Identifying the Economic Performance of Heat-Based Industrial Symbiosis Networks
A Simulation Study

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Bachelor Thesis Industrial Engineering and Management

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8-1-2019

Summary

Energy-based industrial symbiosis is recognized as an effective strategy to reduce the amount of energy produced by using traditional fuels as well as to create economic value-added from the reuse of waste heat. However, implementing industrial symbiosis based on waste heat recovery faces a variety of challenges as additional infrastructure is required to operate the industrial symbiosis and the individual technical, operational, and economic needs of involved companies vary.

Aim and Scope of the Study

This study aims at assessing the economic feasibility of waste heat-based industrial symbiosis in a theoretical scenario via adopting a discrete simulation approach. An industrial symbiosis network composed of multiple companies producing and requiring different amounts of waste heat is analysed taking into account the following parameters: the number of pipeline links implementable amongst involved companies, the (mis-)match between excess heat supply and demand, the distance between companies, operational availability of waste heat producers and receivers, and the price of natural gas.

This study presents a framework for investment costs and annual savings for a heat-based industrial symbiosis network. To support the framework the costs and benefits that were relevant were identified, as well as drivers for investing in such a project. To measure profitability, three performance indicators were identified and thresholds were assigned to the indicators. These performance indicators are annual savings, payback period, and net present value. The role of the government to increase profitability is also identified.

Conclusion

According to the results implementing heat-based industrial symbiosis is profitable in the right circumstances. The profitability highly depends on the amount of waste heat that can be transferred and the price of natural gas. When demand is high, it is beneficial to add producers to recover as much waste heat as possible. However, overcompensating causes high investment costs that cannot be recovered in time. It can be concluded that there is a high potential for implementation, but the circumstances have to be identified beforehand. Meaning that the price of natural gas should be high enough to recover the investment costs.

Networks with high redundancy and subsequently high investment costs have high economic and environmental potential. This is in line with the effect of redundancy on the stability of the network. The government benefits if networks are resilient and continuously exchange value streams which improve economic and environmental performances. Therefore, the government should assess a network before funding the implementation. It would benefit from high redundancy high-value networks, and thus should only give funding to resilient networks. While low redundancy and subsequently low investment costs networks can be formed without incentive; the networks with high redundancy need a stimulus up front.

Table of Contents

1. Introduction

This chapter introduces the bachelor thesis. Section 1.1 introduces main concepts and identifies the problem. This section presents the scope of the study. Section 1.2 continues with the problem-solving approach. Research questions are presented to guide the problem-solving approach. Next to that, this section covers design choices and structure of the thesis. Section 1.3 gives an outline and contents of the study.

1.1 Problem Identification

Recently, sustainable development is becoming more important in the context of circular economy. In 2015, 193 countries adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (“Sustainable Development”, n.d.). One of the goals is to ensure sustainable consumption and production patterns meaning that resources and energy must be used more efficiently. However, energy use in OECD countries is continuing to grow another 35 per cent by 2020 (“Sustainable Development”, n.d.). While only one-fifth of the worlds final energy consumption in 2013 was from renewables (“Sustainable Development”, n.d.). By 2030, waste generation must be substantially reduced through prevention, reduction, recycling and reuse. The countries that adopted this agenda aim to move from linear to a circular economy. Such that resource use and pollution decreases which increases the social and environmental sustainability.

Industrial symbiosis, an emerging field of industrial ecology, is an example of moving from linear throughput to closed loop material and energy use. The key concept of industrial symbiosis is that, otherwise discarded, waste material and/or waste energy replaces the input resources of otherwise unrelated firms. Two or more firms of different industries develop mutually rewarding business networks aiming to achieve simultaneously economic, environmental and social advantages (Mirata, 2004), by making productive use of underutilized resources (Lombardi, Lyons, Shi, & Agarwal, 2012).

The underutilized resources that can replace input resources of other firms are wastes that otherwise would be discarded. These wastes include for instance wastewater, recovered energy, waste heat and material by-products (Chertow and Ehrenfeld, 2012). Industrial symbiosis converts negative environmental externalities, in the form of waste that used to be discarded, into positive environmental externalities. For instance, industrial symbiosis decreases pollution and reduces the need for raw material imports (Chertow and Ehrenfeld, 2012).

Industrial symbiosis is aimed at achieving at the same time economic, environmental and social advantages. These advantages involve resource efficiency, waste efficiency and energy efficiency. It also helps reducing costs of raw materials and reducing carbon emissions. Furthermore, industrial symbiosis increases the number of outputs that have value by selling waste resources, creating extra revenue by substituting the cost of discarding the waste. An example of a social advantage is the strong relationships that are built with other businesses. In other words, industrial symbiosis is aligned with the triple bottom line of sustainability.

Energy-based industrial symbiosis involves the use of residual energy in liquids or steam emerging from one process to provide heating, cooling, or pressure for another process (Ehrenfeld and Gertler, 1997). Energy-based industrial symbiosis is different from material IS, because waste energy is not as tangible as waste material. This makes transportation more complex. Many firms need heat as input and/or have excess heat as output. Normally, these firms have to buy heat (for instance, natural gas) and need to discard the excess heat in the air. Producers of waste heat link up with firms that have heat demand, aiming to increase the sustainability of the whole network. Transportation is done via pipelines, which are a long-term investment to be made.

Symbiotic relationships can be vulnerable to changes and interruptions. These changes include among others the amount of produced wastes, required inputs, waste disposal cost and input purchase cost (Fraccascia, Giannoccaro, & Albino, 2017). Changes in the amount of produced waste cause mismatches of demand and supply of waste, while the changes in waste disposal and input purchase cost affect the monetary value of the mismatch. When a mismatch increases, the economic performance of the network decreases. The match between waste supply and demand quantities is an important factor influencing the overall performance of a network because a mismatch must be compensated by either buying extra materials or discarding the waste that cannot be used.

Demand levels and failure rates are two main examples of factors that change the amount of produced wastes or required inputs and therefore can cause interruptions in the industrial symbiosis network. Waste is not produced on demand, waste emerges from the demand of main products of the firm. Similarly, the waste required as raw material is also emerging from the demand of main products. Therefore, the demand/supply match of waste is solely based on the demand for the main product of the firms involved in the exchange. A demand/supply mismatch often occurs. This causes uncertainty and complexity when firms search for the right match, because it leads to potential economic loss. Likewise, failure rates are causing insecurity in the amount of waste produced. Failure rate is the frequency with which a process fails expressed in failures per unit of times. High failure rates cause an unsteady output of waste heat and therefore interruptions of steady waste flows.

Redundancy is used to decrease the risks of interruptions and disturbances. For ecosystems, redundancy refers to the number of species that perform the same ecological function. In an industrial setting, redundancy refers to the number of firms that deliver the same product or have the same function, in this case providing excess heat or demanding excess heat. Redundancy compensates the risk of failing firms in the network. If one firm fails to produce waste, other firms can compensate. In case of no redundancy, the failure of one firm causes the whole network to collapse since there is not an extra firm that has the same function. Redundancy helps to maintain continuous operations.

Implementing industrial symbiosis in energy-based processes has proven to be environmentally beneficial (Dong et al., 2016; Jacobsen, 2008; Li, Dong, & Ren, 2015; Wu, Qi, & Wang, 2016), but the economic side is harder to grasp (Jacobsen, 2008). The problem is balancing risk and costs. To decrease risk, redundancy can be increased, because by increasing the redundancy of IS relationships, firms can become less vulnerable to disruptive events. But higher redundancy increases the supply chain complexity and increases transaction costs, a challenge for the firms to deal with. A higher number of partners for a given waste (high redundancy) results in higher long-term benefits because of decreasing risks and higher flexibility. However, high redundancy causes lower short-term benefits because of additional transaction costs. An example of a transaction cost that increases because of high redundancy is the investment into pipelines between firms to transfer heat and condensate. These costs are high and the consequences are long-term.

Concluding, Energy-based industrial symbiosis is recognized as an effective strategy to reduce the amount of energy produced by using traditional fuels as well as to create economic value-added from the reuse of waste heat. However, implementing industrial symbiosis based on waste heat recovery faces a variety of challenges as additional infrastructure is required to operate the industrial symbiosis and the individual technical, operational, and economic needs of involved companies vary. This study will explore the economic side of the implementation of energy-based industrial symbiosis, in particular the use of excess heat via pipeline systems between companies from otherwise unrelated industries.

1.2 Problem Solving Approach

The problem that will be solved in this bachelor project is that firms have no indication of the economic side of implementing industrial symbiosis in an energy-based system. The problem analysis results in the following research question:

Is implementing heat-based industrial symbiosis profitable?

This will be researched via literature research and a simulation based on a hypothetical case and supported by the literature research. This simulation will take into account different types of redundancy and other important variables presented in the problem identification like failures and demand/supply mismatches.

This study is subdivided into three parts. These are 1) the theoretical background of industrial symbiosis in heat-based systems, 2) a practical framework, and 3) a simulation based on a hypothetical case study. The first two parts provide information and a framework for the simulation and support the result. The simulation uses the information about costs and revenues and simulates a self-organized industrial symbiosis network. The practical framework is based on important parameters that are discovered in the first part. All the combinations of parameters are simulated in a discrete simulation and via the results there can be concluded if industrial symbiosis is profitable and therefore a beneficial investment for heat-based networks.

1.2.1 Knowledge Problems

To answer the research question, the following knowledge problems need to be answered. These knowledge problems serve as sub-questions. The questions are subdivided into the three parts presented in Section 1.2:

Part 1

- How can industrial symbiosis be implemented and maintained in heat-based networks?
- How can the economic performance be measured?
- What is the role of governments in case of economically unstainable cases?

These knowledge problems will be solved via literature research. This is the scope of the theoretical background for the practical framework and the simulation (part 2 & 3). It is important to know how industrial symbiosis can be implemented and how the performance of such a network can be measured. This is the foundation of the simulation study. Next to those two sub-questions, it is needed to look at the role of the government. The government can potentially boost the economic performance of the network, which causes more firms to cooperate.

Part 2 & 3

- What is the impact of redundancy on the supplier and receiver side on the economic performance of a heat-based industrial symbiosis network?
- What are the impacts of demand/supply mismatches and failure rates on the economic performance of a heat-based industrial symbiosis network?

These knowledge problems will be presented in the practical framework and answered via discussion of the results of the simulation case study. Answering these questions indicates how the network performs for different types of redundancy and levels of disturbance. As well as indicating if the network is still profitable within good or bad circumstances.

Using, among others, demand for waste and failure rates as changing factors in the simulation there can be investigated what the effect of industrial symbiosis is on the economic performance of the network. The variables demand and failure rates are moderating variables. A moderating variable is a second independent variable that is included because it is believed to have a significant contributory effect on the IV-DV relationship (Cooper & Schindler, 2014). The IV (industrial symbiosis/redundancy) directly impacts the DV (economic performance) and the MVs (demand & failure rates) affect the relationship.

Moderating variables are used when the researcher has a greater interest in the predictor variable and by changing different MVs, the reliability of the predictor variable can be tested. A moderating variable can increase or diminish the relationship, or even change the direction of the relationship from positive to negative. This research is interested in the effect of industrial symbiosis on the economic performance, MVs can radically change the direction of the relationship, therefore they have to be included.

1.3 Outline

This thesis is divided into 7 chapters, comprising the theoretical background, practical framework and simulation. In these chapters, the problem is investigated and the research questions will be answered.

Chapter 1 covers the introduction for this bachelor assignment, the introduction states the problem identification, problem-solving approach and research questions. In chapter 1 the main concepts will be defined as well, particularly in the problem identification.

Chapter 2 provides the theoretical background for the simulation via literature research. This chapter will elaborate on the first three sub-questions: “How can industrial symbiosis be implemented and maintained in heat-based networks?”, “How can the economic performance be measured?” and “What is the role of governments in case of economically unstainable cases?”.

Chapter 3 presents the simulation model of the industrial symbiosis network. In this chapter, the practical framework for the simulation is introduced based on the theoretical background. This chapter provides the design of the simulation and main scenarios, as well as equations for costs and savings.

Chapter 4 covers the case example. This case example is based on chapter 3 and fits the requirements set in chapter 3. First, this chapter defines the main features of the hypothetical case and performance indicators. Next to that, the scenario setting is presented.

Chapter 5 elaborates on the results of the simulations. First, the investment costs of the scenarios are presented. Secondly, the performance indicators introduced in chapter 4 are investigated. Finally, the effect of redundancy on resilience to disturbances is presented.

Chapter 6 discusses the simulation results of the hypothetical case study. This chapter will elaborate on the last two sub-questions: “What is the impact of redundancy on the supplier and receiver side on the economic performance of a heat-based industrial symbiosis network?” and “What are the impacts of demand/supply mismatches and failure rates on the economic performance of a heat-based industrial symbiosis network?”.

Chapter 7 provides conclusions of the research and recommendations for further research. The last chapter answers the research question: “Is implementing heat-based industrial symbiosis profitable?”. Next to that, the effect of limitations and simplifications are discussed, resulting in recommendations for further research.

Lastly, extended simulation results are presented in the appendix. Results of all the scenarios are presented in terms of payback periods, net present values and return on investments.

2. Theoretical Background

This chapter provides the theoretical background for the simulation study via literature research. This chapter will elaborate on the first three sub-questions: “How can industrial symbiosis be implemented and maintained in heat-based networks?” covered in Section 2.1, “How can the economic performance be measured?” covered in Section 2.2 and “What is the role of governments in case of economically unstainable cases?” covered in Section 2.3.

2.1 Implementation of Industrial Symbiosis

Industrial symbiosis involves cooperative management and exchange of resource flows through networks of companies (Chertow & Ehrenfield, 2012). Industrial symbiosis includes all arrangements where enterprises exchange outputs that, in the case of no cooperation, would be discarded and hence become treated as environmental externalities (Chertow & Ehrenfield, 2012). By collaborating, the firms involved in an industrial symbiosis network expect a collective benefit which is greater than the sum of individual benefits they had when working alone (Chertow, 2000). Thus, economic gains are the main driver for firms willing to implement industrial symbiosis, the environmental gains are secondary.

To implement industrial symbiosis, an industrial symbiosis network needs at least two parties, one producer and one receiver. A collaboration can be formed if the waste of the producer and the input resource needed by the receiver have the same properties. In case of heat-based industrial symbiosis, one heat source and one heat sink. The producer has waste heat that otherwise is discarded in the air, and the receiver needs heat to produce their main product. Condensate of the exchanged heat can be transferred back to the producer, to create a closed loop. This is done via pipelines, which are a costly investment. In comparison with material-based industrial symbiosis, energy-based industrial symbiosis is a long-term investment. This is because of the high initial investment. It will take multiple years to recover the initial investment cost.

