The value of Integrated Community Energy Systems for the energy community of Buiksloterham

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Contents

Executive summary

With the growing population and urbanization of the living environment, challenges have come up for cities to bring down their emissions and become more smart. Smart city development can respond to these challenges. This means a change in the way in which the energy system is organized. In this research, the concept of Integrated Community Energy Systems (ICES) is applied to the energy community of Buiksloterham. The ICES concept tries to find solutions for amongst others the optimal integration of renewable energy sources and reach a better synergy between different energy carriers such as electricity and heat. This research looks into the value that the ICES approach can have for the energy system of the Buiksloterham community. A literature study and simulation model study have been performed. In the exploratory simulation model, a community point of view is taken to answer the main research question of this research:

'What value does ICES have for the community of Buiksloterham to reach the sustainable energy goals of their smart community development?'

To find an answer to the main research question, the technologies related to ICES have to be investigated. These technologies can be integrated in community energy systems and are part of the ICES approach. The ICES technologies that are investigated in this research are energy efficient buildings, household RES in the form of solar panels on rooftops, community RES in the form of wind turbines in Buiksloterham and electrical heat pumps that can be installed in households. The formulated key performance indicators are able to measure the performance of the energy grid of Buiksloterham. These KPIs are based on both the goals of the energy community of Buiksloterham and goals that other energy communities could have in their sustainable energy transition.

Different scenarios of ICES developments in Buiksloterham are tested with the simulation model that is created. These scenarios differ in the level of integration of the four different ICES technologies. The model simulates the year 2034, which means that the values of different factors can change in the future. For this reason, different uncertain future developments, such as the development of the electricity price and the energy demand, are also included in the simulation study.

The simulation results show that for Buiksloterham to meet the most ambitious sustainability goals of 50% self-sufficiency and a lower energy demand and CO_2 emission, large ICES investments are needed. These large investments lead however to high payback times of the ICES related technologies. It is recommended for the energy community of Buiksloterham to invest in energy efficient building and renewable energy sources. Community RES investments have a more beneficial influence on the KPIs than household RES investments. Energy efficient buildings are decreasing the CO_2 emissions more than RES, relative to the investment costs of these technologies, but RES also increase the self-sufficiency slightly. The integration of electrical heat pumps, combined with a high integration of RES so that renewable energy inputs can be used, are important for a high self-sufficiency of energy communities. The investment costs and payback time of an ICES with a full integration of heat pumps are however high and possibly not acceptable for the end-users of the system. A full ICES technology integration composition without heat pumps gives a more appealing payback time of around 12 years, but with less beneficial results on the sustainability goals. Dependent on the direction of the uncertain future developments, such as when the capital

investments decrease in the future, a number of heat pumps could be implemented in some or all of the households to achieve this much higher self-sufficiency level and lower CO_2 emissions. The limiting factor is however the investment costs and payback time that are connected to this. Further exploration of the uncertain future developments could give an even better idea of the value and necessity in reaching the goals of the energy community of Buiksloterham.

The integration of renewable energy sources is important for other energy communities that are also using heat pumps as a thermal energy technology. The heat pumps are namely giving the best results when having input from renewable energy sources. Energy communities that would make use of other sustainable heating options, such as solar boilers and city heating are less dependent on the integration of renewables, as these options already have sustainable inputs. Integration of renewable energy sources, of which community RES is most effective, influence mainly the self-sufficiency of a community. Other ICES technologies investments, such as in electricity storage, are needed to always meet the demand in a grid-defected ICES. Thermal energy technologies are also of greater importance in a grid-defected ICES, as gas import is not possible. The value of energy efficient buildings, which can be found mostly in bringing down CO_2 emissions, is dependent on whether (most of) the buildings are already built and whether the buildings are possible to be made more energy efficient if they are currently at a low level of energy efficiency. The most important and influential uncertain development is the development of the electricity price that used on the APX market. This development is however not having effect on energy communities that are grid-defected.

Further research could be done by expanding the simulation study with more ICES technologies to integrate. The willingness of the end-users of the energy system to participate in an ICES could also be researched. Finally, the model validation that is proposed in this research could be performed on the simulation model.

Chapter 1: Introduction

The energy consumption and the organization of the energy supply in urban areas have changed drastically over the last years. Scientists that study the pattern of greenhouse gas (GHG) emissions and the climate agree that rising CO_2 and other greenhouse gas emissions are causing climate change (EPA, 2016). According to estimations, cities are responsible for 75% of global CO_2 emissions of which buildings and transport are major contributors (UNEP, 2016). The rising use of the concept of smart cities is a response to the, amongst others energy related problems that have come with the growth of the urban population and the rapid urbanization of the living environment (Chourabi et al., 2012). The growth of people living in urban areas instead of rural areas is expected to continue in the coming decades. This makes the problems and possible response strategies even more urgent.

It is difficult to give a generally accepted definition of a smart city (Hollands, 2008). It involves a wide range of subjects such as information technology, governance and sustainability, and often the opinions differ on how to relate these things to each other. The municipality of Amsterdam sees smart cities as ''*cities that maximise social and environmental capital in the competitiveness of urban areas through the use of modern infrastructure, highly efficient resource management, and active citizen participation*.'' (Gladek et al., 2014, pp. 14).

For this research the concept of smart city development is used in the case of Buiksloterham, a district in the North of Amsterdam. Buiksloterham is an area that has the ambitions of becoming a sustainable and circular community. The concept of smart cities can be used in Buiksloterham by referring to the term 'smart community'. This research will focus on the smart development of the energy system in the district of Buiksloterham. Currently amongst others the building of houses and companies in Buiksloterham is done in a more energy efficient way and with possibilities for providing infrastructure for photovoltaic panels (Gladek et al., 2014). The further development of the energy supply in the area is most interesting for this research, as the energy supply of such urban areas can have a large influence on the problems related to climate change and the goals of smart city development.

The subject of interest of this research is the development of energy communities. The Integrated Community Energy System (ICES) approach is taken because of the completeness and its multi-faceted character, which will be explained later. Previous studies on ICES applications (Koirala et al., 2016, van den Hil, 2015) have optimized a certain energy technology set for specific households in an energy community to see how these households together can provide for instance low emissions or high self-sufficiency. This study takes a view that is on the community level and explores the value of different ICES compositions in different possible futures for energy communities. This value can be defined in many indicators of performance that are important for the performance of energy communities. An explanation of the subject of this research is given in sections 1.1 to 1.3. The motivation behind this research, together with the research questions and the structure of the research, are explained in sections 1.4 to 1.6.

1.1 The rise of energy community initiatives

Looking at the ambitions that are set for the development of the community of Buiksloterham, the concept of community energy could be valuable for its energy system, as it shares the most important ambitions on amongst others bringing down emissions and energy consumption with the municipality of Amsterdam. Community energy involves small scaled, locally based projects that are dependent on engagement of the end users of the energy system (Oteman et al., 2014). The last years, the possibility of power generation by the end users of an energy system has increased significantly. Important reasons for this are the drop on costs of photovoltaic (PV) systems and the commoditization of panels and inverters of these systems (Khalilpour et al., 2015). Together with the increasing social acceptance this has led to the global cumulative installed PV capacity growing from 1.4 GW in 2000 to over 100 GW at the end of 2013 (EPIA, 2013). PV capacity, other renewable energy sources and the increasing use of energy storage systems are technologies that have the potential to increase the efficiency of an energy system largely. Energy transmission and distribution losses are smaller because there is less need for import of energy from centrally placed generators when more energy comes from decentralized generators. This principle is a starting point for energy communities.

The research on energy communities has increased in the last years and in the UK many projects on energy communities have been supported by government policy (Walker et al., 2010). Community-based implementation of renewable energy technologies is on the rise (Oteman et al., 2014) and is widely seen as ‘a way of implementing renewable energy technologies, emphasizing themes of self-sufficiency, local determination, engagement and empowerment’ (Walker, 2008, p. 4401). Community initiatives are decentralized initiatives of local communities and citizens, focusing on the successful implementation of renewable energy sources (Oteman et al., 2014). It makes the consumers pro-active instead of passive. These consumers often have a common goal of for instance bringing down the energy costs or emissions (Koirala, 2015). In Germany, there have come up over 700 registered community energy initiatives in the last years (Holstenkamp and Müller, 2012) and almost 500 initiatives in the Netherlands (HIERopgewekt, 2015). The community of Buiksloterham does not present itself as an energy community because of their focus on a sustainable and circular area development that covers more than only subject of energy. The principles of community energy systems are however applicable and interesting for the development of the energy system in Buiksloterham.

There are some important incentives for creating a community energy system and thus implementing community ownership of the energy grid in a community such as Buiksloterham. First of all, return of investment is feasible because of the possibility to sell generated electricity to neighbouring grids. This return of investment is of course dependent on the market price of electricity that could be influenced by factors such as hourly (renewable) electricity generation. Together with the creation of employment that energy communities push, this can generate local income (Walker, 2008). Next to this, community ownership will lead to the projects being better accepted on the local level than others projects on a hierarchical level. Other incentives are the fact that control on the development of the project will be more easily maintainable, than when community projects are owned by a hierarchically higher authority. Also load management, that is problematic for large-scale implementation of renewables, is likely to be more overview clear, and thus less problematic in smaller-scale projects than when trying to arrange the integration of renewables on a national scale (Hain et al., 2005). This means that for the sustainable development of the energy system of Buiksloterham, the energy community approach can be of value.

1.2 Integrated Community Energy Systems approach

There are multiple options that can make an energy system 'smarter' and integrate distributed energy sources. Different frameworks and concepts, such as community micro-grids (Koirala et al., 2015), virtual power plants (Ravindra, et al., 2014), energy hubs (Koirala et al., 2015) and community energy systems (Walker et al., 2012) have been developed to facilitate this community energy approach. These frameworks and concepts for community energy focus mainly on only electricity and not on all energy carriers. A concept that is different from these, is developed through the notion of the changing energy landscape and the upcoming locally organized energy communities is the Integrated Community Energy Systems concept (Koirala et al., 2015). The ICES concept tries to find solutions for the drawbacks that can be found with the optimal integration of renewable energy sources into the energy system. These drawbacks are amongst others the flexibility of the grid, the full integration of renewable energy sources as main energy source and the transmission losses. With ICES, the energy requirements of local communities can be fulfilled by reaching a better synergy between different energy carriers such as heat, gas and electricity (Koirala et al., 2015).

ICES is about the design, analysis, construction and long term utilization of the energy system at the local, regional and household level (Cartes et al., 2007). With the development of a smart community, which is driven by the municipality of Amsterdam, the use of the concept of ICES is a way to improve its energy system and thus contribute in this transition to a smart city. It is therefore interesting to see what value the use of ICES can exactly have for the energy system in this ambitious community and to contribute to further research in seeing the value ICESs can have for other energy communities. The application of ICESs is not straightforward and can be done in many different ways. For communities it is valuable to know which technologies of ICESs and thus what type of ICES composition can lead to certain results in the trend of becoming a sustainable energy community.

The ICES concept can also be used to balance the own community energy system with neighbouring energy systems, of which the latter could be the larger, national energy system. The grid of the community could have a 'storage function', providing flexibility, when the ICES is integrated with other energy grids. An example is that the national energy system could benefit from communities implementing the concept of ICES by trading energy and receiving flexibility services. Integrated Community Energy System have been demonstrated internationally to enlarge the sustainability, security of supply, self-reliance and independence of the energy system (Koirala et al., 2016). Engagement in local energy systems through the application of ICES can motivate new investments in power lines, so that eventually system peaks are reduced and distributing load is more evenly spread over the day. ICES can be seen as multi-dimensional approach that stimulates delivering sustainable electricity, heat and cold to decentralized communities. With ICES, the population in a community can benefit in a technical, as well as in an economic, environmental and social way (Mendes et al., 2011).

1.3 The energy system of Buiksloterham

The Buiksloterham district is currently mainly used as a business site with only 234 registered residents in 2014 (Gemeente Amsterdam Noordwaarts, 2009). The plans of the municipality of Amsterdam and many other organisations and companies are to transform Buiksloterham into a sustainable and circular district. The Circular Buiksloterham Manifest was signed in 2015 by twenty different organisations and companies. It is the first part of the city to implement 'circular, smart and bio based development' (Amsterdam City, 2016). It serves as a living lab to explore the possibilities of transforming Amsterdam into a smart city. There are multiple projects and experiments in and around the area taking place. Energy, infrastructure, water, material, ecosystems are the most important topics that the project of Circular Buiksloterham focuses on. There is a growing commitment of many parties, organizations and individuals in the community to use Buiksloterham as a 'test-case' for the city of Amsterdam as a whole. The aim is that in 2034 there will be around 3500 households in the Buiksloterham district (BIES, 2016). Many plans for the building of these new houses have already started.

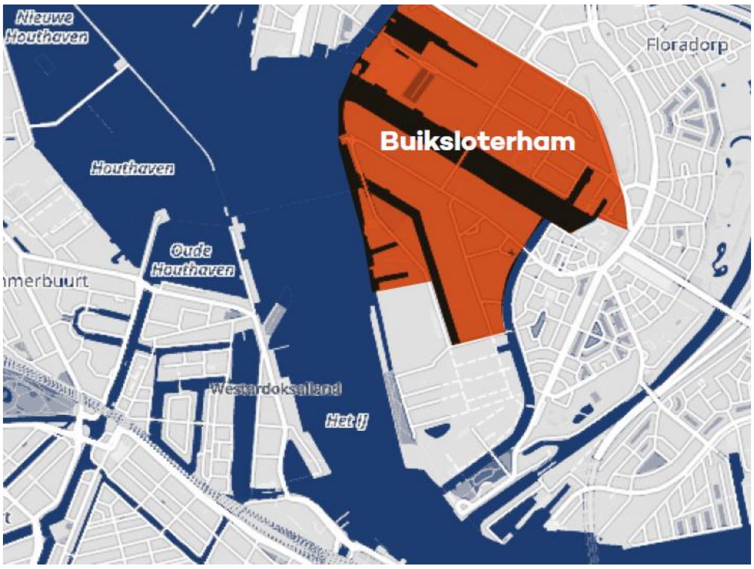


Figure 1.1: Map of Buiksloterham (Gladek et al., 2014)

Not only technical solutions, but also the actors involved with the Circular Buiksloterham Manifest themselves, are influencing how the community energy system could be changed. The parties, especially the residents, who are the energy consumers and end users of the energy system, are influencing what can be achieved with the application of the concept of ICES and how this should be achieved. The level and type of involvement of the residents is an important part of this. Involvement is already taking place in subjects, other than energy, in the community, with programs such as TransformCity and Amsterdam Smart Citizens Lab (Amsterdam City, 2016). Data from research in energy communities in the UK shows that people generally find the role of participant attractive; however taking control by having a role of project leader is not attractive for the households (Rogers, 2008). Total control by the community itself is less attractive and residents do not feel qualified for this. Another research states that for community initiatives, access to a resource base where there is expertise in the development of the community and in technical issues is required (Letcher et al., 2007). To have full participation from the energy consumers in an energy community, so that this energy community can function optimally, institutional support from for example local authorities, government policy, or other parties are needed (Rogers, 2008). Different policies already promote energy communities, for example in UK with the community energy strategy and on European level with the EU 2030 framework (Koirala et al., 2015). The barriers and opportunities of ICES are therefore further researched in the next section.

1.4 Research problem

The research in this project is about the possible changes in the energy system of communities that could lead to improvement of the performance of energy systems. The concept of ICES can offer solutions to the integration of these different energy carriers and in this way improve the energy efficiency of the system (NRCAN, 2014). This concerns amongst others the use of (sustainable) electricity, gas and heating. Using this concept on energy systems can improve the integration of renewables and can bring down the emission of greenhouse gases. What is now unclear and what this research wants to find out, is which technologies and developments that are part of the ICES approach lead to which improvements of the performances of energy systems. In order to do so, the technologies that the ICES approach includes should be found, as well as which factors determine the performance of an energy system. After this, the value that the integration of certain ICES related technologies can offer for the performance of energy community grids needs to be explored.

The application of an ICES on an energy community means that different levels of integration of ICES parts needs to be chosen. In this research, a case study is used to find the value that different ICES applications can have for a specific energy community. The case is about the energy community of Buiksloterham, which is a neighbourhood in the city of Amsterdam. This community is interesting because of the sustainable goals that the municipality has and the fact that this neighbourhood is still far away from their desired end-situation. The neighbourhood is in development, is growing in buildings and smart city development initiatives are coming up, as is explained in the previous sections. It is a community in one of the most liberal and progressive cities in the world (Gilderbloom et al., 2009). The municipality of Amsterdam wants to start sustainable development of energy systems and starts this in a community that has large potential for this. In this research, a simulation model about the application of the ICES approach on the community of Buiksloterham is developed to find the value of an ICES for energy communities. To be able to create a simulation model and use this to evaluate the value of ICES, it needs to be clear which ICES compositions are available and how they can be translated to an exploratory simulation study.

Previous studies on the application of ICES have developed optimization models with which they want to find the optimal set of energy technologies for one or multiple households in the energy community. These studies focus on the household level ICES application and try to see what the optimal decisions are for a household in an energy community. For this, certain boundaries on for example the maximum expenses of a household or the payback time of technologies are used. These studies optimize on for instance self-sufficiency or CO_2 reduction. In this study, an exploratory focus is taken and the focus is on the energy community as a whole. The simulation model that is developed is not an optimization model. By varying the inputs of the model, and through creation of scenarios in which the properties of an ICES differ, the value of the ICES approach for energy communities are examined in an exploratory manner. With this study the effect of community level ICES applications on the functioning of this energy community can be analysed. One of the objectives of the research is to find the value of ICES for the community of Buiksloterham and provide recommendations to the municipality of Amsterdam. Besides this, it is shown how the ICES approach can be used by other energy communities to explore their smart community development possibilities. The knowledge gaps that this research aims to close are firstly about which ICES technologies and compositions are available for energy communities, secondly about how an exploratory model on a community level point of view can be developed to be used by energy communities, and thirdly which factors of performance of energy systems are influenced by ICES and how large the value is that they can have on the different performance factors of energy communities. To close the knowledge gaps, research questions are formulated in section 1.5.

The scientific relevance of this research can be found in that the value of the application of the ICES approach on energy communities is investigated in an exploratory way of modelling. A simulation model that simulates the energy system of the community of Buiksloterham specifically can give insight in this. The goal is to find the value of the ICES approach for Buiksloterham and to find which insight that are gained from this study can be used by other energy communities that are interested in the ICES approach.

1.5 Research questions

To find solutions for the research problem that is described in the previous section, different research questions can be formulated to structure the research in this research. Firstly, the main research question is formulated as follows:

'What value does ICES have for the community of Buiksloterham, to reach the sustainable energy goals of their smart community development?'

To give an answer to this research question, two sub-questions have been formulated. The sub-questions are broken down into sub-sub-questions to show the steps and provide guidance in finding an answer to the sub-questions. The following research questions have been formulated:

1. How can the development of an ICES in the community of Buiksloterham be quantified for a model study?
    - 1.1 What are the most important input variables in quantifying an ICES in Buiksloterham?
    - 1.2 In which way can the national energy system be included in the simulation model?
    - 1.3 What are the most important indicators for measuring the performance of the energy system of the community of Buiksloterham?

2. What value can different ICES compositions in different scenarios have for the community energy system in Buiksloterham in 2034?
    - 2.1 Which scenarios can be chosen to analyse the effect of ICES on the KPIs of the community energy system?
    - 2.2 What effect do different ICES compositions have on the KPIs that measure the performance of the community energy system?
    - 2.3 How can the scoring on the KPIs be interpreted so that an advice regarding the value of ICES can be given for the energy community of Buiksloterham?

1.6 Approach and structure

The approach that is used in this research is finding answers to the research questions by doing a literature study and an exploratory modelling study. For the first sub question, on how the development of an ICES can be quantified, a literature study is performed. To find information about all the possibilities, characteristics and drawbacks, as well as the related institutions and technologies of Integrated Community Energy Systems, chapter 2 of this research is about the concept of ICES and the current research that has been done on this topic. Subsequently, chapter 3 is about the Buiksloterham ambitions and goals, and the current progress and outlook of the community. This also includes an analysis about the stakeholders involved in the transition of Buiksloterham and the possibilities of applying the ICES concept specifically in Buiksloterham. The second research question on what value different ICES compositions can have for the community energy system of Buiksloterham, is answered by performing and evaluating an exploratory simulation study. Chapter 4 is focused on quantitative research in order to develop a simulation model that, using key performance indicators of the community of Buiksloterham, can find the value of different ICES compositions for energy communities. Chapter 5 analyses the results of the model study which thereafter leads to the discussion in chapter 6 and the conclusion of the research in chapter 7.

