grid. For this analysis, a fictitious grid was used due to a lack of advanced grid data. This has led to a grid that is based on a calibration technique in which a grid is set up where no congestion occurs given the hourly demand patterns described by Voulis (2019). This approach has a significant impact on the validity and interpretation of the results.

It is first important to recognize that the demand patterns described by Voulis (2019) do not directly relate to the actual demand patterns within the Business Park Technopolis. Nevertheless, these demand patterns were used in the creation of demand profiles for the power flow analysis to provide the best possible indication of the role of the model within the decision-making. For example, based on data from the BAG, a categorization of the different types of actors within the Business Park Technopolis has been performed. Based on these type of end-users, demand patterns have been drawn up. It is further assumed that each type of end-user characterizes the same demand patterns and that the number of mapped end-users will not change before 2050. In interpreting the results, it is important to recognize that the demand patterns are drawn up for illustrative purposes only. After all, the model only works if demand patterns are defined as input data.

Furthermore, the network used is based on a calibration technique where a network was developed where no congestion occurs resulting in a network configuration that says nothing about the actual power grid in the Business Park Technopolis. Moreover, the model assumes that 14 buses are connected to an average of four end-users. Adjustments in the network configuration cause significant differences in results, as was discovered during the calculations. When interpreting the results, it is, therefore, important to recognize that the visualized network cannot be used to analyze the actual impact of the all-electric strategy on the power grid within the Business Park Technopolis. The model developed was designed to describe a method rather than an actual analysis. If a modeler has access to advanced grid data, such as grid configurations and real-time demand patterns, then an opportunity arises to use the tool to analyze the actual impact of the all-electric strategy on a power grid.

## 8.8 – Conclusion to sub-question three

In this chapter, a model is developed that can facilitate decision-making by identifying potential congestion points in the existing power grid after the electrification of the total heat demand. To indicate the contribution of the model within decision-making, a neighborhood within the municipality of Delft is used that features the lowest national costs for the all-electric strategy. By using a real-life case, an answer was formed to the following sub-question: *How could the results of the Vesta MAIS model be used to assess the feasibility of the heat transition in terms of grid congestion?*

This chapter has described a method for developing an energy model whose outcomes can be interpreted by actors with less expertise. In this way, the application of the model helps to improve decision-making in the heat transition by extending the technical aspects of the Vesta MAIS model. For example, the modeler can add input variables, such as line, bus, and external grid configurations. Besides, the modeler can define hourly demand patterns, transformers, hourly load supplies, load constraints, and controllers. These input variables can, if the modeler has access to advanced grid data, be based on an existing grid configuration. If this data is not available to the modeler, then, as in this study, a calibration method can be performed to provide an indication of the impact of electrifying the heat demand. However, the choice of input variables affects the interpretability of the results. When using existing grid configurations, the actual impact of the all-electric strategy on the power grid can be analyzed, while a fictitious grid configuration can only be used to describe a method to analyze the impact.

The application of the model to the Business Park Technopolis showed that the peak generation capacity after the electrification of the heat demand is located in the morning while the situation before electrification featured a peak in the evening. The peak generation after electrification is ~11MW while the peak before the electrification was ~4MW. In addition, the results showed that electrifying the heat demand leads to congestion in the lines. This line congestion occurs throughout the day. Furthermore, the model showed that most buses are not faced with congestion since the voltages are within the lower and upper limits of the bus voltages. However, calculating congestion for buses depends on the connection to the type of end-user. It has been found that a different classification of end-users has a significant impact on the results of the model. Finally, using Pandapower, a grid was visualized showing the location of congestion. The results showed that congestion mainly occurs at the large consumers, such as supermarkets, large offices, and hotels. Because the visualized network shows an easy to interpret result, the tool can be used by decision-makers to identify where reinforcements are necessary to successfully electrify the heat demand. In this way, the developed tool contributes to facilitating decision-making within the heat transition.

# Chapter 9 – Discussion

This study is designed to describe a systematic approach that can contribute to the facilitation of decision-making within the heat transition. This chapter reflects on the systematic approach. For example, section 9.1 reflects on the assumptions used for the power flow analysis, while section 9.2 reflects on the scientific and social contribution of the study. Section 9.3 describes the limitations of the systematic approach. The generalizability of the systematic approach is described in section 9.4. Finally, future research recommendations are described in section 9.5.

## 9.1 – Reflection on assumptions

The first assumption made when creating the energy model is that electrifying the heat demand only affects the power grid in a single neighborhood. This assumption was made because the energy model describes a distribution network. Therefore, the model can only be used to analyze the impact of the heat transition on the power grid of an individual neighborhood. The advantage of this assumption is that it allows the energy model to be used to determine on a neighborhood level whether congestion occurs as a result of the heat transition. This capability allows municipalities to determine at a neighborhood level whether a heat transition vision is feasible in terms of grid congestion, making the model suitable to contribute to the local approach used in the Netherlands. The disadvantage of this assumption is that the feasibility at the municipal level, using the energy model developed, is more difficult to determine. This is because surrounding neighborhoods often have access to the same energy sources and will therefore generally use an equivalent heat transition vision. Analyzing the impact of electrifying the heat demand on the power grid at the neighborhood level says nothing about the feasibility of the heat transition vision at the municipal level.

Another important assumption applied in the development of the energy model relates to the hourly demand patterns. The uncertainties regarding technological developments and new construction projects in the municipality have led to a lack of reliable demand patterns. Since the energy model can only be applied if hourly demand patterns are defined as an input, demand patterns were established using a study by Voulis (2019). Within this study, it was assumed that these demand patterns are representative of the Business Park Technopolis. Moreover, it has been assumed that each type of end-user features the same hourly demand patterns. The advantage of these assumptions are that in this way the model can easily be used to analyze the impact on the power grid without the modeler having access to advanced and uncertain hourly demand patterns. The disadvantage of this assumption, however, is that the model describes a flawed reality. Indeed, it can be assumed that the hourly demand patterns in the Business Park Technopolis are different from the demand patterns described by Voulis (2019).

In preparing the hourly demand patterns as input data for the power flow analysis, it was further assumed that the total demand for natural gas for space heating and tap water heating is completely replaced by electricity. This assumption implies that no efficiency improvements are made by replacing the total demand for natural gas with electricity. The advantage of this assumption is that it allows demand patterns to be established without the modeler having access to advanced data related to hourly demand patterns. The disadvantage of this approach is that the electricity demand is overestimated because it can be expected that efficiency improvements reduce the electricity demand. For example, it can be assumed that insulation improvements will lead to reduced electricity demand. However, because this assumption leads to an overestimation of electricity demand, it can impact the feasibility of a heat transition vision. This is because the power grid has both an upper and a lower limit capacity. The electricity demand must be within these limits to ensure that the network remains operational. If an overestimation of the demand for electricity leads to a “real” value that is below the lower limit, then the model will identify a feasible scenario while in reality, this does not lead to a feasible situation.

Furthermore, when the network is created in Pandapower, it is assumed that there are 14 buses and 13 lines in the distribution network within the Business Park Technopolis. These data were randomly chosen to create a first guess, which is necessary for calibrating the model. In addition, when classifying the type of end-users into the network, a logical positioning was assumed. The location of the end-user and the classification, as shown when running the model, has a significant impact on the results of the power flow analysis. The advantage of these assumptions are that a modeler without access to geographic grid data can run a power flow analysis to gain generic insights into the impact of the heat transition on the power grid. The disadvantage of this assumption, however, is that the results of the power flow analysis say nothing about the actual impact of the electrification of the heat demand on the existing power grid in the Business Park Technopolis.

Finally, using a power flow analysis, the impact of electrifying the heat demand is based on the impact relative to a calibrated network. This calibrated network is set up to create a network in which, given the hourly demand patterns described by Voulis (2019), there is no congestion. The advantage of this assumption is that the modeler can obtain a general indication of the impact of electrifying the heat demand on the power grid without having access to advanced grid data (e.g., bus en line capacities). The disadvantage of this assumption, however, is that the results of the power flow analysis say nothing about the actual impact of the electrification of the heat demand on the power grid in Business Park Technopolis. If the modeler has access to advanced grid data, then the developed model can be used to simulate an existing power grid.

## 9.2 - Reflection on scientific and social contribution

Due to a lack of data and the assumptions used to perform a power flow analysis described in the previous section, this study was designed to describe an approach rather than an actual analysis. Nevertheless, the described approach showed an attempt to fill the knowledge gap described in section 1.4.1. This knowledge gap describes the lack of an approach that integrates social, technical, and economic aspects to facilitate decision-making within the heat transition at the municipal level. This study aimed to describe an approach consisting of three steps that considers the socio-technical environment in which the heat transition is embedded. In this way, the study has a scientific contribution in that it can (partially) fill the knowledge gap. Moreover, this study has a social contribution in that the systematic approach helps to solve two main social problems. First, the systematic approach contributes to the process of replacing thermal energy produced by natural gas sources with sustainable alternative heat sources. Second, the study describes a way to design an approach based on imperfect data that helps facilitate decision-making in the heat transition.

However, there are two reasons why this study did not entirely fill the knowledge gap. The first reason relates to the lack of a method to directly translate the data from the Vesta MAIS model into suitable input data for a power flow analysis. The Vesta MAIS model can be used to calculate annual average electricity demand, while a power flow analysis uses hourly demand patterns to analyze the impact on the power grid. This causes stagnation in the proposed systematic approach because going through the approach requires an advanced translation method to make the results of the Vesta MAIS model complementary to the power flow analysis input requirements. The second reason relates to the integration of an actor analysis. Because the systematic approach is characterized by an actor analysis performed separately from the Vesta MAIS model and power flow analysis, the actor analysis can only be used to contextualize the systematic approach. To integrate social aspects quantitatively into the Vesta MAIS model, there is an opportunity, as described in section 5.6, to integrate an ABM.

The literature review in section 1.4 showed several attempts to describe an approach that can contribute to the facilitation of decision-making within the heat transition while considering the surrounding socio-technical environment. There have been attempts to link quantitative energy models, which are capable of providing technical and economic insights, to socio-technical modeling approaches. This study did not aim to integrate these modelling approaches into one single model, but to identify the social insights separately from the quantitative modelling approaches. In this way, an equivalent method to the multi-model ecology described by Bollinger et al. (2018) was performed in this study. The difference, however, is that the approach in this study assumes bounded rationality and a lack of data for decision-makers. In this way, the approach described in this study is considered more capable of being used at the municipal level.

## 9.3 – Limitations of the systematic approach and result validation methods

In designing a systematic approach that contributes to facilitating decision-making within the heat transition, the importance of the right data has been demonstrated. Because the approach described is based on a fictitious grid, the systematic approach cannot be used to analyze the actual impact of the heat transition on the power grid. The lack of data affects the feasibility of the approach. Indeed, if decision-makers do not have access to advanced grid data, then the proposed approach can only serve as an indication and not for facilitating data-driven decision-making. Besides the lack of advanced grid data, comprehensive validation methods are recommended before applying the systematic approach for facilitating decision-making.

The first method recommended to validate the systematic approach is to present the approach to experts. The experts can then contribute to triangulating the approach by providing professional insights. Grid operators can serve as experts because these operators can relate advanced grid data to the systematic approach. The second method uses an equivalent study. This could include a study in which an attempt has been made to describe a systematic approach that considers the socio-technical context. Finally, the systematic approach can be validated by application to an existing power grid. This requires the power flow analysis to be based on existing grid configurations, including grid capacities and coordinates. By comparing the outcomes of the systematic approach with the outcomes of grid operators, it is expected that a clear understanding of the validity of the systematic approach can be obtained.

## 9.4 – Generalizability of the systematic approach

Although the systematic approach described has been prepared using a case, the approach can also be applied in other municipalities. To explain how the systematic approach can be generalized, the heat plan described in Chapter 4 is used. In this section, first, the role of the systematic approach is determined within the heat plan of Delft. Then it has been examined what role the systematic approach can have within other municipalities.

Chapter 4 showed that the heat plan is based on a district-oriented approach. This corresponds to the proposed systematic approach that can be applied at the district level to facilitate decision-making (Ministry of Economic Affairs and Climate Policy, 2019; Tolliver et al., 2019). Moreover, the municipality of Delft can use the systematic approach in assessing and guaranteeing the principles that form the basis of the heat plan (See section 4.2). For example, the systematic approach can be used to (1) identify affordability and costs, (2) to assess the feasibility of an envisioned scenario pathway, and (3) for the the integral approach. The application of the techno-economic Vesta MAIS model can be used to calculate the national costs per transition vision to determine the affordability, in terms of economic aspects, per vision. In addition, the feasibility based on technical aspects can be determined using a power flow analysis. This analysis can be applied to determine the feasibility of a transition vision on the power grid in terms of grid congestion. Finally, the systematic approach contributes to the integral approach since the actor analysis allows the municipality of Delft to identify actors with corresponding interests and objectives. In this way, the municipality can use an approach that not only leads to improving sustainability but also to improving the living environment.

The municipality of Delft is not the only municipality in the Netherlands with a heat plan. Every municipality in the Netherlands is required to have a heat transition vision in place by 2021 describing a district-oriented approach to implement the heat transition vision (Henrich et al., 2021; Xavier & Hesselink, 2021). This district-oriented approach is described in a "Wijkuitvoeringsplan" (district implementation plan) in which the municipality together with other parties involved, including the housing corporations, describes the heat transition vision (Diran et al., 2020; Henrich et al., 2021). The “Wijkuitvoeringsplan” consists of three main aspects including substantive features, participation and alignment, and decision-making (PAW, 2022). The substantive features consist of the agreements made in the (inter)national climate agreement, providing insights into the timeline, scale, and the goals of insulating and making buildings natural gas-free (Henrich et al., 2021). Participation and alignment focus on involving stakeholders, including residents, building owners, and other actors. Decision-making includes plans based on a district-oriented approach (Henrich et al., 2021; PAW, 2022). Based on the aspects of the “Wijkuitvoeringsplan”, the role of the systematic approach becomes clear to other municipalities. The approach can contribute to guaranteeing social participation and to the identification of substantive features in a district-oriented manner. When municipalities use the systematic approach, it will be possible to facilitate decision-making that contributes to the heat transition based on the necessary aspects of the “Wijkuitvoeringsplan”.