Because resource flows are exchanged, the firms in the network should be close to another, this is defined as geographic proximity (Chertow, 2004). Geographic proximity is important because transferring resource flows via pipelines or transportation is expensive. If the distance between firms is low, a network has fewer investment costs and/or transportation costs compared to a network with larger distances. Geographic proximity enables the network to cooperate, while it does not cause a network to form. Meaning that distance is not the main driver for implementation; however, implementing industrial symbiosis at firms which are far apart is likely to fail and discontinue.

There are two main ways an industrial symbiosis network can form: Self-Organized and Designed. The conditions required for implementing both self-organized and designed industrial symbiosis facilities share many similarities (Baas, 2011), such as a trust-based inter-firm relationship, long-term interdependence and personal relations. The main difference between the two is which parties are involved when forming the cooperation and the main driver for collaboration.

In self-organized industrial symbiosis relationships, firms can autonomously choose the number of partners in exchanging a given waste. When one firm quits the network, firms can still form relationships with others. Secondly, it is important to note that in in the case of self-organizing industrial symbiosis, the exchange network is not developed with the aim of establishing environmental benefits by the symbiotic exchange of by-products (Gabriel, Schöggl, & Posch, 2017). Rather, the network forms autonomously because firms expect to gain advantages. Therefore, the driver for self-organized IS relationships is money and relies on self-interest.

That is in contrast with designed industrial symbiosis relationships. In designed industrial symbiosis there is a group of actors that design the whole network. Thus, designed industrial symbiosis is a top-down approach. Public or private developers create a park or zone and seek firms that are suitable to collaborate (Chertow, 2012). An example of a group of actors that can potentially design IS relationships is the government (See Section 2.3). The whole network is designed in advance, and the driver is next to economic benefits, environmental benefits. A designed industrial symbiosis network does not naturally rely on self-interest; however, it relies on mutual interests. When designing a network, more emphasis can be put on the environmental benefits, while maintaining sufficient economic benefits.

The benefits for each company must exceed the total of costs for each firm to sustain an industrial ecosystem. An industrial ecosystem is defined as "the network of interrelated symbiotic links among firms in an area" (Ehrenfeld and Gertler, 1997, p.68). In the case of industrial symbiosis, all the firms in the network should aim to achieve positive net private benefits for all the parties involved (Chertow and Ehrenfeld, 2012). If a symbiotic relationship becomes not economically convenient for one firm, such a firm may decide to interrupt the relationship with its partner(s). This causes an interruption of the environmental and economic benefits of the network. Therefore, it is very important to collaborate and make sure that every firm has positive net private benefits.

As explored in Section 1.1, having no redundancy is risky for the long-term benefits of an industrial symbiosis network. Stability in an industrial symbiosis network is crucial for maintaining a profitable network (Wang et al., 2017). A stable network continuously exchanges resource flows. The ability to maintain stability is called resilience. Resilience of industrial symbiosis networks is the ability to "maintain their defining feature of eco-efficient material and energy flows under disruptions" (Mannino, Ninka, Turvani, & Chertow, 2015, p.288) such as changes in production and demand levels, failures and bankruptcy. Therefore, it is important to investigate how much redundancy will be implemented when designing or organizing a network. Since firms can compensate the effect of those disturbances when there are more firms in the network with the same industrial function.

Summarizing, industrial symbiosis needs at least two parties that exchange waste materials to reduce among others, input purchase costs, waste disposal costs and negative environmental externalities. The waste product should have the same properties and/or function as the raw material it replaces. Industrial symbiosis relies strongly on geographic proximity and collaboration. Geographic proximity is important to decrease investment and transportation costs. Especially when exchanging energy, because installing pipelines is expensive. Collaboration is essential to maintain a profitable and continuous network. If a symbiotic relationship becomes not economically convenient for one firm, a network can be disrupted.

2.2 Economic Value of Implementing Energy-Based Industrial Symbiosis

In self-organized industrial symbiosis networks, the most important motivation for companies to be involved within the network is the realization of economic benefits (Gabriel et al., 2017), and as discussed in Section 2.1 the need for positive net private benefits is crucial for a network to form and to maintain resilient to disturbances. According to Jacobsen (2008), the economic aspects of exchange relationships are a combination of investments at the time of initiation and the direct and indirect economic savings. These investments and savings are discussed in respectively Section 2.2.1 and Section 2.2.2.

2.2.1 Investment Costs

Investment costs are needed to initiate the network. This is due to the fact that infrastructure is needed for the transportation of the exchanged material. In this case, there is need for pipelines to transfer the heat via water or steam to the heat sinks. The cost of pipelines depends on multiple factors, for instance the diameter of the pipeline and the length of the pipeline. The diameter has to be sufficient to transfer the expected heat load. Geographic proximity benefits the total length of the pipeline network, and therefore the distance between firms enables the network to form. Since pipeline costs increase significantly if the distance increases. To maintain the effectiveness of the pipelines, there is need for annual maintenance costs. These maintenance costs are used to keep the system running.

2.2.2 Economic Savings

The benefits of implementing industrial symbiosis for the whole network are comprised of savings. These savings include avoided disposal costs (Jacobsen, 2008; Rosa & Beloborodko, 2015; Gabriel et al., 2017), reduced input purchase costs (Jacobsen, 2008; Gabriel et al., 2017; Lehtoranata et al., 2011), avoiding transport costs (Lehtoranta, Nissinen, Mattila, & Melanen, 2011) and increased income by selling by-products (Jacobsen, 2008; Gabriel et al., 2017; Rosa & Belobordko, 2015). However, by treating the parties involved in the network as one coherent system, the question of pricing the by-product can be avoided. This is because, when analysing the profitability of this project the increased incomes of selling by-products of one provider results in increased costs at the receiver side. Meaning, this only shifts the value between the firms but it does not impact the overall profitability. Thus, the value of the transportation of waste heat can be neglected. Pricing the waste heat is applicable after there is proven that the network is profitable, afterwards the profit can be allocated to the firms. Secondly, in the case of heat-based industrial symbiosis, disposal costs of heat are usually non-existent. The waste heat can be disposed via flue gas into the air for free.

Concluding, the economic value of implementing industrial symbiosis is comprised of the economic savings due to exchanging input with by-products, which reduces purchase costs, maintenance costs and the cost of investments. For a network to be profitable, all investment costs need to be recovered via savings in a sufficient time period. This means that in year 0 the investment needs to be made and due to reduced costs in the following years the cost of investment will be recovered.

2.3 Governmental Policies

The implementation of self-organized industrial symbiosis is driven by economic gains for the firms involved in the exchange. However, for the government environmental benefits are as important as economic benefits. Yet, potential self-organized networks will not initiate despite having positive effect on the environment, because of economic reasons. Meaning the firms in the network do not have positive private benefits. Therefore, the government can and should use a few tools to stimulate the implementation of industrial symbiosis.

While self-organized industrial symbiosis networks are created due to economic reasons, designed networks can be created for environmental gains. Linkages that are driven by land development and infrastructure construction, cause the motivation to cooperate of the companies in the network to be weak (Wen et al., 2018). This is because the economic private benefits are not clear or not sufficient. The involvement of the companies in the network is a major disadvantage for designed networks. Therefore, when the government or another entity design an industrial symbiosis network, the government needs to create or increase economic profitability of the network, otherwise the companies potentially will not cooperate.

In both self-organized and designed networks, the government can increase economic profitability by giving financial incentives in the form of funding (Dong et al., 2016; Velenturf, 2016; Wen et al., 2018). Incentives reduce the initial investment costs and therefore the investment can be recovered faster. Before funding, the government should check whether the plan of the companies in the network is effective and beneficial both economically and environmentally (Dong et al., 2016; Wen et al., 2018).

Another tool to stimulate the implementation of industrial symbiosis is to raise taxes of wasteful input materials/energy (Dong et al., 2016). Taxes are used by the government to regulate behaviour of firms. Increasing the overall price of these materials/energy is a driver for companies to look for cheaper solutions, for instance using waste. Taxes cause the economic savings to increase, and thus an investment can be recovered faster, making industrial symbiosis more beneficial.

Often, stronger regulations regarding waste emissions are used. However, incentive policies as mentioned are more favourable to industrial symbiosis formation than regulatory policies (Yu, Han, & Cui, 2015). This is due to the fact that companies are motivated to design an effective network when it will result in incentives, it is a positive approach. For instance, Yu et al. (2015, p.340) state that “in European Union countries, policy has a positive influence on industrial symbiosis development through indirect incentives and not through direct obligations to improve the environment performances”.

Concluding, in cases of economic unsustainability the government should try to motivate the plants to form an industrial symbiosis network. This should be done by reducing investment costs or increasing economic savings instead of stronger regulations. These incentives boost the economic profitability and therefore help to motivate the companies applicable for industrial symbiosis to invest in implementing industrial symbiosis.

3. The Simulation Model of the Network

In this chapter the practical framework for the simulation is introduced based on the theoretical background. In section 3.1, the design of the model is presented. This section covers, among others, the costs and savings occurring when implementing industrial symbiosis and presents assumptions that were made designing the simulation model. Section 3.2 describes and discusses four main scenarios involving redundancy. This section provides design choices and expected results.

3.1 Description of the Network

There is considered a given amount of plants of otherwise unrelated industries in a general geographic area. There are two types of plants: producers and receivers. The producer plants generate waste heat that otherwise would be discarded in the air for free. The receiver plants use heat as input, and their natural gas usage can be exchanged with the waste heat of the producers. Next to the exchange of waste heat, the condensate of the usage of waste heat is returned from the receiver the producer. Therefore, two streams will flow between the producers and receivers: Waste Heat and Condensate. An example of exchanges of one producer and one receiver is shown in Figure 3.1.

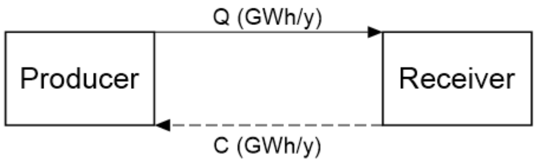

Figure 3.1. Waste exchanges between producer and receiver. Q is the amount of waste heat that is exchanged and C is the amount of condensate that is returned.

The producers have a fixed amount of waste heat which they can transfer when they are available. During downtime, the production of their main product cannot continue, and subsequently, waste heat is not produced and cannot be transferred. On the other side, the receivers need heat for the production of their main product, when they use heat they create condensate which will be transferred back when they are available. During downtime, the production of their main product cannot continue, and subsequently, condensate is not produced and cannot be transferred.

The amount of heat that is exchanged in the network (Q) is set to be the most as possible. Thus, the amount of heat that can be exchanged is the minimum of either the total demand for waste heat or the total supply of the available producers. In this way, the network works to its full potential. The amount of exchanged heat per time unit potentially changes during downtime of one of the producers. The total supply of available producers can be lower than the demand if one producer in the network is down, in that case the heat load changes to the supply instead of the demand. The condensate (C) that returns to the producer is decided by the heat load that is transferred to the receiver. For every unit of heat, x units of condensate can be returned; this is decided by the condensation factor. The condensation factor is a factor between 0 and 1. The heat load and condensate are expressed as follows:

$$Q = Min\{Total\ supply\ of\ available\ producers, Total\ demand\ of\ receivers\} \quad (1)$$

$$C = Q * Condensation\ Factor \quad (2)$$

Availability is defined as the percentage of the operation time a firm can transfer waste streams. Failure rates and operational availability of a plant are connected. If a component or process fails, the plant is not available for the time it takes to repair the failure. If a plant is available there are no failures that need to be repaired. However, failure rates are very plant- and component-specific. There is not much data that can be used in the simulation. Consequences of failure are also very plant-specific, and not usable in a hypothetical case. Therefore, generalizing failure rate is very unreliable.

The average operational availability consists of both the number of failures and the time to repair. A company with many failures but fast repair time and a company with fewer failures but slow repair time can be available for the same time. Therefore, the availability of a plant is more important to analyse the network than individual failure rates. As a function:

$$Availability = \frac{MTBF}{MTBF + MTTR} \quad (3)$$

Where MTBF stands for the mean time between failures and MTTR stands for the mean time to repair.

The network gains economic benefits from exchanging natural gas with waste heat at the receiver side and exchanging natural gas with condensate at the producer side. In this way, the network saves input costs. Since disposing heat in the air is free, there are not any savings in disposal cost. These benefits are expressed as annual savings.

The annual savings are calculated via the amount of gas that is substituted by waste heat (both the waste heat and the condensation). The availability is thus involved with both the producers and receivers. There is assumed that the downtimes of the firms do not overlap and therefore if one firm is unavailable due to failure the other firms continue to work and thus can transfer their heat. There is also assumed that 1 MW waste heat substitutes 1 MW of natural gas. In that way, the price of natural gas can be multiplied with the heat load. Due to geographic proximity, there will not be any significant heat loss that has to be considered (Kim, Yoon, Chae, & Park, 2010). The annual savings are computed using the following equation:

$$\begin{aligned} AS = &((1 - n_{producers} * (1 - Availability)) * Q_{AllFirmsAvailable} * P \\ &+ \sum_{X=1}^{n_{producers}} ((1 - Availability) * Q_{DuringDowntimeOfProducerX} * P)) \\ &* \big((1 + Availability) * Condensation\ Factor\big) \end{aligned} \quad (4)$$

where n is the number of producers in the network, Q the amount of waste heat that is exchanged and P is the price of natural gas. The equation consists of the value of the heat load that is exchanged during the availability of all the producer plants added with the value of heat loads during downtime of one of the producer plants, times the availability of the receivers multiplied with the condensation factor. During downtime of one of the firms, the total amount of heat that can be exchanged might be lower than during uptime of all the firms. Therefore, those downtimes have to be considered in the calculation. To simplify, in this study there is assumed that for 1 MW of waste heat 1 MW of condensate is produced, so the condensation factor is assumed to be 1:1.

To connect the firms, pipelines have to be installed. Every producer is connected to all the receivers and every receiver is connected to all the producers. Every connection contains two pipelines, one for waste heat and one for condensate. The number of pipelines in the network can thus be computed as follows:

$$Pipelines = n_{producers} * n_{receivers} * 2 \quad (5)$$

The investment costs are based on the diameter of the pipelines and the distance between firms. A generalized pipeline equation (Parker, 2004) is used to give an accurate estimation of the pipeline cost:

$$Construction\ Cost\ (d, l) = (674d^2 + 11754d + 234085)l + 405000 \quad (6)$$

where the Diameter d is in inches, the Distance between firms l is in miles and Cost is in dollars. The calculation of the construction costs for pipelines contains labour costs, material costs and extra costs like surveying, all included in Equation 8.