Chapter 2: Integrated Community Energy Systems

Energy communities are formed because of their potential in moving towards a sustainable energy system. A reason for opposition against renewable energy developments are the scale of the development, the unacceptably high ratio of local costs to benefits and a lack of adequate communication (Rogers, 2008). In research, it has been seen that residents are far more likely to support a smaller project that is proposed by a local group, when it is controlled by the community. A higher degree of public participation should be thus reached. Using decentralized, community-based renewable energy schemes is one way to achieve this. The current perception of a power system is centralised and hierarchical, with the rise of energy communities, this perception is changing.

2.1 Changing the energy system with ICES

A power system consists of different sources, loads and interconnections so that the load that is required by consumers can be supplied by any of the sources (Cartes et al., 2007). The general design purpose of the power system is to make sure that the demand can be met by the power sources in the system. When incorporating renewables as the main source of the system, many changes have to be made to the way the traditional power systems are built up. The power system needs to be 'managed' more in order to deal with peaks of supply of energy and periods where there is less power generation possible. The management of this system will have to be done by making use of both technological and 'social' assets. To achieve the sustainability and/or self-sufficiency goals that many communities have, a new power system design has to be made. An enabling environment for communities or consumers to disconnect from the grid is created with the increasing costs of energy supply from the national grid, which is heavily dependent on exhaustible fossil energy sources, and on the other hand the decreasing costs of distributed energy sources such as wind and solar energy (Koirala, 2016).

In the field of energy management, there are multiple options that can integrate distributed energy sources in an energy system. For communities that want to reach a certain degree of self-sufficiency, several approaches on the concept of energy hubs, micro-grids and virtual power plants have been used before. However, these approaches focus very much on improving the current centralised grid. Most research that has been done on local energy systems focus on the implementation of individual energy system related technologies, they less focus on an integrated and comprehensive approach to change the energy system as a whole.

The Integrated Community Energy Systems (ICES) approach can be seen as a 'multifaceted smart energy system that optimizes the use of all local distributed energy resources, dealing effectively with a changing local energy landscape' (Koirala, 2017, p.366). This approach captures attributes of many energy system integration options such as virtual power plants and energy hubs and applies them to a community level energy system (Koirala, 2015). The ICES approach leads to energy systems where distributed energy sources play a large role. This could lead to electrification of the grid, when all demands for energy (amongst others heating and cooling) are fulfilled by electricity. In this development energy systems are trying to get rid of the situation of being dependent on the use of fossil fuels.

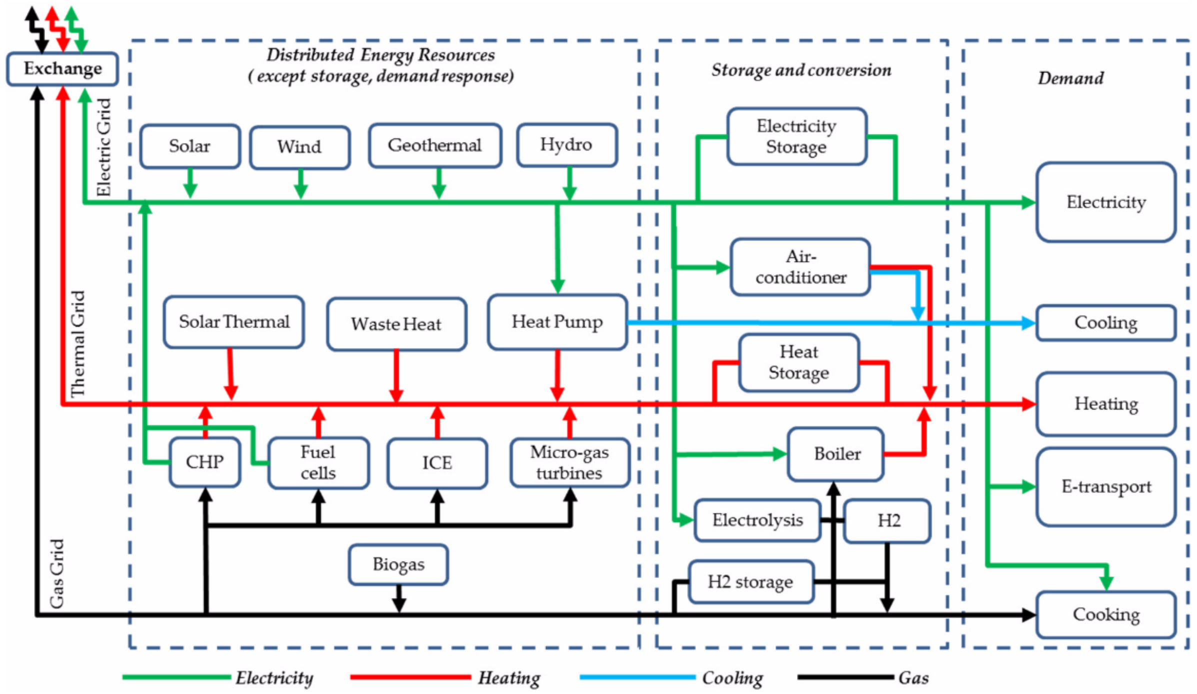


Figure 2.1: Multi-carrier energy flows in an integrated energy system (Koirala et al., 2016).

ICESs provide local energy systems with the possibility to optimize themselves, depending on the conditions in which this local community is settled (Koirala et al., 2016). It is thus dependent on the characteristics of the community how this ICES should be constituted (Sassen, 2011). This also means that when using the ICES approach in the development of smart cities, the same solution is not applicable for all cities (Townsend et al., 2010). In the research on ICESs, there can be found two forms in which the systems are formed. Firstly, there can be an energy system that is part of the bigger system, the national energy system, and thus has dependencies on this national energy system. On the other hand, there could be a system that has no interconnections with the outside grid and is completely independent of this grid. This means, there can either be a grid integrated ICES, or a grid defected ICES (Koirala et al., 2016). In the grid-defected system, the demand needs to be met locally by own power generation, no energy imports from other energy communities or the national energy system is possible. In a grid-integrated system, the deficit of energy can be imported from the national system so that the demand is always met.

2.2 Technologies connected to ICES

Different technologies are involved with ICES. Technologies on generating renewable energy via renewable energy sources, such as solar panels and wind turbines are an example of this. With these sources the community as a whole, or households in the community individually, can generate electricity with low emissions and low variable costs. This generation can take place both at the household level, for example when households have solar panels on their roofs, or at community level, which is the case when for example a community as a whole invests in a wind turbine that generates electricity for the community energy system. Koirala et al. (2015) mention the usage of energy storage systems at the community level that are beneficial for the performance of ICESs in terms of providing flexibility in the energy load. These energy storage systems could also help to increase the effective use of renewable energy by the community. Renewable energy could be stored in times that the generation is higher than the demand for energy, in this way this energy could be used at a later point in time instead of having to leave the system. Both electricity and thermal storage are technological options in ICESs. Figure 2.2 is a conceptual design of an ICES. This figure shows the possible technologies that can be involved with ICESs at household and community level and their connection to the national grid or neighboring communities.

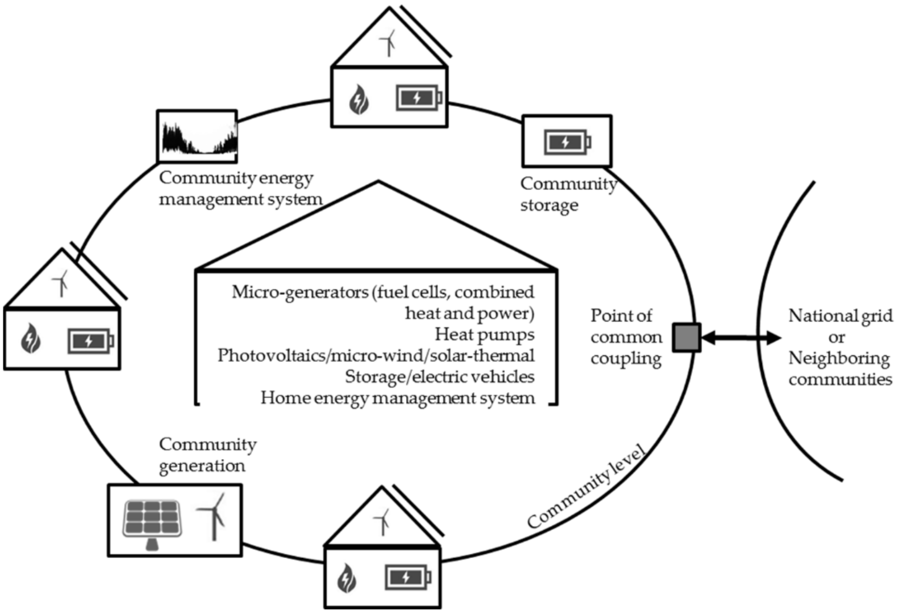


Figure 2.2: Conceptual design of ICES (Koirala et al., 2016).

Technologies that are part of electrification of the energy grid can also be linked to ICESs. Electric vehicles, which have a large impact on the demand for electricity, are an example of this. Also thermal energy technologies, that make it possible to meet heat demand by making use of electricity as a source instead of conventional sources such as natural gas, are ICES technologies. Because almost all types of energy demand could ideally be met with electricity, ICESs include technologies that are part of this electrification of the grid. Flexible micro-generators are therefore often integrated in energy communities; these are amongst others fuel cells, combined heat and power generation and heat pumps. These are all technologies that change the way in which the community deals with energy demand. The discussed technologies, together with smart local consumption, are needed to enable a good power balance in the community (Koirala, 2015). Smart local consumption can be reached through for instance the use of energy management systems. Home energy management systems and community level energy management systems are also technologies that are associated to ICES. With these management systems, energy consumption and generation is shifted in a way that an optimal balance between demand and supply can be found for a community.

The exact application of the ICES concept depends on the available technologies and the composition and the preferences of the community. Barriers and opportunities that can stimulate or hinder the creation of Integrated Community Energy Systems also have a role in this application. These are therefore discussed in section 2.3.

2.3 Barriers and opportunities for ICES

The creation of Integrated Community Energy Systems can be influenced by barriers and opportunities of many kinds. Structures that allow communities to deal with any issues between them and the corporate- and municipal entities that they are connected to are also desired. The government also has a role in preparing the public's expectations and behaviour in the future success of energy communities. Barriers for communities taking an ICES approach can be found in regulations made by the government. These could be regulations that hinder storage systems to be installed between photovoltaic generation units and the (smart) metering system (Soshinskaya, 2014). Some other regulations, in this case in Spain, make the consumers that are produce their own energy are obliged to pay system costs on the same level as consumers that are not self-producing energy. These regulations can hinder the development of micro grids that are needed for decentralized energy communities.

When applying the concept of ICES, economic incentives are often needed to make communities go renewable. This makes the role of the government also important in these bottom-up approaches (Cartes, 2007). Economic incentives such as subsidies can encourage communities or households to make the required investments. The possibility of sales of locally generated electricity is an opportunity of Integrated Community Energy Systems to receive a return of investment (Walker, 2008). This can be the case when the ICES is grid integrated with the national energy grid or other energy communities. When the supply of self-generated renewable energy is higher than the demand of the community, this energy does not always have to be wasted and can be sold. Next to the fact that the cost of operation of decentralized renewable energy sources is relatively low, this makes it possible to earn back the high up-front investments of ICESs over time. Also, the fact that ICES are owned by the community themselves, are making it more easy to obtain planning permission and to gain acceptability by the members of the energy community (Walker 2008). Other opportunities for energy communities and ICESs are that they are stable and not dependent on large upgrade of the national energy grid. When renewable energy sources would be implemented on large-scale and on one grid, this would require large upgrades and extensions of the networks. Large, central outages are less likely to happen with different isolated energy grids that have a high security of supply (Hain et al., 2005).

These barriers and opportunities of ICES can influence the possible applications of ICES in Buiksloterham. This is discussed in chapter 3, together with the situation of Buiksloterham in their development to a smart energy community.

Chapter 3: The smart transition in the Buiksloterham community

The smart transition in Buiksloterham is driven by the plans and ambitions of the municipality. Different parties are involved in this transition, and they are explained in this chapter. The community characteristics that are important for the goal of this research project and the possible applications of ICES are also discussed.

3.1 Plans of municipality

In 2009 a destination plan for the area of Buiksloterham was written by the municipality of Amsterdam. The plans for Buiksloterham can be seen as part of the larger plans to develop around 50,000 new households in Amsterdam in a sustainable way in the years 2010 to 2030 (Gemeente Amsterdam Noordwaarts, 2009). The aim of the development of the area of Buiksloterham is that in the future there will be a mixed living and working area (Gemeente Amsterdam Noordwaarts, 2009). This means that in the community there will be a mix of residential and industrial consumers of energy. At this moment, the Buiksloterham area is mianly used for industrial purposes, as there are only 252 registered residents in 2014 (Gladet et al., 2014). The destination plan states that, with the development of this area, more residential space will be created, next to the already existing industrial activities in Buiksloterham.

Figure 3.1: Left: Area of Buiksloterham, Right: functions of current buildings (purple areas are industry, yellow areas are offices).

The ambitions of the community of Buiksloterham are widespread and focus on different themes of a circular city. On the energy management field of the development of this circular city the ambitions of the community can be seen as goals that are desired to be reached in the year 2034. The general overarching ambitions for Circular Buiksloterham concerning the energy theme are as follows:

- The total project energy demand is being reduced by 75% compared to the current energy demand of the community.
- 100% of the remaining energy demand is supplied with renewable energy sources.
- Local energy production is maximized to satisfy at least 50% of the total energy demand.
- Energy distribution system losses are reduced by 30% compared to the current distribution system losses.

- The development of a smart energy management system that includes monitoring and feedback, a local smart grid and the use of electric vehicles for electricity storage.

Currently, the transition in Buiksloterham is still in the start-up phase. Different lots are already for sale and a widespread variety of (small-scale) projects are brought up amongst others via a cooperatively used community website. Active progress to an energy community that could be independent from the national energy grid however is not yet taking place. The local effort of the end users in an (energy) community is called bottom-up governance when it leads to problem-solving behaviour through collective action (Huybrechts, 2013). Both creative thinking and investments are needed to make the transition a success. Energy supply is one part of the transition to a smart city, the governance behind this part has had little development yet (Gladek et al., 2014). The plans that are presented for Buiksloterham are about building the fundaments of a renewable based energy community, but not on how this community should function. The functioning of the governance in the city is critical to the success of smart cities (Alawadhi et al., 2012).

In the development of local energy communities, less attention is paid to using a comprehensive and integrated approach that covers all energy carriers and all aspects of the community, instead of only focusing on separate sustainable energy technologies. Next to this, stakeholder relations can be seen as a critical governance factor in determining the success of government projects that involve the use of IT technologies, such as in the case of the development of smart communities (Scholl et al., 2009). This means that there could be, in the case of the Buiksloterham, opportunities for the application of approaches or frameworks that are aimed at structuring development of smart communities. The ICES approach can provide guidance and coordination for the bottom-up approaches that take place in the community of Buiksloterham with respect to the energy supply part of a smart community. This energy supply could be developed as a decentralized energy system at a community level.

3.2 Possible applications of ICES in Buiksloterham

For the transition in Buiksloterham, no prescribed way of achieving the increase of sustainably built residential area is presented. The community still needs to be formed, as not many residents live there yet; the projected 3500 households are at this moment scheduled for building. This means that in advance there are not any ICES compositions that are more desired or less desired to implement. When talking about ICES compositions for Buiksloterham, this means that different technologies, related to ICES, which could be implemented in the community. The implementation of these technologies can happen at household level or at the community level and can be done in different penetration levels. For example solar panels on the rooftop of houses can be considered household level renewable energy sources and the capacity in which they are placed there determines the penetration of this technology. A large wind turbine that is placed by the community as a whole is a community level renewable energy source.

For the exploring of the value of ICES in the energy community of Buiksloterham, multiple ICES technologies could be implemented separately or at the same time. The combination of those ICES technologies forms an ICES composition that can be evaluated as a whole, but by looking at different compositions the ICES technologies can also be evaluated separately. It can then be seen what influence they have on the functioning of the future community energy grid. This functioning of the grid has to be indicated by values for different variables of the energy system. The technologies that are taken into account in the simulation study to see their value for the energy system of the community of Buiksloterham are discussed in chapter 4. The way in which the functioning of the energy system is evaluated is discussed in the next paragraph.

3.3 Key Performance Indicators of the energy community

To evaluate the value that an ICES has for the functioning of the energy system of Buiksloterham, Key Performance Indicators (KPIs), that measure the performance of the energy system, can be used. Different literature sources that look at performance of energy communities or grids have been consulted. These studies both look at mainly environmental and economic benefits that renewable developments of energy grids can bring. Modelling and literatu studies from BIES (2016), Koirala et al (2016), van den Hil (2015), Voulis et al., (2016), Stadler et al. (2016), and Koirala et al. (2016) have been used to select a list of key performance indicators that are most aligned to the goals of both energy community development in general and the goals of the community of Buiksloterham. The chosen KPIs also have to align with type of simulation model that is created in this research. Energy communities can have different sustainable purposes when forming an ICES, for instance on having a high self-sufficiency, a low CO_2 emission, or a high self-consumption of the produced renewable energy. For this reason a list of key performance indicators that express the measurable values that an ICES can have for energy communities such as Buiksloterham is used in this study.

Table 3.2 shows the KPIs together with the unit in which they can be measured in the model study, together with a description of what they mean. Both the advantages and downsides of the choice for the development of an Integrated Community Energy System could be expressed in the KPIs. For this reason the KPIs have been separated in goal-related and conditional key performance indicators. Some of the KPIs are related to being a disadvantage for the development of the energy community, namely the payback time of ICES related capital cost, the capital costs of the ICES components and the maximum line flow capacity, rather than that they are a goal of the community development. These can be seen as conditions under which the ICES is developed in an energy community. Goal-related key performance indicators that have been chosen in this research can, as explained before, reflect the goals that a community has in the development of an ICES. For some communities one of the KPIs can be more important than the other, dependent on the community goals. Appendix A shows the equations on how the values of the Key Performance Indicators are calculated in the simulation model.

Goal-related KPI	Unit	Description
1. CO_2 emission	Ton CO_2/year	One of the goals that the Buiksloterham community has set is to lower the CO_2 emissions in the area.
2. Self-sufficiency	%	Percentage of consumed energy that has been generated through locally placed renewable energy sources to show independence of the central energy grid.
3. Total energy demand per household	GJ/household/year	One of the goals of the Buiksloterham community is to bring down the total energy demand by making efficient use of energy.
4. Yearly cost of the ICES of Buiksloterham	€/household/year	The yearly cost of operation of the ICES to supply the community with energy.
5. Total renewable energy exported to the central grid	GJ/year	The total GJ of energy that the community exports to the national energy grid. This shows the value that the community can offer to the central grid and how large the overproduction of renewable electricity is.
6. Self-consumption	%	Percentage of electricity that has been generated locally and is actually utilised for the energy consumption of the energy community.
Conditional KPI	**Unit**	**Description**
7. Maximum line capacity flow	kWh	The highest capacity of electricity that runs over the electricity distribution lines in the community of Buiksloterham at a certain hour of simulation. A high number could potentially lead to overloading of the distribution grid.
8. Capital costs of the ICES components	€/household	The average capital cost that a household has to spend in total for the community to develop a specific type of ICES.
9. Payback time of ICES related capital costs	Years	The payback time of the community for the capital investments of ICES related technologies. To calculate the payback time of technologies, the capital costs are divided by the difference in variable costs between the current ICES and the simulated variable costs without integration of ICES technologies.

Table 3.2: Key Performance Indicators of the functioning of the energy system of Buiksloterham.