## 9.5 – Future research recommendations

After conducting this study, there are some future research recommendations. The first recommendation is described in section 5.6 and describes the added value of an ABM within the techno-economic Vesta MAIS model. Integrating an ABM can add value by enriching the Vesta MAIS model with social aspects. The second future research recommendation focuses on developing a “bridge” between the Vesta MAIS model and a power flow analysis. Due to a lack of advanced data regarding hourly demand patterns, the demand patterns described by Voulis (2019) were used in this study. However, these demand patterns are not representative of the Business Park Technopolis. Follow-up research is needed to discover what possibilities there are to translate the average annual electricity demand into hourly demand patterns. In this way, the results of the Vesta MAIS model can be used directly in a power flow analysis. The third future research recommendation relates to the development of an energy model focused on the impact of the heat transition on the gas and heat grid. After all, the heat transition also affects the demand for gas and heat. It is therefore important that decision-makers have access to a model that analyzes this impact to examine the feasibility of envisaged scenario pathways. Finally, a future research recommendation is formed by applying the power flow analysis based on an existing network, including grid capacities and grid coordinates, to determine the reliability of the energy model. In this way, the role of the energy model within data-driven policymaking can be investigated as the model can be supplemented with existing grid data.

# Chapter 10 – Conclusion

In this research, an answer is formed to the main research question and corresponding sub-questions as formulated in section 1.5. The main research question that is answered in this study is *How could an approach be designed to improve decision-making within the heat transition at the municipal level while considering the surrounding socio-technical environment?* Because the heat transition is embedded in a socio-technical environment, it is recommended to establish a systematic approach that considers the interaction between social, technical, and economic aspects.

To form an answer to the main research question, the first sub-question was formulated: *How could an actor analysis be integrated into an approach aimed at facilitating decision-making at the municipal level within the heat transition?* The results showed that the current Vesta MAIS model, which can be used by municipalities to determine the most appropriate heat transition vision, is hardly capable of integrating social aspects. The model predominantly focuses on economic and technical aspects. Although these aspects play an important role in decision-making, the model lacks the ability to integrate all non-rational aspects, including the willingness to participate in the heat transition and technological preferences. To integrate these non-rational aspects, this study showed an opportunity to perform an actor analysis before running the Vesta MAIS model. To show the contribution of an actor analysis, this study uses the step-by-step actor analysis as described by Enserink et al. (2010). The method is divided into six steps that gradually lead to the identification and categorization of actors and can be used before applying the techno-economic Vesta MAIS model. In this way, the actor analysis can provide valuable non-rational insights which affect the heat transition. The categorization of actors is performed using a power-interest diagram that classifies actors based on the objectives and interests. Here, actors with high power can directly influence decision-making within the heat transition, while actors with less power can only operate within the framework of decision-making. Even though the Vesta MAIS model does not directly distinguish between actors, it has been shown that the results of the model can be interpreted by different actors. For example, the model can describe a cost distribution that distinguishes between the real-estate owner, the grid operator, and the owner of the heat source. Finally, it has been described how an ABM can enrich the existing Vesta MAIS model by adding social factors.

Then, by applying the Vesta MAIS model, an answer was formulated to the following sub-question: *How could the techno-economic outcomes of the Vesta MAIS model be used to facilitate decision-making at the municipal level?* The application of the Vesta MAIS model represents the second step in the systematic approach and is intended to obtain technical and economic insights (e.g., the share of energy carriers and national cost per heat transition vision). Furthermore, it was shown that the Vesta MAIS model can be used by decision-makers as an explorative, informative, and supportive tool in decision-making. In this study, it has been shown that the Vesta MAIS model can generate national costs and identify changes in the share of each energy carrier per heat transition vision. Based on the national costs, the Vesta MAIS model can be used to find the heat transition vision in individual neighborhoods that has the most potential to replace natural gas-driven heat sources. Applying the model to the municipality of Delft, it was found that all neighborhoods with priority face higher national costs regardless of which heat transition vision is followed. Furthermore, it was found that most neighborhoods characterize the lowest national costs with the collective heating strategy using MT-heat sources, where households must have at least insulation label D and utility buildings label B. In addition, the model showed that for the priority neighborhoods, the share of natural gas is going to disappear in 2030 and the share of electricity is going to increase, regardless of the chosen heat transition vision. Thus, analyzing the impact of the heat transition on the power grid is necessary not only for neighborhoods that will electrify the entire heat demand but also for other neighborhoods. Finally, it was found that there are only two neighborhoods in Delft that characterize the lowest national costs for the all-electric strategy. This is because electrifying the heat demand is characterized by high national costs relative to the other heat transition visions, which in many cases makes the strategy unsuitable.

Finally, a power flow analysis is used to answer the following sub-question: *How could the results of the Vesta MAIS model be used to assess the feasibility of the heat transition in terms of grid congestion?* The power flow analysis will be used as a third step in the systematic approach to complement the technical insights obtained from the Vesta MAIS model with insights into grid congestions. To answer this sub-question, a model was developed in which the modeler can mimic an existing network or calibrate a fictitious network. In this study, due to a lack of advanced grid data, a calibration technique was used to establish a fictitious grid. Using the fictitious grid, the modeler can determine the impact of a heat transition vision compared to a power grid that does not contain congestion. In doing so, the modeler can define input variables, including line and bus properties, external grid configurations, hourly demand patterns, transformers, hourly load supplies, load constraints, and controllers. In this study, the contribution of the model in facilitating decision-making was determined by applying the model to an existing neighborhood. The results showed that the model can identify additional technical insights, as the model can determine the location and time of congestion based on hourly demand patterns. In this way, decision-makers can determine at an early stage whether a heat transition vision is feasible and where possible reinforcements or adjustments to the network should be made. Applying the power flow analysis on the Business Park Technopolis, the model showed that congestion occurs mainly at locations where there are large consumers connected, such as hotels, large offices, and supermarkets. In addition, using the model, it is possible to identify at what times the demand for electricity is greatest. For example, the results showed that the peak generation shifted from the evening to the morning after the electrification of the heat demand.

Answering the sub-questions eventually led to answering the main research question. Using a case, a systematic approach was described which contributes to improving decision-making in the heat transition in Delft. A visualization of the approach is depicted in Figure 21. The systematic approach, as proposed in this study, consists of three steps. The first step is characterized by the actor analysis resulting in social insights containing non-rational aspects that affect the heat transition. The second step is characterized by the application of the techno-economic Vesta MAIS model resulting in technical and economic insights. Finally, the technical insights are extended through a power flow analysis. The proposed power flow analysis is set up in such a way that decision-makers with less expertise can interpret the results to facilitate decision-making. Answering the main research question led to a systematic approach that considers social, technical, and economic aspects. Because the drawing up of the systematic approach is described transparently, other municipalities can also learn from this approach allowing other decision-makers to make decisions within the context of a socio-technical environment in which the heat transition is embedded. In this way, this study has both a scientific and social contribution as it is considered that the systematic approach contributes to improving decision-making within the heat transition in the Netherlands.

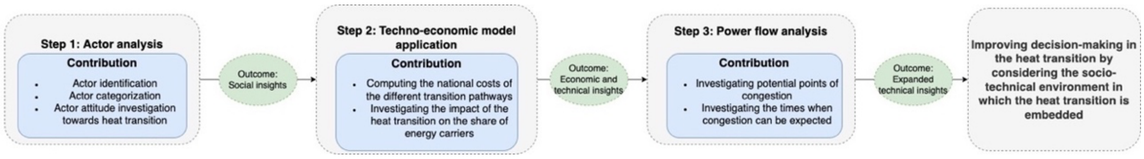



*Figure 21: A visualization of the proposed systematic approach to facilitate decision-making in the heat transition in The Netherlands*

# Reflection

To perform a Master's thesis project, I was looking for a topic that would contribute to the energy transition in the Netherlands. Eventually, this search led to the topic “heat transition”. The topic was proposed by Prof.dr.ir. Z. Lukszo and Caroline Fernandes Faries from TU Delft in collaboration with GO-e project and PBL-Netherlands. The research aimed to develop a spatial energy model that could be used on top of the existing techno-economic Vesta MAIS model to determine the impact of the heat transition in the built environment. The goal was to simulate an existing low/medium voltage grid for a neighborhood. After writing a research proposal the kick-off meeting took place in February 2022. During this kick-off meeting, some adjustments were discussed to ensure that the research was feasible within the available six months. The biggest challenge of the research was finding the appropriate data. Because data related to a power grid is hardly publicly available, I had to come up with a way to conduct the research based on the available data. During the kick-off meeting, it was therefore decided to simulate a distribution network using Pandapower. Using a calibration technique, a fictitious grid was set up. This fictitious grid could then be used to get an indication of the impact of the heat transition on the existing power grid.

During the Master thesis project, I learned a lot about how to conduct research. In addition, the study provided me with insights into the challenges of the energy transition. Besides, I learned that visualizing ideas is often a good way to make clear what needs to be accomplished. When I look back on the past period I think that I could have structured the project more efficiently by making clear in advance what I wanted to achieve. Due to the different insights I gained during the appointments with my supervisors, the research changed several times. In addition, one of the supervisors that had expertise in using Python to develop an energy model quit halfway through the project. The role of this supervisor was eventually filled by another supervisor working within GO-e project. Due to a lack of expertise with Python, it took me a long time to develop the model. Nonetheless, I learned a lot about Python as a result because I had to use the manual and instructional videos. So as far as I know, the model is running as it should. Furthermore, I experienced the importance of a research proposal. These proposals provide structure and support during the project.

In this project, a modeling approach in combination with a case study is used. During the master Complex Systems Engineering and Management (CoSEM) I learned a lot about the complexity of energy transitions. This knowledge I have brought with me to this study. In addition, several courses have contributed to the development and application of energy models for decision-making. I used the knowledge I acquired during these courses to develop an energy model. During the development of the model, I experienced the complexities of a model that tries to describe reality as well as possible. Therefore, several iterations have been used. In addition, I learned what role an energy model can have when there is hardly any reliable data available as input. The knowledge and experience I have gained in the past six months will contribute to the execution of future projects.

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# Appendix

## Appendix A – Introduction and problem identification

### Appendix A1 - A visualization of the energy regions in the Netherlands


Source: (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022)

### Appendix A2 – Sector specific GHG emissions in terms of CO2 equivalents from 1990 - 2020

| Year | Industry | Electricity | Mobility | Agriculture and land use | Built environment | Total |
|---|---|---|---|---|---|---|
| 1990 | 86,4 | 39,6 | 32,2 | 32,4 | 29,9 | 220,5 |
| 1991 | 87,5 | 40,1 | 32,7 | 33,7 | 34,1 | 228,1 |
| 1992 | 89 | 40,6 | 34,1 | 33,5 | 31,5 | 228,7 |
| 1993 | 85,5 | 41,9 | 35,2 | 33,6 | 33,3 | 229,5 |
| 1994 | 86,7 | 45,7 | 34,6 | 32,1 | 31,1 | 230,2 |
| 1995 | 81,9 | 47,8 | 35,2 | 32,1 | 33,2 | 230,2 |
| 1996 | 84,8 | 48,3 | 36,6 | 32,8 | 38,5 | 241 |
| 1997 | 84,6 | 48,5 | 36,6 | 30,6 | 32,7 | 233 |
| 1998 | 84,8 | 50,2 | 37,3 | 29,7 | 31,3 | 233,3 |
| 1999 | 76 | 47,2 | 38,1 | 28,9 | 29,7 | 219,9 |
| 2000 | 74,3 | 48,4 | 37,9 | 27,8 | 29,6 | 218 |
| 2001 | 69,9 | 51,9 | 38,2 | 27,2 | 31,4 | 218,6 |
| 2002 | 69,1 | 53 | 38,7 | 25,5 | 30,2 | 216,5 |
| 2003 | 67,8 | 53,7 | 39,1 | 25,2 | 31,3 | 217,1 |
| 2004 | 67,9 | 54,9 | 39,5 | 25,2 | 31,1 | 218,6 |
| 2005 | 66,3 | 52,1 | 39,8 | 25,4 | 29,3 | 212,9 |
| 2006 | 64,9 | 47,9 | 40,7 | 25 | 29,4 | 207,9 |
| 2007 | 64,1 | 50,6 | 39,7 | 25,6 | 26,3 | 206,3 |
| 2008 | 59,8 | 50 | 39,9 | 26,7 | 29,3 | 205,7 |
| 2009 | 55,8 | 49,9 | 38,3 | 26,7 | 29,3 | 200 |
| 2010 | 58,8 | 52 | 39 | 28,3 | 33,9 | 212 |
| 2011 | 57,6 | 47,8 | 38,9 | 26,8 | 26,6 | 197,7 |
| 2012 | 56,3 | 44,8 | 37,1 | 26,6 | 28,8 | 193,6 |
| 2013 | 55,8 | 44,9 | 36,3 | 26,8 | 30 | 193,8 |
| 2014 | 54,6 | 48,6 | 34,3 | 25,6 | 22,9 | 186 |
| 2015 | 54,4 | 53,1 | 34,6 | 26,6 | 24,4 | 193,1 |
| 2016 | 55 | 52 | 34,8 | 26,7 | 25,1 | 193,6 |
| 2017 | 55,9 | 48,3 | 35,3 | 27 | 24,6 | 191,1 |
| 2018 | 54,7 | 44,6 | 35,8 | 26,7 | 24,2 | 186 |
| 2019 | 53,9 | 41,5 | 35,1 | 26,5 | 23,1 | 180,1 |
| 2020 | 53,1 | 32,7 | 30,6 | 26,2 | 21,8 | 164,4 |
| **Share of each sector** | 0,322993 | 0,198905109 | 0,18613139 | 0,159367397 | 0,132603406 | 164,4 |