The diameter of the pipeline depends on the heat load it has to transfer. To calculate the heat load that a pipeline has to transfer the demand is divided by the operating hours of 8000. A table of standardized pipeline diameters and the maximum heat load (Svensk Fjärrvärme, 2017) is used and the diameter that fits the heat load is chosen. The maximum heat load which a pipeline should carry is either the total amount of waste heat divided by the number of receivers if there is more demand than supply, or the demand of the receivers if the producer has more heat than the receivers need.

Additional costs to the investment costs are the maintenance and operation costs. These costs are made to keep the network running. The annual maintenance and operation costs of the constructed pipelines are considered to be 2% of the investment costs (Hackl & Harvey, 2013), and it is assumed that the maintenance and operation costs stay 2% of the investment costs every year.

3.2 Scenarios

The simulation is divided into four scenarios. These differ in redundancy on the producer as well as the receiver side. The networks are modelled such that the number of plants increases, in this way the simulation can test the impact of extra firms on the economic performance. The networks are modelled as follows in terms of the number of producers and receivers:

- Base Scenario 0: 1-1 Network

- Scenario 1: 1-3 Network
- Scenario 2: 2-3 Network
- Scenario 3: 3-3 Network

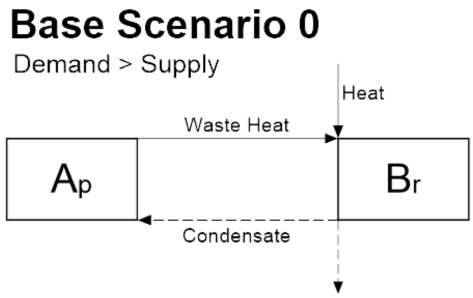

Figure 3.2. Base Scenario 0. This scenario includes one producer (A) and one receiver (B), this results in two pipelines. Due to the demand-supply mismatch, firm B has to purchase extra heat.

In the base scenario, there is one producer and one receiver (1-1 Network) plus a demand-supply mismatch. Which means that the receiver needs more heat as input than the producer can deliver. Because the demand for heat cannot be fulfilled, the receiver plant has to buy the missing heat. However, these extra input purchase costs ((Demand – Q) * P) are not considered as costs in the model since these costs were also made in case of no industrial symbiosis. This scenario is used to measure the initial effect of industrial symbiosis without redundancy. Since there is one producer and one receiver, only two pipelines are needed. However, this network is potentially prone to disturbances which limit the effectiveness of the network.

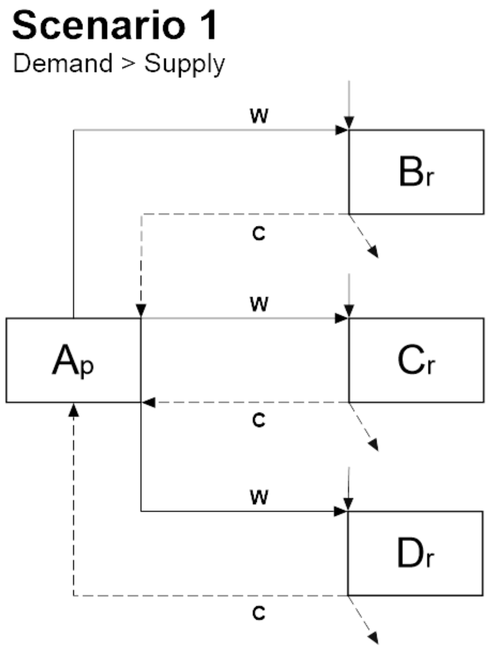

Figure 3.3. Scenario 1. This scenario includes one producer (A) and three receivers (B, C and D), this results in 6 pipelines. W is the waste heat load that is transferred to the receivers and C is the condensate that is returned. Due to the demand-supply mismatch, firms B, C and D have to purchase extra heat.

Scenario 1 replaces the receiver of scenario with three receivers. The total amount of demand for waste heat remains the same as in scenario 0. The demand of the receiver of scenario 0 is divided by three and those thirds are allocated to the new receivers. In this way, demand and supply remain the same as in scenario 0, which makes them comparable. This scenario tests the impact of redundancy at the receiver side. Because the supply and demand did not change there is still a demand-supply mismatch. The number of pipelines which are required to make this network work is six, since there are respectively three waste heat and condensate streams.

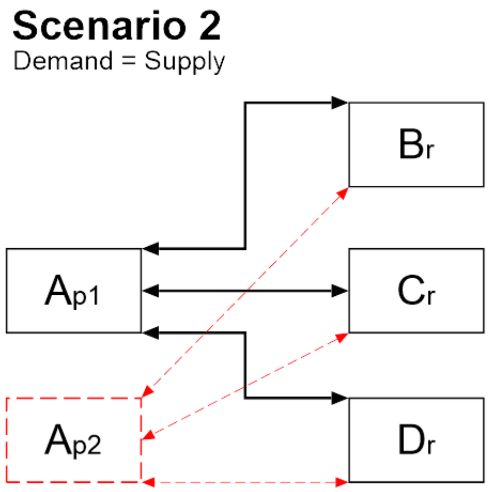

Figure 3.4. Scenario 2. This scenario includes two producers (A_{p1} and A_{p2}) and three receivers (B, C and D), this results in twelve pipelines. Each double-headed arrow represents two streams: waste heat which transfers from the producer to the receiver and condensate which transfers from the receiver to the producer.

In scenario 2 a second producer is added, producer 2. This creates a 2-3 network. This second producer is modelled as roughly the same size as producer 1. The supply of waste heat increases due to the extra producer, which compensates the initial demand-supply mismatch in some of the cases. The second producer solves the mismatch problem if the total demand is lower than the sum of the waste heat of the two producers combined. The second producer potentially decreases the risk of disturbances because of increased redundancy. When one of the producers is unavailable another mismatch occurs, in this case the supply of the producer that is left is distributed evenly to the receivers. In this way, during downtime exchange of heat can still continue, increasing the annual savings of the whole network. Due to the extra producer the number of streams doubles, which increases the network complexity.

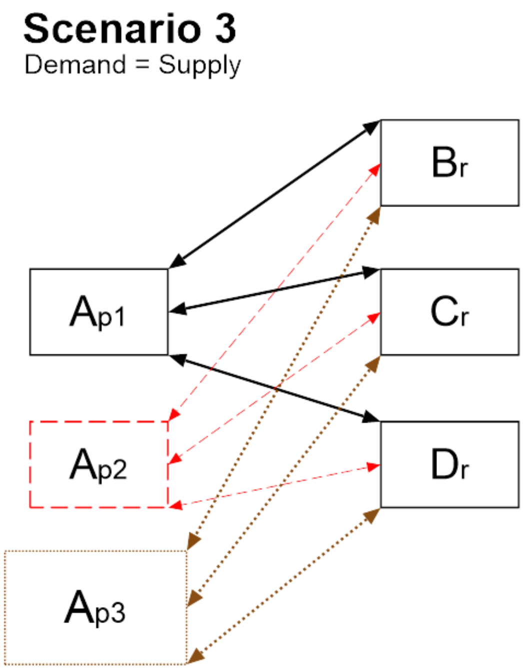

Figure 3.5. Scenario 3. This scenario includes three producers (A_{p1}, A_{p2} and A_{p3}) and three receivers (B, C and D), this results in sixteen pipelines. Each double-headed arrow represents two streams: waste heat which transfers from the producer to the receiver and condensate which transfers from the receiver to the producer.

In scenario 3 another producer is added to the network, a significantly larger one, in terms of waste heat, than the other two. This producer fully compensates the demand-supply mismatch in all of the cases when this third producer is available. The produced waste heat of the third producer is modelled to be higher than the total demand of the receivers. This scenario provides even more redundancy, and therefore the risks of unavailability will be lower than the risks in the previous scenarios. An overview of the four scenarios is presented in Table 3.1.

Table 3.1
Scenario overview

	#Producers	#Receivers	#Pipelines	Is there a Demand-Supply Mismatch?
Scenario 0	1	1	2	Yes. Demand is always higher than supply.
Scenario 1	1	3	6	Yes. Demand is always higher than supply.
Scenario 2	2	3	12	Sometimes. Demand is sometimes higher than supply.
Scenario 3	3	3	18	No. The third producer fully compensates the mismatch.

4. Case Example

In this chapter, the hypothetical case example is presented. Section 4.1 presents the main features of the case example. These main features include, among others, the allocation of a main product and waste heat supply to the producer and the scenario setting. Section 4.2 defines the performance indicators which measure the profitability and economic performance of the industrial symbiosis network.

4.1 Main Features

To run simulations, the main features of the hypothetical case study have to be defined. The three otherwise unrelated producers presented in Section 3.1, have been allocated a main product and subsequently, a waste heat supply. Data is based on a study that featured a table with total excess heat per industry (plus the number of sites analysed) in Denmark (Bühler, Petrović, Karlsson, & Elmegaard, 2017). Three of the industries which discarded the most excess heat have been averaged to a single plant and rounded to simplify the model, which is shown in Table 4.1. The three producers resemble 3 average plants with high energy waste, and therefore implementing industrial symbiosis could have great potential. The supply levels of the producers are fixed in the simulation. Which means that in scenario 0 and 1 there is 7.50 GWh/y of waste heat, in scenario 2 13.50 GWh/y and in scenario 3 188.50 GWh/y. This fits the network modelling presented in Section 3.1.

Table 4.1
Waste heat producers

	Produced Material	Waste Heat	Unit
Producer 1	Rockwool	*7.50*	GWh/y
Producer 2	Enzymes	*6.00*	GWh/y
Producer 3	Oil Refinery	*175.00*	GWh/y

The receivers or heat sinks B, C and D are hypothetical and have a variable distance (1, 2 or 3 km) to the producers. The distances are based on the fact that industrial symbiosis relies on geographic proximity, discussed in Section 2.1. They could be any firm that uses heat to produce their main product. Heat sinks B, C and D are not defined because, in reality, producers can decide with which plants they want to cooperate. A second reason is to test the economic performance of the network the demand levels will be changed and thus demand is variable. In this way, the compensation factor of redundancy can be tested. Because more compensation can occur if there is more demand for waste heat, when there is initially a high demand/supply mismatch

The total demand of the heat sinks is set via w/r ratio. The w/r ratio indicates the difference between waste and demand. Using this ratio different levels of initial demand/supply mismatches can be analysed. For instance, a ratio of 0.5 means that there is twice as much demand than supply and a ratio of 0.2 indicates a mismatch of 5 times the supply. The demand levels are set based on scenario 0 when there is one producer. In scenario 1, 2 and 3 the total demand remains the same, however, new producers are added which decrease or nullify the demand/supply mismatch. The ratios used are shown in table 4.2.

When plants are unavailable their output stream (waste heat or condensate) will stop. All the plants operate for 8000 hours per year and heat can be transferred into the system continuously if the firms are available. Literature research shows that most average availabilities range from 85-98% (Barringer, 1997; Malaret, 2018; Oyedepo, Fagbenle, & Adefila, 2015; Wels, 2007; World Energy Council, 2007). The industries analysed in the articles are different and because the data is mostly the same range it can be generalized for this case. Three levels of availability are considered: 85%, 90% and 95%.

Table 4.2

Scenario overview: Supply and Demand

Scenario 0	Waste Heat (GWh/y)	Demand (GWh/y)	Demand (GWh/y)	Demand (GWh/y)	Demand (GWh/y)	Demand (GWh/y)
W/R Ratio		**0.2**	**0.4**	**0.6**	**0.8**	**1**
Producer 1	7.50					
Receiver 1		37.5	18.75	12.5	9.375	7.5
Total	7.50	37.5	18.75	12.5	9.375	7.5
Scenario 1						
Producer 1	7.50					
Receiver 1		12.5	6.25	4.167	3.125	2.5
Receiver 2		12.5	6.25	4.167	3.125	2.5
Receiver 3		12.5	6.25	4.167	3.125	2.5
Total	7.50	37.5	18.75	12.5	9.375	7.5
Scenario 2						
Producer 1	7.50					
Producer 2	6.00					
Receiver 1		12.5	6.25	4.167	3.125	2.5
Receiver 2		12.5	6.25	4.167	3.125	2.5
Receiver 3		12.5	6.25	4.167	3.125	2.5
Total	13.50	37.5	18.75	12.5	9.375	7.5
Scenario 3						
Producer 1	7.50					
Producer 2	6.00					
Producer 3	175.00					
Receiver 1		12.5	6.25	4.167	3.125	2.5
Receiver 2		12.5	6.25	4.167	3.125	2.5
Receiver 3		12.5	6.25	4.167	3.125	2.5
Total	188.50	37.5	18.75	12.5	9.375	7.5

To calculate the annual savings, the price of the exchanged material has to be defined. The material that is exchanged is natural gas. Natural gas does not have a fixed price all over the world. Comparing the prices of natural gas in Europe, Japan, China & Canada (Andrews & Pearce, 2011; Bluegold Research, 2018; Eurostat, 2018) show the price ranges from 5.8 to

11.57 \$/GJ. Prices of 6, 8 and 10 dollars per gigajoule will be analysed to fit the different economies.

Summarizing, the simulations scenarios are set by varying 5 variables shown in table 4.3. The simulation plan consists of 540 different scenarios, which will be assessed via performance indicators presented in Section 4.2.

Table 4.3
Scenario setting. Values of the variables for simulated scenarios

Variable	Modelling Variable	Values
Redundancy	Number of producers and receivers in the network. (#producer-#receiver)	1-1, 1-3, 2-3 & 3-3
Demand/Supply Mismatch	Total demand of receivers (GWh/y)	37.5, 18.75, 12.5, 9.375 & 7.5
Value of Savings	Price of natural gas (\$/GJ)	P = 6, 8 & 10
Investment Costs	Distance between firms (Km)	D = 1, 2 & 3
Failures	Availability of a plant	85%, 90% & 95%
		Total scenarios: 540 (4x5x3x3x3)

4.2 Performance Indicators

Performance Indicators have to be defined to assess the economic viability of the industrial symbiosis network. In addition to investment costs and annual savings, three extra performance indicators are used to assess the economic benefits caused by the implementation of industrial symbiosis. Those are the payback period, the net present value (NPV) and the return on investment (ROI). These three indicators are capital budgeting methods that value an investment. In Section 4.2.1 the calculation of the cash flows is introduced, these cash flows are the main input for calculating the performance indicators. Section 4.2.2 covers the payback period and Section 4.2.3 elaborates on both the NPV and ROI.