Chapter 4: Model study Buiksloterham energy system

The information on the principles of the ICES approach on smart community development in chapter 2, and the information on the goals and characteristics of Buiksloterham from chapter 3 are used as input for the model study of the energy system of Buiksloterham. This chapter gives an answer to the first research sub-question: 'How can the development of an ICES in the community of Buiksloterham be quantified for a model study?' In order to do so, in section 4.1 a system demarcation is made and the approach of this modelling study is explained. Section 4.2 provides an overview of the data that has been found necessary for the development of the simulation models. Finally, in section 4.3 the verification and validation of the simulation model is treated.

4.1 System demarcation and the simulation model

Before creating the simulation model, a system demarcation has been made to make clear what should be included and what should not be included in the model. As explained before, the neighbourhood of Buiksloterham, as a remote energy community, is taken into account in the model. The households in Buiksloterham and their demand patterns form the energy community. The model can simulate the energy production and usage over the course of a year in 2034. This represents the year where the desired situation of a community with around 3500 households has been reached. This is the number of households that the municipality of Amsterdam expects Buiksloterham to be able to reach in 2034. The year is interesting because it's the year for which the municipality of Amsterdam has set their goals to make Buiksloterham a circular city. There are many possibilities for what type of energy system will be present in this year, depending on the choices that the community makes now.

In the simulation, the users and producers of energy are the households, the community as a whole and the central energy grid (the national energy grid that can exchange energy with grid integrated ICESs such as Buiksloterham). The modelling approach that is taking for this simulation study is to create the model in MATLAB. MATLAB is a computing environment in which simulation models can be developed. MATLAB is chosen because of the large and multitude of datasets that need to be used, and the calculations that need to be made. With MATLAB large datasets of information can easily be imported and complex calculations and simulations can be run.

4.1.1 Simulation model of Buiksloterham in 2034

The model, that simulates the community of Buiksloterham in 2034, has a heat and electricity demand profile that is linked to the number of households of Buiksloterham. This demand has to be fulfilled by a supply that matches the demand in every hour of the year. In this model, the energy infrastructure is based on a traditional gas- and electric infrastructure. The electricity supply can be (partly) generated by different renewable energy sources that are set up in the community, either at the household or community level. The heat demand could also be fulfilled with electricity supply by the integration of thermal energy technologies such as electrical heat pumps. Household level renewable energy sources are here represented by solar PV panels that are placed on the roofs of buildings in Buiksloterham, whereas the community renewable energy sources are community owned wind turbines.

The simulation model is at the community point of view. The demand and the supply are determined for the whole community, not for the single households in the community. The model is not an optimization of ICES related technologies for each of the households, but explores the value of an ICES for the whole community. The simulation study is exploratory and gives output of different ICES compositions on all the key performance indicators at the same time. The ICES related technologies and other input values have their influence on these variables and eventually on the key performance indicators of this study. In the simulation model, the main principles are that when the locally generated supply of electricity cannot fulfil the demand, the supply has to be met by buying electricity from the central energy grid.

Electricity can thus be generated locally, while the supply of gas is in this model arranged via the traditional way of central supply. When there is an oversupply of locally generated energy, this can be sold to the central energy grid at the APX price level. This means that the simulation model looks at:

- Demand: the community heating and electricity demand profiles.
- Supply: penetration of renewable energy sources at household level.
- Supply: penetration of renewable energy sources at community level.
- The energy efficiency level of buildings in Buiksloterham.
- The exchange of energy between the central energy grid and the community energy grid of Buiksloterham.
- Integration of thermal energy technologies to meet the heat demand.

This means that different scenarios are possible to investigate with the model. These scenarios represent the different choices that can be made in creating ICES in Buiksloterham in 2034. These choices are in the scenarios translated to levels of integration of different ICES related technologies. The scenarios also take into account different uncertain future factors that affect the simulation of the Buiksloterham energy system in 2034. The scenarios and how they are formed are explained in section 4.1.2. The goal of this simulation is to see what effect the different scenarios have on the values of the key performance indicators of the functioning of the energy system of Buiksloterham.

Figure 4.1 gives a systematic overview of the model study. First, the integration level of the ICES related technologies, explained in section 4.1.2, which are determined by the scenarios that are simulated, are the input for the first blue box activity: forming the energy demand and supply data. This data is specific for every scenario that is simulated for the energy community of Buiksloterham. Together with the RES production potential and the energy demand time series the integration levels form the demand and supply. This data is the input for the second activity: simulating the energy system of Buiksloterham 2034. Uncertain future developments, which are also explained in section 4.1.2 are influencing this simulation. Using more inputs of required information, which will be explained in section 4.2 and is needed to simulate the model, the energy system of Buiksloterham 2034 can be simulated. The outputs of this simulation are the values of the key performance indicators of the study.

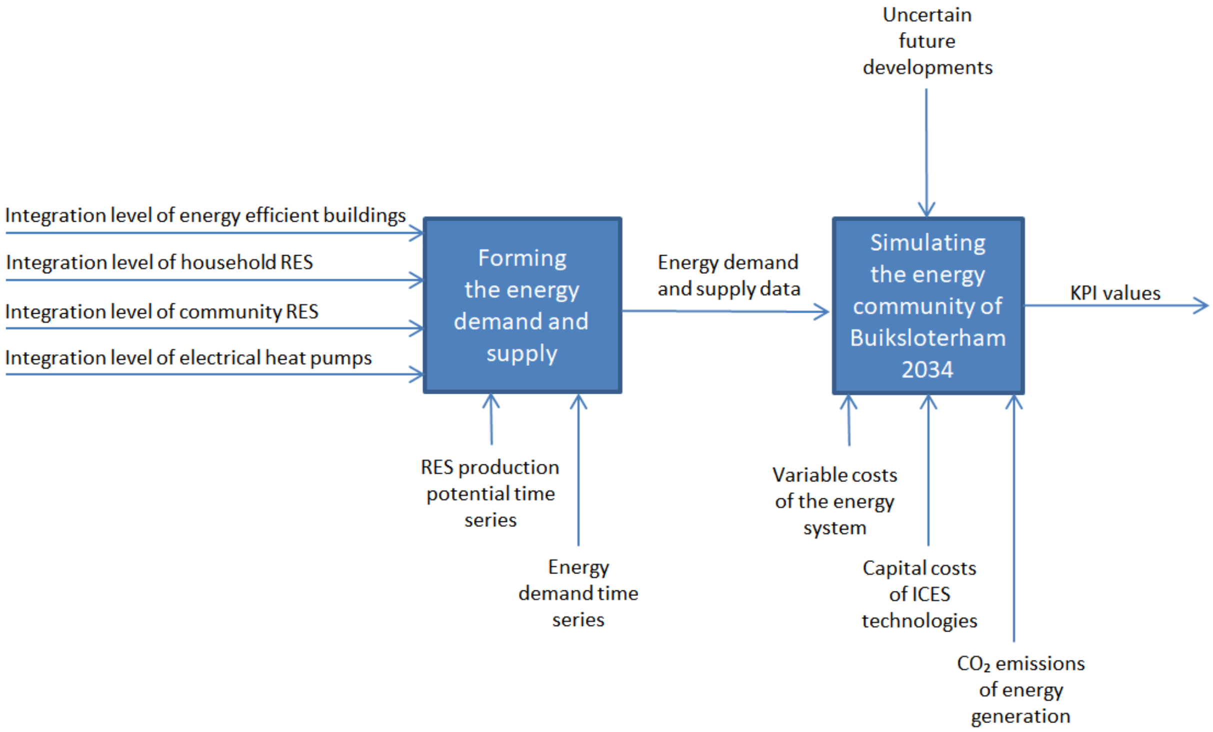


Figure 4.1: Systematic overview of the model study.

4.1.2 Scenarios in the model study

Different scenarios can be explored with the simulation model. These scenarios are formed by first taking the choices on different levels of integration of different ICES technologies into account. In addition to this, the scenarios differ on possible future developments of certain factors in the energy. The scenarios are firstly formed by choosing the level of integration of the following **ICES technologies:**

- *Integration of energy efficient buildings in Buiksloterham (full, medium or none)*
  An option for the municipality of Amsterdam is to build the new buildings that should be completed in 2034 in a more energy efficient way than is done with current new buildings. The energy demand of Buiksloterham is influenced by this energy efficiency level of the buildings in the community. When having the option of 'full' energy efficient buildings in the community, this means that all the new 4000 buildings (the households and the work units combined) will be built in the most energy efficient way. The medium option corresponds with 50% of the buildings being built in the most energy efficient way, and the last option is to build the buildings at the 'regular' minimal energy efficiency level. The integration of energy efficient buildings in Buiksloterham will have an influence on the energy demand of the community. The integration of energy efficient buildings is explained further in section 4.2.

- *The penetration of household renewable energy sources (high, medium or low)*
  The integration of household renewable energy sources is translated in the model with the capacity of household rooftop solar panels that are present in the community. Depending on the capacity of connected solar panels and the weather conditions, an hourly generation of renewable electricity is available for the households in the community. Different levels of

penetration are possible to explore in the model study. A high penetration means 8000 kW, which is equal to when around 80% of the total rooftop capacity available for solar panels is actually used for this capacity. A medium penetration is set at 5000 kW, which is equal to around 50% of the total rooftop capacity available for solar panels. The low penetration is set at 2000 kW, which is equal to around 20% of the total rooftop capacity available for solar panels. The exact percentages of the penetration levels, here chosen to be 20, 50 or 80 per cent are not of great importance. The main purpose of the different levels is to find out how a higher or lower penetration of RES influences the performance of the energy community. This could be explored by using a low, medium or high level of integration.

- *The penetration of community level renewable energy sources (high, medium or low)*
  The integration of household renewable energy sources is translated in the model with the capacity of wind turbines that are built in the community. Again, depending on the capacity and the weather conditions, an hourly generation of renewable electricity is available for the community. Different levels of penetration are again explored in the model study, using the same penetration levels as with the integration of household renewable energy sources. A high penetration also means 8000 kW of wind turbine capacity. A medium penetration is set at 5000 kW wind turbine capacity, and a low penetration of community level renewable energy sources is set at 2000 kW, which is equal to around 20% of the total possible rooftop capacity used for solar panels.

- *Integration of thermal energy technology (full, medium or none)*
  Different options are possible for the design of the thermal grid, dependent on the choices that the Buiksloterham community makes. In 2034 there could still be a traditional gas infrastructure for the thermal energy demand of Buiksloterham. Looking at the principles and applications of ICES however, other options concern the use of heat pumps, solar thermal installations or waste/district heat to fulfil this thermal energy demand, instead of natural gas (Koirala, 2016). Heat pumps make it possible to generate heat in houses by using only electricity. Solar thermal installations make sustainable heat generation possible at community or at household level. By integrating these technologies, an all-electric energy infrastructure could for example be made possible. In this simulation study, the integration of heat pumps is investigated as an electrical option for supplying heat for the community of Buiksloterham. This is because it is pragmatically the most straightforward option to include in the simulation model. The demand for heat can be easily transformed into an extra demand for electricity. Including this ICES technology gives this research the opportunity to investigate to see what the value can be of fulfilling the heat demand with supply that could be renewable (electricity), instead of using natural gas. This different thermal energy option will have its impact on the energy demand and energy costs of Buiksloterham. It is therefore interesting to see what effect it has on the performance of the energy community and take this into the simulation study. The full integration of thermal energy technologies means that every household in the community owns an electrical heat pump in 2034. The medium setting means that half of the households own a heat pump, while the last option means no integration of heat pumps in the households of Buiksloterham.

The level of integration of the different ICES technologies form the first part of the scenarios of the modelling study in this research. All the ICES technologies, together with their possible levels of integration are summarized in table 4.1. An example of the technology integration mix in a scenario could be: medium efficient buildings, low household RES, high community RES and medium integration of thermal energy technology.

ICES technologies	Level of integration		
Energy efficient buildings	None	Medium	Full
Household RES	Low	Medium	High
Community RES	Low	Medium	High
Thermal energy technology	None	Medium	High

Table 4.1: ICES technology integration levels that form a scenario.

For this study, it is valuable to see how the results change when the choice of the ICES technologies above are affected by different uncertain future developments. Because the model simulates the community in the future, it is unsure which value some model factors will have 2034. The uncertain future developments have been chosen by selecting model parameters of which its values are historically proven to be variable over time. The following **future developments** are investigated in the model study:

- *The electricity demand by end users of the energy system in 2034 (30% higher, stable, 30% lower)*
  The average electricity demand per household has been stable for the last ten years, but has always been growing before this time (Milieucentraal, 2017). For the simulation of the year 2034, it is unsure how the electricity demand will continue to develop; however, different scenarios are possible. The electrification of the grid reaches further than only finding other options than gas for heating. An example of this is the increasing use of electric vehicles for transport (Zhou et al., 2015). The electrification of the grid and the 'common' development of welfare could lead to a higher demand for electricity in the year 2034 compared to the current electricity demand. On the other hand, when the electrification of the grid does not push through in the coming years, there is a possibility of having the same electricity demand in 2034 as in the present time. The electricity demand can also possibly decrease when technological developments lead to more efficient use of electrical devices. The scenarios that are used in the model study differ with 30% to see how a significant, but not very large, increase of this value influences the results of the model study.

  The demand of gas is not analysed in the scenarios, as there is a prediction of the 2034 gas demand used in gathering the data of gas demand (see section 4.2). Next to this, the demand of gas is largely dependent on the energy efficiency of buildings and the integration of thermal energy technologies, which are already taken into account in the ICES related technologies that are part of the scenarios.

- *The ICES technology related capital costs in 2034 (stable, 15% lower, 30% lower)*
  It is known what the current capital costs are of technologies that are implemented with forming the ICES. However with technological improvements there are scenarios possible

where the capital costs of those technologies go down. The expectance is for solar panels and wind turbines that these costs will decrease over the coming years (The Guardian, 2016). The costs of implementing heat pumps are also expected to go down, looking at the expectancy of current R&D activities in this field (IRENA, 2013). Subsidies that could be given on the investment in ICES related technologies are not taken into account separately. The future subsidies are eventually also influencing the actual capital costs for the community. With the creation of these scenarios, both the influence of subsidies and the decrease of technological costs over the year can be seen back in the simulation results.

- *The APX electricity price in 2034 (stable, 20% lower)*
  The past development of the level of the electricity price shows that there has been a large increase in this price since 2000, but that the electricity price is relatively stable since 2011 (Energieperspectief, 2017). There could be different future developments for the APX electricity price towards 2034. This can be caused by for instance tax schemes and supply of domestic or foreign generated renewable energy in the national energy grid. It is important to take this uncertainty into account to evaluate the model study results. The future development of the APX price being lower in 2034 than the current APX price can be explained by the possible availability of 'variable costs free' renewable energy. With more renewable energy source capacity installed in 2034 in the Netherlands and in neighbouring countries this could lead to lower hourly APX electricity prices during the hours that a high generation of renewable energy is possible. A research about scenario developments on the energy supply of the Netherlands in 2030 mentions that the Netherlands could have 10 GW of wind capacity installed in 2030 (Rooijers et al., 2014). Research about the influence of wind power generation in the Netherlands on the average APX prices, shows that an increase of 8 GW of wind capacity in Netherlands, leads to 12% lower APX prices (Nieuwenhout & Brand, 2011). An increase of 6 GW, as mentioned by Rooijers et al., would decrease the APX price with around 9%. This information is used together with the assumption that solar energy could do the same in the Netherlands. Both of these future RES developments together could make the average APX electricity price 20% lower in 2034. This is incorporated in some of the scenarios by modifying the APX electricity price time series.

- *The natural gas price in 2034 (stable, 50% higher)*
  The development of the price of natural gas has recently been estimated by IMF and World Bank. The expectation for the coming 10 to 20 years is that the gas price will slowly increase (Knoema, 2017). A natural gas price in around the year 2030 that is 50% higher in Europe than it is today is expected in these studies. For this reason, concerning this future development, the simulation study also works with a natural gas price that could be 50% higher in 2034 than the current natural gas price in 2017. There is thus also the possibility of the height of the gas price staying stable towards the future, which can be the case when for example new discovery of gas supplies happen, or research and development activities in efficient use of resources are successful.

When running a scenario formed with integration levels of ICES technologies from table 4.1, the results are the output values of the earlier mentioned Key Performance Indicators. To evaluate the outputs of the model and see how sensible they are to changes of input parameters, the scenarios are also compared on the direction of different uncertain future developments. The results of a scenario can differ when the electricity demand in 2034 is the same as it is today, 30% lower, or 30% higher than the current average electricity demand. The difference between the outputs can also be analysed with lower values for capital costs, lower electricity prices, or a higher natural gas price. The uncertain future developments, together with the possible directions that they take, are summarized in table 4.2.

Uncertain future development	Direction of the development		
Electricity demand in 2034	30% Lower	Stable	30% Higher
ICES related capital costs in 2034	Stable	15% Lower	30% Lower
APX electricity price in 2034	Stable	20% Lower	
Natural gas price in 2034	Stable	50% Higher	

Table 4.2: Uncertain future developments that have an effect on the scenario simulation run results.

4.2 Modeling data and assumption

The models that are constructed should be based on the future situation of Buiksloterham in 2034. What is known for this future is that the plans of the municipality are that there should around 3500 households and that there is also an increase in industrial activity. Data is first of all needed to model the desired profile of Buiksloterham 2034. For this reason information is needed on amongst others energy demand of these future households, rooftop surfaces and emission levels. Next to this, data is needed to be able to apply an ICES composition on this model. Information on amongst others renewable energy production, exchange with the national energy grid, capital and variable costs is needed for this. Assumptions on different topics are made to form the eventual inputs of the simulation model. The next sections show and explain the information that is found for the modelling of the energy community and which assumptions are made to turn this into model data.

4.2.1 Household and community renewable energy sources generation

To find out what the generation potential of energy production in Buiksloterham in 2034 can be, data on the number of households, and the characteristics of these households is required. A research project on a sustainable and integrated energy system in Buiksloterham (BIES, 2016) has made multiple assumptions on the future build area of Buiksloterham. These assumptions are based on amongst others the destination plan of the municipality of Amsterdam (Gemeente Amsterdam Noordwaarts, 2009).

Type of building	Surface (m^2)	Rooftop surface (m^2/unit)	Available rooftop surface for PV cells (m^2/unit)	Number of units in the area
Apartment	105	13.1	10	2,998
Ground built households	125	41.7	25	453
Work units (100 m^2)	100	12.5	10	544

Table 4.3: Assumptions on new buildings in Buiksloterham in 2034 (BIES, 2016).

From table 4.3, the rooftop surface that is available for PV cells can be used to calculate the maximum capacity of solar PV panels that can be set up in Buiksloterham. By multiplying the available rooftop surface for the different types of buildings with the expected number of these buildings in Buiksloterham in 2034, a total rooftop surface of 65 thousand square meters can be found. Because of 260 Wp capacity that a typical solar panel has (Milieucentraal, 2016) with its area of 1.63 square meters (Zonnepanelen, 2017), per square meter solar panels have a watt peak capacity of 159 Wp. This means that the total maximum capacity of solar panels on rooftops in Buiksloterham in 2034 is 64,963 * 159 = 10 megawatt.

To simulate the solar electricity production for every hour of the year 2034, a time series of solar irradiation that gives the energy output in kWh per kWp of installed capacity is needed, next to the installed capacity of PV cells. The time series that is found is a series for average energy output in kWh per kW of installed capacity delivered to the grid, based on the solar irradiation in the Netherlands in the year 2013 (Martínez-Anido, 2013). By multiplying this time series with the total capacity that is set up in Buiksloterham, the total generated solar electricity by the community energy system for every hour of the year is found.

For setting up community renewable energy sources, wind turbines are used in this model. The capacity of wind turbines is cannot placed directly into someone's backyard and would be financed and owned by multiple residents or other stakeholders in the community. To calculate the output that the total set up wind turbine capacity in the community can produce every hour, again a time series is required. The same research (Martínez-Anido, 2013) provides a time series for average energy output in kWh per kW of installed capacity delivered to the grid in the Netherlands in 2013, based on wind speed at different heights and roughness length constants (expressing the roughness of the terrain). By again multiplying this time series with the total capacity installed in Buiksloterham, the total generated wind electricity for every hour of the year can be calculated.