Source: (CBS, 2022)

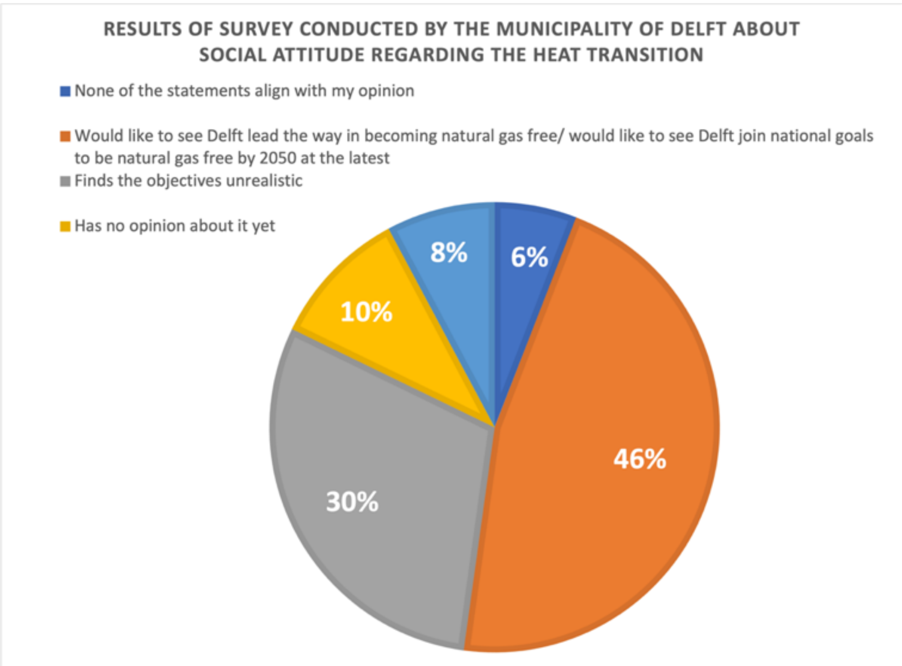
## Appendix A3 – GHG emissions in terms of CO2 equivalents from the built environment

| | Households | Utility buildings |
|---|---|---|
| 1990 | 21,5 | 8,4 |
| 1991 | 24,6 | 9,5 |
| 1992 | 22,7 | 8,8 |
| 1993 | 23,8 | 9,5 |
| 1994 | 22,3 | 8,8 |
| 1995 | 24,1 | 9 |
| 1996 | 28,1 | 10,4 |
| 1997 | 23,6 | 9,1 |
| 1998 | 22,4 | 8,8 |
| 1999 | 21,3 | 8,4 |
| 2000 | 21,3 | 8,3 |
| 2001 | 22,5 | 8,9 |
| 2002 | 21,7 | 8,4 |
| 2003 | 22,2 | 9,1 |
| 2004 | 21,3 | 9,8 |
| 2005 | 20,5 | 8,8 |
| 2006 | 20,6 | 8,8 |
| 2007 | 18,4 | 7,9 |
| 2008 | 20,8 | 8,5 |
| 2009 | 20,7 | 8,6 |
| 2010 | 24,1 | 9,8 |
| 2011 | 18,8 | 7,8 |
| 2012 | 20 | 8,7 |
| 2013 | 21,2 | 8,7 |
| 2014 | 15,9 | 6,9 |
| 2015 | 17 | 7,4 |
| 2016 | 17,7 | 7,5 |
| 2017 | 17,2 | 7,4 |
| 2018 | 17 | 7,2 |
| 2019 | 16,1 | 6,9 |
| 2020 | 15,3 | 6,3 |

Source: (CBS, 2022)

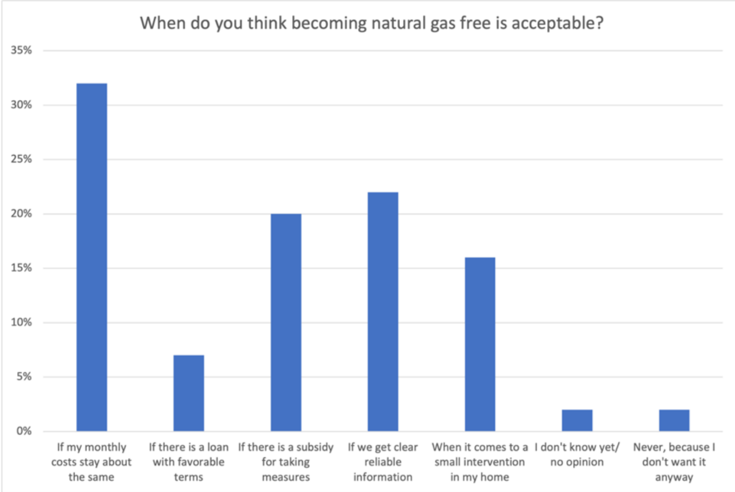
# Appendix B - Case study: The municipality of Delft

## Appendix B1 – Overview of the results of the study conducted by the municipality of Delft in determining social attitudes towards the heat transition




Source: (Delft, 2021)

### Appendix B2 - An overview of end-user reasons for accepting natural gas-free heat sources




Source: (Delft, 2021)

## Appendix C – Case study-Delft

### Appendix C1 – Weighting criteria attached to the criteria in prioritizing the neighborhoods

| ***Criteria*** | ***Weight*** |
|---|---|
| *National costs* | 3 |
| *End user costs* | 5 |
| *$CO_2$ reduction* | 3 |
| *Availability of renewable gas* | 3 |
| *Connecting to ongoing energy projects* | 5 |
| *Connecting to new construction / neighborhood improvements* | 5 |
| *Planned work: sewerage* | 4 |
| *Planned work: Gas grid* | 1 |
| *% Corporate ownership* | 4 |
| *% private rent* | 2 |

Source: (Delft, 2021)

## Appendix D – Actor analysis

### Appendix D1 – Actor identification

The end-users consist of the various households and utility owners within the municipality of Delft. The households are comprised of private end-users while the utility owners are comprised of owners of businesses, hotels, schools, hospitals, and shops (PBL, 2022). The housing corporations are all non-departmental public bodies that rent housing to people. Local neighborhood initiatives are, for example, local initiatives aimed at making their own neighborhood more sustainable. An example of such a local initiative is the energy cooperative Deelstroom Delft (Delft, 2021).

The operational parties include investors and banks, installation companies, project developers, and research institutes. In the municipality of Delft, the grid operator Stedin is an important installation company because Stedin can make adjustments and reinforcements to the existing energy network (Henrich et al., 2021). Gasunie also plays an important role in making adjustments to the gas network. For instance, Gasunie is the developer of WarmtelinQ (Delft, 2021). Besides, Netverder is an important installation company involved in the development of heat networks in Delft (Delft, 2021). The project developers in Delft are mainly departments of the municipality combined with some external collaborations with specialized companies. Investments are made by banks and investment companies such as pension funds (Delft, 2021). Finally, there are some research institutes that contribute to the heat transition in Delft. The main actors here are TU Delft and CE Delft (Delft, 2021).

The regulating parties are formed by international, national, provincial, and municipal agreements. The international agreements are formed by all actors that have signed the Paris climate agreement. However, since the international agreements do not directly affect the heat transition in Delft, it is not considered in the actor analysis. The national regulating parties are formed by the Dutch government, the provincial parties by the Rotterdam-The Hague metropolitan region, and the municipal regulating party is formed by the municipality of Delft (Delft, 2021).

Finally, the energy suppliers. These are formed by the energy providers, grid operators, energy cooperation's, and heat source owners. As the end-user is allowed to choose the energy providers, various parties can be identified in this respect. Large energy providers in Delft are Vattenfall, Eneco, Essent, Engie, NLE, OXXIO, United Consumers, Pure Energie, Budget Energie, Van de Bron, Delta, Powerpeers, and Noord Energie (Delft, 2021). The grid operators comprise both Distribution System Operators (DSO) and Transmission System Operators (TSO). The DSO is responsible for local energy exchange, while the TSO is responsible for the transmission of energy from the energy source to the local distribution grids (Hadush & Meeus, 2018). The owners of a heat source consist of all actors that have an influence on the production of heat. In the case of district heating, this might include factories that produce residual heat. Current companies that supply natural gas are also important actors in the heat transition. Finally, an important actor is formed by energy corporations. These corporations were founded to represent the interests of both the energy provider and the end user and contribute to the purchase of sustainable energy (Delft, 2021).

## Appendix D2 - Identification of interests and objectives of the identified actors

### *Appendix D2.1 - The municipality of Delft*

As described in the introduction, the municipality of Delft is seen as the problem owner of the heat transition within the municipality. The municipality, therefore, has a high interest in the heat transition. This high interest is underpinned by the desire for regional economic development and improving prosperity within the municipality (Henrich et al., 2021). In addition, an important interest is formed by the improvement of sustainability within the municipality to meet international and national climate targets in the long term (Skjærseth et al., 2021). These interests are then translated into strategic and problem-specific objectives. The strategic objective of the municipality is to make life within the city as comfortable as possible by showing understanding, help, and support to the inhabitants (Tolliver et al., 2019). The problem-specific objective is based on the national objectives. In other words, the problem-specific objectives are encompassed by the reduction of greenhouse gases and the reduction of dependency on the natural gas heat network. In addition, the municipality has the objective of providing its residents with the right information and knowledge to ensure that all residents can participate in the heat transition (Khaldi & Sunikka-Blank, 2020; Tolliver et al., 2019).

### *Appendix D2.2 – The province: South-Holland*

The municipality of Delft is located in the province of South-Holland and is therefore dependent on the regulations agreed with all municipalities within the province. Because the province does not have to comply directly with the national targets agreed by the national government, the province has a lower interest than the municipality of Delft. The main justification for the province's interest is to guarantee protection for people and the ecosystem (Tolliver et al., 2019). The main strategic objective of the province is formed by the monitoring of laws and regulations relating to water, air, and soil (Rosas, Gerritsen, Kooij, Groenleer, & Van Der Krabben, 2022; Tolliver et al., 2019). An important problem-specific objective for the municipality is formed by discovering new (sustainable) technological heat sources that can replace the natural gas-driven heat sources (Rosas et al., 2022). Here, the potential of solar, water, and wind energy are considered.

### *Appendix D2.3 – The national government*

The Dutch government is responsible for achieving the targets set in the Paris climate agreement. Moreover, the national government is responsible for translating the national targets into regional targets for the different RES areas (Henrich et al., 2021; Nies & Delors, 2019). Therefore, the national government has a high interest in the heat transition. This high interest is underpinned by the government's desire to improve the national economy, prosperity, and welfare of the population (Nies & Delors, 2019). In addition, the government has the desire to phase out natural gas by 2050 to reduce greenhouse gas emissions and to reduce international dependence (Skjærseth et al., 2021). The main strategic objective of the Dutch government is to guarantee a safe and qualitative living environment for all inhabitants of the Netherlands (Nies & Delors, 2019). To guarantee this, the national government can integrate laws and regulations into society. The problem-specific objective is formed by the desire to reduce greenhouse gas emissions (Khaldi & Sunikka-Blank, 2020; Nies & Delors, 2019; Spier, 2020). Because the Dutch government has signed the Paris climate agreement, it must be actively involved in achieving this reduction. The problem-specific objective of the Dutch government is therefore to comply with the agreements (Nies & Delors, 2019).

### *Appendix D2.4 – Housing corporations*

The housing corporations have a medium interest in the heat transition. This is because the housing corporations are primarily looking for houses with the best living standards (Rosas et al., 2022). Indeed, these types of houses are the most profitable. It does, however, not necessarily mean that the most profitable houses are connected to an alternative heating source. Besides, the highest living standards are not affected by the heat transition. The strategic objectives of the housing corporations are to rent out the highest quality homes possible at the most affordable prices for tenants. The problem-specific objective is to discover the most favorable pathways for the rented houses to meet the standards required of houses during and after the heat transition.

### *Appendix D2.5 – Real estate owner*

Real estate owners have a high interest in the heat transition because this group of actors is directly affected by measures that contribute to the heat transition. This includes, for example, insulation measures. This high interest is underpinned by the fact that real-estate owners are looking for the cheapest alternative to replace conventional technologies with alternative heat sources (Crowe et al., 2011; Rosas et al., 2022). The strategic objective of real-estate owners is formed by the desire to maintain current living habits as far as possible and to retain or increase the value of the building (Rosas et al., 2022). The problem-specific objective is to find the cheapest technological alternatives to replace the natural gas-driven heat sources.

### *Appendix D2.6 – Neighborhood initiatives*

The neighborhood initiatives are characterized by a high level of interest in the heat transition, as this group is driven by the need to improve the quality of life and spread the costs of this over the participants (Hoppe & Miedema, 2020). The strategic objective of these initiatives is to translate collective plans into sustainable developments whereby the costs of the developments are spread among the participants involved in the initiative (Hoppe & Miedema, 2020; Kwakkel & Yücel, 2014). The problem-specific objective is to develop plans that contribute to making specific residential areas more sustainable to contribute to the heat transition while minimizing costs (Hoppe & Miedema, 2020).