4.2.1 Cash flows

Annual cash flows have to be defined for the three performance indicators. There is assumed that revenues are achieved from day one and that the investment is done at the start of the project completely. Therefore, the investment is taken into account in the cash flow for year one. The cash flows consist of annual savings and maintenance/operation costs. The maintenance/operation costs are as mentioned 2% of the investment costs.

$$Cash\ Flow\ (year = 1) = -Investment + Annual\ Savings - 2\% * Investment \quad (7)$$

$$Cash\ flow\ (year\ > 1) = Annual\ Savings - 2\% * Investment \tag{8}$$

The cash flows are discounted with an interest rate of 2.5%. The cash flows are discounted to take into account the time value of money, which is presented as the idea money flows now are worth more to a firm than money flows in the future. Therefore, cash flows are discounted with a compounded interest rate.

Using a high or low time value of money depends on the amount of risk an investor wants to take. A high interest rate indicates an investors reluctance for risk. Fast payback is the objective when using a high interest rate, later cash flows are deemed as less important or not certain. Low interest rates or no interest rates are used when an investor regards present and future cash flows as fairly certain and aims for a high payoff in the end.

The interest rate of 2.5% is chosen because this project is long-term and therefore the cash flows of years in the future are still important. However, not taking the value of time in consideration will provide results that will be too optimistic, because money in the future is not worth the same as money now, due to the fact that money in the present has earning capacity. The objective of this study is to assess the economic viability and potential of the proposed network. Therefore, the interest rate is chosen to be right in between low and high values, to generate general results and a good assessment of the potential of the different scenarios. As well as taking into account a certain amount of risk.

4.2.2 Payback Period

The payback period is the length of time in which an investment is recovered via discounted annual cash flows. The payback period is an important determinant of whether to invest in a project or to refrain from investing. It indicates after what time period the investment will be profitable. When the payback period is low, it means that a firm will make a profit sooner than with a higher payback period.

The discounted payback period (DPP) is calculated by cumulating the discounted cash flows (DCF) until the value is positive. Consequently, the investment in year 1 is recovered as the cumulative cash flows are positive.

$$DPP = A + \frac{B}{C} \tag{9}$$

$$A = Last\ period\ with\ negative\ cumulative\ DCF$$
$$B = Absolute\ value\ of\ cumulative\ DCF\ at\ the\ end\ of\ Period\ A$$
$$C = DCF\ during\ the\ period\ after\ A$$

Whether a payback period is sufficient depends on the useful life of the project or another predetermined time decided by the investor. In this study the threshold for passing is 25 years, this project is long-term and a high value investment, thus a long payback period can be sufficient. However, a payback period between 1 and 10 is favourable. While a payback period equal or lower than 25 will be sufficient for the whole network, for plants 25 years is a long time. Therefore, the payback period alone cannot be used, since the payback period only indicates a time period. A project with a payback period above 10 years can be more profitable than a project that seems to be the best because of the low period. Therefore, the net present value and ROI after 25 years are also taken into account.

4.2.3 Net Present Value and Return on Investment

The Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time (Žižlavský, 2014). The NPV is the value of a project at this moment for a certain amount of time. NPV is used to analyse the profitability after a period time of an investment.

$$Net\ Present\ Value\ (x\ years) = \sum_{y=1}^{x} \frac{Cash\ Flow(y)}{(1+r)^y} \tag{10}$$

The NPV is calculated by accumulating discounted cash flows with interest rate r is 0.025 and number of years x is 25. After x years the NPV is either positive, negative or zero. The project may be accepted if the NPV after x periods is positive, thus profitable and acceptable (Li, Cui, & Han, 2014). Evidently, higher NPVs are more desirable. If the NPV after x amount of time is negative, then there is no reason for the investor to accept the project since it will not create value for the company.

Advantages of this capital budgeting approach are that it connects a cash value to an investment project, rather than a time period or relative rate (Li et al., 2014). The NPV gives a quick indication of the profitability of an investment, without needing an arbitrary threshold value. A disadvantage of NPVs is that you compare monetary values while comparing different investments, instead of the efficiency and effectiveness of an investment.

In contrast to the NPV, the return on investment (ROI) evaluates the effectiveness of the investment itself. ROI calculation returns a percentage, and therefore it can be easily compared to other projects. ROI measures the benefits of an investment, relative to the investment. It shows how much is done with the investment, therefore a higher percentage is more favourable than a low percentage. The ROI is calculated by dividing the earnings from the investment minus the costs of the investment with the initial investment value. Thus, dividing the NPV with the Investment.

$$Return\ on\ Investment = \frac{Net\ Present\ Value}{Investment} * 100\% \tag{11}$$

ROI adds to the NPV by showing how much is done per dollar of invested money. So high NPVs can have low effectiveness and are therefore not favourable. An investor strives for high effectiveness of the invested money. The ROI takes in regard the costs of investment and therefore adds to the payback period and NPV.

Subsequently to the payback period, the time period of the NPV and ROI calculation is 25 years. Using these three capital budgeting methods a complete view will be measured for a long-term project. There is measured when the project is profitable, how profitable the project is and how effective benefits are generating from a project. Evidently, the aim is a low payback period, a high NPV after 25 years and a high ROI percentage.

5. Results

All simulations results of the performance indicators are shown in Appendix A. Table 5.1 shows the investment costs per scenario. Logically, the investment costs increase per scenario due to the fact that the number of pipelines per scenario is respectively 2, 6, 12 and 18. The costs are consistently increasing, except for the distance of 3 km in Scenario 2 and the distance of 1 km in Scenario 3. Despite having 6 more pipelines, having shorter distance results in lower costs. On average, increasing the distance from 1 to 3 km increases the costs with 57.28%. In scenario 3, the investment costs increase when there is higher demand, this is because the large extra producer can transfer more heat when there is more demand for heat. Consequently, the diameter of the pipelines from and to this producer increase and thus the investment cost increases.

Table 5.1
Investment Costs ($)

Distance between firms	Total Demand (GWh/y)	*Scenario 0*	*Scenario 1*	*Scenario 2*	*Scenario 3*
1km	**37.50**	1,143,734	3,398,584	6,776,398	10,290,471
	18.75	1,143,734	3,398,584	6,776,398	10,207,603
	12.50	1,143,734	3,398,584	6,776,398	10,207,603
	9.38	1,143,734	3,398,584	6,776,398	10,175,009
	7.50	1,143,734	3,398,584	6,776,398	10,175,009
2km	**37.50**	1,477,468	4,367,168	8,692,797	13,290,942
	18.75	1,477,468	4,367,168	8,692,797	13,125,207
	12.50	1,477,468	4,367,168	8,692,797	13,125,207
	9.38	1,477,468	4,367,168	8,692,797	13,060,019
	7.50	1,477,468	4,367,168	8,692,797	13,060,019
3km	**37.50**	1,811,202	5,335,753	10,609,195	16,291,413
	18.75	1,811,202	5,335,753	10,609,195	16,042,810
	12.50	1,811,202	5,335,753	10,609,195	16,042,810
	9.38	1,811,202	5,335,753	10,609,195	15,945,028
	7.50	1,811,202	5,335,753	10,609,195	15,945,028

Figure 5.1 presents the annual savings for the different simulation scenarios. Firstly, there can be noted that redundancy has a positive impact on the annual savings. Adding extra producers decreases the total unavailability of the network and increases the amount of waste heat that can be recovered. This is due to the extra supply of waste heat. The annual savings in Scenario 3 are the highest when the total demand of the receivers is equal or more than 18.75 GWh/year. The value surpasses one million dollars per year in most of the scenarios. When

total demand is low the extra producers do not add much value in comparison with the high extra investments costs. Dividing one receiver into three receivers does not have an impact on the annual savings, the same amount of excess heat and condensate is transferred despite having more receivers. Since the investment costs of scenario 1 are higher than scenario 0, the NPVs and ROIs (figure 5.2 and figure 5.3) are significantly lower.

Annual Savings per year				Scenario 0			Scenario 1			Scenario 2			Scenario 3		
				Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)		
				6	8	10	6	8	10	6	8	10	6	8	10
Availability	0.85	Total Demand (GWH/y)	37.50	254,745	339,660	424,575	254,745	339,660	424,575	458,541	611,388	764,235	1,354,644	1,806,192	2,257,740
			18.75	254,745	339,660	424,575	254,745	339,660	424,575	458,541	611,388	764,235	717,781	957,042	1,196,302
			12.50	254,745	339,660	424,575	254,745	339,660	424,575	430,569	574,092	717,615	499,500	666,000	832,500
			9.38	254,745	339,660	424,575	254,745	339,660	424,575	343,156	457,542	571,927	374,625	499,500	624,375
			7.50	254,745	339,660	424,575	254,745	339,660	424,575	290,709	387,612	484,515	299,700	399,600	499,500
	0.90	Total Demand (GWH/y)	37.50	277,020	369,360	461,700	277,020	369,360	461,700	498,636	664,848	831,060	1,440,504	1,920,672	2,400,840
			18.75	277,020	369,360	461,700	277,020	369,360	461,700	498,636	664,848	831,060	747,954	997,272	1,246,590
			12.50	277,020	369,360	461,700	277,020	369,360	461,700	465,804	621,072	776,340	513,000	684,000	855,000
			9.38	277,020	369,360	461,700	277,020	369,360	461,700	363,204	484,272	605,340	384,750	513,000	641,250
			7.50	277,020	369,360	461,700	277,020	369,360	461,700	301,644	402,192	502,740	307,800	410,400	513,000
	0.95	Total Demand (GWH/y)	37.50	300,105	400,140	500,175	300,105	400,140	500,175	540,189	720,252	900,315	1,528,956	2,038,608	2,548,260
			18.75	300,105	400,140	500,175	300,105	400,140	500,175	540,189	720,252	900,315	778,693	1,038,258	1,297,822
			12.50	300,105	400,140	500,175	300,105	400,140	500,175	502,281	669,708	837,135	526,500	702,000	877,500
			9.38	300,105	400,140	500,175	300,105	400,140	500,175	383,818	511,758	639,697	394,875	526,500	658,125
			7.50	300,105	400,140	500,175	300,105	400,140	500,175	312,741	416,988	521,235	315,900	421,200	526,500

Figure 5.1. Annual Savings. Annual Savings of each scenario for different combinations of Price, Demand and Availability.

The effect of redundancy on the impact of availability is significant. In table 5.2 the decrease of the annual savings is shown when altering the availability from 95% to 85%. In Scenario 2 and 3, when there is more redundancy and thus more recovery of excess heat during downtime of one of the plants, the annual savings decrease less. This shows that more redundancy helps networks to be more resilient to disturbances.

Table 5.2

Decrease of Annual Savings when lowering the availability from 95% to 85%

Total Demand (GWh/y)	*Scenario 0*	*Scenario 1*	*Scenario 2*	*Scenario 3*
37.5	-15.11%	-15.11%	-15.11%	-11.40%
18.75	-15.11%	-15.11%	-15.11%	-7.82%
12.5	-15.11%	-15.11%	-14.28%	-5.13%
9.38	-15.11%	-15.11%	-10.59%	-5.13%
7.5	-15.11%	-15.11%	-7.04%	-5.13%

Figure 5.2 depicts the NPV of the scenarios for the different demand levels for availability level 90%. The threshold for the payback period was set at 25 years, Thus, the NPVs after 25 years are depicted. Negative NPVs do not meet this threshold. Scenario 0 has consistently positive NPVs after 25 years, ranging from 2,259,086 (P=6, D=3, Availability=85%) to 7,678,123 (P=10, D=1, Availability=95%). The NPVs of Scenario 0 rely the most on price, rather than distance or availability. Scenario 0 and 1 do not perform better or worse when total demand changes, this is due to the fact that there is one producer with a supply of 7.50 GWh/y which is lower or equal to all the demand levels. This producer cannot transfer more heat when the demand increases.

As concluded, the impact of the extra producers is not high when the demand is relatively low. Consequently, the NPVs for Scenario 2 and 3 are negative. However, when the extra producers are impactful, the NPVs of Scenario 2 compare to those of Scenario 0 while Scenario 3 outranks those significantly. It is still important that the circumstances are right, meaning high price and low distance are drivers for Scenario 2 and 3. The differences in NPVs are much higher expressed in value. For instance, for a demand of 18.75 GWh/y, distance of 1 km and price of 10 $/GJ, the NPVs of respectively Scenario 0, 2 and 3 are: 6,969,245; 6,203,624 and 9,247,631 dollars. While, for the same demand, a distance of 3 km and a price 6 $/GJ; the NPVs are: 2,669,489; -5,072,733 and -7,782,511 dollars. For the same amount of demand, bad circumstances result in a relatively major loss for the NPVs of Scenario 2 and 3, while the NPV of scenario 0 remains positive. These losses between good and bad circumstances in terms of distance and price are respectively: 4,229,756; 11,276,357 and 17,030,142 dollars. This shows how dependent the scenarios with high investment costs are on good conditions.