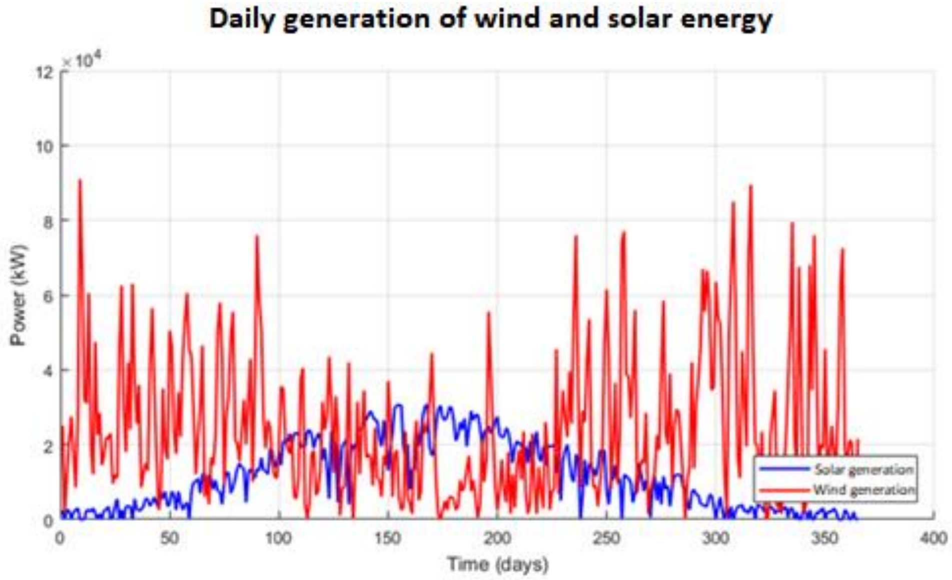


Figure 4.2: Daily generation potential of wind energy and solar energy.

Figure 4.2 shows what the daily total generation of solar and wind energy in the energy community of Buiksloterham looks like in 2034, when the community would install a total capacity of 5000 kW of both solar energy capacity and wind energy capacity. The graph shows the total generated sustainable electricity by the community, for every day of the year at this specific installed capacity.

4.2.2 Energy demand in Buiksloterham

To include the demand for electricity in the model, a time series of electricity demand for every hour of the year is needed. This is done by using open data on electricity usage from a distribution grid operator, and transforming this to create a dataset that could reflect the hourly electricity demand of Buiksloterham in 2034. Liander provides an open data set of hourly electricity consumption of a group of 10,000 households for the year 2009 (Liander, 2017). As the yearly electricity demand of the nearly 500 buildings for industrial purposes (work units) in Buiksloterham in 2034 is similar to the demand of regular households in Buiksloterham, the electricity demand time series of these 10,000 households is reduced to 4000 households (3500 households + 500 work units). The final electricity demand profile that is being used in the simulation can be influenced by the future developments on the energy demand towards the year 2034, as explained in section 4.1.

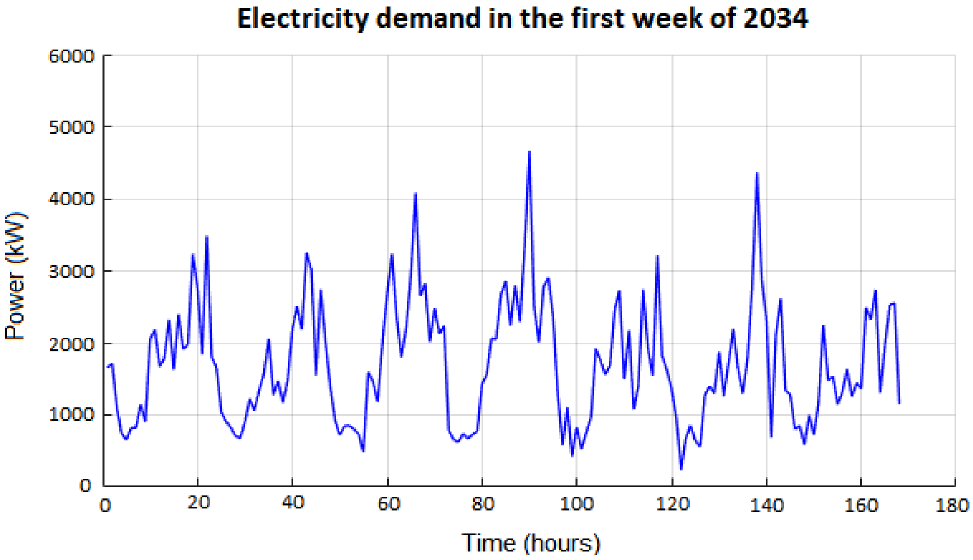


Figure 4.3: Electricity demand in Buiksloterham for every hour in the first week of 2034.

In figure 4.3, the hourly electricity demand of the community of Buiksloterham is displayed. This is an example of the electricity demand in one run, when the buildings are built on the minimum energy efficient level and only the stable future developments are taken. Every run the electricity demand slightly differs, because of the stochasticity that the model has, which will be further explained in section 4.2.7.

A heat demand time series of Buiksloterham for every hour of the year is needed and is also provided by Liander open data (Liander, 2017). This time series is then also transposed to create a fitting hourly heat demand time series for Buiksloterham in the year 2034. This done by firstly only using the trend of the amount of heat used throughout the year (from Liander data), that is heavily influenced by the weather of the seasons, and then using the expected heat demand for the buildings in Buiksloterham in 2034, that can be found in table 4.4 (BIES, 2016). With the data in the table and the total number of buildings, the total energy demand for heat can be calculated. This data can, together with the trend of the amount of heat usage throughout the year, be used to create a time series of gas demand in Buiksloterham for the year 2034. Again, this is the basic profile and can be influenced by scenarios during simulation of the model. Here, the heat demand also differs in every run due to stochastic inputs that are used.

As explained in section 4.1, when buildings with the highest energy efficiency level are integrated, both the electricity demand and the heat demand (of which the latter is expressed in table 4.4), can be brought down. The electricity demand can be brought down by 20% and the heat demand can be lowered with 40% (BIES, 2016). This will however give time- and cost issues. The trade-off between these can be investigated in the model study.

Type of building	Energy demand for heat (GJ/year)
Apartment	16.6
Ground built households	18.8
Work units (100 m²)	15.3

Table 4.4: Energy demand for heat for the different types of buildings (BIES, 2016).

4.2.3 Capital costs of the energy system

The capital costs of the energy system in Buiksloterham refer to the ICES technologies that are implemented in the different scenarios. For the calculation of capital cost of renewable energy generation sources, the capital costs in euro per kW of generation technology is needed. This calculation is needed for the household renewable energy sources (the solar panel capacity) and the community renewable energy sources (the wind turbine capacity). The capital costs of building at the most energy efficient level and the capital costs of installing electrical heat pumps in buildings are also needed for the simulation. In this study, the assumption is to use the current capital prices of technologies. The model simulates possible ICES compositions that are ready in 2034. These compositions of technologies are part of the scenarios that are simulated in the next chapter. To have a functioning ICES in 2034 the technologies that belong to an ICES need to be implemented around this year. The capital costs are unknown for the future, but are known for the present. For this reason, the current capital cost values are used for the standard model. However, possible future developments of the capital costs levels of technologies have been taken into account in the simulation study. The capital costs of the technologies can be influenced by this future development. The expectance is that, as is described in section 4.1.2, these costs will go down in the future.

To install 2600 Wp of solar panels the current capital cost are 4600 euros, including the inverter and the installation costs (Milieucentraal, 2016). As the installed solar energy in the model will be included in the model by working with euros per capacity, the capital cost are assumed to be 4600 euros per 2.6 kWp. By dividing 4600 by 2.6 kWp, this makes the total capital costs of solar panels to be 1800 euro per kWp. The current capital costs of installing wind turbines are found to be on average 1450 euro per kW of installed wind turbine capacity (IRENA, 2012).

An assumption for the characteristics of the integrated heat pumps in the model needs to be made. The type of heat pump that is chosen for the simulation of the community is a ground source multi-heat pump that can both heat space as well as tap water. The indication of the current capital costs of this heat pump for a single household are €9075 (BIES, 2016). For this model study, this is the only type of heat pump that has been taken into account, as it fits the ambitions of the municipality to become less dependent on fossil fuels such as natural gas. The coefficient of performance (COP) of 5.1 that this electrical heat pump has, means that with an input of 1 unit of electrical energy, 5.1 units of thermal energy can be produced by the heat pump. This is possible because heat is also provided from the ground.

Concerning capital costs of buildings at the highest energy efficient level, compared to building houses at the minimum energy efficiency level, an estimation per building is made. The extra costs involved with energy efficient buildings are estimated by taking into account the adjustments that are done to regular buildings. The most important adjustments are cavity wall insulation, LED lighting, high efficiency boilers and quadruple glazing of windows (RVO, 2017) (BIES, 2016). The combined costs of these investments are lower because the buildings are not build yet; no adjustments have to be done to existing buildings. The costs of building at the highest energy efficient level, compared to building at the minimum energy efficiency level are estimated at around 5000 euro per building (Gevelenwand, 2017, Modernize, 2016).

Table 4.5 summarizes the exact values of the capital costs of the ICES related technologies together with the unit in which they are measured. These numbers are used in the simulation model of the community of Buiksloterham.

Type of ICES technology	Capital cost	Unit
Solar energy	1769	€/KW
Wind energy	1446	€/KW
Electrical heat pump	9075	€/household
Energy efficient buildings	5000	€/household

Table 4.5: Capital cost of the ICES related technologies.

4.2.4 Variable costs of the energy system

The variable costs of the energy system are determined by the price of the imported electricity, the cost price of the imported gas, the operational and maintenance costs of different technologies. All these costs together determine the variable costs of the energy system of Buiksloterham in 2034. An assumption here is that the current price levels of these variable costs elements can be used for this, as this is the most recent information that is available. However, to take future changes of the variable costs into account, uncertain future development directions were formulated in section 4.1.2.

Cost price of imported electricity

To calculate the variable costs of operation of the energy grid, the import of electricity is an important part. Electricity is imported from the national grid when the electricity that is generated by the community is not enough to fulfill the demand. Importing electricity from the national grid is done at the retail price of electricity. How this retail price is formed is explained later in this section. Next to these costs on electricity imports, there are profits on exporting electricity produced by the community to the national grid, in times where there is an oversupply of electricity in the community. The price that they receive for this electricity export is the APX electricity price. For this, hourly data of the APX price in the year 2013 is used (Apxgroup.com, 2013). This dataset gives the APX price of electricity for every hour of the year 2013 in euro per MWh of electricity. This dataset is then transformed to an hourly electricity price in euro per kWh of electricity. By multiplying this dataset with the dataset of hourly electricity export, the dataset of hourly electricity export gains is created.

The APX price that is used is also subject to uncertain future developments. Because of the volatility of the APX price, the future development of the reduction of the APX price is done in the following way. In some hours the potential of renewable electricity generation is higher than in other hours. In these hours renewable generation outside of the community, dependent of course on the installed capacity outside of the community, is also higher. In the simulations where the future development of having a lower APX price in the future is true, because of an expected high (inter)national integration of renewables, the APX price is significantly lower in some of the hours. These are the hours where the potential of renewable electricity generation is high (simply put: when the sun shines and the wind is strong). It is assumed that in these hours there will namely be a large production of renewable electricity with no variable and marginal costs. This renewable electricity production, possibly taking place in the Netherlands or neighboring countries such as Germany, will reduce the APX electricity market price in some hours because of its low marginal costs and high availability. In the simulation model, the APX price is reduced by multiplying the original APX price with a factor that is higher or lower according to the potential renewable generation of that hour. This makes the model behave more logical; it shows that in a market for electricity, the price goes down when the supply of extra renewable generated electricity is high. This factor is also influenced by a random normal distribution to take the volatility of a market price into account and add stochastic inputs to the simulation model. This is further explained in section 4.2.7.

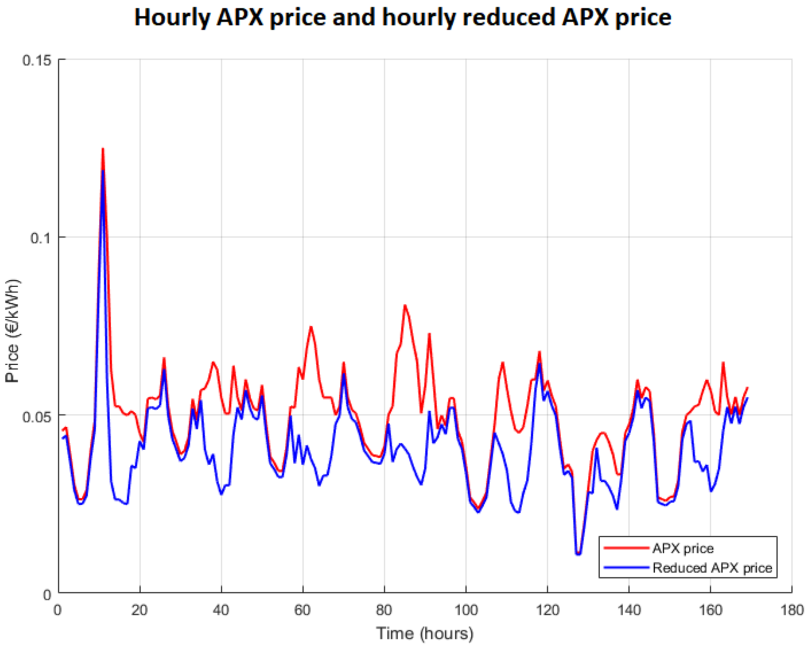


Figure 4.4: The hourly APX price and reduced APX price in week 26 of the year 2034.

In total the APX price over the year is reduced with on average 30%. Figure 4.4 shows the original and the reduced hourly APX price that is used in the model for week 26, which is in the middle of the year 2034. As can be seen, in some of the hours the reduced APX price is much lower than the APX price than in other hours. The bigger this difference is, the higher the wind and solar energy generation potential is in this hour.

To calculate the hourly retail price of electricity, that is used for the cost of electricity imports, different components of this retail price should be added on top of the APX price of electricity. Table 4.6 shows of which components the retail price of electricity is built up and what the price level of these components is in euro per kWh. This is done for a random hour in the simulation. All components together form the final retail price of electricity. With this calculation, the APX price hourly dataset is transformed into a retail price hourly dataset. By multiplying the datasets of imported electricity and retail price of electricity, the dataset of electricity import costs is created.

Component	Price (EUR/kWh)
APX price	0.0420 (at one of the hours)
Energy supplier surplus (2017)	0.0080 (in 2017)
Regulating energy taxes (2017)	0.1013 (in 2017)
Sustainable energy storage (2017)	0.0074 (in 2017)
VAT (21%)	0.1587 (subtotal) * 0.21 = 0.033327
Retail price	0.1920 (total price at one of the hours)

Table 4.6: Retail price of electricity imported from the national grid calculation (Milieucentraal, 2017).

Cost price of imported gas

To calculate the costs of importing gas, the average retail price of gas of 0.63 euro per cubic meter in the year 2016 is used (Milieucentraal, 2017). The price of gas is then transformed to a price per GJ of energy, which is done by taking into account the energy level of 35.17 MJ per cubic meter of gas (Energieconsultant, 2017). This price is then multiplied with the time series of hourly heat demand to form the time series of variable cost of gas import in Buiksloterham in 2034.

Operational costs of ICES technologies

The operation and maintenance (O&M) costs of solar panels and wind turbines are also taken into account when calculating the variable costs of the energy system of Buiksloterham. The yearly O&M costs of solar panels are at the level of 6 euros per kW of peak capacity per year, while the costs for wind turbine operation and maintenance are set to be 5 euro per kW of capacity per year (Koirala, 2016). The operation and maintenance costs per household heat pump that could be installed in Buiksloterham are 194 euros per year (IRENA, 2013). These operational costs of do not include the costs that are involved with the import of electricity that is used as an input for the heat pump, as this will be part of the costs for importing electricity. The heat pump has a COP of 5.1 so that with 1.0 kWh of electricity 3.6 * 5.1 =18,36 MJ of heat is generated (BIES, 2016). For the model this means that for 1 GJ of heat demand 277.77 divided by 5.1 = 53.31 kWh of electricity input is needed.

4.2.5 CO_2 emissions of energy generation

To calculate the CO_2 emissions that are produced by the energy system of Buiksloterham, over the year 2034, the emission factors of electricity and gas are needed. The CO_2 emission of (gray) electricity is 0.526 kg per kWh electricity, while the CO_2 emission of gas is 1.884 kg per Nm3 of gas (CO_2emissiefactoren, 2017). The CO_2 emissions can be calculated by multiplying these emission factors with the quantities of gas and electricity that are consumed during the year.

The CO_2 emissions when producing renewable energy are zero. The possible CO_2 emissions that are emitted with the production of the solar panels and wind turbines are out of scope of this research. This simulation runs the year 2034 and shows what is emitted or generated in this year. Table 4.7 gives an overview of the CO_2 emissions per energy generation type.

Energy generation type	Emission	Unit
Gray electricity (imported)	0.526	kg CO_2/kWh
Natural gas (imported)	1.884	kg CO_2/Nm3
Wind energy (produced)	0	kg CO_2/kWh
Solar energy (produced)	0	kg CO_2/kWh

Table 4.7: CO_2 emissions per energy generation type.

4.2.6 Line capacity

To see whether overloading of the distribution grid is a risk for the ICES that could be formed in Buiksloterham, the line capacity of the electricity grid should be known. To find this value, the following calculation is made. A distribution transformer typically has 139 households connected to itself. This distribution transformer has a capacity of 630 kVA (Westland-Infra, 2016). This means that per household a capacity of 4.53 kVA is assigned, which is equal to 3,85 kW per household. Taking 4000 building units of Buiksloterham into account this means that there should be a maximum line capacity of 3.85 * 4000 = 15,400 kW available. This means that every hour a maximum of 15,400 kWh can flow over the lines of the energy system of Buiksloterham. The maximum flow of capacity over the lines at a certain hour in the simulation was taken as a key performance indicator of the simulation study. If this value exceeds the maximum line capacity, this means that the distribution grid will be overloaded.

4.2.7 Stochastic inputs in the simulation model

In the writing of the simulation model, stochastic inputs have been used to reflect the unpredictability of some of the input factors. The demand for heat and the demand for electricity by the community is first implemented in the model as a static list of 8760 hourly demand values. The creation of these lists is explained in section 4.2.2. By then adding a random normal factor that influences the actual value of the lists of heat- and electricity demand for every hour of the year, stochasticity is introduced in this part of the model. A value, with a mean parameter of 1 and a standard deviation of 0.25 is multiplied with the heat- and electricity demand hourly input of the model.

With determining the APX price, both when the APX price would be 30% lower in 2034 (which is one of the uncertain future development settings) or not, a more complex stochastic factor is been taken into account. The APX price determines amongst others the amount of money that the community of Buiksloterham receives when selling an overproduction of renewable generated electricity to the national energy grid. The hourly APX prices that are used in the simulation are firstly taken from data that is found in section 4.2.4. In the future development where APX electricity prices are going down, the expectance is that these hourly prices are influenced by the hourly production potential of renewables, as is explained in section 4.2.4. To simulate the volatility of the market price, the multiplication factor that reduces the hourly prices, which is different for every hour (dependent on the renewable energy production potential), is multiplied with a random normal factor as well to reflect the unpredictability of the electricity price. In total, this determination of the APX price will lead to an hourly APX price that is 30% lower on average over the whole year 2034. When the future development of a lower APX electricity price in 2034 is not applied, the model only uses the random normal factor to add stochastic inputs to the APX electricity price data that is imported to the simulation model.

With these stochastic model inputs, most of the output values of the Key Performance Indicators for the simulation runs are influenced, and will thus be slightly different for every run. The implication of this introduction of stochastic factors in the model is that the output values of every simulation run are not the same. This means that a simulation setting needs to be run different times to find reliable ‘average’ results. The simulation settings that will be used in the simulation study, and how the simulations are run, are explained in more detail in section 5.1.

4.3 Model verification and validation

The simulation model that has been created is verified by doing multiple tests. To verify the working of the simulation model of the energy community of Buiksloterham, firstly the natural process of debugging the model is performed, as explained in section 4.3.1. Next to this, a sensitivity analysis is performed in section 4.3.2 to check the change of model outputs to numerical value changes of input parameters (Pianosi et al., 2016). In section 4.3.3 an extreme values test is performed. Possible approaches on the validation of the simulation model are discussed in section 4.3.4.