### *Appendix D2.7 – Investors and banks*

Investors and banks are instrumental in bringing about the heat transition. The banks themselves have a lower interest in the heat transition because they are not directly affected by what is decided in a heat transition vision (Henrich et al., 2021). The strategic objective of the investors and banks is to make money by lending money. Here, the goal is to invest in the most profitable projects (Khaldi & Sunikka-Blank, 2020). The problem-specific interest is formed by the fact that an investor or bank can provide loans to bring about the heat transition. In this way, money becomes available that can be used, for example, to expand or adapt the energy network (Tolliver et al., 2019). In addition, capital is provided that can be used in the development of new technologies and improvement of existing technologies. Investors also contribute to the implementation of technologies at both neighborhood and building level (Henrich et al., 2021; Tolliver et al., 2019).

### *Appendix D2.8 – Installation companies*

The installation companies themselves have a medium interest in the heat transition. This is because the interest of an installation company is mainly formed by the desire to compete with other companies (Grabowski & Roberts, 1999). In addition, an installation company often receives orders from actors directly involved. The strategic objective is formed by the desire to be profitable during operations. Here, it is assumed that the installation company is a commercial company driven by profitability (Hoppe & Miedema, 2020). The problem-specific objective is formed by the competition with other companies within the heat transition. After all, a competition battle determines which company is allowed to perform the installations. This is often done through tendering, whereby the company with the lowest costs will be awarded the project (Ministry of Economic Affairs and Climate Policy, 2019).

### *Appendix D2.9 – Project developers*

Project developers have a high interest in the heat transition. This is because a project developer determines how a project will be classified based on the lowest cost (Hoppe & Miedema, 2020). In addition, the project developer has a direct impact on the success of the heat transition. The strategic objective of the project developer is to set up a profitable project where sufficient investors are attracted to ensure that the predetermined goals are achieved (Hoppe & Miedema, 2020; Khaldi & Sunikka-Blank, 2020). The problem-specific objective is that the project developer must compete with other developers. Just as with an installation company, the project developer is chosen who can develop a project at the lowest cost (Hoppe & Miedema, 2020).

### *Appendix D2.10 – Research institutes*

The research institutes have a high interest in heat transition. This is because these institutes have a social obligation to improve the quality of life (Hoppe & Miedema, 2020; Ministry of Economic Affairs and Climate Policy, 2019). The ultimate goal of the heat transition is to reduce greenhouse gas emissions resulting from the burning of fossil fuels. In doing so, the heat transition improves well-being within the neighborhood (Kwakkel & Yücel, 2014). The strategic objective of a research institute is formed by the desire for an improved living environment using scientific opportunities. In addition, cooperation with large-scale social problems has a positive effect on the image of an institute (Hoppe & Miedema, 2020; Ministry of Economic Affairs and Climate Policy, 2019). The problem-specific objective is formed by the desire to carry out a successful heat transition in which scientific possibilities contribute to the lowest possible national costs (Hoppe & Miedema, 2020).

### *Appendix D2.11 – Grid operators*

Grid operators also have a high interest in the heat transition. This is because the grid operator is made responsible for implementing adjustments to the energy grid when requested to do so by the municipality (Hoppe & Miedema, 2020; Rosas et al., 2022). In addition, the grid operator is responsible for guaranteeing energy supply at the lowest possible prices (Hoppe & Miedema, 2020). Changes following the heat transition can, as shown in Chapter 6, have a direct impact on the energy grid. The strategic objective of the grid operator is formed by the desire to establish a profitable energy network in which a stable exchange of energy can take place between the supplier and the end-user (Hoppe & Miedema, 2020; Rosas et al., 2022). The problem-specific objective is formed by the desire of a grid operator to discover possible adjustments in time so that the grid does not experience disruptions during and after the heat transition. In addition, the grid operator must ensure that investments in the heat transition are profitable so that it is attractive for investors to invest (Hoppe & Miedema, 2020).

### *Appendix D2.12 – Energy providers*

Energy companies have a high interest in the heat transition. This is because energy companies are focused on profitability. Changes in the heat transition will lead to changes in the energy mix, which can affect profitability (Kwakkel & Yücel, 2014). The strategic objective of an energy company is to conclude the most profitable contract with the end-user. Furthermore, the energy company has to compete with other companies (Khaldi & Sunikka-Blank, 2020). The energy company also has a problem-specific objective. An energy company is looking for the most profitable technologies that contribute to guaranteeing sufficient energy to meet the demand of the end-user (Khaldi & Sunikka-Blank, 2020; Scholten et al., 2016).

### *Appendix D2.13 – Energy cooperation*

Energy cooperation's have a high interest in heat transition. This is because these cooperation's have an interest in making the energy mix more sustainable and thereby contributing to improving the health of humans and ecosystems (Hoppe & Miedema, 2020). The strategic objective of the energy cooperation is to increase the share of sustainable energy sources within the energy mix (Hoppe & Miedema, 2020; Khaldi & Sunikka-Blank, 2020). The problem-specific objective is to find opportunities to collect joint investments that contribute to the development of smart and sustainable energy solutions in the heat transition within the municipality (Hoppe & Miedema, 2020).

### *Appendix D2.14 – Owner of the heat resource*

The owner of the heat sources has a high interest in the heat transition. This is because the type of heat source depends on the strategy taken within a neighborhood. For instance, heat sources driven by renewable gas are not considered in an all-electric strategy (PBL, 2022). The type of strategy determines what type of technologies can generate a profit while operating. It, therefore, affects the decision of an owner of a specific heat source to put its technology into operation. The strategic objective of the owner of the heat source is to avoid disturbances in the heat supply, ensure flexibility, and profitably produce heat (Hoppe & Miedema, 2020). The problem-specific objective is to find ways to improve the efficiency of the technology. This can be done, for example, by also using the waste heat in providing heat (Henrich et al., 2021; Hoppe & Miedema, 2020).

## Appendix D3 – Identification of the interrelationships between the identified actors

### *Appendix D3.1 – "Keep satisfied"*

The "keep satisfied" box is characterized by high power with low interest. Within this box are the investors and banks and the province. As shown earlier, the investors and banks do not directly have a high interest in the heat transition in the municipality of Delft. The objective of this group of actors is to make profitable investments (Henrich et al., 2021). On the other hand, the heat transition cannot take place if there is not sufficient capital available. This means that investors and banks have a high power within the heat transition. Project initiators must convince these group of actors to make investments. In addition, the province is classified into this box. Within the Netherlands, the targets for the heat transition have been implemented at the municipal level. The province, therefore, does not immediately have an interest in the heat transition. However, the province does have an important objective in securing the health of people and ecosystems (Hoppe & Miedema, 2020; Rosas et al., 2022). In addition, the national government uses a provincial level to assess the progress in the heat transition (Hoppe & Miedema, 2020). So, in this project, the province has high power in the heat transition.

### *Appendix D3.2 – "Keep informed"*

The "keep informed" box is characterized by low power and high interest. This box includes housing corporations, energy providers, neighborhood initiatives, real-estate owners, and the owner of heat resources. The housing corporation has a high average interest in the heat transition. This is because these corporations are looking for homes with the highest living standards. However, the level of living standards is not only determined by the heat transition, but also by other factors (Rosas et al., 2022). In addition, housing corporations have no direct influence on policymaking within the heat transition in Delft. The energy providers have a higher interest because changes as a result of the heat transition may affect their business model. For example, alternative energy sources typically have lower operating costs, but the new technology must be paid off (Kwakkel & Yücel, 2014; Rose et al., 2017; Tolliver et al., 2019). In addition, an energy provider can improve its image by increasing the share of renewable energy sources (Rosas et al., 2022). However, an energy provider has no direct influence on the decision-making within the heat transition in Delft (Bessette & Arvai, 2014).

The neighborhood initiatives have high interest because these initiatives often proactively participate in making the neighborhoods more sustainable. However, these initiatives operate within the agreed policy guidelines for heat transition within the municipality of Delft (Hoppe & Miedema, 2020). Furthermore, the real-estate owners can be categorized within the "keep informed" box. Within this group of actors, as shown in Chapter 4, costs often play the largest role in contributing to the attitude towards the heat transition. When the cost of a technological alternative is equivalent to the cost of the conventional energy portfolio, this group of actors is more willing to contribute to the heat transition (Appendix B2). However, all activities carried out by this group of actors are subject to the policies within the heat transition. The real-estate owners have no direct influence on this (Kwakkel & Yücel, 2014). Finally, the owners of the heat sources are classified within the "keep informed" box. This group of actors has a high interest in the heat transition, in that the potential of specific technology can be increased if a particular municipality goes for a specific strategy. However, the owners of the heat source have no direct influence on the policymaking and choice of a specific heat transition vision within the municipality (Hoppe & Miedema, 2020).

### *Appendix D3.3 – "Manage closely"*

Finally, the "manage closely" box. This box is characterized by high power and interest level. This box includes the national government, the municipality of Delft, the research institutes, the project developers, the owners of the heat resource, the grid operators, installation companies, and energy cooperation's (Figure 7).

The national government is characterized by the relatively highest interest and power. This is because the national government signed the Paris climate agreement, which gives the government a direct interest in the heat transition within the municipalities. In addition, the national government has established policy guidelines and goals that are used as a basis by municipalities to create the heat transition vision. As a result, the municipality has the same level of interest, but a lower power level compared to the national government. Furthermore, it is assumed that the research institutes have a similar level of interest with the municipality and the national government. On the other hand, the research institutes operate under the policymaking of both the municipality and the national government (Hoppe & Miedema, 2020). The project developers are classified with a lower interest, because this group of actors also have a commercial desire outside the sustainability desire (Henrich et al., 2021; Hoppe & Miedema, 2020). In addition, this group of actors also operates within the policy guidelines of the municipality, so a lower power level is assumed for this group of actors.

Within this research it is assumed that project developers are responsible for creating the heat transition vision with the lowest national cost. As a result, project developers indirectly influence which technological alternatives will be deployed within a given strategy. This implies that the owners of heat technologies are influenced by the choices made by the project developer. This is the reason that the owner of a heat resource is assumed to have a lower power level than project developers. However, the interest level of this group of actors is considered higher than the project developers, because a specific heat transition vision determines whether the specific technology is part of the proposed energy portfolio (Hoppe & Miedema, 2020).

In addition to the influence a project developer has on the owners of heat resources, decisions made by this group of actors also affect grid operators. When a project developer has developed a strategy, this may require reinforcements in the energy network. In this way, the grid operator operates at the behest of the project developer. However, the grid operator is considered to have a higher interest level compared to the project developer. This is because the grid operator is responsible for maintaining energy security (Hoppe & Miedema, 2020; Rosas et al., 2022).

The installation companies also work on behalf of the project developer. This results in a lower relative power compared to the project developer. In addition, the installation companies are considered to have a lower interest level, as these companies are also driven by profitability (Hoppe & Miedema, 2020).

Finally, the Energy corporation. These actors have an advisory role for both the project developer and the municipality of Delft. This is because these types of actors are driven by increasing the share of renewable energy sources within the energy mix (Rosas et al., 2022). Technological alternatives are continuously being examined. This also leads to the fact that the interest level of energy cooperation is considered higher in comparison to project developers.

## Appendix E – The identification of the heat transition visions

### Appendix E1 – All-electric strategy

| Technological alternative | Heat source & supply temperature | Working principle | Installation | Insulation label and heat temperature |
|---|---|---|---|---|
| *S1a* | Air source heat pump<br><br>Supply temperature: n/a | Upgrading the collected outdoor air with an outdoor unit to the desired temperature | Each utility building has one unit while multiple households are connected to one unit | Household: B+<br>Utility: B+<br><br>Space heating: 50°C |
| *S1b* | Bottom-heat pump<br><br>Supply temperature: n/a | Upgrading the collected underground water with a soil collector to the desired temperature | The soil collector is installed individually for both households and utility buildings. | Household: B+<br>Utility: B+<br><br>Space heating: 50°C |

### Appendix E2 – Collective heating strategy with MT heat sources

| Technological alternative | Heat source & supply temperature | Working principle | Installation | Insulation label and heat temperature |
|---|---|---|---|---|
| *S2a* | Medium temperature waste heat<br><br>Supply temperature: 70°C | Neighborhoods use nearby existing (or planned) medium- and high-temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S2b* | Medium temperature geothermal energy<br><br>Supply temperature: 70°C | Heat is pumped from underground | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S2c* | Medium temperature geothermal energy everywhere<br><br>Supply temperature: 70°C | Heat is pumped from underground | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S2d* | Medium temperature waste heat | Neighborhoods use nearby existing (or planned) medium- and high-temperature heat | Buildings will be connected to a new heat grid to be developed | Households: D+<br>Utility: B+ |

| | | | | |
|---|---|---|---|---|
| | Supply temperature: 70°C | sources of, for example, industrial waste heat | | Space heating: 70°C |
| *S2e* | Medium temperature geothermal energy<br><br>Supply temperature: 70°C | Heat is pumped from underground | Buildings will be connected to a new heat grid to be developed | Households: D+<br>Utility: B+<br><br>Space heating: 70°C |
| *S2f* | Medium temperature geothermal energy everywhere<br><br>Supply temperature: 70°C | Heat is pumped from underground | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: D+<br><br>Space heating: 70°C |