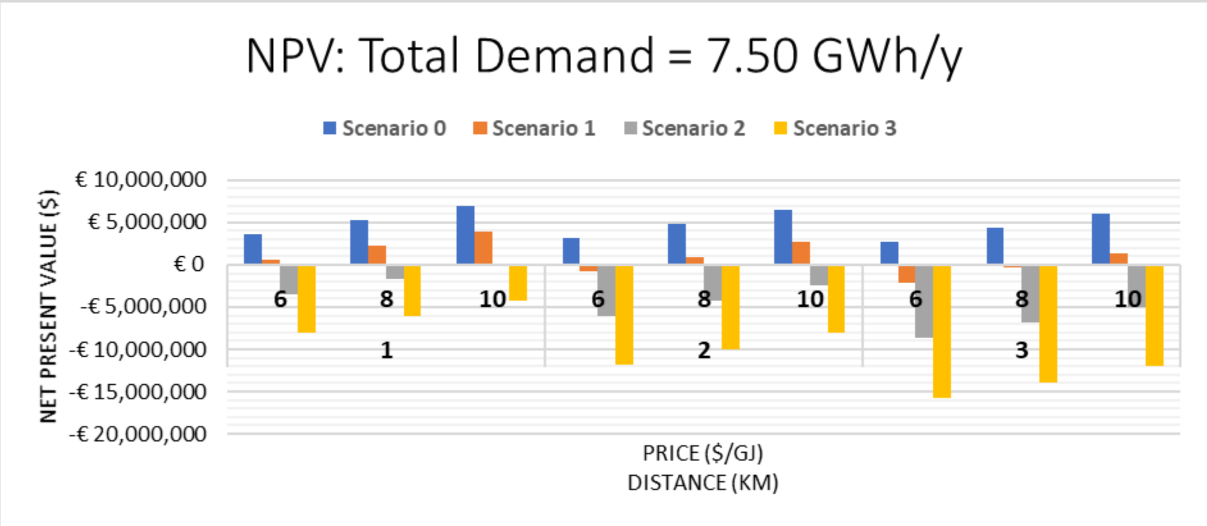

Figure 5.2a. Net Present Value ($) for total demand = 7.50 GWh/year and availability = 0.90%

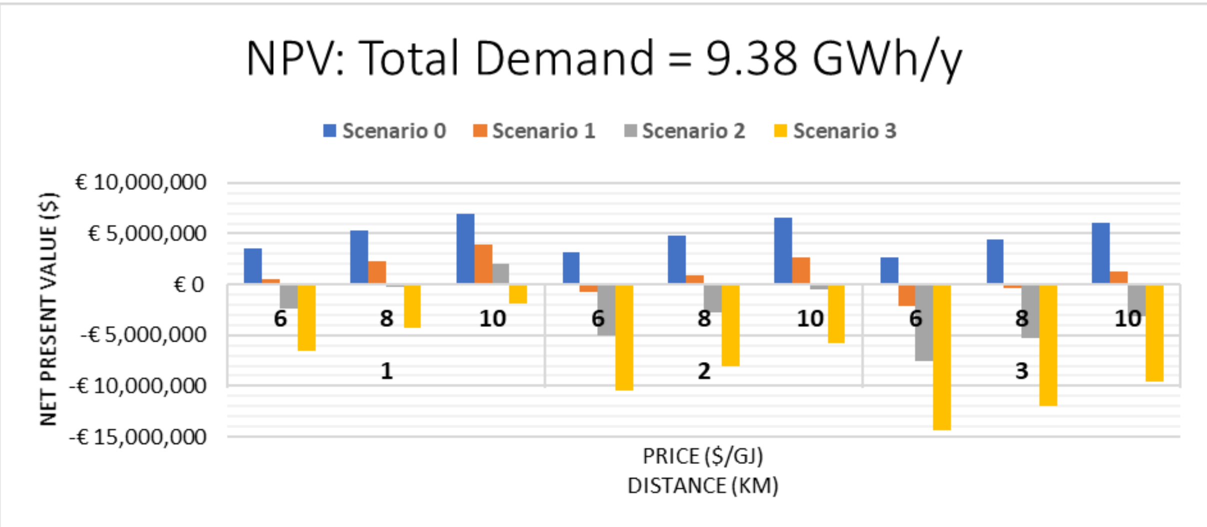

Figure 5.2b. Net Present Value ($) for total demand = 9.38 GWh/year and availability = 0.90%

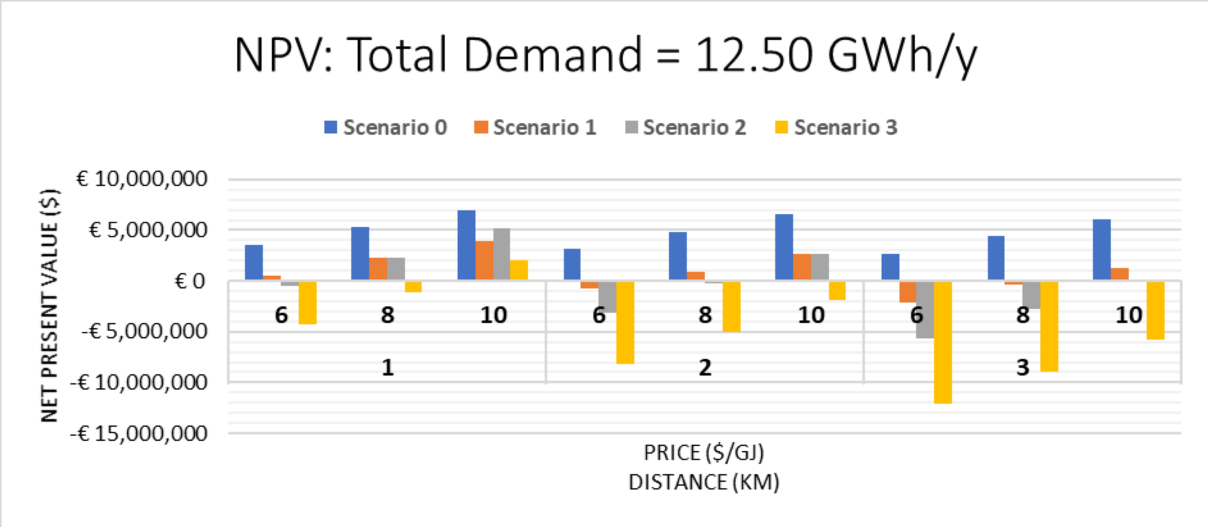

Figure 5.2c. Net Present Value ($) for total demand = 12.50 GWh/year and availability = 0.90%

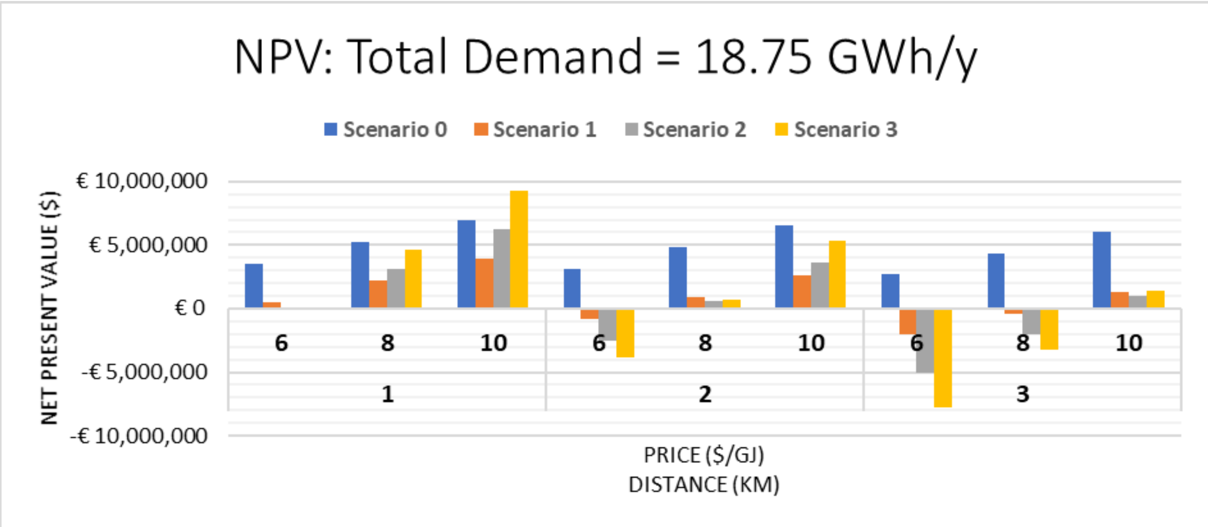

Figure 5.2d. Net Present Value ($) for total demand = 18.75 GWh/year and availability = 0.90%

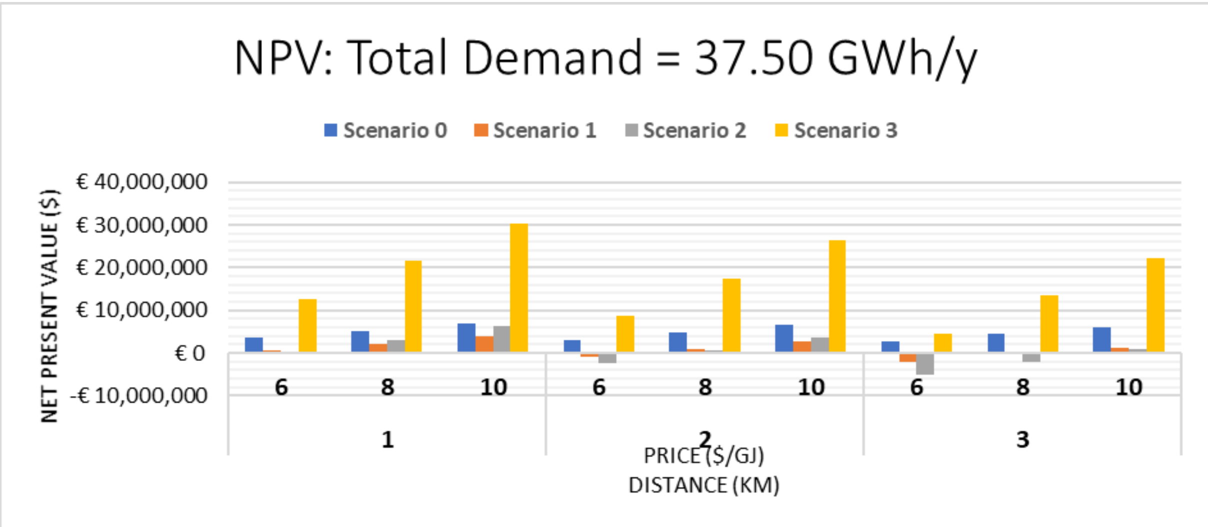

Figure 5.2e. Net Present Value ($) for total demand = 37.50 GWh/year and availability = 0.90%

Figure 5.3 depicts the ROI percentages belonging to the NPVs. It can be clearly seen that Scenario 0 provides the most value per money. If the price is 6 $/GJ the ROI of scenario 0 ranges from 161.58% to 385.88%, and for 10 $/GJ it ranges from 334.34% to 708.17%. The ROI, when the distance is 3 km and the price is 10 $/GJ, is lower than if the distance is 1 and the price is 6. Meaning that the investment costs are more important for the ROI than the value of savings.

At demand level 37.50 GWh/y, the ROIs of Scenario 3 are positive, however, Scenario 3 does not outrank Scenario 0. While allowing more savings, the investment costs are higher in absolute value as seen in table 5.1, but in relative value as well. Still, the return of investment of scenario 3 in good circumstances (high demand and high price) is acceptable.

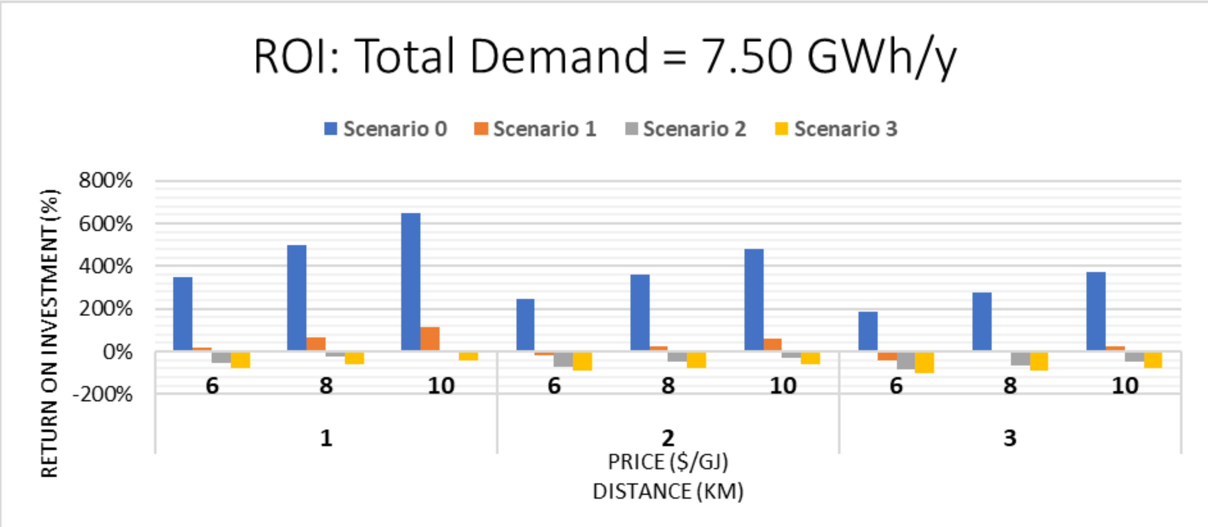

Figure 5.3a. Return on Investment (%) for total demand = 7.50 GWh/year and availability = 0.90%

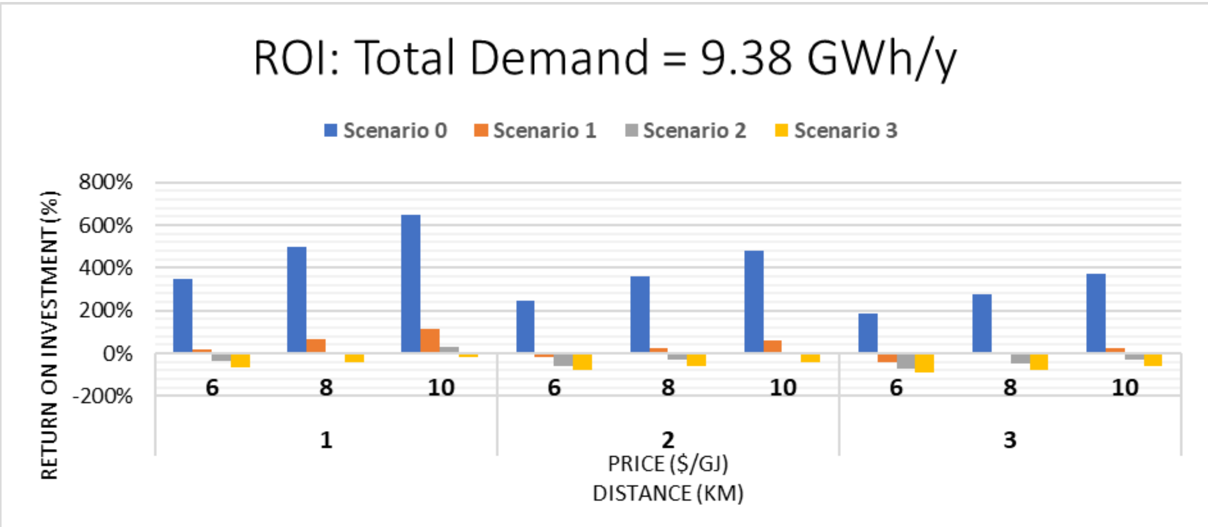

Figure 5.3b. Return on Investment (%) for total demand = 9.38 GWh/year and availability = 0.90%