4.3.1 Verification: debugging process

The model has been debugged while it was build up in incremental steps. The building of the model and the associated debugging activities are a form of verifying whether the model works how it should work in the conceptual model that has been sketched in section 4.1. The most important debugging activities that were done are checking whether the calculation inside the model would lead to correct model properties and model output. An example of this is the combination of the time series of generation potential of renewable energy sources and the installed RES capacity. This combination needs to lead to a correct and complete time series of hourly electricity produced by household and community level renewable energy sources. Another important part of the model was to make sure that every hour an excess of electricity would be sold for the right price (APX price) to the national grid and that a deficit would be bought from the national grid at retail price. Other smaller debugging activities are found in checking whether the total CO_2 emissions equation is actually correctly adding up all the CO_2 emissions caused in the energy system, so that a correct total number of CO_2 emissions of the energy system is found.

4.3.2 Verification: sensitivity analysis

The reference model that is used in this analysis is the model with all ICES technologies integrated at the medium level. One of the input parameters of the model is then slightly changed and the output of the two simulations is compared with each other. The parameters that are varied here are the heating demand and the capital costs of community RES.

Table 4.8 shows that the payback time of the ICES decreases with around 10 percent when the heating demand is 1.5 times lower. It increases with around 20 percent when the heating demand is 1.5 times higher. This is caused by the same type of increase and decrease in the yearly cost of operations of the ICES.

	Yearly cost of operation of the ICES of Buiksloterham per household (€/household)	**Payback time (years)**
Heating demand *Normal*	378	16.67
Heating demand *1.5 times lower*	292	14.87
Heating demand *1.5 times higher*	464	20.04

Table 4.8: Sensitivity of heating demand.

The capital costs of community RES is varied and the results are shown in table 4.9. It is clear that the capital cost will respond in the same, but reverse way to an increase or decrease of capital costs of community RES. The community RES capital costs are a part of the total capital costs in this scenario, that include all ICES technologies, and so the capital costs and payback time will slightly respond.

	Capital costs of the ICES components (€/household)	**Payback time (years)**
Heating demand *Normal*	44,075,000	16.67
Capital costs of community RES *1.5 times lower*	41,665,000	15.83
Capital costs of community RES *1.5 times higher*	47,690,000	17.68

Table 4.9: Sensitivity of capital costs of community RES.

The sensitivity tests show that the output of the model changes in a logical way when small changes are made to the model input. This verifies that at least these parts of the model are modeled in the correct way.

4.3.3 Verification: extreme values test

In the extreme values test, the same reference model as in the sensitivity analysis is now analyzed with large changes of input parameters. The input parameters that are varied are the hourly APX electricity price, the heating demand of the community and the hourly production potential of renewable energy sources. The results are shown in table 4.10 to 4.12.

Extreme value testing of APX electricity price

Table 4.10 shows that the yearly cost of operation of the ICES gets lower by about a third when the import price of electricity is ten times lower. A ten times higher price gives a large rise in the yearly cost of the ICES. This means that the model reacts as expected with these input changes. The yearly costs are not increased or decreased by a factor ten because of the fact that the electricity costs are only one part of the total variable costs of the system, which also include gas costs and operation and maintenance costs. With the lower electricity import price, the payback time of the ICES technologies also drops with a couple of years. With a ten times higher electricity import price, as expected, the payback time is infinite. There are no savings possible with the ICES technology investments, when the electricity that needs to be bought is much more expensive than the electricity that is sold at the APX price. Concerning the changes made in the electricity price, the outputs that are given are to be expected.

	Yearly cost of operation of the ICES of Buiksloterham per household (€/household)	**Payback time (years)**
Electricity import price *Normal*	378	16.67
Electricity import price *10 times lower*	244	13.14
Electricity import price *10 times higher*	2158	N.A.

Table 4.10: Extreme value testing of APX electricity price.

Extreme value testing of electricity demand

Table 4.11 shows that when the electricity demand of the community is decreased with a factor 10, the total renewable energy exported to the central grid is almost threefold. When the electricity demand is enlarged by a factor 10, the total renewable energy exported decreases to only 8 GJ a year. The relation between electricity demand and energy exported is not linear, which can be explained by a simple example. When for example 4 GJ is generated in one hour, and 1 GJ is demanded by the energy community of Buiksloterham, 3 GJ can be exported. With a ten times lower electricity demand 3,9 GJ would be exported in this example. On the other side, with a 10 times higher demand, the exported electricity is not just 10 times lower. The higher demand will lead to very few hours where there is any excess of produced electricity and thus a very low exported renewable energy. The yearly cost of operation of the ICES is influenced in the same way; the high or low exchange of electricity leads to a low or high yearly cost of operation. Here, the outputs of the varying electricity are thus as expected.

	Total renewable energy exported to the central grid (GJ/year)	**Yearly cost of operation of the ICES of Buiksloterham per household (€)**
Electricity demand *Normal*	15,539	378
Electricity demand *10 times lower*	39,135	99
Heating demand *10 times higher*	8	5024

Table 4.11: Extreme value testing of electricity demand.

Extreme value testing of generation potential of renewable energy sources

Table 4.12 shows that the total renewable energy exported to the central grid is strongly influenced by the generation potential of RES. Almost no energy is exported when the generation potential would be ten times lower; over twenty times more energy is exported when this is ten times higher. The exported electricity is enlarged with a factor higher than 10 in the last case, because the higher generation means that no (almost) hours will be left where the generation of RES is lower than the electricity demand of the community, while in the normal case these hours are still there. The self-sufficiency is with the high generation potential at 57.59. It is not higher because no matter how high the generation of renewable electricity is, there is still a demand for gas in this ICES with medium penetration of the ICES technologies. This means that the output of the sensitivity analysis of the generation potential of RES are also as expected.

	Total renewable energy exported to the central grid (GJ/year)	**Self-sufficiency (%)**
Generation potential RES *Normal*	15,539	46.31
Generation potential RES *10 times lower*	0.18	7.56
Generation potential RES *10 times higher*	312,510	57.59

Table 4.12: Extreme value testing of generation potential of renewable energy sources.

4.3.4 Model validation

The validation of the simulation model is not performed in this research, however, this could be a valuable addition The validation of a model that simulates the future could be done in a couple of ways. A first type of validation that could be suitable for this simulation is structural validation. In structural validation, the structure of a simulation model is evaluated by comparing this to the structure of the system that is being simulated (Pascual, 2015). As the real characteristics of an ICES in 2034 are not information that is at hand, the model structure would be compared to knowledge combined with expectances and assumptions about an energy system in 2034.

Another validation method that could be used is expert validation. Here, expert opinions are asked about mainly the conceptual model to gather information about the correctness in which the model is simulated is. Experts in the field of energy communities or energy systems in general can have important insights in the system that is modeled. Different type of experts could be asked for interviews to evaluate whether the model is reasonable for its purpose. Considering the type of research that is performed, experts in the field of for instance renewable energy sources, energy markets, energy supply systems and energy communities can be consulted.

The model study of this research has an exploratory purpose and is not able to be compared to actual data of an existing ICES in the future. What therefore could also be valuable is to perform cross validation (Kohavi, 1995). A suitable type of cross validation here would be to make use of another simulation model that, like the simulation model in this research, also simulates an energy system in a future point in time. This other model could be seen as a model that predicts the output values of an energy system in the future. With this, the simulation model of Buiksloterham could be tested when comparing the predicted results of the other model to the simulation results of the Buiksloterham model. The difficulty in doing this is that a simulation model that is very similar to the simulation model of Buiksloterham is required. With the stochastic inputs that the simulation model has, this will even be more complicated. A more simplistic way of cross validation could therefore to find a similar model on developed future energy systems and compare this to the simulation model of Buiksloterham. The differences and similarities between the models can be input to say something about the validity of the Buiksloterham model.

Chapter 5: Simulation results of the model of Buiksloterham

The results of the simulation are needed in order to give an answer to the second research sub-question of this research: 'What value can the development of an ICES have on the community energy system in Buiksloterham? These results are shown and discussed in this chapter.

5.1 Investigated scenarios and future developments

The simulation model that is created in MATLAB simulates, as mentioned in the previous chapter, an Integrated Community Energy System in Buiksloterham in 2034, including the following simulation elements that were discussed in section 4.1:

- Demand: the community heating and electricity demand profiles.
- Supply: penetration of renewable energy sources at household level.
- Supply: penetration of renewable energy sources at community level.
- The energy efficiency level of buildings in Buiksloterham.
- The exchange of energy between the central energy grid and the community energy grid of Buiksloterham.
- Integration of thermal energy technologies to meet heat demand.

The scenarios are formed by choosing a level of integration for each ICES technology as follows:

ICES technology→ Scenario↓	**Energy efficient buildings**	**Household RES**	**Community RES**	**Thermal energy technology**
Scenario 1: Minimum ICES investments	None	Low	Low	None
Scenario 2: Maximum ICES investments	Full	High	High	Full
Scenario 3: Medium ICES investments	Medium	Medium	Medium	Medium
Scenario 4: Maximum RES and full energy efficient buildings	Full	High	High	None
Scenario 5: Maximum RES and full heat pump investments	None	High	High	Full
Scenario 6: Maximum RES investments	None	High	High	None
Scenario 7: Full heat pumps and energy efficient buildings, low household and community RES	Full	Low	Low	Full
Scenario 8: Maximum ICES investments, but low community RES	Full	High	Low	Full
Scenario 9: Maximum ICES investments, but low household RES	Full	Low	High	Full
Scenario 10: Maximum ICES investments, but medium heat pump investments	Full	High	High	Medium

Table 5.1: The ten scenarios that are explored in the simulation.

The scenario results are then also evaluated by seeing how they score when different uncertain future developments with different directions of these developments are applied.

Uncertain future development	Direction of the development		
Electricity demand in 2034	30% Lower	Stable	30% Higher
ICES related capital costs in 2034	Stable	15% Lower	20% Lower
APX electricity price in 2034	Stable	30% Lower	
Natural gas price in 2034	Stable	50% Higher	

Table 5.2: The uncertain future developments that are analysed in the simulation.

By running simulations of the scenarios with different directions of future developments, model output tables are formed. To show how the model output tables for the scenarios are formed, which is through taking the mean values of duplication runs for each uncertain developments direction, appendix B can be consulted. In this appendix, the full output of running scenario 1 is given and the mean values of the key performance indicators of the duplication runs are taken. Every scenario in combination with an uncertain future development is run ten times because the values of the KPIs are different between the runs due to the stochastic inputs of the model. As explained in section 4.2.6, some parameters in the model contain random factors that will change the value of amongst others the APX electricity price for every run. Appendix B shows that the mean value of the CO_2 emission in scenario 1 is 8414 with a standard deviation of 21.69 when this scenario is run ten times. This shows that the output values of the different runs do not differ significantly. The results seem to be robust on the aggregated level regarding the stochasticity that has been added to the simulation model. This could be explained by the fact that not many factors in het model contain stochastic inputs, while the KPI values are calculated by using many different model factors. When these other factors would also contain stochastic inputs, it could be possible that more simulation runs are needed to give robust output values.

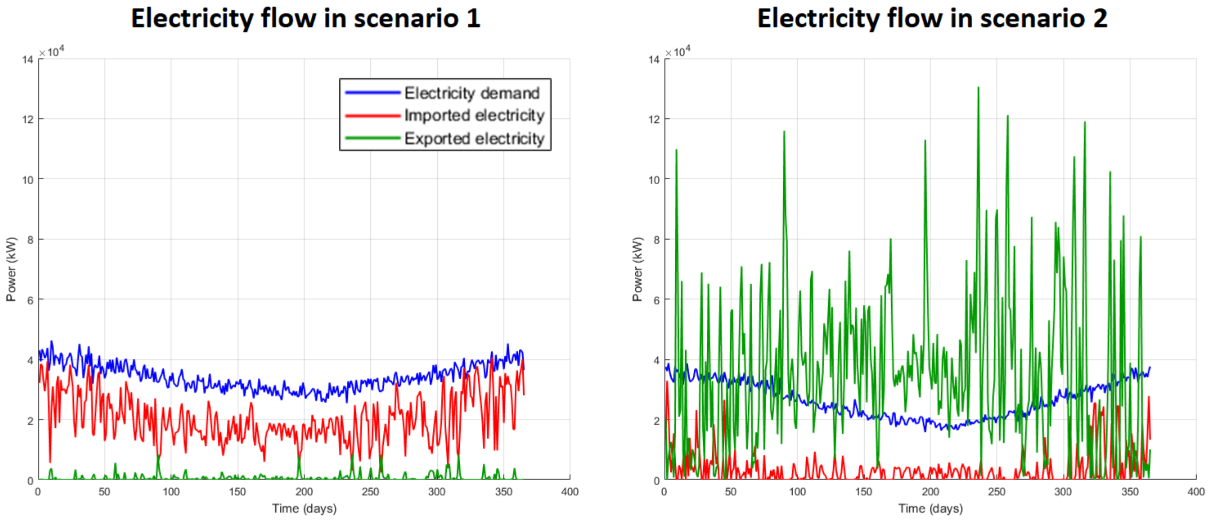
The model is run by simulating the scenarios one by one. Each scenario is first being simulated in the original ‘stable’ future development, where all uncertain future developments take the stable option from table 5.2. This run is duplicated ten times and the average value of the key performance indicators is then taken. The scenario is thus also simulated ten times for when the electricity demand would be 30% lower, when the electricity demand is 30% higher, when the ICES related capital costs are 15% lower, and for the other future development directions. Simulations of combinations of uncertain future development directions are not performed, to keep the results clear and easy to overview. Also, the influence of a single future development direction on the numerical outputs of the simulations already gives sufficient information on the influence of these developments on the results of the research. All of the scenarios are simulated in the same way. The full results of the simulation study, with the output values of all the scenarios, are presented in the tables of appendix C.

5.2 Electricity flow of Buiksloterham 2034

This section discusses graphical results for each scenario that is explored in the model study. Section 5.2.1 shows the graphs of the daily electricity demand, the imported electricity from the national energy grid and the exported locally generated electricity for every day of the year 2034 for the ten scenarios. Section 5.2.2 shows the seasonal differences between import- and export of electricity in two of the scenarios

5.2.1 Electricity flow over the year

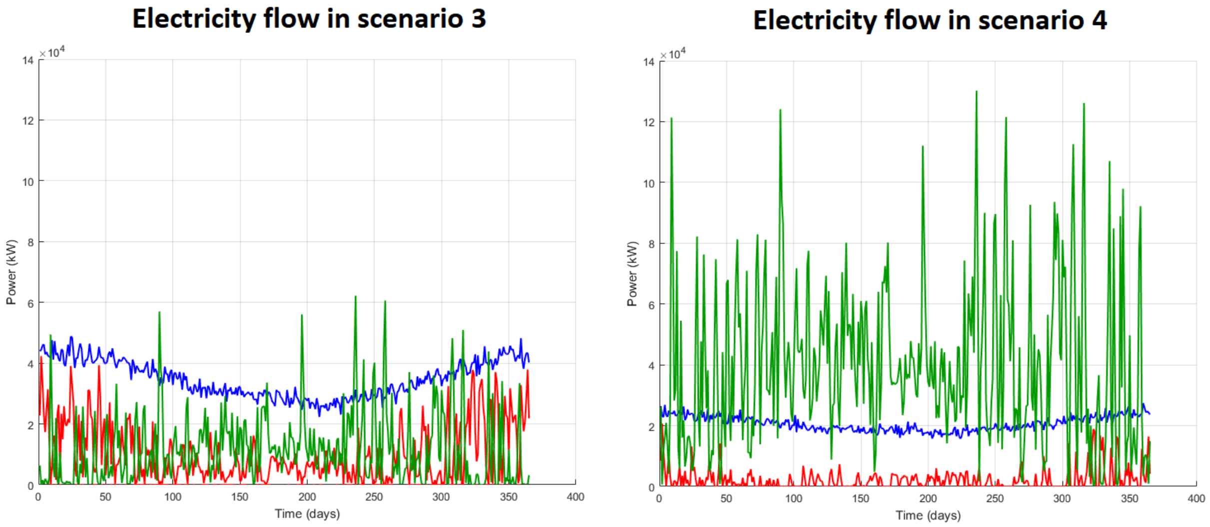
The electricity flow graphs indicate the dependence of Buiksloterham on the national energy grid over the course of the year, as well as the amount of electricity demand that can be fulfilled by renewable energy sources. The latter can be found because the graphs show how many electricity needs to be imported on every day of the year. The graphs also show the value of the community's renewable electricity production in terms of export (sales) to the national energy grid. The time in days is on the x-axis, while the power in KW is on the y-axis.



Electricity flow in scenario 1

Electricity flow in scenario 2

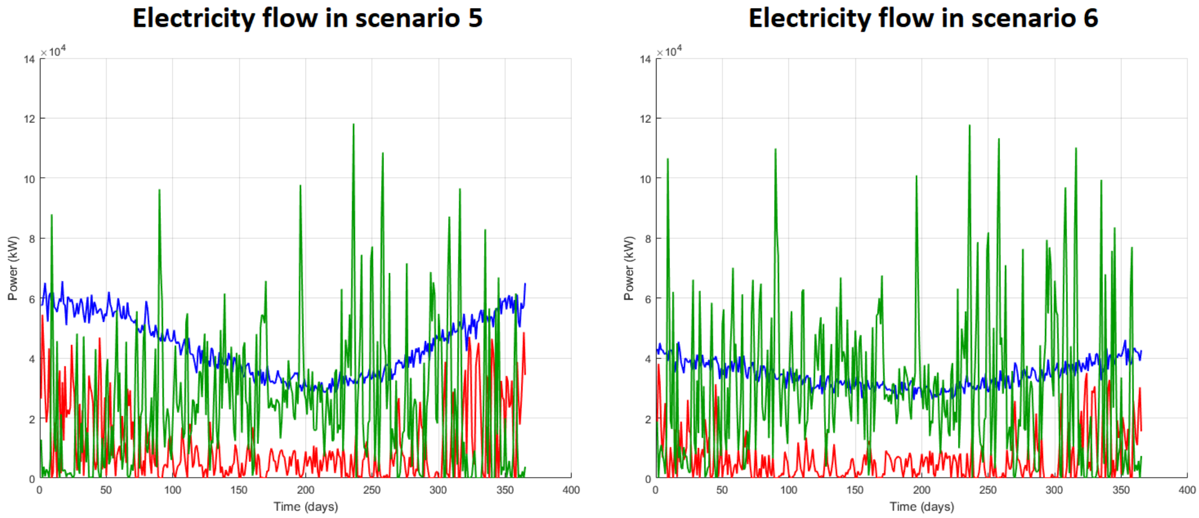
Figure 5.1: Electricity flow every day of the year 2034 in scenario 1 and scenario 2.



Electricity flow in scenario 3

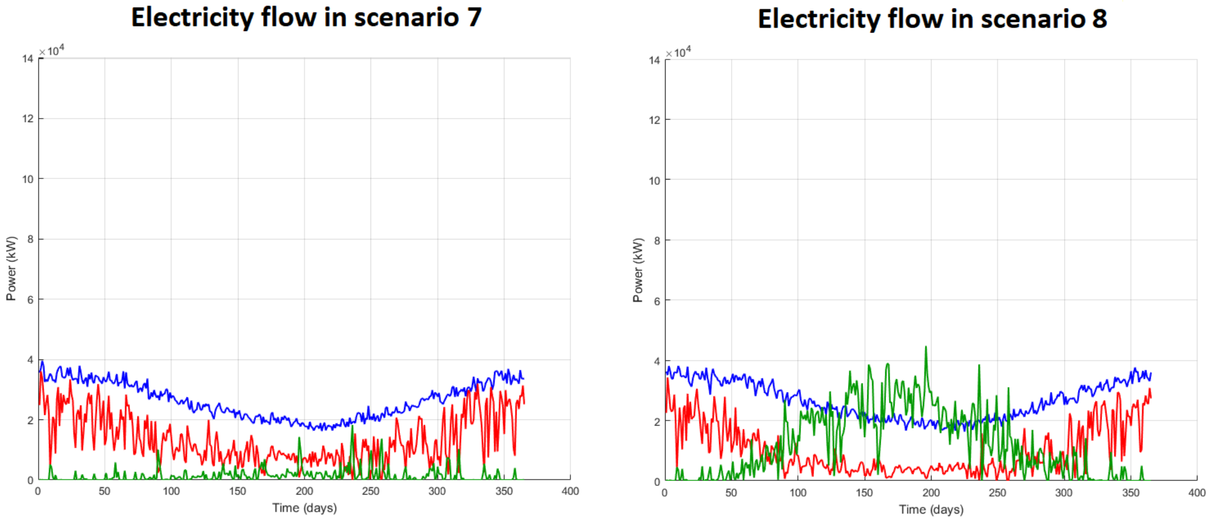
Electricity flow in scenario 4

Figure 5.2: Electricity flow every day of the year 2034 in scenario 3 and scenario 4.