## Appendix E3 – Collective heating strategy with LT heat sources

| **Technological alternative** | **Heat source & supply temperature** | **Working principle** | **Installation** | **Insulation label & heat temperature** |
|---|---|---|---|---|
| *S3a* | Low temperature heat source<br><br>Supply temperature: 30°C | Neighborhoods use nearby existing (or planned) low temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: B+<br><br>Space heating: 50°C |
| *S3b* | Low temperature heat source<br><br>Supply temperature: 70°C | Neighborhoods use nearby existing (or planned) low temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S3c* | Thermal storage<br><br>Supply temperature: 70°C | Neighborhoods use nearby existing (or planned) low temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S3d* | Thermal storage<br><br>Supply temperature: 50°C | Neighborhoods use nearby existing (or planned) low temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: B+<br><br>Space heating: 50°C |

| | | | | |
|---|---|---|---|---|
| *S3e* | Thermal energy from surface water and thermal storage<br><br>Supply temperature: 70°C | Neighborhoods use nearby existing (or planned) low temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S3f* | Low temperature heat source<br><br>Supply temperature: 70°C | Neighborhoods use nearby existing (or planned) low temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: D+<br>Utility: B+<br><br>Space heating: 70°C |
| *S3g* | Thermal storage<br><br>Supply temperature: 70°C | Neighborhoods use nearby existing (or planned) low temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: D+<br>Utility: B+<br><br>Space heating: 70°C |
| *S3h* | Thermal energy from surface water and thermal storage<br><br>Supply temperature: 70°C | Neighborhoods use nearby existing (or planned) low temperature heat sources of, for example, industrial waste heat | Buildings will be connected to a new heat grid to be developed | Households: D+<br>Utility: B+<br><br>Space heating: 70°C |

## Appendix E4 – Renewable gas strategy

| Technological alternative | Heat source & supply temperature | Working principle | Installation | Insulation label & heat temperature |
|---|---|---|---|---|
| *S4a* | Green gas with hybrid heat pump<br><br>Supply temperature: n/a | The hybrid heat pump consumes green gas and electricity to produce heat | Each building is connected to the gas network | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S4b* | Green gas with a boiler<br><br>Supply temperature: n/a | The boiler consumes green gas to produce heat | Each building is connected to the gas network | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S4c* | Green gas with hybrid heat pump | The hybrid heat pump consumes green gas and | Each building is connected to the gas network | Households: D+<br>Utility: B+ |

| | | | | |
|---|---|---|---|---|
| | Supply temperature: n/a | electricity to produce heat | | Space heating: 70°C |
| *S4d* | Green gas with a boiler<br><br>Supply temperature: n/a | The boiler consumes green gas to produce heat | Each building is connected to the gas network | Households: D+<br>Utility: B+<br><br>Space heating: 70°C |

### Appendix E5 – Hydrogen strategy

| Technological alternative | Heat source & supply temperature | Working principle | Installation | Insulation label & heat temperature |
|---|---|---|---|---|
| *S5a* | Hydrogen with hybrid heat pump<br><br>Supply temperature: n/a | The hybrid heat pump uses hydrogen and electricity to produce heat | Each building is connected to the gas network | Households: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S5b* | Hydrogen with boiler<br><br>Supply temperature: n/a | The boiler uses hydrogen to produce heat | Each building is connected to the gas network | Household: B+<br>Utility: B+<br><br>Space heating: 70°C |
| *S5c* | Hydrogen with hybrid heat pump<br><br>Supply temperature: n/a | The hybrid heat pump uses hydrogen and electricity to produce heat | Each building is connected to the gas network | Households: D+<br>Utility: B+<br><br>Space heating: 70°C |
| *S5d* | Hydrogen with boiler<br><br>Supply temperature: n/a | The boiler uses hydrogen to produce heat | Each building is connected to the gas network | Household: D+<br>Utility: B+<br><br>Space heating: 70°C |

## Appendix F – Outcomes of the Vesta MAIS model

### Appendix F1 – Share of each energy carrier in the total heat demand in the thirteen prioritized neighborhoods in Delft in 2019

| Neighborhood | Average Natural gas input [GJ per Building per year) | Average renewable gas input [GJ per building per year] | Average electricity input [GJ per building per year] | Average MT heat source input [GJ per building per year] | Average LT heat source input [GJ per building per year] | Average waste heat input [GJ per building per year] |
|---|---|---|---|---|---|---|
| Het Rode Dorp | 28 | 0 | 9 | 0 | 0 | 0 |
| Gillisbuurt | 33 | 0 | 9 | 0 | 0 | 0 |
| Aart van der Leeuwbuurt | 46 | 0 | 14 | 0 | 0 | 0 |
| Juniusbuurt | 21 | 0 | 16 | 11 | 0 | 0 |
| Fledderusbuurt | 33 | 0 | 12 | 0 | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Buitenhof-Noord | 32 | 0 | 11 | 0 | 0 | 0 |
| Mythologiebuurt | 28 | 0 | 13 | 0 | 0 | 0 |
| TU-Noord | 42 | 0 | 19 | 0 | 0 | 0 |
| Roland Holstbuurt | 33 | 0 | 13 | 0 | 0 | 0 |
| Reinier De Graafbuurt | 47 | 0 | 22 | 0 | 0 | 0 |
| Kuyperwijk-Zuid | 32 | 0 | 11 | 0 | 0 | 0 |
| Multatulibuurt | 26 | 0 | 12 | 17 | 0 | 0 |
| TU Campus | 28 | 0 | 19 | 3 | 0 | 0 |
| Average | 33 | 0 | 13,85 | 2,38 | 0 | 0 |
| Total | 49,23 | | | | | |
| Share | 67,03% | 0,00% | 28,13% | 4,84% | 0,00% | 0,00% |

### Appendix F2 – Outcomes of the Vesta Leidraad concerning the most appropriate heat transition vision based on the calculated national costs with the Vesta Leidraad

| Neighborhood | National costs in 2030 [Euro per year] | National costs in 2019 [Euro per year] | Heat transition vision |
|---|---|---|---|
| Het Rode Dorp (S2d) | € 158.585 | € 70.429 | S2d |
| Gillisbuurt (S2e) | € 289.739 | € 83.398 | S2e |
| Aart van der Leeuwbuurt (S2d) | € 501.950 | € 145.643 | S2d |
| Juniusbuurt (S2d) | € 274.092 | € 116.286 | S2d |
| Fledderusbuurt (S2d) | € 162.756 | € 90.390 | S2d |
| Buitenhof-Noord (S2d) | € 925.204 | € 290.902 | S2d |
| Mythologiebuurt (S2d) | € 437.728 | € 227.599 | S2d |
| TU-Noord (S4d) | € 663.918 | € 280.678 | S4d |
| Roland Holstbuurt (S2d) | € 932.187 | € 323.912 | S2d |
| Reinier de Graafbuurt (S3h) | € 535.747 | € 255.108 | S3h |
| Kuyperwijk-Zuid (S2d) | € 446.482 | € 149.642 | S2d |
| Multatulibuurt (S4d) | € 441.985 | € 119.487 | S4d |
| TU Campus (S4d) | € 2.232.634 | € 1.029.532 | S4d |

### Appendix F3 – Share of each energy carrier in the total heat demand in the thirteen prioritized neighborhoods in Delft in 2030

| Neighborhood | Average Natural gas input [GJ per Building per year) | Average renewable gas input [GJ per building per year] | Average electricity input [GJ per building per year] | Average MT heat source input [GJ per building per year] | Average LT heat source input [GJ per building per year] | Average waste heat input [GJ per building per year] |
|---|---|---|---|---|---|---|
| Het Rode Dorp | 0 | 7 | 9 | 24 | 0 | 0 |
| Gillisbuurt | 0 | 8 | 10 | 28 | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Aart van der Leeuwbuurt | 0 | 8 | 15 | 29 | 0 | 0 |
| Juniusbuurt | 0 | 6 | 16 | 23 | 0 | 0 |
| Fledderusbuurt | 0 | 7 | 12 | 27 | 0 | 0 |
| Buitenhof-Noord | 0 | 7 | 11 | 27 | 0 | 0 |
| Mythologiebuurt | 0 | 6 | 13 | 22 | 0 | 0 |
| TU-Noord | 0 | 19 | 19 | 0 | 0 | 0 |
| Roland Holstbuurt | 0 | 8 | 13 | 28 | 0 | 0 |
| Reinier De Graafbuurt | 0 | 0 | 32 | 0 | 8 | 0 |
| Kuyperwijk-Zuid | 0 | 7 | 11 | 27 | 0 | 0 |
| Multatulibuurt | 0 | 21 | 12 | 13 | 0 | 0 |
| TU Campus | 0 | 17 | 20 | 1 | 0 | 0 |
| Average | 0 | 9,31 | 14,85 | 19,15 | 0,62 | 0 |
| Total | 43,92 | | | | | |
| Share | 0,00% | 21,19% | 33,80% | 43,61% | 1,40% | 0,00% |

### Appendix F4 – The calculated national costs of all the heat transition visions for the Neighborhood Business Park Technopolis and Stationsbuurt

| Strategy | Technopolis | Stationsbuurt |
|---|---|---|
| s1a | € 1.347.453,00 | € 145.278,00 |
| s1b | € 1.006.732,00 | € 75.572,00 |
| | | |
| s2a | € 1.527.332,00 | |
| S2b | | € 152.001,00 |
| s2c | € 1.527.332,00 | € 152.001,00 |
| s2e | € 1.525.525,00 | € 152.001,00 |
| s2f | € 1.525.525,00 | € 152.001,00 |
| | | |
| s3a | € 1.147.415,00 | |
| s3b | € 1.079.945,00 | |
| s3c | € 1.993.197,00 | € 229.942,00 |
| s3d | € 1.068.461,00 | € 90.342,00 |
| s3e | € 1.031.270,00 | € 92.884,00 |
| s3f | € 1.172.775,00 | |
| s3g | € 1.991.493,00 | € 229.942,00 |
| s3h | € 1.028.977,00 | |
| | | |
| s4a | € 1.154.688,00 | € 97.990,00 |

| | | |
|---|---|---|
| s4b | € 1.024.630,00 | € 86.024,00 |
| s4c | € 1.152.988,00 | € 97.990,00 |
| s4d | € 1.023.113,00 | € 86.024,00 |
| | | |
| s5a | € 1.343.254,00 | € 123.225,00 |
| s5b | € 1.300.842,00 | € 137.013,00 |
| s5c | € 1.341.569,00 | € 123.225,00 |
| s5d | € 1.299.392,00 | € 137.013,00 |

### Appendix F5 – The share of each energy carrier to the total heat demand in the Business Park Technopolis in 2019 and 2030

| Neighborhood code | Strategy | Total_input | Natural gas input [GJ per building per year] | Renewable gas [GJ per building per year] | Electricity input [GJ per building per year] | MT heat source input [GJ per year per building] | LT heat source input [GJ per building per year] | Waste heat input [GJ per building per year] |
|---|---|---|---|---|---|---|---|---|
| BU05032901 | s1b | 66 | 0 | 0 | 43 | 0 | 0 | 22 |
| BU05032901 | s2e | 66 | 0 | 6 | 40 | 19 | 0 | 3 |
| BU05032901 | s3h | 66 | 0 | 0 | 43 | 0 | 0 | 22 |
| BU05032901 | s4b | 66 | 0 | 21 | 39 | 0 | 0 | 6 |
| BU05032901 | s5b | 66 | 0 | 20 | 39 | 0 | 0 | 7 |
| BU05032901 | 2019 | 81 | 38 | 0 | 39 | 0 | 0 | 5 |
| | Total | 81 | | | | | | |
| | Share 2019 | | 46,91% | 0,00% | 48,15% | 0,00% | 0,00% | 6,17% |
| | | 66 | | | | | | |
| | Share 2050 S1b | | 0,00% | 0,00% | 65,15% | 0,00% | 0,00% | 33,33% |