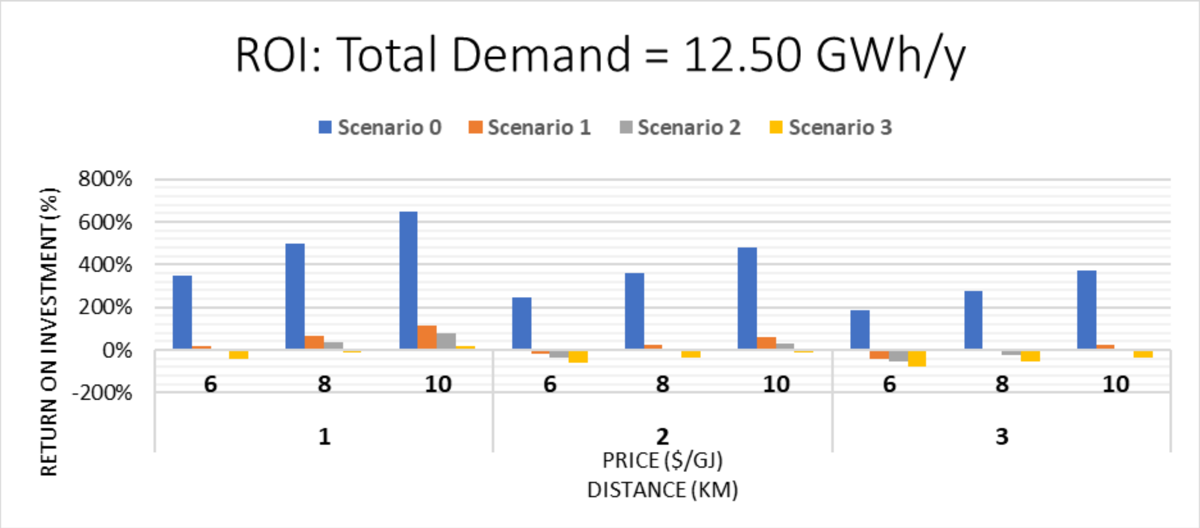

Figure 5.3c. Return on Investment (%) for total demand = 12.50 GWh/year and availability = 0.90%

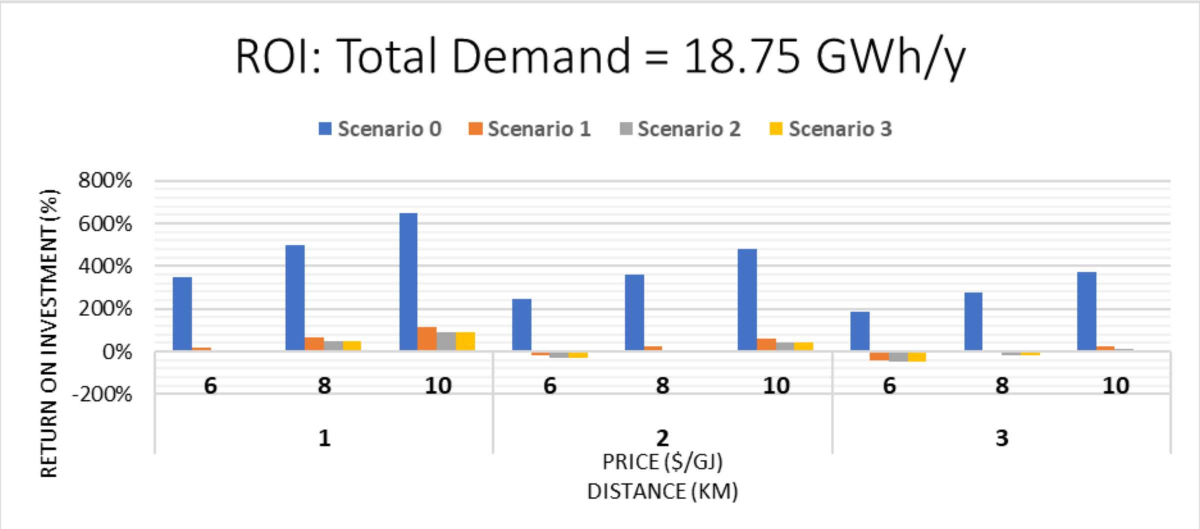

Figure 5.3d. Return on Investment (%) for total demand = 18.75 GWh/year and availability = 0.90%

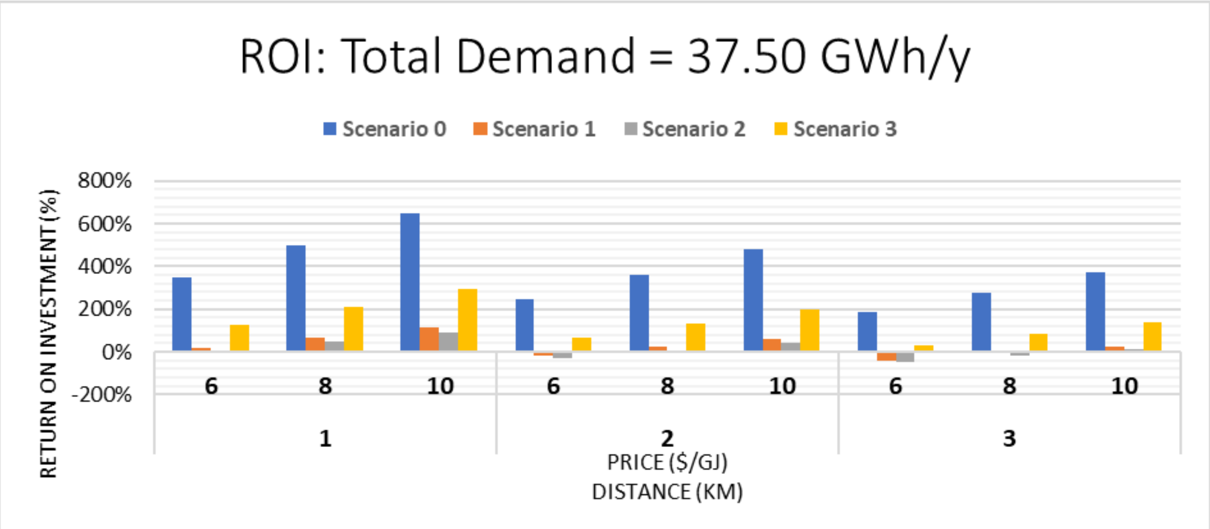

Figure 5.3e. Return on Investment (%) for total demand = 37.50 GWh/year and availability = 0.90%

6. Discussion of Results

The simulation results show that the heat-based industrial symbiosis network in the simplest form is profitable (Scenario 0; 1-1 network). The amount of savings in the network are sufficient to recover the investment, therefore the payback periods are low (see Appendix A.1) and favourable for plants. The payback periods of Scenario 0 are lower than 10 years in every simulation scenario. This means that based on the payback periods alone, firms will most likely collaborate. The ROI of this scenario is also higher than the other networks, indicating high value for money. However, the network is very vulnerable to disturbances due to the fact that downtime of one of the two plants causes one of the two streams to discontinue. In the simulation, only one result of disturbances is implemented. This result is the availability of the firm which indicates the time a firm can produce goods. During disturbances, there is downtime. The three availability levels were analysed and while, for every level, the network is economically viable, other disturbances like a reduction of waste supply, decrease of demand or bankruptcy cannot be compensated by extra producers or receivers. While the economic side seems to be profitable, external effects can negatively influence the overall long-term performance of the network. Therefore, other networks were tested.

Dividing one receiver into three receivers while maintaining the same total demand does not have a significant impact on the annual savings (Scenario 1; 1-3 network). The investment costs increase due to the extra pipelines but the division of receivers does not add extra savings. For every performance indicator and every combination of variables, the results are worse than Scenario 0, meaning that on an economic level Scenario 1 is worse than Scenario 0. However, in practice, a 1-3 network would be less vulnerable to disturbances. Due to modelling decisions, the disturbance of unavailability has no impact on the savings when dividing receivers. This is because the heat that is received by the receivers is the same, and each receiver has the same availability percentage. If the receivers would have different demand levels and availability percentages this scenario would have different annual savings in comparison to scenario 0.

Scenario 2 (2-3 network) returns higher annual savings. The demand/supply mismatch is lowered and during unavailability, the extra producer can still continue supplying waste. This causes for higher annual savings because more heat can be recovered during downtime. Another advantage of Scenario 2 compared to Scenario 0 and 1 is the increased recovery of waste heat during uptime of both producers. This means that more demand can be fulfilled when the total demand level increases. For instance, when the total demand is 18.75 GWh/year, Scenario 0 and 1 can recover 7.50 GWh/year during uptime, while due to the extra producer Scenario 2 can recover 13.50 GWh/year. Yet, these increases in annual savings do not compensate the increase of investment due to the fact that the investment costs increase relatively more than the annual savings compared to values in scenario 0. This results in lower performance indicators in comparison with the scenarios with less redundancy. When prices are high, in this case 10 $/GJ, Scenario 2 returns better performance indicators than Scenario

1 due to the compensation. However, if the value of the exchanged material is not high enough, adding a producer to the network can work counterproductive, resulting in a loss.

Adding a big producer that compensates all the mismatch has proven to be very beneficial in case of high demand (Scenario 3; network 3-3). The demand level even limits the potential of Scenario 3, since this network could potentially recover even more waste heat and therefore the savings would be even higher. In Scenario 3, for the case of the largest demand, there is 151 GWh/y of waste heat which is not used. Meaning that if more demand was added, the annual savings would increase and subsequently the results of performance indicators would improve. For Scenario 3 the total demand level is a driver to succeed. For instance, when demand is 18.75 GWh/y, the NPVs of Scenario 3 outrank those of the other scenarios. However, the investment costs are very high due to the total length of pipelines, and thus the ROI is lower than in scenario 0. Comparing to the base scenario, the payback periods are slightly longer but the payoff after 25 years is more.

As explored in Section 2.1 distance is not a driver for collaboration, however, a short distance enables collaboration. This is also shown by the results of the simulation. A short distance, in this case 1 km, returns higher values for the performance indicators that in cases of high distance. These differences are significant. The different distances show that in some cases for the same variables the profitability of the scenario depends on the distance between firms. Therefore, the distance between firms is crucial for implementation reasons.

The effect of redundancy on the resilience of a network to disturbances is proven via the percentage change of annual savings when reducing the availability (table 5.2). The compensation factor of more producers lowers the decrease of annual savings when firms have more downtime. The more supply compared to demand, the more compensation due to redundancy. So, when a future network is proven to be highly vulnerable to disturbances adding producers will help increasing resilience.

Due to these findings, the government should invest in industrial symbiosis networks similar to Scenario 3. The overall resilience to disturbances of those networks is higher, the amount of saved waste and therefore the impact on the environment is higher and the potential for creating value is higher. The biggest limitation of this scenario is the large investment and the effect this investment has on the performance indicators. Governmental institutes could give incentives to plants that are willing to cooperate in such a network. In this way the ROI of those plants will increase, making it more favourable for the plants to invest in a network with higher redundancy. Consequently, the network is less likely to implode. This is favourable for the government because the network will create higher value streams and decrease pollution continuously.

In general, a heat-based industrial symbiosis network is profitable when there is enough waste heat that can be exchanged and if the value of the material that is exchanged is high. These two factors influence the balance with the investment costs. Implementing more redundancy causes a network to be more resilient and stable long-term. The base scenario provides the best values for payback periods and ROI. Meaning that implementing a 1 on 1 network would be fast payback and high effectiveness. However, this network is vulnerable to disturbances. Scenario 3 provides the best values for annual savings and NPVs, but the circumstances have to be beneficial. Since the payback period is longer, investing in scenario 3 involves more risk but has a higher payoff than the other scenarios.

7. Conclusions and Recommendations

In this chapter, the conclusions of the simulation are drawn and potential applications of the research are given. Next to that, this chapter will continue with a critical discussion of the thesis, because there are some limitations that potentially could influence the results of the simulation. Based on those limitations, recommendations for further research are suggested.

7.1 Conclusions

In this thesis, the profitability of heat-based industrial symbiosis is investigated. The profitability is tested and analysed via discrete simulation of different scenarios involving redundancy, failure rates and demand levels.

This study presents a framework for investment costs and annual savings for a heat-based industrial symbiosis network. To support the framework the costs and benefits that were relevant were identified, as well as drivers for investing in such a project. To measure profitability, three performance indicators were identified and thresholds were assigned to the indicators. To assess the profitability, a hypothetical case study was presented supported by literature. This case study is reliable and via varying different variables generalisable to different economies.

According to the results implementing heat-based industrial symbiosis is profitable in the right circumstances. The profitability highly depends on the amount of waste heat that can be transferred. When demand is high, it is beneficial to add producers. However, overcompensating causes high investment costs that cannot be recovered in time. It can be concluded that there is high potential for implementation, but the circumstances have to be identified beforehand. Firms that are interested in implementing IS can use this study to assess the economic viability of real-life networks via the results in the appendix or using the model. Due to the different variables for the main influencers, this study can be generalized to multiple networks in multiple geographic contexts.

An important factor for economic viability is the price of natural gas. This study presents results for 6, 8 and 10 $/GJ and as discussed, it is highly favourable if this price is as high as possible. However, most networks are not economically viable when the price of natural gas is low (in this case: 6 $/GJ). To compare this to different countries, it matters if the input natural gas is imported from other countries or if the natural gas comes from the country itself. It has a significant impact on the price of raw materials and thus the value of the savings. For instance, Russia has the highest natural gas reserves in the world and a side effect is that the price of natural gas is therefore low (Eurostat, 2018), respectively 6.9 $/GJ. Similarly, the price of natural gas in Canada is only 6 $/GJ (Andrews & Pearce, 2011). Implementing industrial symbiosis in countries with high import prices on natural gas n more favourable, for instance in Sweden where the price of natural gas is 10.28 $/GJ (Eurostat, 2018). This four-dollar difference is crucial to be profitable as seen in the results of the simulation.

The impact of unavailability is reduced when the amount of redundancy is increased. This is shown by the percentage change of annual savings when reducing the availability. When there are more firms in the network the annual savings decrease relatively less. This can be generalized to other disturbances, so if a network is very vulnerable for interruptions more redundancy helps lower the vulnerability and increase the stability of the network. This fact is really important when designing a network, because if it is known that one of the firms in a potential network is unstable, it is beneficial to add another firm with the same function.

To overcome the problem of the big initial investment or low natural gas prices, the government should use financial incentives. In particular, financial funding up front to reduce the initial investment. This is the best way to increase economic profitability in terms of NPV and ROI and a direct decrease of negative cash flows at the initiation of the project. This decrease in initial negative cash flows will reduce the threshold to invest in Industrial Symbiosis. Another way to motivate firms to invest in industrial symbiosis is raising taxes on natural gas, especially in countries where this price is low compared to the rest of the world. The savings are comprised of the price of natural gas and the only way for the government to increase economic savings. Therefore, increasing the price of natural gas will cause firms to look for different solutions, like industrial symbiosis.