Electricity flow in scenario 5

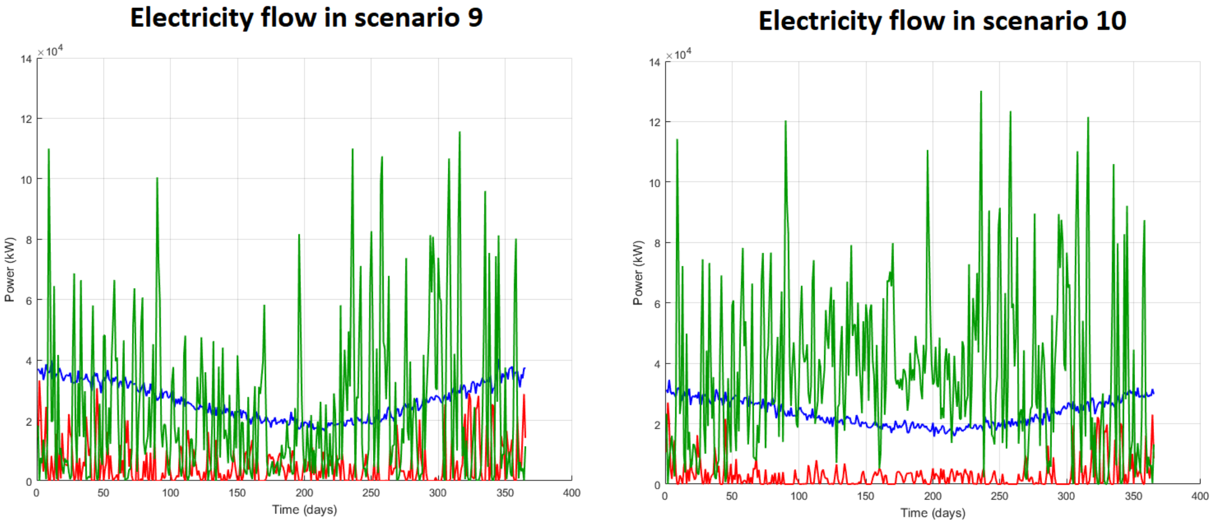
Electricity flow in scenario 6

Figure 5.3: *Electricity flow every day of the year 2034 in scenario 5 and scenario 6.*


Electricity flow in scenario 7

Electricity flow in scenario 8

Figure 5.4: *Electricity flow every day of the year 2034 in scenario 7 and scenario 8.*


Electricity flow in scenario 9

Electricity flow in scenario 10

Figure 5.5: *Electricity flow every day of the year 2034 in scenario 9 and scenario 10.*

It can be seen from the figures that in the scenarios where large investments in renewable energy sources are done, such as in scenario 2 and 4, a lot of electricity can be exported to the national grid. The green lines have very high peaks and this will, dependent on the APX electricity price that the community receives for this export, lead to a lower operational cost of the ICES. The difference between electricity exported in scenario 2 and 4 is very small. The biggest difference between these scenarios can be found in the import of electricity. In scenario 4, no electrical heat pumps are integrated in the ICES. In scenario 2, where there is full integration of electrical heat pumps, there is a need for electricity and consequently a larger import of electricity, especially at the first and last days of the year (the winter months). Investing in only household RES (solar energy installations) as is done scenario 8, results in an electricity flow that clearly shows a higher export of electricity in the summer months, and less sales in the winter.

5.2.2 Seasonal variations in the exchange with the national energy grid

In the figure below, the differences between the seasons in the export of electricity to the national grid and the import of electricity from the national grid are demonstrated. For the spring season the months March-May have been chosen, for summer June-August, for autumn September-November and for winter December-February have been chosen. Scenario 2 and 8 are analyzed because scenario 2 has both household and community renewable energy sources set up at the maximum, while scenario 8 has the highest degree of penetration of household renewables (solar energy) and the lowest degree of penetration of community renewables (wind energy). Electricity flow differences between seasons should be noticeable in these two scenarios. Figure 5.6 and 5.7 shows the seasonal export and import of electricity in 2034 in the community of Buiksloterham, for scenario 2 and scenario 8.

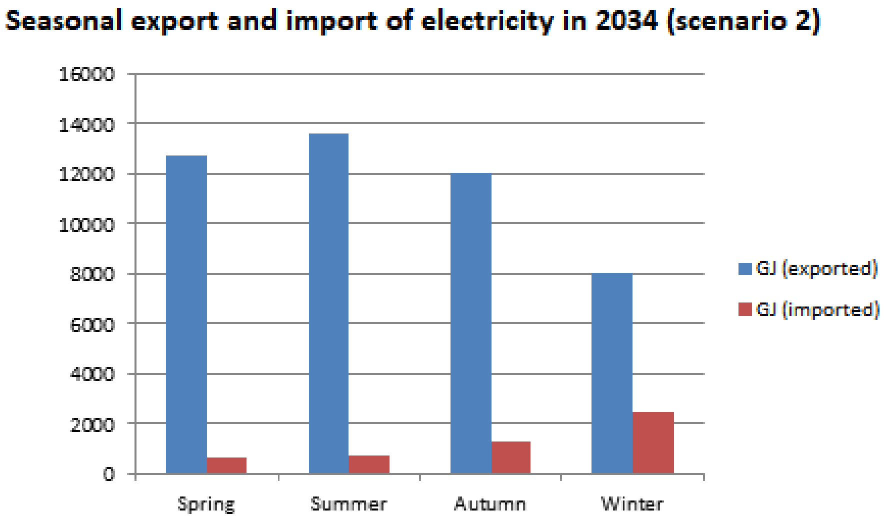


Figure 5.6: Seasonal differences in export and import of electricity in scenario 2.

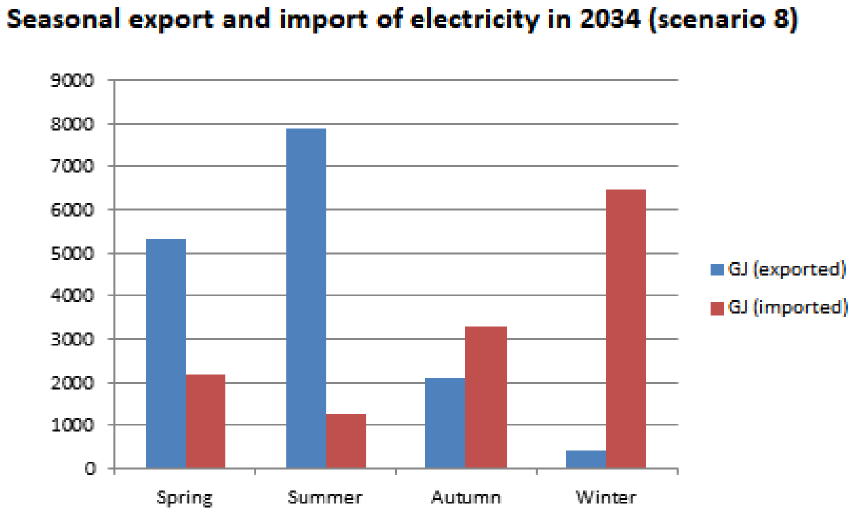


Figure 5.7: Seasonal differences in export and import of electricity in scenario 8.

In scenario 2, less electricity is exported in the winter months while more electricity is imported compared to in the other seasons. This can be explained by the fact that the demand in the winter is higher while the production of electricity by renewable energy sources is lower. This is the same in scenario 8, where it is also noticeable that the numbers of import and export of electricity vary a lot between the seasons. Because of the set-up of many solar panels most of the renewable energy is generated in the summer months, the export is the highest in these months, while the import is the lowest. The opposite happens in the winter months, where the import of electricity is more than five times higher than in the summer. This shows the influence of seasons on the production of renewables, especially with solar energy and the influence of this on the need for import and possibility of export of electricity by the energy community. In scenario 8, with only household RES there is a larger difference in export and import of electricity between the months of the year than in scenario 2 where both types of renewable energy sources are implemented.

5.3 Results on Key Performance Indicators

In this section, the results of the key performance indicator outputs of the model study are discussed. The KPI categories and scenarios are explained in section 5.3.1. As discussed before, the KPIs are divided in categories, this helps when evaluating the results of the simulation model.

5.3.1 KPI categories

The Key Performance Indicators that have been introduced before are divided into two sub categories; goal-related and conditional KPIs. The goal-related KPIs are related to the goals that both the community of Buiksloterham and energy communities in general aim to achieve. These are the following four:

- CO_2 emission [ton/year]
- Self-sufficiency [%]
- Total energy demand per household [GJ/household/year]
- Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]
- Self-consumption [%]

The other KPIs can be considered as conditions that need to be kept as less disadvantageous as possible. They are not related to goals of energy community development. The output of the following two conditional KPIs are investigated in this section:

- Capital costs of the ICES components [€]
- Payback time of ICES related capital costs [years]

The maximum line capacity is not discussed in this chapter, as its value is never too high in any of the simulation, however it can differ largely between the scenarios and uncertain future developments.

The next section 5.3.2 presents the results of the scenario exploration under a 'stable future development'. For the readability of this part, table 5.3 again shows the scenarios that are used in this simulation study with a description of their choice of ICES components penetration level. The influence of the uncertain future developments on the key performance indicator outputs of the model study are taken into account in section 5.4. The full results of the simulation study can be found in Appendix C, where the numerical output of each of the scenarios, under each of the uncertain future development directions is displayed.

Scenario	Description
1	Minimum ICES investments
2	Maximum ICES investments
3	Medium ICES investments
4	Maximum RES and full energy efficient buildings
5	Maximum RES and full heat pump investments
6	Maximum RES investments
7	Full heat pumps and energy efficient buildings, low household and community RES
8	Maximum ICES investments, but low community RES
9	Maximum ICES investments, but low household RES
10	Maximum ICES investments, but medium heat pump investments

Table 5.3: The scenarios of the simulation study with their description.

5.3.2 Full KPI outputs for each of the scenarios

In the following figures, the goal-related key performance indicators and the conditional key performance indicators are displayed with blue and red colored bar charts. As explained before, the presented results are based on the simulation results that are not influenced by uncertain future developments.

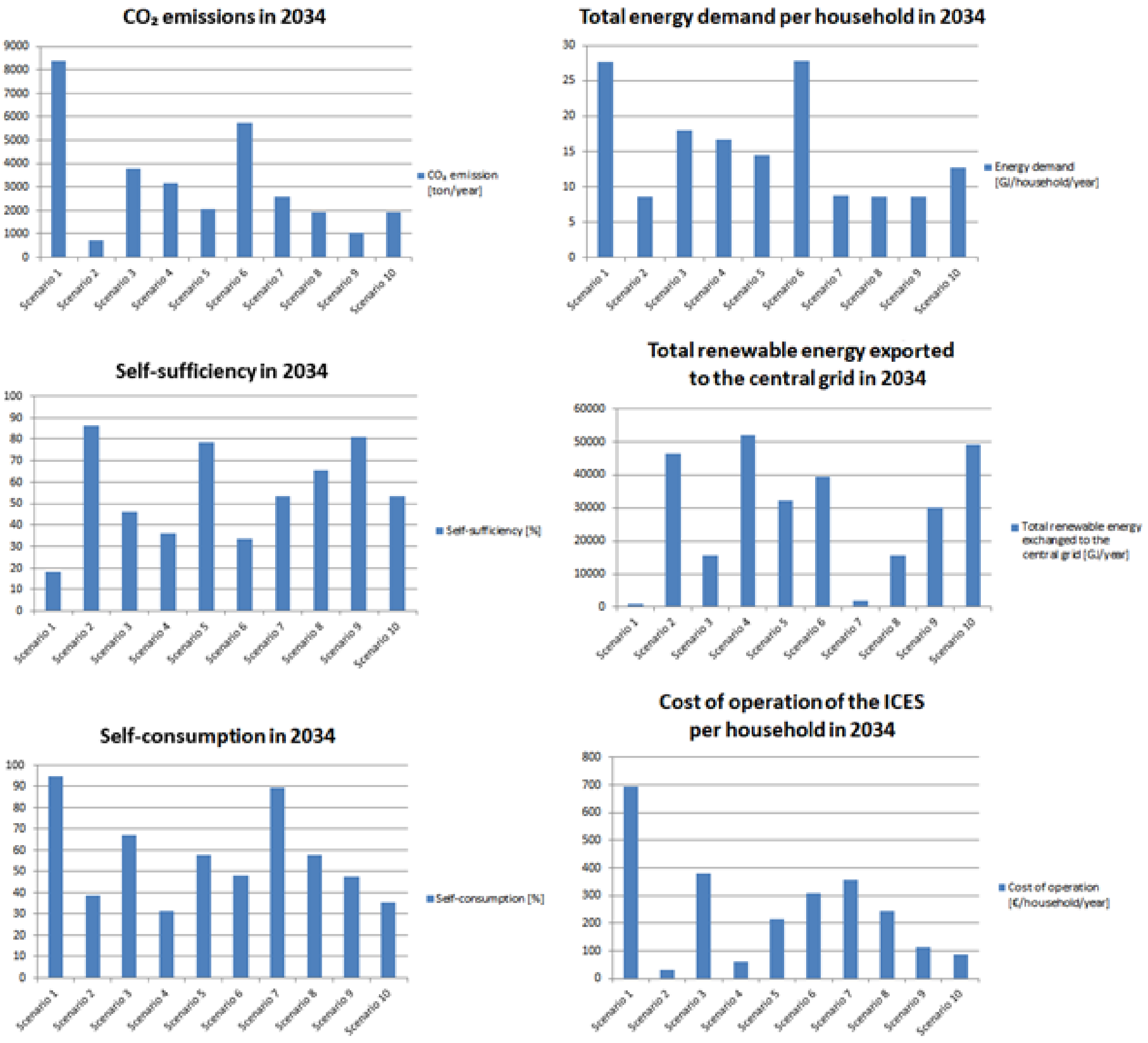


Figure 5.8: Model outputs on the goal-related KPIs for every scenario (with stable uncertain future developments).

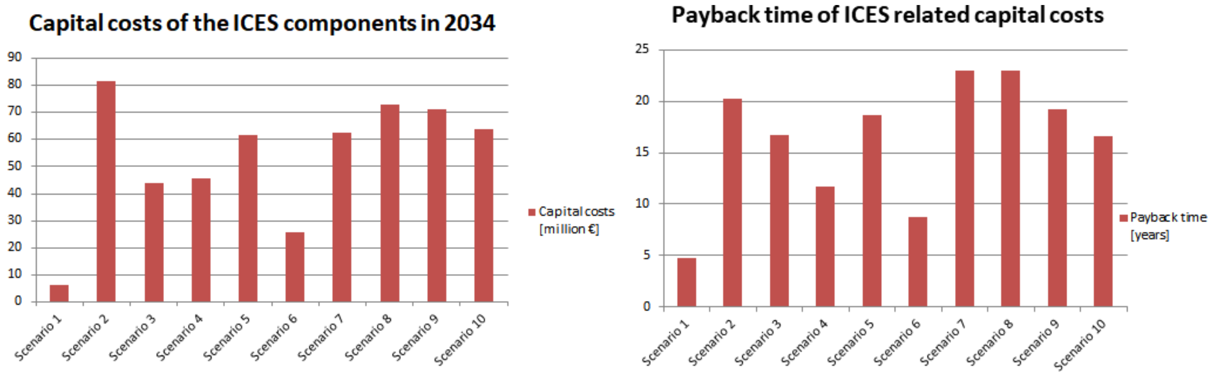


Figure 5.9: Model outputs on the conditional KPIs for every scenario with (stable uncertain future developments).

Self-consumption, which is the percentage of self-produced renewable electricity that is actually used by the community itself is not a goal of Buiksloterham on itself. The output values of this KPI show that the self-consumption reaches the lowest value in scenario 2, 4 and 10. In these scenarios the installed renewable generation capacity and the energy efficiency of buildings is the highest. This means that in many hours more electricity produced than that is needed for the community, so a low self-consumption. The highest self-consumption is found in scenarios 1 and 7, where the production of renewable energy is low. The self-consumption values show that it is not yet possible, with the ICES technologies that are taken into account in this study, to efficiently match own supply with energy demand. Demand response technologies and energy storage technologies could enlarge the self-consumption by matching these and in this way making more efficient use of self-produced renewable energy.

Concerning the other key performance indicators, the figures show that scenario 1 has a short payback time but that the results on the goal-related KPIs are not ideal, especially in comparison with scenario 2 where there is a maximum ICES investment. In scenario 2, a self-sufficiency of over 86% can be reached and the energy demand and CO_2 emissions are reduced largely. The payback time for scenario 2 is over 20 years and with an amount of 80 million euro of capital investments for the energy community consisting of 4000 buildings. What is kept in mind regarding the payback time of ICES related capital costs is that in survey a large majority of questioned participants is not satisfied with a payback period longer than 10 years (Koirala, 2017). This means that a payback time of 20 years can be considered as (too) high.

Comparing scenario 2 with scenario 4 where no heat pumps are used, it can be observed that the use of heat pumps together with the other ICES technologies does have large benefits for especially the CO_2 emissions and the self-sufficiency of the community. These benefits are missing in the scenario 4 without heat pumps. However, the capital costs are almost doubled in comparison. The payback time is relatively a little more favorable in scenario 2, but at a very high level of over 20 years, while the fourth scenario only has a payback time of 12 years. The payback time of scenario 4 is also low because it has highest renewable energy exported to the central grid of all scenarios, which leads to low cost of operation of the ICES. Because of the fact that there are no heat pumps, less generated electricity is needed and can be sold to the national energy grid.

Scenario 3 has medium ICES investments of which the capital costs are comparable with scenario 4.

The results on the KPIs are however less beneficial and the payback time is much higher in scenario 3. This suggests that, comparing the capital investments of both scenarios, investing this first in energy efficient buildings and renewable energy sources, instead of investing in heat pumps, is more beneficial. What can be seen here is that heat pumps can have a large value for the energy system, but only when combined with other large investments in renewable energy sources and energy efficient buildings. The capital investment of this technology is high compared to the other technologies.

Not investing in energy efficient buildings, but maximum investments in the other ICES technologies, as done in scenario 5, does not give better results than doing maximum ICES investments. The investment costs are a little lower than in scenario 2 with maximum ICES investments. The scores on the KPIs are, except for the self-sufficiency level of the community, a lot less positive. The CO_2 emissions and the energy demand per household are still rather high. It is therefore interesting to see the results when heat pumps or any of the installed renewable energy sources are abolished from the scenario of maximum ICES related technology investments.

Only investing in household and community renewable energy sources, as done in scenario 6, does bring CO_2 emissions down a little, but the energy demand per household is still very high. The self-sufficiency is only at little over 30%, which is the second lowest of the scenario results, after minimum ICES investment. The investments costs are rather low and take less than 9 years to pay back, but it seems that both energy efficient buildings and electrical heat pumps are needed to give good results on the goals of Buiksloterham, which are lower CO_2 emissions, lower energy demand and higher self-sufficiency.

In scenarios 7, 8 and 9, the capital costs as well as the payback time of these scenarios are very high. This is because the cost of operation of the ICES is still relatively high here. In scenario 7 there are low investments in renewable energy sources and high investments and heat pumps and energy efficient buildings. It can be seen that to earn back the investment, a very important factor is the generation of renewable energy, as this makes the community be able to not have to pay for imported electricity and instead sell their own electricity. The results on the goal related KPIs are good in scenarios 7 to 9. Without much renewable generation capacity, relatively low CO_2 emissions are still reached, as well as a low energy demand per household. However, the investment costs are relatively high. Scenario 8 and 9 show that out of the two types of renewable energy source generation, community energy (wind) is the most beneficial. This is because the relatively lower investment costs of wind energy and the better generation possibility of this energy source. Scenario 9 scores better on the goal-related KPIs. Because of the lower cost of operation of scenario 9; the payback time of scenario 9 is also lower than scenario 8. However the payback time and the capital cost investments are still relatively high compared to the other scenarios. The scenarios with a lower RES capacity have a relatively high cost of energy grid operation because more electricity has to be bought from the national grid and less electricity is sold. This results in higher payback times of the ICES.