# Appendix G – Power flow analysis

## Appendix G1 – The hourly demand profiles belonging to the specific end-user category

| Time start | Time end | Large Office after | Large office before | Medium Office after e | Medium office before | Primary School after el | Primary School before elect | Small Office after elec | Small office before electrif | Supermarket after electri | Supermarket before ele | Small Hotel after e | Small Hotel before electri | Household after e | Household before electrification |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28/12/2014 00:00 | 28/12/2014 01:00 | 0,2414698 | 0,2386900 | 0,0347000 | 0,0335750 | 0,0554354 | 0,0554150 | 0,0046901 | 0,0042280 | 0,0888484 | 0,0888280 | 0,0654622 | 0,0367680 | 0,0289192 | 0,0003707 |
| 28/12/2014 01:00 | 28/12/2014 02:00 | 0,2474892 | 0,2394500 | 0,0335954 | 0,0335750 | 0,0554364 | 0,0554160 | 0,0042484 | 0,0042280 | 0,0828876 | 0,0817000 | 0,0598633 | 0,0366970 | 0,0295966 | 0,0002725 |
| 28/12/2014 02:00 | 28/12/2014 03:00 | 0,2485623 | 0,2394500 | 0,0335954 | 0,0335750 | 0,0583535 | 0,0554130 | 0,0046901 | 0,0042280 | 0,0811524 | 0,0811320 | 0,0619448 | 0,0319540 | 0,0306323 | 0,0002293 |
| 28/12/2014 03:00 | 28/12/2014 04:00 | 0,2510010 | 0,2398300 | 0,0425048 | 0,0377260 | 0,0554314 | 0,0554110 | 0,0046901 | 0,0042280 | 0,0807164 | 0,0806960 | 0,0625539 | 0,0319290 | 0,0317525 | 0,0002102 |
| 28/12/2014 04:00 | 28/12/2014 05:00 | 0,2625992 | 0,2516700 | 0,0475550 | 0,0409640 | 0,0585605 | 0,0556200 | 0,0042484 | 0,0042280 | 0,0881116 | 0,0869240 | 0,0653635 | 0,0335250 | 0,0331859 | 0,0002039 |
| 28/12/2014 05:00 | 28/12/2014 06:00 | 0,2920748 | 0,2765000 | 0,0464181 | 0,0397590 | 0,0556204 | 0,0556000 | 0,0046902 | 0,0042280 | 0,0861944 | 0,0861740 | 0,0701068 | 0,0376990 | 0,0366185 | 0,0002069 |
| 28/12/2014 06:00 | 28/12/2014 07:00 | 0,3386944 | 0,3250100 | 0,0502024 | 0,0422750 | 0,0590082 | 0,0563540 | 0,0042484 | 0,0042280 | 0,5137305 | 0,1226400 | 0,0916480 | 0,0581320 | 0,0477356 | 0,0002233 |
| 28/12/2014 07:00 | 28/12/2014 08:00 | 0,3667458 | 0,3498400 | 0,0489210 | 0,0409980 | 0,0584735 | 0,0555330 | 0,0046901 | 0,0042280 | 0,5039669 | 0,1337100 | 0,1142963 | 0,0756080 | 0,0499239 | 0,0002807 |
| 28/12/2014 08:00 | 28/12/2014 09:00 | 0,3577295 | 0,3409200 | 0,0508121 | 0,0413310 | 0,0560403 | 0,0545190 | 0,0043063 | 0,0038442 | 0,5012002 | 0,1656500 | 0,1630455 | 0,0991090 | 0,0556095 | 0,0003747 |
| 28/12/2014 09:00 | 28/12/2014 10:00 | 0,2765448 | 0,2619100 | 0,0338766 | 0,0260750 | 0,0513412 | 0,0473240 | 0,0019454 | 0,0019250 | 0,4556645 | 0,1290500 | 0,1275731 | 0,0769660 | 0,0533580 | 0,0004869 |
| 28/12/2014 10:00 | 28/12/2014 11:00 | 0,2281183 | 0,2126400 | 0,0366719 | 0,0281010 | 0,0499081 | 0,0469660 | 0,0023871 | 0,0019250 | 0,4524588 | 0,1643900 | 0,0963655 | 0,0516320 | 0,0506498 | 0,0005709 |
| 28/12/2014 11:00 | 28/12/2014 12:00 | 0,2317927 | 0,2130200 | 0,0320590 | 0,0257220 | 0,0476964 | 0,0476760 | 0,0023872 | 0,0019250 | 0,4658127 | 0,1963000 | 0,0984153 | 0,0491280 | 0,0454912 | 0,0006127 |
| 28/12/2014 12:00 | 28/12/2014 13:00 | 0,2270010 | 0,2126400 | 0,0359297 | 0,0271870 | 0,0499011 | 0,0469590 | 0,0019454 | 0,0019250 | 0,4472322 | 0,2055300 | 0,0860543 | 0,0492520 | 0,0423950 | 0,0006052 |
| 28/12/2014 13:00 | 28/12/2014 14:00 | 0,2314635 | 0,2130200 | 0,0321317 | 0,0252110 | 0,0499412 | 0,0469990 | 0,0023872 | 0,0019250 | 0,4369644 | 0,2040200 | 0,0891185 | 0,0492280 | 0,0408897 | 0,0005920 |
| 28/12/2014 14:00 | 28/12/2014 15:00 | 0,2276800 | 0,2126400 | 0,0345242 | 0,0270380 | 0,0470374 | 0,0470170 | 0,0023871 | 0,0019250 | 0,4245312 | 0,2003800 | 0,0879750 | 0,0491630 | 0,0389116 | 0,0005829 |
| 28/12/2014 15:00 | 28/12/2014 16:00 | 0,2319148 | 0,2130200 | 0,0328123 | 0,0255480 | 0,0470254 | 0,0470050 | 0,0019454 | 0,0019250 | 0,4192814 | 0,1968700 | 0,0889423 | 0,0488080 | 0,0395392 | 0,0005843 |
| 28/12/2014 16:00 | 28/12/2014 17:00 | 0,3140802 | 0,2957100 | 0,0465581 | 0,0379790 | 0,0555615 | 0,0526210 | 0,0039225 | 0,0034604 | 0,4300399 | 0,2068900 | 0,0813716 | 0,0588650 | 0,0386154 | 0,0006638 |
| 28/12/2014 17:00 | 28/12/2014 18:00 | 0,3730192 | 0,3498500 | 0,0486127 | 0,0413920 | 0,0554994 | 0,0554790 | 0,0046901 | 0,0042280 | 0,4356332 | 0,1819400 | 0,0924272 | 0,0698920 | 0,0381016 | 0,0008117 |
| 28/12/2014 18:00 | 28/12/2014 19:00 | 0,3705109 | 0,3494700 | 0,0544909 | 0,0438510 | 0,0584235 | 0,0554830 | 0,0042484 | 0,0042280 | 0,4542434 | 0,1876800 | 0,1087722 | 0,0846980 | 0,0368216 | 0,0008411 |
| 28/12/2014 19:00 | 28/12/2014 20:00 | 0,3500983 | 0,3254000 | 0,0488912 | 0,0415300 | 0,0557204 | 0,0557000 | 0,0046901 | 0,0042280 | 0,4363551 | 0,1701000 | 0,1155704 | 0,0857440 | 0,0351048 | 0,0008341 |
| 28/12/2014 20:00 | 28/12/2014 21:00 | 0,3466881 | 0,3250200 | 0,0543028 | 0,0437580 | 0,0557074 | 0,0556870 | 0,0046901 | 0,0042280 | 0,4262313 | 0,1614700 | 0,1168900 | 0,0921620 | 0,0334786 | 0,0007962 |
| 28/12/2014 21:00 | 28/12/2014 22:00 | 0,3262716 | 0,3009600 | 0,0487534 | 0,0414620 | 0,0585185 | 0,0555780 | 0,0042484 | 0,0042280 | 0,3636912 | 0,1467800 | 0,1201884 | 0,0899470 | 0,0306143 | 0,0007063 |
| 28/12/2014 22:00 | 28/12/2014 23:00 | 0,2975001 | 0,2761300 | 0,0538468 | 0,0435320 | 0,0554484 | 0,0554280 | 0,0046901 | 0,0042280 | 0,0934494 | 0,0934290 | 0,0975251 | 0,0668860 | 0,0309273 | 0,0006115 |
| 28/12/2014 23:00 | 29/12/2014 00:00 | 0,2764720 | 0,2520700 | 0,0480064 | 0,0410920 | 0,0590796 | 0,0561390 | 0,0046901 | 0,0042280 | 0,1295375 | 0,1283500 | 0,0732892 | 0,0431410 | 0,0271105 | 0,0004568 |