Summarizing, the networks with high redundancy and subsequently high investment costs have high economic and environmental potential. This is in line with the effect of redundancy on the stability of the network. The government benefits if networks are resilient and continuously exchange value streams which improve economic and environmental performances. Therefore, the government should assess a network before funding the implementation. It would benefit from high redundancy high value networks, and thus should only give funding to resilient networks. While low redundancy and subsequently low investment costs networks can be formed without incentive; the networks with high redundancy need a stimulus up front.

7.2 Recommendations for further research

Limitations of the results are that no economies of scale were taken into account while calculating the investment costs. In practice, it is likely that if a network needs more pipelines the value of each individual pipeline would decrease. However, in this simulation every pipeline has the same cost regardless of how many pipelines are built in total. Implementing economies of scale would reduce the investment costs slightly, and in that case the performance indicator of Scenario 2 and 3 would increase. Due to the fact that Scenario 2 and 3 provide a large increase in pipeline kilometres. At first, these economies of scale were considered to be included in this study; however, there was not any scientific evidence for there being of economies of scale when constructing pipelines. Therefore, further research should investigate if there are economies of scale when building pipelines or if the installation of pipelines is truly linear. If there are economies of scale, the effect of those benefits on the performance indicators should be investigated. For instance, if the economies of scale do exist it could potentially change the outcome of this thesis, scenarios which were not profitable can become profitable through the decreased investment costs. Another effect could be that even longer distances could become profitable.

Another factor that could potentially influence the results are ratios that were used. In this study, for simplification reasons, there is assumed that the ratio between excess heat and condensate was 1:1 and the ratio between excess heat and natural gas was 1:1 as well, in reality, this could be different and highly case-specific. The ratios mean that for 1 unit of excess heat, 1 unit of condensate could be returned. Likewise, 1 unit of excess heat could potentially exchange 1 unit of natural gas. In this study, these values are chosen for simplification reasons. Changing these two ratios could potentially have a big effect on the performance indicators. Therefore, these ratios should be identified and investigated in future research. An important aspect could be if these ratios can be generalized to different cases, or if they are highly case-specific.

The last limitation is that in the simulation the receivers all have the same availabilities and demand. Because of this fact, only the producers had effect on the economic benefits. Thus, this study gives limited insight into the role of receivers. Future research should be focussed on the effect of different sorts of receivers, in terms of availability and demand, and the impact they have on the overall performance of the network. This will give a complete overview of the effect of different kinds of producers and receivers and it will be easier to apply this study to real-life networks.

In general, future research should focus on creating even more scenarios and generalizing data. Creating a scenario database can help firms plan ahead and truly know if investing in heat-based industrial symbiosis is profitable. As well as indicating the effect of adding or removing one or two extra firms to an already existing or beginning network. More scenarios will also increase the reliability of the conclusions and applications. Next to the changes in ratios and receiver properties; more producers and receivers can be added as well as different distances and other calculations for investment costs. This will rule out uncertainty and it will generalize the study even more.

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Appendix A. Simulation Results:

In this appendix extended simulation results are presented on Payback Periods (A.1), Net Present Values (A.2) and Return on Investments (A.3).

A.1 Payback Periods:

Appendix A.1 presents the payback periods for all the scenarios. The payback periods are measured in years. The colour coding presents a quick overview of which combinations of variables provide good payback periods. Values under 25 years are acceptable.

Payback Period					Distance Between Firms: 1			2			3		
					Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)		
					6	8	10	6	8	10	6	8	10
Scenario 0	Availability	0.85	Total Demand (GWH/y)	37.50	5.33	3.83	2.99	7.26	5.14	3.98	9.41	6.55	5.02
				18.75	5.33	3.83	2.99	7.26	5.14	3.98	9.41	6.55	5.02
				12.50	5.33	3.83	2.99	7.26	5.14	3.98	9.41	6.55	5.02
				9.38	5.33	3.83	2.99	7.26	5.14	3.98	9.41	6.55	5.02
				7.50	5.33	3.83	2.99	7.26	5.14	3.98	9.41	6.55	5.02
		0.90	Total Demand (GWH/y)	37.50	4.84	3.49	2.73	6.55	4.66	3.62	8.44	5.92	4.56
				18.75	4.84	3.49	2.73	6.55	4.66	3.62	8.44	5.92	4.56
				12.50	4.84	3.49	2.73	6.55	4.66	3.62	8.44	5.92	4.56
				9.38	4.84	3.49	2.73	6.55	4.66	3.62	8.44	5.92	4.56
				7.50	4.84	3.49	2.73	6.55	4.66	3.62	8.44	5.92	4.56
		0.95	Total Demand (GWH/y)	37.50	4.41	3.19	2.50	5.95	4.25	3.31	7.63	5.38	4.16
				18.75	4.41	3.19	2.50	5.95	4.25	3.31	7.63	5.38	4.16
				12.50	4.41	3.19	2.50	5.95	4.25	3.31	7.63	5.38	4.16
				9.38	4.41	3.19	2.50	5.95	4.25	3.31	7.63	5.38	4.16
				7.50	4.41	3.19	2.50	5.95	4.25	3.31	7.63	5.38	4.16
Scenario 1	Availability	0.85	Total Demand (GWH/y)	37.50	24.58	15.19	11.02	42.77	22.96	15.84	93.71	34.43	22.04
				18.75	24.58	15.19	11.02	42.77	22.96	15.84	93.71	34.43	22.04
				12.50	24.58	15.19	11.02	42.77	22.96	15.84	93.71	34.43	22.04
				9.38	24.58	15.19	11.02	42.77	22.96	15.84	93.71	34.43	22.04
				7.50	24.58	15.19	11.02	42.77	22.96	15.84	93.71	34.43	22.04
		0.90	Total Demand (GWH/y)	37.50	21.13	13.41	9.85	34.71	19.83	13.96	61.93	28.72	19.09
				18.75	21.13	13.41	9.85	34.71	19.83	13.96	61.93	28.72	19.09
				12.50	21.13	13.41	9.85	34.71	19.83	13.96	61.93	28.72	19.09
				9.38	21.13	13.41	9.85	34.71	19.83	13.96	61.93	28.72	19.09
				7.50	21.13	13.41	9.85	34.71	19.83	13.96	61.93	28.72	19.09
		0.95	Total Demand (GWH/y)	37.50	18.46	11.96	8.87	29.15	17.39	12.44	47.40	24.56	16.77
				18.75	18.46	11.96	8.87	29.15	17.39	12.44	47.40	24.56	16.77
				12.50	18.46	11.96	8.87	29.15	17.39	12.44	47.40	24.56	16.77
				9.38	18.46	11.96	8.87	29.15	17.39	12.44	47.40	24.56	16.77
				7.50	18.46	11.96	8.87	29.15	17.39	12.44	47.40	24.56	16.77
Scenario 2	Availability	0.85	Total Demand (GWH/y)	37.50	30.10	17.82	12.72	58.37	27.81	18.59	99.00	44.22	26.52
				18.75	30.10	17.82	12.72	58.37	27.81	18.59	99.00	44.22	26.52
				12.50	34.58	19.77	13.93	75.91	31.71	20.67	99.00	53.46	30.13
				9.38	68.54	30.24	19.90	99.00	58.83	31.97	99.00	99.00	54.13
				7.50	99.00	45.15	26.91	99.00	99.00	48.70	99.00	99.00	99.00
		0.90	Total Demand (GWH/y)	37.50	25.45	15.62	11.31	44.79	23.67	16.26	99.00	35.71	22.67
				18.75	25.45	15.62	11.31	44.79	23.67	16.26	99.00	35.71	22.67
				12.50	29.13	17.38	12.44	55.24	26.95	18.12	99.00	42.36	25.72
				9.38	55.20	26.94	18.11	99.00	48.77	28.37	99.00	99.00	45.47
				7.50	99.00	40.85	25.06	99.00	99.00	43.78	99.00	99.00	98.82
		0.95	Total Demand (GWH/y)	37.50	21.97	13.86	10.14	36.43	20.54	14.40	66.96	29.90	19.72
				18.75	21.97	13.86	10.14	36.43	20.54	14.40	66.96	29.90	19.72
				12.50	25.10	15.45	11.19	43.89	23.36	16.08	99.00	35.10	22.37
				9.38	46.44	24.23	16.59	99.00	41.73	25.45	99.00	87.72	39.23
				7.50	99.00	37.30	23.43	99.00	90.83	39.79	99.00	99.00	79.11
Scenario 3	Availability	0.85	Total Demand (GWH/y)	37.50	10.27	7.10	5.43	14.75	9.84	7.39	20.41	13.03	9.59
				18.75	27.82	16.77	12.04	51.66	25.90	17.54	99.00	40.31	24.82
				12.50	80.81	32.57	21.10	99.00	67.95	34.72	99.00	99.00	62.04
				9.38	99.00	79.45	37.56	99.00	99.00	92.86	99.00	99.00	99.00
				7.50	99.00	99.00	79.45	99.00	99.00	99.00	99.00	99.00	99.00
		0.90	Total Demand (GWH/y)	37.50	9.47	6.59	5.05	13.47	9.08	6.85	18.42	11.94	8.85
				18.75	25.66	15.73	11.37	45.64	23.96	16.43	99.00	36.40	23.00
				12.50	70.88	30.74	20.16	99.00	61.04	32.68	99.00	99.00	56.29
				9.38	99.00	69.87	35.24	99.00	99.00	79.37	99.00	99.00	99.00
				7.50	99.00	99.00	69.87	99.00	99.00	99.00	99.00	99.00	99.00
		0.95	Total Demand (GWH/y)	37.50	8.76	6.13	4.71	12.36	8.41	6.37	16.74	11.00	8.20
				18.75	23.79	14.79	10.76	40.89	22.27	15.44	84.54	33.16	21.41
				12.50	63.53	29.10	19.30	99.00	55.60	30.89	99.00	99.00	51.63
				9.38	99.00	62.73	33.21	99.00	99.00	70.03	99.00	99.00	99.00
				7.50	99.00	99.00	62.73	99.00	99.00	99.00	99.00	99.00	99.00

Figure A.1. Payback period in years for all scenarios.

A.2 Net Present Value (25 years):

Appendix A.2 presents the NPVs for all the scenarios. The NPVs are measured in dollars and are measured after 25 years. The colour coding presents a quick overview of which combinations of variables provide relatively good NPVs. All red values are negative, and therefore unacceptable.