To see the effect of heat pumps better, and have an alternative for the high investments costs of scenario 2, scenario 10 shows the results of an ICES with half of the households owning electrical heat pumps. The payback time of this scenario is 16.6 years and the capital costs are 63 million euros instead of 80 million euros. However, the CO_2 emissions are over two times higher and the self-sufficiency is only 53 percent compared to the more than 86% self-sufficiency in scenario 2. Comparing costs and benefits of these two scenarios with each other, it seems that the full integration of electrical heat pumps, in combination with full integration of the other ICES technologies, is relatively more beneficial than the medium integration of heat pumps in scenario 10.

Comparing scenarios 7 to 9 to scenario 4 and scenario 6, where no heat pumps are installed, shows that heat pumps are of importance to bring up the self-sufficiency of the ICES, but cause large investments cost and payback times. Scenario 4 and 6 have a more appealing payback time of around 10 years. Scenario 6, with only household and community RES at the maximum, has a rather low investment costs but due to the relatively high variable costs of the energy supply, the payback time is around 8 years, compared to 12 years of scenario 4. The almost two times larger investments of scenario 4 bring better scores on lowering the energy demand and CO_2 emissions and on the self-sufficiency, but has a higher payback time than scenario 6. The integration of energy efficient buildings on top of maximum RES investments has most effect on CO_2 emissions, which are almost two times lower compared to scenario 6. Moreover, the self-sufficiency is some percent higher in scenario 4. Investing in RES will make the self-sufficiency increase more than with energy efficient buildings integration, but the real profits here are made with investments in electrical heat pumps in combination with installed renewable energy sources.

5.4 Uncertain future developments

The most significant influences of uncertain future developments on the key performance indicators are discussed in this section. To read the full results of all the scenarios and under the influence of the uncertain future developments, see appendix C.

5.4.1 Electricity demand change

This uncertain future development can make the electricity demand 30% lower or 30% higher. A lower electricity demand results in lower **CO_2 emissions**, especially in scenarios where much is invested in ICES technologies. In scenario 2, where maximal ICES investments are done, the emissions are almost two times lower with an electricity demand that is 30% lower than the standard electricity demand. In scenario 6, where minimal investments are in place, the emissions are only 20% lower when having a 30% lower electricity demand. On the other side, when the electricity demand is higher, the CO_2 emissions are also higher and even higher in scenarios with large ICES investments. The scenarios that include investments in heat pumps are also more influenced by a change in the electricity demand. This can be explained because in these scenarios the demand for electricity is very high and even the highest investments in renewable generation are not always enough to cover the electricity demand in the community. Here, a lower demand for electricity always has a direct effect on the needed import of electricity from the national grid.

The **self-sufficiency** changes in the same way, but not in large percentages. However, it is notable that in scenarios 4 and 6, where no heat pumps are present, the self-sufficiency decreases when the electricity demand is lower and increases when the demand is higher. This can be explained by the fact that in these scenarios the extra demand, which comes from electrical heat pumps, is not present. There is however a large capacity of renewable generation capacity installed. For this reason, when the electricity demand is a little higher, the renewables can still fulfil the total electricity demand of the community. In the hours that a lot renewable energy generation is possible, a smaller part of this energy is exported to the national grid and used in own energy community.

The **self-consumption** of the community is lower when the electricity demand of the community is lower, because more electricity will be exported instead of consumed by the own community when this happens. For instance: the self-consumption decreases from 35 to 26 per cent in scenario 10. The opposite is then obviously true for when the electricity demand is higher in the future; the self-consumption then increases from 35 to 44 per cent in scenario 10.

The **total energy demand per household** increases or decreases with the increase and decrease of the electricity demand. The **total renewable energy exported** to the central grid increases largely with a decreasing electricity demand. In many scenarios the exported energy increases with over 30 per cent, when the electricity demand is decreased in the future developments. These increases or decreases of sold energy to the national grid then have their influence on **yearly cost of operation of the ICES** and thus on the **payback time** of the ICES related capital costs. In the scenarios where the yearly cost of operation are relatively high, which is the case when less is invested on ICES technologies, a lower or higher electricity demand can change these yearly costs per household from 695 euros down to 514 or up to 890 euros. These changes in costs can make the payback time go up or down from one year to a couple of years in some scenarios. The **maximum line capacity** increases with an increase in electricity demand in the scenarios where fewer investments are done in ICES. In scenarios with high ICES investments, the line capacity increases with a decrease in electricity demand, because more renewable generated electricity will then flow from the community to the national energy grid. The **capital costs** of the ICES components are logically not influenced by a change in electricity demand.

5.4.2 ICES capital costs change

The uncertain future development of the costs for ICES technologies does not influence many key performance indicators. Logically, the **capital costs of the ICES components** are decreasing by 15 or 30 per cent. For the same reason, the **payback time** of the ICES related capital costs are also decreasing by these percentages. Especially for long term investments as is the case in scenario 1, where the maximum ICES investments are done, the influence of this is considerable. Here the payback time of over 20 years could be brought down to almost 14 years.

5.4.3 APX electricity price change

A decrease of 20% in the APX electricity price has its effect on the **yearly cost of operation of the ICES** per household and on the **payback time** of the ICES related capital costs. The scenarios in which the generation of renewable energy sources by the community is high, which is the case when the capacity of renewable energy sources installed is high, are influenced the most. When the yearly generation of renewables is high, this means that with a lower APX electricity price, less money is earned by selling this electricity to the national grid. The import costs are also lower, but this effect is much lower because the electricity price that is paid for import is only build up for a small portion by the APX price and much more by fees and taxes, as is explained in the previous chapter. In scenario 2, with maximum ICES investments, the yearly cost of operation of the ICES are over three times higher when the APX electricity price is 20% lower than the standard (current) price. This will make the payback time of the capital costs increase with over one and a half year.

5.4.4 Natural gas price change

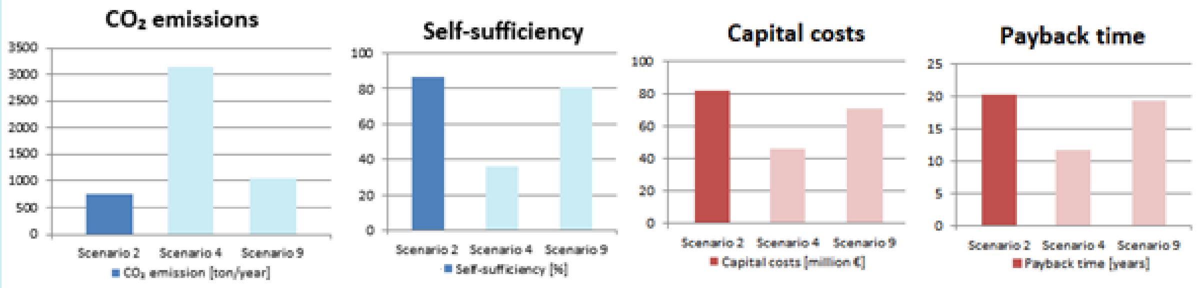
An increase of the natural gas price with 50% will obviously firstly only have an influence on the **yearly cost of operation of the ICES** per household in the scenarios where heat pumps are not fully used. In these scenarios there is namely no demand for gas for heating purposes. In scenario 4, where there are maximum investments in ICES technologies, except for heat pumps, the yearly costs of operation are almost three times higher when the natural gas price is 50% higher. This then causes the **payback time** of the ICES related capital costs to go up from 11.67 to 12.64 years.

What can be seen from the uncertain future developments is that only some of the key performance indicators are influenced by these developments and that these influences vary largely per scenario. Some future developments have larger influences than others. For example the electricity demand can have a large impact on the CO_2 emissions when the number triggers the possibility of fulfilling or not fulfilling the own demand with renewables. Changes that influence the KPIs, such as developments in ICES capital costs, can have large impacts when the number that they influence is already high. An example of this is a high payback time in some of the scenarios, which will relatively be more affected by lower capital costs than scenarios with a lower payback time. The developments are not having game changing influences on the simulation results in the way that they change the ranking of scenarios in terms of favorableness. They do however change the results of a scenario in positive and negative ways.

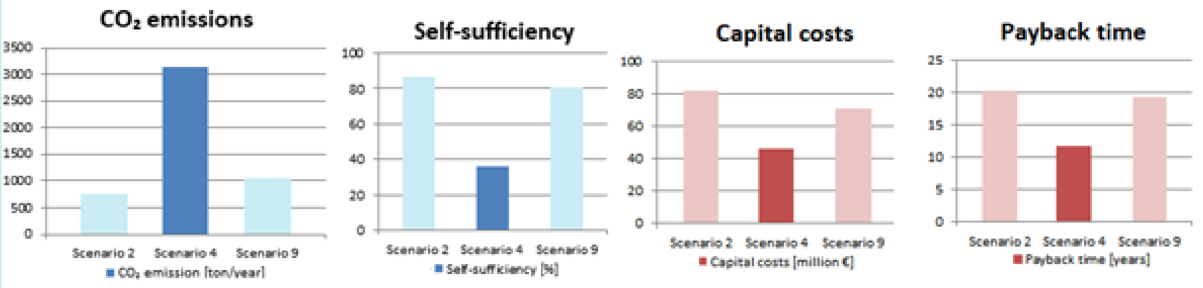
5.5 Implications of the simulation output

Different ICES compositions, coming forth from the technologies related to Integrated Energy Communities that could be fitting for the energy community of Buiksloterham, have been tested in the model study. The goals of the municipality with the sustainable transition of the energy community of Buiksloterham to a smart community are most importantly to reach at least 50% of the energy demand to be locally fulfilled. Also, the energy demand should be lowered as well as the CO_2 emissions caused by the operation of the energy system. No specific targets were set for this by the municipality. The most important scenario simulation results that have been found are shown in figure 5.9 on the next page. For the most important ICES compositions that are formed in scenario 2, 4 and 9, the output values of the most important KPIs are shown.

Scenario 2: Maximum ICES investments



Scenario 4: Maximum ICES investments, but without heat pumps



Scenario 9: Maximum ICES investments, but without household RES

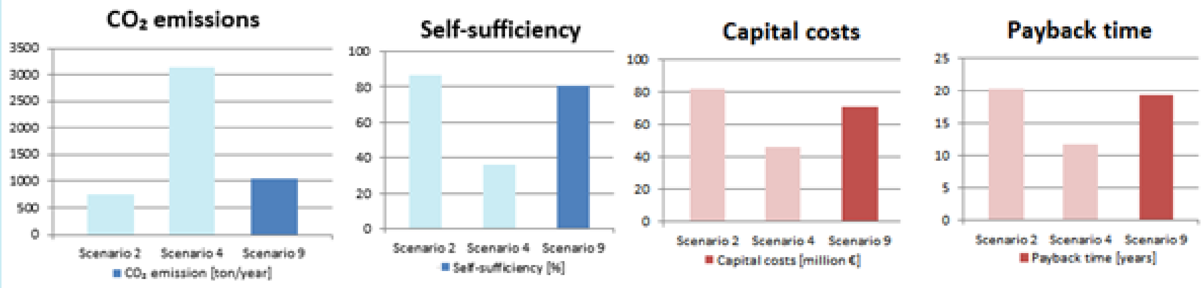


Figure 5.10: Overview of the most important scenario simulation results.

Scenario 2 with maximum ICES investments, which means introduction of heat pumps to the households that are all built at the highest level of energy efficiency and with full integration of household renewable energy sources and community renewable energy sources, can reach a self-sufficiency of over 86% and very large CO_2 reductions as well as a low energy demand. These investments require high investment costs. The investments will eventually pay back after 2034 because the costs of operation of the ICES are lower than what the cost of operation would be in an energy system without ICES investments. The payback time for this ICES composition is 20 years. This payback time 20 years can be influenced by the development of ICES capital costs, and could therefore become 17 or 14 years in the most beneficial case. It could also be influenced by other developments, namely a higher electricity demand or a lower APX price, to become 22 years; this is less impactful. With the development of a lower electricity demand in the future this could be even lower. This is however a high payback time, especially when comparing this to the 14% of the respondents of a survey that is willing to have a payback time for ICES investments, longer than 10 years (Koirala, 2017). Investing at the maximum on all ICES technologies except for heat pumps, as is the case in scenario 4 is at the same investment level as the scenario with medium ICES investments, and has better results. Medium investments in all ICES technologies are less favorable; electrical heat pumps are expensive and bring the best results when combined with a large capacity of renewable energy sources so that renewable electricity can be used by the heat pumps.

When not investing in electrical heat pumps, but for the rest integrating ICES technology at the same level as in the maximum investment scenario, scenario 4 is formed. The payback time and capital investment costs here are significantly lower and could become closer to acceptable, especially with some future developments of decreasing electricity demand and capital costs. The scenario scores less beneficial on KPIs than the maximum ICES investments with or without household RES, the self sufficiency of this scenario is at almost 36%. The payback time with stable future developments is at less than 12 years. The ICES compositions without heat pumps show that the payback time of this scenario is more appealing; around 10 years with stable future developments. It also shows that heat pumps are important for especially the self-sufficiency of the ICES. As explained in section 5.3, community RES investments are more effective on the KPI results than household RES investments. For this reason, to find another less expensive alternative scenario for scenario 2, scenario 9 has a low integration of household renewable energy sources. This scenario has a slightly lower payback time and its capital costs are 15% lower than in scenario 2. The self-sufficiency and CO_2 emissions are however slightly less beneficial. These two scenarios seem to, relatively to the costs, achieve the same level of favorableness. The results on CO_2 emission can be influenced largely, especially by the development of the electricity demand in the future. A 30% lower electricity demand would in the scenarios with large ICES investments lead to an almost two times lower CO_2 emission. A lower electricity price in the future can influence the payback time of large ICES investment scenarios. This is because electricity sold by the community will receive a lower compensation. In none of the scenarios, combined with uncertain future developments, the maximum line capacity is reached.

It is clear that to meet the goals of the municipality of Amsterdam regarding the smart transition of Buiksloterham, the maximum ICES investments composition would give good results on the KPIs. The integration of heat pumps lead to a high self-sufficiency and also lower CO_2 emissions, but the capital costs of this option are very high. Some uncertain future developments could help this option to be more applicable, but the option without heat pumps remains more affordable. The problem of this latter option is that the latter option does not seem to reach the sustainable energy goals of the community of Buiksloterham. What is clear is that a higher penetration of RES is always beneficial and that when given the choice, community RES is more suited than household RES. As explained in section 5.3.2, investing in energy efficiency buildings lowers the CO_2 emissions more than with RES investments, relative to the investment costs of these technologies. Investments in RES decrease the CO_2 emissions and also increase the self-sufficiency of the community. The choice to invest in heat pumps could be made, but the risks of an acceptably high payback time are there. This is not certain because of some future developments that can affect this, mainly only in a positive way. The option without heat pumps gives less risk on acceptability, because the investment is almost two times lower. The CO_2 emissions in this scenario 4 are however four times higher than in scenario 2. Compared to scenario 2 the self-sufficiency drops from 86 per cent to 36 percent.

Chapter 6: Discussion

In the previous chapter, the results of the simulation study have been discussed. The purpose of this part of the study was to find an answer to the second research question: What value can different ICES compositions in different scenarios have for the community energy system in Buiksloterham in 2034? In order to answer this question best, it is necessary to look at how this research has been performed. Before the simulation study was performed, data had to be found and assumptions had to be made. Assumptions have been made throughout the entire research when choosing what to simulate, how to simulate this to eventually give a valuable answer to the main research question. In order to give a judgment about the value of the results that have been presented and discussed in the previous chapter, it is important to reflect on the assumptions that have been made in performing this research. This is also important to be able to see how the ICES approach, which is investigated and applied to the case study of Buiksloterham in this research, can be used on other energy communities.

The most important assumptions that have been made will be reflected upon in section 6.1. After this, the value of the ICES approach for other energy communities is discussed in section 6.2. Finally, section 6.3 discusses future research that could be done.

6.1 Assumptions

First of all, the simulation study is chosen to be performed at the community level. This is done because of the fact that previous studies on ICES application focused on optimization of household level ICES applications. The scenarios that have been investigated in the previous chapter are also evaluated on the community level. For a community as a whole it is clearer which composition of ICES technologies or which technology is more beneficial to a certain community goal than others. The advantage with this is that recommendations can be given regarding the direction that a municipality wants to follow, such as the municipality of Amsterdam in the case study of Buiksloterham. This is less possible in studies that use the household level point of view, where recommendations would mainly be given in order to help single households achieve their individual goals in the energy community. The disadvantage of this point of view is that the feasibility of the scenarios that have been simulated is more difficult to evaluate. In the end, the energy community is formed by the end users of the energy grid. This means that they are the ones who actually need to use the technologies and install them. The willingness of end users to invest in, and use the ICES types is not in the scope of this research, as this research explores the energy community value of the ICES approach on the higher level.

Assumptions have been made regarding the ICES technologies that were included in the simulation model. Results are now shown for integration of four ICES technologies, namely energy efficient building, community RES, household RES and electrical heat pumps. This means that in the value that is assigned to the approach of ICES in this study, it must be noted that these technologies were tested in the model, and no others. ICES is a broad approach that can include many technologies as has been discussed in chapter 2. Because of pragmatic reasons such as time scope of the project, not all technologies could be included. The conclusions on the value of ICES for energy communities is thus limited to ICES compositions build upon the technologies that were included in this research. In the ICES technologies that were included in this research some choices were also made. Electrical heat pumps were chosen as a thermal energy technology option and wind turbines and solar panels were chosen as renewable energy generation options. Especially other types of thermal energy technologies, such as solar boilers could give other simulation results. The type of heat pump that is used, which is explained in chapter 4, is also of importance in the final simulation results. The choice that was made on these technologies was based on the fact that these technologies seemed best fitting in the simulation model and are well-known and documented ICES related technologies. The levels of integration of the technologies were chosen so that an exploration of what the effect is on the performance of the energy system, when having a higher level of integration of one technology or the other. Looking at the simulation results, the right amount of integration levels have been chosen, as more scenarios would lead to a large number of scenarios that could make the results section of the simulation less clear and there are still enough scenarios to get results from.

Concerning the uncertain future developments it can be seen that some of the developments that were chosen indeed work through on many key performance indicators of the simulation study. Especially electricity demand is important in this and can influence many of the KPIs. Both the scenario where this demand goes higher and where this demand goes lower in the future are taken into account. It was more difficult to find values for the future electricity demand, but sources were found in chapter 4 to back the reasoning about the possible directions of this development. This uncertain future development shows what direction the KPIs would go when this demand would be lower or higher in the future, the exact numbers of less importance. For the APX price, finding values for 2034 situations was relatively challenging. The assumption here was to look at different reports that analyze the possible increase of RES in the Netherlands in the future and the influence of wind power generation on the APX price in the Netherlands. It was also assumed that the same APX price decrease would be true for the increase of solar energy. In this way the direction of a 20% decrease of the APX price in 2034 was found. Another notable future development is the capital costs development. This only has effect on the payback time and the capital investments of the energy community; not many KPIs are influenced by this future development. This shows that some of the uncertain future developments are more complex in the way in which they influence the system than others.

As discussed before, to find data and process this data in order to create the right model input, many assumptions had to be made. For the costs of electricity imports and the revenue of electricity exports, the hourly APX price of 2013 is used. The assumption here is that the price could be the same in 2034, however this price level is again influenced by the uncertain future development that the APX electricity price could become lower in the future. In the simulation results, the effect of this APX drop can be clearly seen, as is discussed in chapter 5. This means that the way of modeling this part of the energy system can be seen as satisfactory. The imported electricity price is modeled by adding taxes and surpluses to the APX electricity price. The values of these price elements were based on data of the year 2017. The volatility of government policies this could potentially have effect on the modeling results in terms of the received income for generated electricity that is sold to the national grid. It is therefore important to note that the different energy policies that could be used in the future are outside the scope of this research but could influence the financial parts of the modeling results.