## Appendix G2 – Pandapower codes used to perform the power flow analysis

```
#Identification of the data sources
import os
from pandapower.toolbox import clear_result_tables
import pandas as pd
from pandapower.timeseries import DFData

def data_source(input_dir):
        df = pd.read_excel('/Users/markhoveling/Documents/TU Delft jaar 2/Master thesis/Pandapower codes/GridOriginal/Data/powerbytype.xls')
    print(df)


    profiles = pd.DataFrame()

    profiles["Load R1"] = df ["Load R1"]
    profiles["Load R2"] = df ["Load R2"]
    profiles["Load CI1"] = df ["Load CI1"]
    profiles["Load CI2"] = df ["Load CI2"]
    profiles["Load CI3"] = df ["Load CI3"]
    profiles["Load CI4"] = df ["Load CI4"]
    profiles["Load CI5"] = df ["Load CI5"]
    profiles["Load CI6"] = df ["Load CI6"]
    profiles["Load CI7"] = df ["Load CI7"]
    profiles["Load CI8"] = df ["Load CI8"]
    profiles["Load CI9"] = df ["Load CI9"]
    profiles["Load CI10"] = df ["Load CI10"]
    profiles["Load CI11"] = df ["Load CI11"]
    profiles["Load CI12"] = df ["Load CI12"]
    profiles["Load CI13"] = df ["Load CI13"]
    profiles["Load CI14"] = df ["Load CI14"]
    profiles["Load CI15"] = df ["Load CI15"]
    profiles["Load CI16"] = df ["Load CI16"]
    profiles["Load CI17"] = df ["Load CI17"]
    profiles["Load CI18"] = df ["Load CI18"]
    profiles["Load CI19"] = df ["Load CI19"]
    profiles["Load CI20"] = df ["Load CI20"]
    profiles["Load CI21"] = df ["Load CI21"]
    profiles["Load CI22"] = df ["Load CI22"]
```

```
    profiles["Load CI23"] = df ["Load CI23"]
    profiles["Load CI24"] = df ["Load CI24"]
    profiles["Load CI25"] = df ["Load CI25"]
    profiles["Load CI26"] = df ["Load CI26"]
    profiles["Load CI27"] = df ["Load CI27"]
    profiles["Load CI28"] = df ["Load CI28"]
    profiles["Load CI29"] = df ["Load CI29"]
    profiles["Load CI30"] = df ["Load CI30"]
    profiles["Load CI31"] = df ["Load CI31"]
    profiles["Load CI32"] = df ["Load CI32"]
    profiles["Load CI33"] = df ["Load CI33"]
    profiles["Load CI34"] = df ["Load CI34"]
    profiles["Load CI35"] = df ["Load CI35"]
    profiles["Load CI36"] = df ["Load CI36"]
    profiles["Load CI37"] = df ["Load CI37"]
    profiles["Load CI38"] = df ["Load CI38"]
    profiles["Load CI39"] = df ["Load CI39"]
    profiles["Load CI40"] = df ["Load CI40"]
    profiles["Load CI41"] = df ["Load CI41"]
    profiles["Load CI42"] = df ["Load CI42"]
    profiles["Load CI43"] = df ["Load CI43"]
    profiles["Load CI44"] = df ["Load CI44"]
    profiles["Load CI45"] = df ["Load CI45"]
    profiles["Load CI46"] = df ["Load CI46"]
    profiles["Load CI47"] = df ["Load CI47"]
    profiles["Load CI48"] = df ["Load CI48"]
    profiles["Load CI49"] = df ["Load CI49"]
    profiles["Load CI50"] = df ["Load CI50"]
    profiles["Load CI51"] = df ["Load CI51"]
    profiles["Load CI52"] = df ["Load CI52"]
    profiles["Load CI53"] = df ["Load CI53"]
    profiles["Load CI54"] = df ["Load CI54"]
    profiles["Load CI55"] = df ["Load CI55"]

    profiles["PV 3"] = df ["PV 3"]
    profiles["PV 4"] = df ["PV 4"]
    profiles["PV 5"] = df ["PV 5"]
    profiles["PV 6"] = df ["PV 6"]
    profiles["WD 7"] = df ["WD 7"]
    profiles["PV 8"] = df ["PV 8"]
    profiles["PV 9"] = df ["PV 9"]
    profiles["PV 10"] = df ["PV 10"]
    profiles["PV 11"] = df ["PV 11"]

    ds = DFData(profiles)

    print("data source: OK")
    print (profiles)

    return ds
```

```
#Network creation
import pandapower as pp
import pandapower.networks as pn
from pandas import read_json

def create_cigre_network_mv():

    net_cigre_mv = pp.create_empty_network()

# Linedata
    line_data = {'c_nf_per_km': 151.1749, 'r_ohm_per_km': 0.501,
                 'x_ohm_per_km': 0.716, 'max_i_ka': 0.21,
                 'type': 'cs'}
    pp.create_std_type(net_cigre_mv, line_data, name='CABLE_CIGRE_MV',
element='line')
line_data = {'c_nf_per_km': 10.09679, 'r_ohm_per_km': 0.510,
                 'x_ohm_per_km': 0.366, 'max_i_ka': 0.10,
                 'type': 'ol'}
    pp.create_std_type(net_cigre_mv, line_data, name='OHL_CIGRE_MV',
element='line')

# Busses
    bus0 = pp.create_bus(net_cigre_mv, name='Bus 0', vn_kv=110, type='b',
zone='CIGRE_MV')
    buses = pp.create_buses(net_cigre_mv, 14, name=['Bus %i' % i for i in range(1,
15)], vn_kv=20,type='b', zone='CIGRE_MV')

# Lines
    pp.create_line(net_cigre_mv, buses[0], buses[1], length_km=1.82,
                   std_type='OHL_CIGRE_MV', name='Line 1-2')
    #pp.create_line(net_cigre_mv, buses[0], buses[13], length_km=7.82,
                   #std_type='CABLE_CIGRE_MV', name='Line 0-13')
    #pp.create_line(net_cigre_mv, buses[1], buses[2], length_km=1.82,
                   #std_type='OHL_CIGRE_MV', name='Line 2-3')
    pp.create_line(net_cigre_mv, buses[2], buses[3], length_km=1.82,
                   std_type='CABLE_CIGRE_MV', name='Line 3-4')
    #pp.create_line(net_cigre_mv, buses[4], buses[10], length_km=1.82,
                   #std_type='CABLE_CIGRE_MV', name='Line 5-11')
    pp.create_line(net_cigre_mv, buses[3], buses[13], length_km=5.50,
                   std_type='OHL_CIGRE_MV', name='Line 3-12')
    pp.create_line(net_cigre_mv, buses[4], buses[5], length_km=1.82,
                   std_type='CABLE_CIGRE_MV', name='Line 5-6')
    pp.create_line(net_cigre_mv, buses[6], buses[7], length_km=1.82,
                   std_type='CABLE_CIGRE_MV', name='Line 7-8')
    pp.create_line(net_cigre_mv, buses[6], buses[13], length_km=1.82,
                   std_type='CABLE_CIGRE_MV', name='Line 6-13')
    pp.create_line(net_cigre_mv, buses[7], buses[8], length_km=0.60,
                   std_type='CABLE_CIGRE_MV', name='Line 8-9')
    pp.create_line(net_cigre_mv, buses[8], buses[9], length_km=0.60,
                   std_type='CABLE_CIGRE_MV', name='Line 9-10')
    pp.create_line(net_cigre_mv, buses[9], buses[10], length_km=1.82,
```

```
                  std_type='CABLE_CIGRE_MV', name='Line 10-11')
    #pp.create_line(net_cigre_mv, buses[2], buses[7], length_km=5.50,
                  #std_type='CABLE_CIGRE_MV', name='Line 3-8')
    #pp.create_line(net_cigre_mv, buses[2], buses[11], length_km=5.50,
                  #std_type='CABLE_CIGRE_MV', name='Line 2-11')
    pp.create_line(net_cigre_mv, buses[11], buses[12], length_km=5.50,
                  std_type='OHL_CIGRE_MV', name='Line 12-13')
    #pp.create_line(net_cigre_mv, buses[12], buses[13], length_km=2.99,
                  #std_type='CABLE_CIGRE_MV', name='Line 13-14')
    #pp.create_line(net_cigre_mv, buses[0], buses[13], length_km=8.50,
                  #std_type='CABLE_CIGRE_MV', name='Line 0-13')
    pp.create_line(net_cigre_mv, buses[1], buses[12], length_km=5.50,
                  std_type='OHL_CIGRE_MV', name='Line 2-13')
    pp.create_line(net_cigre_mv, buses[3], buses[12], length_km=5.50,
                  std_type='OHL_CIGRE_MV', name='Line 4-13')
    #pp.create_line(net_cigre_mv, buses[0], buses[11], length_km=5.50,
                  #std_type='CABLE_CIGRE_MV', name='Line 2-12')
    pp.create_line(net_cigre_mv, buses[13], buses[7], length_km=2.,
                  std_type='OHL_CIGRE_MV', name='Line 13-14')
    #pp.create_line(net_cigre_mv, buses[10], buses[3], length_km=0.49,
                  #std_type='OHL_CIGRE_MV', name='Line 8-14')
    #pp.create_line(net_cigre_mv, buses[5], buses[7], length_km=5.5,
                  #std_type='CABLE_CIGRE_MV', name='Line 8-6')
    line6_7 = pp.create_line(net_cigre_mv, buses[5], buses[6], length_km=4.24,
                            std_type='CABLE_CIGRE_MV', name='Line 6-7')
    #line4_11 = pp.create_line(net_cigre_mv, buses[10], buses[3], length_km=0.49,
                             #std_type='OHL_CIGRE_MV', name='Line 11-4')
    #line8_14 = pp.create_line(net_cigre_mv, buses[13], buses[7], length_km=2.,
                             #std_type='OHL_CIGRE_MV', name='Line 14-8')
    #line2_7 =  pp.create_line(net_cigre_mv, buses[2], buses[7], length_km=5.5,
                             #std_type='CABLE_CIGRE_MV', name='Line 7-2')

# Ext-Grid
    pp.create_ext_grid(net_cigre_mv, bus0, vm_pu=1.03, va_degree=0.,
                       s_sc_max_mva=5000, s_sc_min_mva=5000, rx_max=0.1,rx_min=0.1)
    pp.create_ext_grid(net_cigre_mv, buses[13], vm_pu=1.03, va_degree=0.,
                       s_sc_max_mva=5000, s_sc_min_mva=5000, rx_max=0.1,rx_min=0.1)

#Trafos
    trafo0 = pp.create_transformer_from_parameters(net_cigre_mv, bus0, buses[0],
sn_mva=25,vn_hv_kv=110, vn_lv_kv=20, vkr_percent=0.16,vk_percent=12.00107,
pfe_kw=0, i0_percent=0,shift_degree=30.0, name='Trafo 0-1')

    trafo1 = pp.create_transformer_from_parameters(net_cigre_mv, bus0, buses[11],
sn_mva=25,vn_hv_kv=110, vn_lv_kv=20, vkr_percent=0.16,vk_percent=12.00107,pfe_kw=0,
i0_percent=0,shift_degree=30.0, name='Trafo 0-12')




#Household load
```

```
    pp.create_load_from_cosphi(net_cigre_mv, buses[0], 3.06, 0.95, "underexcited",
name='Load R1', index = 0)
    pp.create_load_from_cosphi(net_cigre_mv, buses[0], 3.06, 0.95, "underexcited",
name='Load R2', index = 1)


# Commercial / Industrial - reactive load
    pp.create_load_from_cosphi(net_cigre_mv, buses[0], 3.06, 0.95, "underexcited",
name='Load CI1', index = 2)
    pp.create_load_from_cosphi(net_cigre_mv, buses[0], 3.06, 0.95, "underexcited",
name='Load CI2', index = 3)
    pp.create_load_from_cosphi(net_cigre_mv, buses[0], 3.06, 0.95, "underexcited",
name='Load CI3', index = 4)
    pp.create_load_from_cosphi(net_cigre_mv, buses[1], 4.89, 0.95, "underexcited",
name='Load CI4', index = 5)
    pp.create_load_from_cosphi(net_cigre_mv, buses[1], 4.89, 0.95, "underexcited",
name='Load CI5', index = 6)
    pp.create_load_from_cosphi(net_cigre_mv, buses[1], 4.89, 0.95, "underexcited",
name='Load CI6', index = 7)
    pp.create_load_from_cosphi(net_cigre_mv, buses[1], 4.89, 0.95, "underexcited",
name='Load CI7', index = 8)
    pp.create_load_from_cosphi(net_cigre_mv, buses[2], 4.89, 0.95, "underexcited",
name='Load CI8', index = 9)
    pp.create_load_from_cosphi(net_cigre_mv, buses[2], 4.89, 0.95, "underexcited",
name='Load CI9', index = 10)
    pp.create_load_from_cosphi(net_cigre_mv, buses[2], 4.89, 0.95, "underexcited",
name='Load CI10', index = 11)
    pp.create_load_from_cosphi(net_cigre_mv, buses[2], 4.89, 0.95, "underexcited",
name='Load CI11', index = 12)
    pp.create_load_from_cosphi(net_cigre_mv, buses[3], 5.13, 0.95, "underexcited",
name='Load CI12', index = 13)
    pp.create_load_from_cosphi(net_cigre_mv, buses[3], 5.13, 0.95, "underexcited",
name='Load CI13', index = 14)
    pp.create_load_from_cosphi(net_cigre_mv, buses[3], 5.13, 0.95, "underexcited",
name='Load CI14', index = 15)
    pp.create_load_from_cosphi(net_cigre_mv, buses[3], 5.13, 0.95, "underexcited",
name='Load CI15', index = 16)
    pp.create_load_from_cosphi(net_cigre_mv, buses[4], 5.13, 0.95, "underexcited",
name='Load CI16', index = 17)
    pp.create_load_from_cosphi(net_cigre_mv, buses[4], 5.13, 0.95, "underexcited",
name='Load CI17', index = 18)
    pp.create_load_from_cosphi(net_cigre_mv, buses[4], 5.13, 0.95, "underexcited",
name='Load CI18', index = 19)
    pp.create_load_from_cosphi(net_cigre_mv, buses[4], 5.13, 0.95, "underexcited",
name='Load CI19', index = 20)
    pp.create_load_from_cosphi(net_cigre_mv, buses[5], 5.13, 0.95, "underexcited",
name='Load CI20', index = 21)
    pp.create_load_from_cosphi(net_cigre_mv, buses[5], 5.13, 0.95, "underexcited",
name='Load CI21', index = 22)
    pp.create_load_from_cosphi(net_cigre_mv, buses[5], 5.13, 0.95, "underexcited",
name='Load CI22', index = 23)
```

```
    pp.create_load_from_cosphi(net_cigre_mv, buses[5], 5.13, 0.95, "underexcited",
name='Load CI23', index = 24)
    pp.create_load_from_cosphi(net_cigre_mv, buses[6], 0.27, 0.95, "underexcited",
name='Load CI24', index = 25)
    pp.create_load_from_cosphi(net_cigre_mv, buses[6], 0.27, 0.95, "underexcited",
name='Load CI25', index = 26)
    pp.create_load_from_cosphi(net_cigre_mv, buses[6], 0.27, 0.95, "underexcited",
name='Load CI26', index = 27)
    pp.create_load_from_cosphi(net_cigre_mv, buses[6], 0.27, 0.95, "underexcited",
name='Load CI27', index = 28)
    pp.create_load_from_cosphi(net_cigre_mv, buses[7], 0.27, 0.95, "underexcited",
name='Load CI28', index = 29)
    pp.create_load_from_cosphi(net_cigre_mv, buses[7], 0.27, 0.95, "underexcited",
name='Load CI29', index = 30)
    pp.create_load_from_cosphi(net_cigre_mv, buses[7], 0.27, 0.95, "underexcited",
name='Load CI30', index = 31)
    pp.create_load_from_cosphi(net_cigre_mv, buses[7], 0.27, 0.95, "underexcited",
name='Load CI31', index = 32)
    pp.create_load_from_cosphi(net_cigre_mv, buses[8], 12.95, 0.95, "underexcited",
name='Load CI32', index = 33)
    pp.create_load_from_cosphi(net_cigre_mv, buses[8], 12.95, 0.95, "underexcited",
name='Load CI33', index = 34)
    pp.create_load_from_cosphi(net_cigre_mv, buses[8], 12.95, 0.95, "underexcited",
name='Load CI34', index = 35)
    pp.create_load_from_cosphi(net_cigre_mv, buses[8], 12.95, 0.95, "underexcited",
name='Load CI35', index = 36)
    pp.create_load_from_cosphi(net_cigre_mv, buses[9], 12.95, 0.95, "underexcited",
name='Load CI36', index = 37)
    pp.create_load_from_cosphi(net_cigre_mv, buses[9], 12.95, 0.95, "underexcited",
name='Load CI37', index = 38)
    pp.create_load_from_cosphi(net_cigre_mv, buses[9], 12.95, 0.95, "underexcited",
name='Load CI38', index = 39)
    pp.create_load_from_cosphi(net_cigre_mv, buses[9], 12.95, 0.95, "underexcited",
name='Load CI39', index = 40)
    pp.create_load_from_cosphi(net_cigre_mv, buses[10], 12.95, 0.95,
"underexcited", name='Load CI40', index = 41)
    pp.create_load_from_cosphi(net_cigre_mv, buses[10], 12.95, 0.95,
"underexcited", name='Load CI41', index = 42)
    pp.create_load_from_cosphi(net_cigre_mv, buses[10], 12.95, 0.95,
"underexcited", name='Load CI42', index = 43)
    pp.create_load_from_cosphi(net_cigre_mv, buses[10], 12.95, 0.95,
"underexcited", name='Load CI43', index = 44)
    pp.create_load_from_cosphi(net_cigre_mv, buses[10], 12.95, 0.95,
"underexcited", name='Load CI44', index = 45)
    pp.create_load_from_cosphi(net_cigre_mv, buses[11], 12.95, 0.95,
"underexcited", name='Load CI45', index = 46)
    pp.create_load_from_cosphi(net_cigre_mv, buses[11], 12.95, 0.95,
"underexcited", name='Load CI46', index = 47)
    pp.create_load_from_cosphi(net_cigre_mv, buses[11], 12.95, 0.95,
"underexcited", name='Load CI47', index = 48)
```

```
    pp.create_load_from_cosphi(net_cigre_mv, buses[11], 12.95, 0.95,
"underexcited", name='Load CI48', index = 49)
    pp.create_load_from_cosphi(net_cigre_mv, buses[12], 12.95, 0.95,
"underexcited", name='Load CI49', index = 50)
    pp.create_load_from_cosphi(net_cigre_mv, buses[12], 12.95, 0.95,
"underexcited", name='Load CI50', index = 51)
    pp.create_load_from_cosphi(net_cigre_mv, buses[12], 12.95, 0.95,
"underexcited", name='Load CI51', index = 52)
    pp.create_load_from_cosphi(net_cigre_mv, buses[12], 12.95, 0.95,
"underexcited", name='Load CI52', index = 53)
    pp.create_load_from_cosphi(net_cigre_mv, buses[13], 6.19, 0.95, "underexcited",
name='Load CI53', index = 54)
    pp.create_load_from_cosphi(net_cigre_mv, buses[13], 6.19, 0.95, "underexcited",
name='Load CI54', index = 55)
    pp.create_load_from_cosphi(net_cigre_mv, buses[13], 6.19, 0.95, "underexcited",
name='Load CI55', index = 56)

#power supply:

    pp.create_sgen(net_cigre_mv, buses[2],  0.020, q_mvar=0, sn_mva=0.02, name='PV
3', type='PV', index = 0)
    pp.create_sgen(net_cigre_mv, buses[3],  0.020, q_mvar=0, sn_mva=0.02, name='PV
4', type='PV', index = 1)
    pp.create_sgen(net_cigre_mv, buses[4],  0.030, q_mvar=0, sn_mva=0.03, name='PV
5', type='PV', index = 2)
    pp.create_sgen(net_cigre_mv, buses[5],  0.030, q_mvar=0, sn_mva=0.03, name='PV
6', type='PV', index = 3)
    pp.create_sgen(net_cigre_mv, buses[6],  1.500, q_mvar=0, sn_mva=1.50, name='WKA
7', type='WP', index = 4)
    pp.create_sgen(net_cigre_mv, buses[7],  0.030, q_mvar=0, sn_mva=0.03, name='PV
8', type='PV', index = 5)
    pp.create_sgen(net_cigre_mv, buses[8],  0.030, q_mvar=0, sn_mva=0.03, name='PV
9', type='PV', index = 6)
    pp.create_sgen(net_cigre_mv, buses[9],  0.040, q_mvar=0, sn_mva=0.04, name='PV
10', type='PV', index = 7)
    pp.create_sgen(net_cigre_mv, buses[10], 0.010, q_mvar=0, sn_mva=0.01, name='PV
11', type='PV', index = 8)

# Bus geographical data
    net_cigre_mv.bus_geodata = read_json(
"""{"x":{"0":7.0,"1":4.0,"2":4.0,"3":4.0,"4":2.5,"5":1.0,"6":1.0,"7":8.0,"8":8.0,"9
":6.0,"10":4.0,"11":4.0,"12":10.0,"13":10.0,"14":10.0},"y":{"0":16,"1":15,"2":13,"3
":11,"4":9,"5":7,"6":3,"7":3,"8":5,"9":5,"10":5,"11":7,"12":15,"13":11,"14":5}}""")
# Match bus.index
    net_cigre_mv.bus_geodata = net_cigre_mv.bus_geodata.loc[net_cigre_mv.bus.index]

    return net_cigre_mv


net = create_cigre_network_mv()
```

```
from pandapower.plotting import simple_plot, simple_plotly, pf_res_plotly
simple_plot(net)

# Here I am going to read the results files to determine how many times we would
have congestion
import os
from numpy.lib.function_base import append
import pandas as pd
import numpy as np
import numpy as np; np.random.seed(0)
from matplotlib import pyplot as plt
import seaborn as sns; sns.set_theme()
from matplotlib.colors import LinearSegmentedColormap
import matplotlib.colors as colors

output_dir = "/Users/markhoveling/Documents/TU Delft jaar 2/Master
thesis/Pandapower codes/GridOriginal/Grid results"

def constraints(output_dir):
    vm_pu_file = os.path.join(output_dir, "res_bus", "vm_pu.csv")
    vm_pu = pd.read_csv(vm_pu_file, index_col=0, sep=";")
    ll_file = os.path.join(output_dir, "res_line", "loading_percent.csv")
    line_loading = pd.read_csv(ll_file, index_col=0, sep=";")

    vec1 = line_loading.to_numpy().flatten()
    vec2 = vm_pu.to_numpy().flatten()

#constrain factor
    load_limit = 80
    vm_max_pu = 1.05
    vm_min_pu = 0.95

#loading line limit
    load_constraints = []
    exceded_count = 0
    for i in range(0,len(line_loading)):
        for j in range(0,len(line_loading.columns)):
            if line_loading.loc[i][j] > load_limit:
                exceded_count +=1
        load_constraints.append((i,100*exceded_count/len(line_loading.columns)))
        exceded_count = 0
    plt.bar_label(plt.bar([t[0] for t in load_constraints],[t[1] for t in
load_constraints]), fmt="%d", padding=3)
    plt.ylabel("Loading Constraints on lines (%)")
    plt.xlabel("Hours")
    plt.show()

#Voltage bus limit
    bus_constraints = []
    exceded_voltage_count = 0
    for i in range(0,len(vm_pu)):
```

```
        for j in range(0,len(vm_pu.columns)):
            if vm_pu.loc[i][j] > vm_max_pu or vm_pu.loc[i][j] < vm_min_pu:
                exceded_voltage_count +=1
        bus_constraints.append((i, 100*exceded_voltage_count/len(vm_pu.columns)))
        exceded_voltage_count = 0
    plt.bar_label(plt.bar([t[0] for t in bus_constraints],[t[1] for t in 
bus_constraints]), fmt="%d", padding=3)
    plt.ylabel("Voltage Constraints on busses (%)")
    plt.xlabel("Hours")
    plt.show()

# Line Loading histogram
    plt.hist(vec1, bins=20,  histtype='bar', align='mid')
    plt.xlabel("Line loading [%]")
    plt.ylabel("Frequency")
    plt.show()

    #line loading heat map
#https://matplotlib.org/stable/gallery/color/named_colors.html
    newcolors = plt.get_cmap('viridis', 100).colors
    newcolors[  : 60:] = colors.to_rgba('lightgreen')
    newcolors[60: 90:] = colors.to_rgba('lightyellow')
    newcolors[90: 100:] = colors.to_rgba('lightcoral')
    custom_color_map = colors.ListedColormap(newcolors)
    ax = sns.heatmap(line_loading, linewidth=0.5, cmap=custom_color_map, vmax=100, 
annot=True, annot_kws={"size": 8}, fmt=".2f")
    plt.title( "Line Loading (%)" )
    plt.xlabel("Line")
    plt.ylabel("Hour")
    plt.show()

# #Voltage bus histogram
    plt.hist(vec2, bins=20, histtype='bar', align='mid')
    plt.xlabel("Voltage (pu)")
    plt.ylabel("Frequency")
    plt.show()

#Voltage bus heatmap
    ax = sns.heatmap(vm_pu, linewidth=0.5, cmap="coolwarm", vmax= 1.10, vmin=0.90, 
annot=True, annot_kws={"size": 8}, fmt=".2f")
    plt.title( "Voltage (pu)" )
    plt.xlabel("Bus")
    plt.ylabel("Hour")
    plt.show()

constraints(output_dir)

# Controler creation
from pandapower.control import ConstControl
from Utils.net import create_cigre_network_mv
```

```python
def create_controllers(net, ds):

    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[0],
profile_name=["PV 3"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[1],
profile_name=["PV 4"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[2],
profile_name=["PV 5"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[3],
profile_name=["PV 6"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[4],
profile_name=["WD 7"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[5],
profile_name=["PV 8"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[6],
profile_name=["PV 9"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[7],
profile_name=["PV 10"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "sgen", "p_mw", element_index=net.sgen.index[8],
profile_name=["PV 11"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[0],
profile_name=["Load R1"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[1],
profile_name=["Load R2"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[2],
profile_name=["Load CI1"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[3],
profile_name=["Load CI2"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[4],
profile_name=["Load CI3"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[5],
profile_name=["Load CI4"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[6],
profile_name=["Load CI5"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[7],
profile_name=["Load CI6"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[8],
profile_name=["Load CI7"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[9],
profile_name=["Load CI8"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[10],
profile_name=["Load CI9"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[11],
profile_name=["Load CI10"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[12],
profile_name=["Load CI11"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[13],
profile_name=["Load CI12"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[14],
profile_name=["Load CI13"], data_source=ds, order=0, level =0, recycle = False)
```

```
    ConstControl(net, "load", "p_mw", element_index=net.load.index[15],
profile_name=["Load CI14"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[16],
profile_name=["Load CI15"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[17],
profile_name=["Load CI16"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[18],
profile_name=["Load CI17"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[19],
profile_name=["Load CI18"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[20],
profile_name=["Load CI19"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[21],
profile_name=["Load CI20"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[22],
profile_name=["Load CI21"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[23],
profile_name=["Load CI22"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[24],
profile_name=["Load CI23"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[25],
profile_name=["Load CI24"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[26],
profile_name=["Load CI25"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[27],
profile_name=["Load CI26"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[28],
profile_name=["Load CI27"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[29],
profile_name=["Load CI28"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[30],
profile_name=["Load CI29"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[31],
profile_name=["Load CI30"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[32],
profile_name=["Load CI31"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[33],
profile_name=["Load CI32"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[34],
profile_name=["Load CI33"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[35],
profile_name=["Load CI34"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[36],
profile_name=["Load CI35"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[37],
profile_name=["Load CI36"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[38],
profile_name=["Load CI37"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[39],
profile_name=["Load CI38"], data_source=ds, order=0, level =0, recycle = False)
```

```
    ConstControl(net, "load", "p_mw", element_index=net.load.index[40],
profile_name=["Load CI39"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[41],
profile_name=["Load CI40"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[42],
profile_name=["Load CI41"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[43],
profile_name=["Load CI42"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[44],
profile_name=["Load CI43"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[45],
profile_name=["Load CI44"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[46],
profile_name=["Load CI45"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[47],
profile_name=["Load CI46"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[48],
profile_name=["Load CI47"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[49],
profile_name=["Load CI48"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[50],
profile_name=["Load CI49"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[51],
profile_name=["Load CI50"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[52],
profile_name=["Load CI51"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[53],
profile_name=["Load CI52"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[54],
profile_name=["Load CI53"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[55],
profile_name=["Load CI54"], data_source=ds, order=0, level =0, recycle = False)
    ConstControl(net, "load", "p_mw", element_index=net.load.index[56],
profile_name=["Load CI55"], data_source=ds, order=0, level =0, recycle = False)

    print(net.controller)
    print("Controlers: OK")

#Output writer
from pandapower.timeseries import OutputWriter
from pandapower.timeseries.run_time_series import run_timeseries


def create_output_writer(net, time_steps,output_dir):


#Instead of saving the whole net (which takes a lot of time), I extract only
predefined outputs.
# The variables of create_output_writer are saved to the hard drive after the time
series loop.
```

```
    ow = OutputWriter(net, time_steps, output_path=output_dir,
output_file_type=".csv", log_variables=list())
    ow.log_variable('res_sgen', 'p_mw')
    ow.log_variable('res_gen', 'p_mw')
    ow.log_variable("res_ext_grid","p_mw")
    ow.log_variable("load","p_mw")
    ow.log_variable('res_bus', 'vm_pu')
    ow.log_variable('res_bus', 'va_degree')
    ow.log_variable('res_line', 'loading_percent')
    ow.log_variable('res_line', 'i_ka')

    print("output: OK")

    return ow

#CSV file clearing
import csv
import os


def CsvClearing(output_dir):

    resultFileAvg = open('/Users/markhoveling/Documents/TU Delft jaar 2/Master
thesis/Pandapower codes/GridOriginal/Grid
results/constraints/constraints_result.csv', 'r+') #Limpar o arquivo de resultados
    resultFileAvg.truncate(0)
    resultFileAvg.write("Hour, Line, Line Loading (%) \n")
    resultFileAvg.close()

#Results presentation
import matplotlib.pyplot as plt
import pandas as pd
import os

def resultsplot(output_dir):

#Voltage and line loading results

    vm_pu_file = os.path.join(output_dir, "res_bus",
"/Users/markhoveling/Documents/TU Delft jaar 2/Master thesis/Pandapower
codes/GridOriginal/Grid results/res_bus/vm_pu.csv")
    vm_pu = pd.read_csv(vm_pu_file, index_col=0, sep=";")
    ll_file = os.path.join(output_dir, "res_line",
"/Users/markhoveling/Documents/TU Delft jaar 2/Master thesis/Pandapower
codes/GridOriginal/Grid results/res_line/loading_percent.csv")
    line_loading = pd.read_csv(ll_file, index_col=0, sep=";")

    # sgen results
    sgen_file = os.path.join(output_dir, "res_sgen", "p_mw.csv")
    sgen = pd.read_csv(sgen_file, index_col=0, sep=";")
    ext_grid_file = os.path.join(output_dir, "res_ext_grid", "p_mw.csv")
```

```
    ext_grid = pd.read_csv(ext_grid_file, index_col=0, sep=";")
    load_file = os.path.join(output_dir, "load", "p_mw.csv")
    load = pd.read_csv(load_file, index_col=0, sep=";")

    plt.figure()
    plt.subplot(211)
    plt.plot(sgen.iloc[:,0], label='PV3')
    plt.plot(sgen.iloc[:,1], label='PV4')
    plt.plot(sgen.iloc[:,2], label='PV5')
    plt.plot(sgen.iloc[:,3], label='PV6')
    #plt.plot(sgen.iloc[:,4], label='Wind 7')
    plt.plot(sgen.iloc[:,5], label='PV8')
    plt.plot(sgen.iloc[:,6], label='PV9')
    plt.plot(sgen.iloc[:,7], label='PV10')
    plt.plot(sgen.iloc[:,8], label='PV11')
    plt.title("Local Power Supply")
    plt.legend(loc='upper right')
    plt.xlabel("Time step")
    plt.ylabel("P [MW]")

    plt.subplot(212)
    plt.plot(ext_grid, 'k', label='External Grid', linestyle='--')
    plt.title("External Power Supply")
    plt.legend(loc='upper right')
    plt.xlabel("Time step")
    plt.ylabel("P [MW]")
    plt.show()
    plt.figure()
    plt.plot(load)
    plt.title("Local Demand")
    plt.legend(loc='upper right')
    plt.xlabel("Time step")
    plt.ylabel("P [MW]")
    plt.show()

output_dir = "/Users/markhoveling/Documents/TU Delft jaar 2/Master
thesis/Pandapower codes/GridOriginal/Grid results"
resultsplot(output_dir)

# Initial loadflow

import pandapower as pp
from pandapower.timeseries.run_time_series import run_timeseries
from Utils.net import create_cigre_network_mv
from Utils.data_source import data_source
from Utils.controlers import create_controllers
from Utils.outputwriter import create_output_writer
from Utils.resultsplot import resultsplot
from Utils.constraints import constraints
from Utils.indicador_check import indicator_check
n_timesteps = 24
```

```
time_steps = range(0, n_timesteps)
output_dir = "/Users/markhoveling/Documents/TU Delft jaar 2/Master
thesis/Pandapower codes/GridOriginal/Grid results"
input_dir = "/Users/markhoveling/Documents/TU Delft jaar 2/Master thesis/Pandapower
codes/GridOriginal/Data/powerbytype.xls"

net = create_cigre_network_mv()
ds = data_source(input_dir)
create_controllers(net, ds)
ow = create_output_writer(net, time_steps, output_dir)
run_timeseries(net, time_steps, run=pp.runopp, delta=1e-10)

constraints(output_dir)

indicator_check(output_dir)

from pandapower.plotting import simple_plot, simple_plotly, pf_res_plotly
pf_res_plotly(net)
```