					Distance Between Firms								
					1			2			3		
					Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)		
					6	8	10	6	8	10	6	8	10
Scenario 0	Availability	0.85	Total Demand (GWH/y)	37.50	3,156,228	4,720,734	6,285,240	2,707,657	4,272,163	5,836,669	2,259,086	3,823,592	5,388,098
				18.75	3,156,228	4,720,734	6,285,240	2,707,657	4,272,163	5,836,669	2,259,086	3,823,592	5,388,098
				12.50	3,156,228	4,720,734	6,285,240	2,707,657	4,272,163	5,836,669	2,259,086	3,823,592	5,388,098
				9.38	3,156,228	4,720,734	6,285,240	2,707,657	4,272,163	5,836,669	2,259,086	3,823,592	5,388,098
				7.50	3,156,228	4,720,734	6,285,240	2,707,657	4,272,163	5,836,669	2,259,086	3,823,592	5,388,098
		0.90	Total Demand (GWH/y)	37.50	3,566,631	5,267,938	6,969,245	3,118,060	4,819,367	6,520,674	2,669,489	4,370,796	6,072,103
				18.75	3,566,631	5,267,938	6,969,245	3,118,060	4,819,367	6,520,674	2,669,489	4,370,796	6,072,103
				12.50	3,566,631	5,267,938	6,969,245	3,118,060	4,819,367	6,520,674	2,669,489	4,370,796	6,072,103
				9.38	3,566,631	5,267,938	6,969,245	3,118,060	4,819,367	6,520,674	2,669,489	4,370,796	6,072,103
				7.50	3,566,631	5,267,938	6,969,245	3,118,060	4,819,367	6,520,674	2,669,489	4,370,796	6,072,103
		0.95	Total Demand (GWH/y)	37.50	3,991,958	5,835,040	7,678,123	3,543,387	5,386,469	7,229,552	3,094,816	4,937,898	6,780,981
				18.75	3,991,958	5,835,040	7,678,123	3,543,387	5,386,469	7,229,552	3,094,816	4,937,898	6,780,981
				12.50	3,991,958	5,835,040	7,678,123	3,543,387	5,386,469	7,229,552	3,094,816	4,937,898	6,780,981
				9.38	3,991,958	5,835,040	7,678,123	3,543,387	5,386,469	7,229,552	3,094,816	4,937,898	6,780,981
				7.50	3,991,958	5,835,040	7,678,123	3,543,387	5,386,469	7,229,552	3,094,816	4,937,898	6,780,981
Scenario 1	Availability	0.85	Total Demand (GWH/y)	37.50	125,490	1,689,996	3,254,502	-1,176,381	388,125	1,952,631	-2,478,253	-913,747	650,759
				18.75	125,490	1,689,996	3,254,502	-1,176,381	388,125	1,952,631	-2,478,253	-913,747	650,759
				12.50	125,490	1,689,996	3,254,502	-1,176,381	388,125	1,952,631	-2,478,253	-913,747	650,759
				9.38	125,490	1,689,996	3,254,502	-1,176,381	388,125	1,952,631	-2,478,253	-913,747	650,759
				7.50	125,490	1,689,996	3,254,502	-1,176,381	388,125	1,952,631	-2,478,253	-913,747	650,759
		0.90	Total Demand (GWH/y)	37.50	535,893	2,237,200	3,938,507	-765,978	935,329	2,636,635	-2,067,850	-366,543	1,334,764
				18.75	535,893	2,237,200	3,938,507	-765,978	935,329	2,636,635	-2,067,850	-366,543	1,334,764
				12.50	535,893	2,237,200	3,938,507	-765,978	935,329	2,636,635	-2,067,850	-366,543	1,334,764
				9.38	535,893	2,237,200	3,938,507	-765,978	935,329	2,636,635	-2,067,850	-366,543	1,334,764
				7.50	535,893	2,237,200	3,938,507	-765,978	935,329	2,636,635	-2,067,850	-366,543	1,334,764
		0.95	Total Demand (GWH/y)	37.50	961,220	2,804,302	4,647,385	-340,652	1,502,431	3,345,513	-1,642,523	200,560	2,043,642
				18.75	961,220	2,804,302	4,647,385	-340,652	1,502,431	3,345,513	-1,642,523	200,560	2,043,642
				12.50	961,220	2,804,302	4,647,385	-340,652	1,502,431	3,345,513	-1,642,523	200,560	2,043,642
				9.38	961,220	2,804,302	4,647,385	-340,652	1,502,431	3,345,513	-1,642,523	200,560	2,043,642
				7.50	961,220	2,804,302	4,647,385	-340,652	1,502,431	3,345,513	-1,642,523	200,560	2,043,642
Scenario 2	Availability	0.85	Total Demand (GWH/y)	37.50	-659,807	2,156,304	4,972,415	-3,235,632	-419,522	2,396,589	-5,811,458	-2,995,347	-179,237
				18.75	-659,807	2,156,304	4,972,415	-3,235,632	-419,522	2,396,589	-5,811,458	-2,995,347	-179,237
				12.50	-1,175,173	1,469,149	4,113,470	-3,750,999	-1,106,677	1,537,645	-6,326,825	-3,682,503	-1,038,181
				9.38	-2,785,694	-678,212	1,429,269	-5,361,520	-3,254,038	-1,146,557	-7,937,345	-5,829,864	-3,722,382
				7.50	-3,752,006	-1,966,629	-181,252	-6,327,832	-4,542,455	-2,757,077	-8,903,658	-7,118,280	-5,332,903
		0.90	Total Demand (GWH/y)	37.50	78,919	3,141,271	6,203,624	-2,496,907	565,446	3,627,798	-5,072,733	-2,010,380	1,051,972
				18.75	78,919	3,141,271	6,203,624	-2,496,907	565,446	3,627,798	-5,072,733	-2,010,380	1,051,972
				12.50	-525,990	2,334,726	5,195,442	-3,101,816	-241,100	2,619,616	-5,677,642	-2,816,926	43,791
				9.38	-2,416,331	-185,729	2,044,874	-4,992,157	-2,761,555	-530,952	-7,567,983	-5,337,380	-3,106,778
				7.50	-3,550,536	-1,698,002	154,533	-6,126,362	-4,273,827	-2,421,293	-8,702,187	-6,849,653	-4,997,119
		0.95	Total Demand (GWH/y)	37.50	844,507	4,162,055	7,479,604	-1,731,319	1,586,230	4,903,778	-4,307,144	-989,596	2,327,953
				18.75	844,507	4,162,055	7,479,604	-1,731,319	1,586,230	4,903,778	-4,307,144	-989,596	2,327,953
				12.50	146,076	3,230,814	6,315,552	-2,429,750	654,988	3,739,726	-5,005,576	-1,920,838	1,163,900
				9.38	-2,036,522	320,684	2,677,889	-4,612,348	-2,255,142	102,063	-7,188,173	-4,830,968	-2,473,762
				7.50	-3,346,081	-1,425,395	495,291	-5,921,906	-4,001,220	-2,080,534	-8,497,732	-6,577,046	-4,656,360
Scenario 3	Availability	0.85	Total Demand (GWH/y)	37.50	11,127,077	19,446,567	27,766,058	7,094,152	15,413,643	23,733,133	3,061,228	11,380,718	19,700,208
				18.75	-495,335	3,912,890	8,321,116	-4,416,878	-8,653	4,399,573	-8,338,421	-3,930,195	478,030
				12.50	-4,517,036	-1,449,377	1,618,281	-8,438,579	-5,370,920	-2,303,261	-12,360,121	-9,292,463	-6,224,804
				9.38	-6,773,971	-4,473,227	-2,172,483	-10,651,704	-8,350,960	-6,050,216	-14,529,437	-12,228,693	-9,927,949
				7.50	-8,154,417	-6,313,822	-4,473,227	-12,032,150	-10,191,555	-8,350,960	-15,909,884	-14,069,289	-12,228,693
		0.90	Total Demand (GWH/y)	37.50	12,708,994	21,555,790	30,402,586	8,676,069	17,522,865	26,369,661	4,643,144	13,489,940	22,336,736
				18.75	60,574	4,654,103	9,247,631	-3,860,969	732,560	5,326,089	-7,782,511	-3,188,983	1,404,546
				12.50	-4,268,307	-1,117,738	2,032,830	-8,189,850	-5,039,281	-1,888,713	-12,111,392	-8,960,824	-5,810,255
				9.38	-6,587,424	-4,224,498	-1,861,571	-10,465,157	-8,102,231	-5,739,305	-14,342,891	-11,979,964	-9,617,038
				7.50	-8,005,180	-6,114,839	-4,224,498	-11,882,913	-9,992,572	-8,102,231	-15,760,646	-13,870,305	-11,979,964
		0.95	Total Demand (GWH/y)	37.50	14,338,667	23,728,687	33,118,708	10,305,742	19,695,762	29,085,783	6,272,817	15,662,838	25,052,858
				18.75	626,930	5,409,244	10,191,558	-3,294,612	1,487,702	6,270,016	-7,216,155	-2,433,841	2,348,473
				12.50	-4,019,578	-786,100	2,447,378	-7,941,120	-4,707,642	-1,474,164	-11,862,663	-8,629,185	-5,395,707
				9.38	-6,400,877	-3,975,768	-1,550,660	-10,278,610	-7,853,502	-5,428,393	-14,156,344	-11,731,235	-9,306,127
				7.50	-7,855,942	-5,915,855	-3,975,768	-11,733,676	-9,793,589	-7,853,502	-15,611,409	-13,671,322	-11,731,235

Figure A.2. Net Present Value after 25 years for all scenarios.

A.3 Return on Investment (%):

Appendix A.3 presents the ROIs for all the scenarios. The Return on investment is a percentage and measured after 25 years. The colour coding presents a quick overview of which combinations of variables provide positive returns. All red values are negative, and therefore unacceptable.

					Distance Between Firms								
					1			2			3		
					Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)			Price of Natural Gas ($/GJ)		
					6	8	10	6	8	10	6	8	10
Scenario 0	Availability	0.85	Total Demand (GWH/y)	37.50	312.81%	449.60%	586.39%	220.11%	326.00%	431.89%	161.58%	247.96%	334.34%
				18.75	312.81%	449.60%	586.39%	220.11%	326.00%	431.89%	161.58%	247.96%	334.34%
				12.50	312.81%	449.60%	586.39%	220.11%	326.00%	431.89%	161.58%	247.96%	334.34%
				9.38	312.81%	449.60%	586.39%	220.11%	326.00%	431.89%	161.58%	247.96%	334.34%
				7.50	312.81%	449.60%	586.39%	220.11%	326.00%	431.89%	161.58%	247.96%	334.34%
		0.90	Total Demand (GWH/y)	37.50	348.69%	497.44%	646.19%	247.89%	363.04%	478.19%	184.24%	278.17%	372.10%
				18.75	348.69%	497.44%	646.19%	247.89%	363.04%	478.19%	184.24%	278.17%	372.10%
				12.50	348.69%	497.44%	646.19%	247.89%	363.04%	478.19%	184.24%	278.17%	372.10%
				9.38	348.69%	497.44%	646.19%	247.89%	363.04%	478.19%	184.24%	278.17%	372.10%
				7.50	348.69%	497.44%	646.19%	247.89%	363.04%	478.19%	184.24%	278.17%	372.10%
		0.95	Total Demand (GWH/y)	37.50	385.88%	547.02%	708.17%	276.68%	401.42%	526.17%	207.72%	309.48%	411.24%
				18.75	385.88%	547.02%	708.17%	276.68%	401.42%	526.17%	207.72%	309.48%	411.24%
				12.50	385.88%	547.02%	708.17%	276.68%	401.42%	526.17%	207.72%	309.48%	411.24%
				9.38	385.88%	547.02%	708.17%	276.68%	401.42%	526.17%	207.72%	309.48%	411.24%
				7.50	385.88%	547.02%	708.17%	276.68%	401.42%	526.17%	207.72%	309.48%	411.24%
Scenario 1	Availability	0.85	Total Demand (GWH/y)	37.50	3.69%	49.73%	95.76%	-26.94%	8.89%	44.71%	-46.45%	-17.12%	12.20%
				18.75	3.69%	49.73%	95.76%	-26.94%	8.89%	44.71%	-46.45%	-17.12%	12.20%
				12.50	3.69%	49.73%	95.76%	-26.94%	8.89%	44.71%	-46.45%	-17.12%	12.20%
				9.38	3.69%	49.73%	95.76%	-26.94%	8.89%	44.71%	-46.45%	-17.12%	12.20%
				7.50	3.69%	49.73%	95.76%	-26.94%	8.89%	44.71%	-46.45%	-17.12%	12.20%
		0.90	Total Demand (GWH/y)	37.50	15.77%	65.83%	115.89%	-17.54%	21.42%	60.37%	-38.75%	-6.87%	25.02%
				18.75	15.77%	65.83%	115.89%	-17.54%	21.42%	60.37%	-38.75%	-6.87%	25.02%
				12.50	15.77%	65.83%	115.89%	-17.54%	21.42%	60.37%	-38.75%	-6.87%	25.02%
				9.38	15.77%	65.83%	115.89%	-17.54%	21.42%	60.37%	-38.75%	-6.87%	25.02%
				7.50	15.77%	65.83%	115.89%	-17.54%	21.42%	60.37%	-38.75%	-6.87%	25.02%
		0.95	Total Demand (GWH/y)	37.50	28.28%	82.51%	136.74%	-7.80%	34.40%	76.61%	-30.78%	3.76%	38.30%
				18.75	28.28%	82.51%	136.74%	-7.80%	34.40%	76.61%	-30.78%	3.76%	38.30%
				12.50	28.28%	82.51%	136.74%	-7.80%	34.40%	76.61%	-30.78%	3.76%	38.30%
				9.38	28.28%	82.51%	136.74%	-7.80%	34.40%	76.61%	-30.78%	3.76%	38.30%
				7.50	28.28%	82.51%	136.74%	-7.80%	34.40%	76.61%	-30.78%	3.76%	38.30%
Scenario 2	Availability	0.85	Total Demand (GWH/y)	37.50	-9.74%	31.82%	73.38%	-37.22%	-4.83%	27.57%	-54.78%	-28.23%	-1.69%
				18.75	-9.74%	31.82%	73.38%	-37.22%	-4.83%	27.57%	-54.78%	-28.23%	-1.69%
				12.50	-17.34%	21.68%	60.70%	-43.15%	-12.73%	17.69%	-59.64%	-34.71%	-9.79%
				9.38	-41.11%	-10.01%	21.09%	-61.68%	-37.43%	-13.19%	-74.82%	-54.95%	-35.09%
				7.50	-55.37%	-29.02%	-2.67%	-72.79%	-52.26%	-31.72%	-83.92%	-67.10%	-50.27%
		0.90	Total Demand (GWH/y)	37.50	1.16%	46.36%	91.55%	-28.72%	6.50%	41.73%	-47.81%	-18.95%	9.92%
				18.75	1.16%	46.36%	91.55%	-28.72%	6.50%	41.73%	-47.81%	-18.95%	9.92%
				12.50	-7.76%	34.45%	76.67%	-35.68%	-2.77%	30.14%	-53.52%	-26.55%	0.41%
				9.38	-35.66%	-2.74%	30.18%	-57.43%	-31.77%	-6.11%	-71.33%	-50.31%	-29.28%
				7.50	-52.40%	-25.06%	2.28%	-70.48%	-49.17%	-27.85%	-82.02%	-64.56%	-47.10%
		0.95	Total Demand (GWH/y)	37.50	12.46%	61.42%	110.38%	-19.92%	18.25%	56.41%	-40.60%	-9.33%	21.94%
				18.75	12.46%	61.42%	110.38%	-19.92%	18.25%	56.41%	-40.60%	-9.33%	21.94%
				12.50	2.16%	47.68%	93.20%	-27.95%	7.53%	43.02%	-47.18%	-18.11%	10.97%
				9.38	-30.05%	4.73%	39.52%	-53.06%	-25.94%	1.17%	-67.75%	-45.54%	-23.32%
				7.50	-49.38%	-21.03%	7.31%	-68.12%	-46.03%	-23.93%	-80.10%	-61.99%	-43.89%
Scenario 3	Availability	0.85	Total Demand (GWH/y)	37.50	108.13%	188.98%	269.82%	53.38%	115.97%	178.57%	18.79%	69.86%	120.92%
				18.75	-4.85%	38.33%	81.52%	-33.65%	-0.07%	33.52%	-51.98%	-24.50%	2.98%
				12.50	-44.25%	-14.20%	15.85%	-64.29%	-40.92%	-17.55%	-77.04%	-57.92%	-38.80%
				9.38	-66.57%	-43.96%	-21.35%	-81.56%	-63.94%	-46.33%	-91.12%	-76.69%	-62.26%
				7.50	-80.14%	-62.05%	-43.96%	-92.13%	-78.04%	-63.94%	-99.78%	-88.24%	-76.69%
		0.90	Total Demand (GWH/y)	37.50	123.50%	209.47%	295.44%	65.28%	131.84%	198.40%	28.50%	82.80%	137.11%
				18.75	0.59%	45.59%	90.60%	-29.42%	5.58%	40.58%	-48.51%	-19.88%	8.75%
				12.50	-41.81%	-10.95%	19.91%	-62.40%	-38.39%	-14.39%	-75.49%	-55.86%	-36.22%
				9.38	-64.74%	-41.52%	-18.30%	-80.13%	-62.04%	-43.95%	-89.95%	-75.13%	-60.31%
				7.50	-78.67%	-60.10%	-41.52%	-90.99%	-76.51%	-62.04%	-98.84%	-86.99%	-75.13%
		0.95	Total Demand (GWH/y)	37.50	139.34%	230.59%	321.84%	77.54%	148.19%	218.84%	38.50%	96.14%	153.78%
				18.75	6.14%	52.99%	99.84%	-25.10%	11.33%	47.77%	-44.98%	-15.17%	14.64%
				12.50	-39.38%	-7.70%	23.98%	-60.50%	-35.87%	-11.23%	-73.94%	-53.79%	-33.63%
				9.38	-62.91%	-39.07%	-15.24%	-78.70%	-60.13%	-41.56%	-88.78%	-73.57%	-58.36%
				7.50	-77.21%	-58.14%	-39.07%	-89.84%	-74.99%	-60.13%	-97.91%	-85.74%	-73.57%

Figure A.3. Return on Investment(%) after 25 years for all scenarios.