Literature sources were used to find out what the projected number of buildings for Buiksloterham was in 2034 and how much space these buildings would offer for renewable energy generation. This has influence on the renewable generation of the community and so on many KPIs of energy communities. Another assumption is that the demand for electricity is found with Liander data from the year 2009. The assumption is that this demand would stay the same in 2034. However, the uncertain future development of energy demand does take into account this uncertainty. To model the heating demand, the gas demand hourly trend is taken, as well as the projected heat demand for Buiksloterham in 2034. When other communities would use the simulation model, the energy demand is an important part that needs attention. In this study, the demand was included by also simulating uncertain future developments for data that was from the current year of writing this research, or earlier. In this same way, for including capital costs in the simulation model for instance, prices from the year 2017 were used in the standard model but the development of the capital costs were taken into account with simulating this development as well. Other assumptions that have been made for the capital cost calculation are that one type of heat pump is investigated in the model, with a specific cost level. With the heat pumps that have turned out to be quite expensive for communities to implements, which could be seen in chapter 5, it could be valuable to investigate more types and cost levels of the different heat pumps. This could give more insights to the applicability and value of this specific ICES technology.

The way in which the model works is also based on some assumptions. Most importantly the model is works in the way that the full overproduction of renewable electricity by the energy community is bought (at a certain APX price) and delivered to the central energy grid. In measuring the line capacity there seem to be no point in time where the line capacity is exceeded. This is done with a calculation using data from a distribution transformer operating in a neighborhood in the Netherlands. The key performance indicator concerning the potential congestion on electricity lines is therefore included as a value of the highest reached electricity flow over the lines in the full simulation. A different option would be to put a maximum capacity over the lines in the simulation and then show how often congestion would take place at the electricity grid. Seeing the results of the simulations and comparing this to the calculated theoretical maximum capacity over electricity lines, assumed that this value is calculated correctly, this would however never happen.

A final assumption is the amount of stochastic inputs that have been included in the model. As discussed before in this research, the stochasticity can make let the simulation model behave more realistically when it shows the unpredictability of many factors in an energy system. Depending on the stochasticity of the model, a number of model runs should be done in order to find robust results for every simulated scenario. In the simulation model that is built in this research, a replication number of 10 runs gave robust results. However, when more stochastic inputs would have been added to the model, more replication could have been needed. What could be interesting is to see is the consideration between having to change the simulation approach and the value that is added to the quality of simulation model when adding more stochastic inputs. In this research the stochastic inputs were only chosen for the most obvious model factors that could be modeled most logically with stochastic inputs, such as the APX electricity price.

6.2 ICES approach for other energy communities

This research has been performed to see the value that the ICES approach can have for energy communities. The community of Buiksloterham is used as a case study, the results of the ICES approach on Buiksloterham have been discussed in the previous chapters. With this exploratory modelling that been done for the case study, insights have been gained that could be used by other energy communities. The literature study that has been performed and the case specific simulation model that is created in this research provide these insights. The ICES approach is an approach that could be used on other energy communities as well. It is dependent on the exact characteristics of the community which ICES technologies are available to implement in the energy system. In this section the way in which the research results could be used by other energy communities regarding ICES integration is discussed. The key performance indicators that were used in the simulation study are not only focused on the goals of Buiksloterham, but also on goals that energy communities in general could have. This makes the case study research results more suitable for also looking at other energy communities. As mentioned earlier in this chapter, not all possible ICES related technologies have been used in the simulation model. There are more types of ICES technologies that could be included for energy systems in communities than the four that were investigated in this research.

Two ICES technologies that were included in the simulation model for the generation of electricity by the community are community RES and household RES. To meet the electricity demand of an energy community the integration of renewable energy sources is important. The results of the simulation study show that the integration of community RES give better results on the KPI values than the integration household RES. The biggest value of household or community RES can mainly be found in enlarging the self-sufficiency of the community. For communities that are still directly connected to the central energy grid anymore, which is a grid integrated ICES, there is the possibility of selling an excess of energy to the national energy grid and in this way lowering the cost of operation of the ICES. For a grid-defected ICES this is not the case. Without other investments in for example energy storage installations, the same results as in the simulation study of Buiksloterham are not possible for an energy system of an energy grid-defected community. A grid-defected ICES requires more technologies to optimally make use of the generated energy by renewable energy sources. This could lead to higher investments in renewable energy sources than in the grid-integrated ICES in Buiksloterham, as the produced hourly overcapacity is not sold to the national energy grid but should be stored or converted so that it can be used at a point in time where no or lower renewable generation is possible.

The role of thermal energy technologies, such as heat pumps, will also be more important in a grid-defected ICES, as there is no import of gas for the heating demand. Instead of bringing up the self-sufficiency, as was the case in the study of the energy community of Buiksloterham, they now are viral in order to meet the heating demand of the energy system. This means that a further exploration of other ICES technologies than the ones that are used in the simulation model of this research, is especially important for energy communities that, for example because self-sufficiency purposes, would commit to a grid-defected energy system. An example of this are the other options to integrate thermal energy technologies to meet heat demand in another way.

In the simulation model of this research, electrical heat pumps are used as the thermal energy technology that could be integrated in the energy grid of the community of Buiksloterham. When integrating electrical heat pumps in the energy system, the integration of renewable energy sources at community or household level is important. Renewable generated electricity by the community itself can be sustainable power input for the electrical heat pumps. Integration of RES combined with the integration of electrical heat pumps gives the best results on the KPIs that have been used in the model study. The combination with RES could be less important for the other heating options, as many thermal energy technologies are already sustainable themselves and do not require external input of electricity. An example of this is solar boilers that could also be integrated at the household level to provide heating. More information about the acceptance and possibility of the households (the end users of the energy system) in a specific energy community on doing these investments in thermal energy technologies is of importance here. Most of the thermal energy technologies namely result in large capital investments and long payback periods, as could be seen from the integration of electrical heat pumps in Buiksloterham.

Regarding the ICES technology of building with a high level of energy efficiency, it can be seen that the integration of energy efficient building will also have a positive impact on the performance of other energy communities. The main impact is found in bringing down the CO_2 emissions of the community. In this study however, the effect of Buiksloterham specific energy efficient buildings have been investigated. For other energy communities, the costs of energy efficient buildings is dependent on whether (most of) the buildings are already built and whether the buildings are possible to be made more energy efficient, if the buildings are currently at a low energy efficiency level.

The future developments, which have been investigated in this research, show how the values of the key performance indicators that show the value of an ICES for an energy communities can be affected by different uncertain factors. The most important and influential uncertain development is the development of the electricity price that used on the APX market. For a grid-defected ICES this development is of course not of importance, as no electricity is sold or bought to an external energy grid there. The direction of this development and other future developments affect many of the performance indicators of an energy system in the same way as is explained in chapter 5. The importance of these future developments for energy communities is dependent on which ICES technologies the energy community integrates , as some of the future developments have more influence on some technologies than others. An example of this is the development of the natural gas price that is less important in energy communities that use thermal energy technologies so that less natural gas has to be used. The importance of these future developments for an energy community is dependent on the period of time for which the value of an ICES is measured. In the case of the community of Buiksloterham for example, the goal is to reach a transition in 2034. In the period of time until this year, many factors are expected to change compared to the current situation.

6.3 Scientific contribution and further research

This research has shown, in an exploratory way, from a community level point of view, what value the ICES approach can offer for the community of Buiksloterham. Next to this, the results of the study could be used by other municipalities or communities that want to implement an ICES. For this, the effect of different ICES related technologies and ICES technology composition have been researched in scenario simulations. The results of the simulations give information about the value of different ICES technologies and the ICES approach in general. This information can be valuable input for decisions of both the community of Buiksloterham and other energy communities. With finding out which ICES technologies and compositions are available for energy communities, how an exploratory model of the implementation of an ICES for an energy community can be created and how the ICES scenarios influence the values of performance of an energy system, the knowledge gap that were mentioned in section 1.4 have been closed.

After this study is performed, further research could be done in this topic, which is the exploratory modeling of the value of the ICES approach for energy communities. Firstly, more research on other ICES technologies could be done to expand the simulation study that has been performed in this research. The ICES approach is broad and covers many energy system (related) technologies, as is discussed in the first chapters of this document. Including more technologies in the possible ICES compositions could give more complete information on the value of the ICES approach. In this way, the simulation study could be applied to more energy communities with different characteristics and goals. Not only adding more technologies, but also looking into alternatives for the same technology, such as different types of electrical heat pumps, could be valuable here. Further research could also be done on the willingness of the end-users of the energy system to participate in a certain type of ICES. This research now only focuses on exploring the measurable value that an implemented ICES can have for en energy community. Finally, validation of the simulation model can be an important addition to the research in this report. In this research some methods for validation of the simulation have been discussed but have not been performed.

Chapter 7: Conclusions

In this research, an answer is tried to be found to the sub research questions and the main research question of this study, which were formulated in section 1.4. The main research question of this study is: *'What value does ICES have for the community of Buiksloterham, to reach the sustainable energy goals of their smart community development?'*

In order to do so, the first sub question was formulated: *How can the development of an ICES in the community of Buiksloterham be quantified for a model study?* A MATLAB model is created to simulate the functioning of a future ICES in Buiksloterham in 2034. The most important input variables in the quantification of an ICES in Buiksloterham in this study the generation and demand of energy. Next to this, the ICES related technologies that are included in this research: energy efficiency of buildings, household RES, community RES and electrical heat pumps are important input variables. These input values determine the simulation of the model of the energy system. The national energy system is integrated in the simulation model giving it the function of selling to or buying electricity from the energy community grid of Buiksloterham. The most important indicators for measuring the performance of the energy system are the key performance indicators that can represent sustainable energy community development goals of Buiksloterham and other energy communities.

The KPIs were used to answer the second sub question: *What value can different ICES compositions in different scenarios have for the community energy system in Buiksloterham in 2034?* The different ICES compositions that were tested in the scenarios have different values and costs for the energy community of Buiksloterham. Most importantly, the self-sufficiency of the community should be increased while the energy demand and the CO_2 emissions should be decreased. An ICES composition with maximum ICES investments can reach a high self-sufficiency and large CO_2 reductions and a low energy demand. The payback time and capital investments are however high. Even with favourable future developments of amongst others the ICES related capital costs and the energy demand it seems unlikely that the end-users of the system would be willing to accept these levels payback periods. When using the ICES composition with full ICES investments, but without electrical heat pumps, the effect on the KPIs is less beneficial and does not fit in the sustainable goals of the community of Buiksloterham. As community RES investments are more effective on the KPIs than household RES investments the composition with full ICES investments, but low community RES, is explored. The payback time of this composition is slightly lower than in the full ICES investments composition and the capital costs are 15% lower. Relatively to the costs of the compositions, the results of these two compositions are comparable. The value of the compositions can be influenced by future developments, most importantly so that the CO_2 emissions of large ICES investment scenarios are almost two times lower when the electricity demand is 30% lower in the future.

An answer is then tried to be found to the main research question about the value of ICES for the community of Buiksloterham. The ICES approach in this research is based on four ICES technologies. The most ambitious combination of these technologies will lead to beneficial results but under large costs and pay back periods. The main reason for this is the high investment costs of electrical heat pumps. An ICES without heat pumps, but with high integration of the other ICES technologies gives less risk on acceptability because of lower pay back times and costs, but the self-sufficiency and CO_2

emissions are significantly higher. A high integration of RES is beneficial in mainly lowering the CO_2 emissions of the community and it also leads to self-sufficiency, where energy efficient buildings scores best on CO_2 emission and does not provide for self-sufficiency. The performance of electrical heat pumps are dependent on with which other ICES technologies they are combined. Integration of RES is very important for heat pumps, as it makes the heat pumps able to use self-generated renewable electricity to provide for the heat demand of the energy community. In this way, heat pumps can lead to a high self-sufficiency of the community, because it can provide sustainable supply of heat. Investing in community RES is more attractive than investing in household RES and give, together with investing in energy efficient building, beneficial results on the CO_2 emissions. The consideration is then to invest in heat pumps, which are needed to reach the ambitious goals of Buiksloterham. Relatively to cost, they give the best results with a high integration of heat pumps combined with a high integration of other ICES technologies. The higher this integration of heat pumps is however, the more risk there is in long pay back periods and acceptability of this ICES composition. Investing in the ICES technologies other than electrical heat pumps gives beneficial results, with the side node that the focus should be on community RES. Dependent on the direction of the uncertain developments heat pumps should then be implemented to achieve the more ambitious sustainable goals, for example when capital costs turn out lower in the future.

Other energy communities can learn from the results by taking into account the effect that different ICES technologies and compositions of technologies have on different parameters that measure the performance of the energy system of an energy community. This research has had scientific contribution, mainly in the exploratory and community level point of view that is taken in the creation of the simulation model for the energy system of the community of Buiksloterham. The knowledge gaps that were formulated in section 1.4 of this report have been filled by firstly showing which ICES technologies and compositions could be used by energy communities. A number of these technologies were included in the simulation model that has been developed. Secondly, it was shown how an exploratory model has been developed through gathering data and making different assumptions. Thirdly, the value of the ICES approach has been expressed by discussing the most important influences that different ICES technologies and compositions of technologies have on the performance indicators of energy communities.

Reflection

After finding a suitable subject for my Master thesis project, my supervisors helped me in finding the right direction to go. The kick-off of my research eventually took place about 6 months ago. A lot of time was put into finding the right project proposal to work with. The field of research and subject in which I wanted to do my research is broad and when trying to translate this into a project, the focus would often be so broad and ambitious that unfeasibility was an easy trap. My supervisors helped me a lot in narrowing down the scope of my research project and eventually making clear what I wanted to research and how I wanted to do that.

I learned a lot about doing research from this Master Thesis Project. Not only about the subject where this research is about, but also about the way in which these types of researches can be best executed. Looking back at the process, it would have been helpful to create an idea of what type of simulation model I wanted to create in order to get results. I think the hesitation in the choice of methodology was one of the reasons that made it difficult for me to create a project proposal that was feasible. In future research I would from the beginning try to make clear what I do and what I do not want to include in my research scope so that it becomes clear which methodology is needed for this.

Eventually a literature study and a simulation model study have been performed in this research. Especially the design skills that you learn in the Master programme of CoSeM were useful to create a MATLAB model that would simulate the energy system of the community of Buiksloterham. Regarding the creation of this simulation model I have learned that it is very important to know at which level you are designing something. Before the creation of an actual simulation model, when designing a conceptual model, the level of detail and the scope of the model should be chosen to see what needs to be included and what does not need to be included in the model. For me this was a quite iterative process which might be unavoidable when doing this kind of research, but it is something that you can keep in mind for future projects.

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Appendix A: Equations of KPIs in the simulation model

In the simulation model, the value of the Key Performance Indicators is calculated through different equations. This appendix shows a written-out version of the most important equations regarding the calculation of key performance indicators that are used in the model. In this way, insight can be given in how the model works.

A.1 Symbols and their units

B = Number of energy efficient buildings in the year 2034 (#)

C = Variable costs (EUR/unit)

D = Energy demand (kWh), (m3) or (GJ)

E = Emissions CO_2 for different energy types (kg)

G = Gas load in the BSH energy system (m3)

H = Number of households/buildings in the year 2034 (#)

HP = Number of electrical heat pumps in the year 2034 (#)

P = Electricity load in the BSH energy system (kWh)

I = Installed capacity of renewable energy source (kW)

J = Capital costs per kW installed capacity or per unit (EUR/kW) or (EUR/unit)

K = Capital costs (EUR)

k = CO_2 level of energy type (kg/kWh) or (kg/m3)

t = Specific hour of the year 2034 (#)

T = Number of hours in the year 2034 (#

Z = Payback time of ICES related capital costs (years)

A.2 Abbreviations

- $CoveredbyRES$ = Percentage of electricity demand that is fulfilled by electricity generated by renewable energy sources.
- $Electricity$ = Electricity demand/supply in general.
- $Energyefficientbuildings$ = Buildings that are built in the most energy efficient way.
- $Exchanged$ = Electricity that is exchanged with the national grid.
- $Exported$ = Electricity that is exported to the national grid.
- Gas = Natural gas supply/demand in general.
- $GrayAPX$ = Price of gray electricity on the APX market, used when Buiksloterham exports electricity to the national grid.
- $Grayretail$ = Price of gray electricity from the national grid exported to Buiksloterham, used when Buiksloterham imports electricity to the community grid.

- $Generated$ = Sustainable electricity that is generated in Buiksloterham.

- $Heatpumps$ = Electrical heat pumps.

- $Imported$ = Electricity that is imported from the national grid.

- $Saved$ = The costs that are saved when integrating ICES technologies.

- $Solar$ = Electricity generated by solar panels in Buiksloterham.

- $Total$ = All components combined.

- $Totalperhousehold$ = All components combined per household.

- $Wind$ = Electricity generated by wind turbines in Buiksloterham.

- $WithoutICES$ = The variable costs that the community of Buiksloterham would have without any integration of ICES technologies.

A.3 KPI equations

1. CO₂ emission

$$E_{imported,t} = P_{imported,t} * k_{gray}$$

$$E_{imported} = \sum_{t=1}^{T} E_{imported,t}$$

$$E_{gas,t} = G_t * k_{gas}$$

$$E_{gas} = \sum_{t=1}^{T} E_{gas,t}$$

$$E_{total} = E_{imported} + E_{gas}$$

2. Self-sufficiency

$$Percentage_{coveredbyRES,t} = \frac{(P_{solar,t} + P_{wind,t})}{D_{electricity,t}}$$

If $Percentage_{coveredbyRES,t} > 1$

Then $Percentage_{coveredbyRES,t} = 1$

$$Percentage_{coveredbyRES} = \frac{\sum_{t=1}^{T} Percentage_{coveredbyRES,t}}{T}$$

3. Total energy demand per household

$$D_{electricity} = \sum_{t=1}^{T} P_{,t}$$

$$D_{gas} = \sum_{t=1}^{T} G_{,t}$$

$$D_{total} = D_{electricity} + D_{gas}$$

$$D_{totalperhousehold} = \frac{D_{total}}{H}$$

4. Yearly cost of the ICES of Buiksloterham

$$C_{imported,t} = P_{imported,t} * C_{grayretail}$$

$$C_{imported} = \sum_{t=1}^{T} C_{imported,t}$$

$$C_{exported,t} = P_{exported,t} * C_{grayAPX}$$

$$C_{exported} = \sum_{t=1}^{T} C_{exported,t}$$

$$C_{exchanged} = C_{imported} - C_{exported}$$

$$C_{generated,t} = P_{wind,t} * C_{wind} + P_{solar,t} * C_{solar}$$

$$C_{generated} = \sum_{t=1}^{T} C_{generated,t}$$

$$C_{gas,t} = G_{t} * C_{gas}$$

$$C_{gas} = \sum_{t=1}^{T} C_{gas,t}$$

$$C_{total} = C_{exchanged} + C_{generated} + C_{gas}$$

$$C_{totalperhousehold} = \frac{C_{total}}{H}$$

5. Total renewable energy exported to the central grid

$$P_{imported} = \sum_{t=1}^{T} P_{imported,t}$$

$$P_{exported} = \sum_{t=1}^{T} P_{exported,t}$$

$$C_{exchanged} = C_{imported} - C_{exported}$$

6. Self-consumption

$$P_{exported} = \sum_{t=1}^{T} P_{exported,t}$$

$$P_{generated} = \sum_{t=1}^{T} P_{generated,t}$$

$$Percentage_{selfconsumption} = 100 - (\frac{P_{exported}}{P_{generated}} * 100)$$

7. Maximum line capacity flow

$$P_{maximumlinecap} = \max of(P_{imported,t}, P_{exported,t})$$

8. Capital costs

$$K_{solar} = I_{solar} * J_{solar}$$

$$K_{wind} = I_{wind} * J_{wind}$$

$$K_{energyefficientbuildings} = B * J_{energyefficientbuildings}$$

$$K_{heatpumps} = HP * J_{heatpumps}$$

$$K_{total} = K_{solar} + K_{wind} + K_{energyefficientbuildings} + K_{heatpumps}$$

9. Payback time of ICES related capital costs

$$C_{saved} = C_{withoutICES} - C_{total}$$

$$Z = \frac{K_{total}}{C_{saved}}$$

Appendix B: Forming the simulation output tables

In table B.1 the numerical outputs of the CO_2 emissions in Buiksloterham are given. The final KPI output value is calculated by taking the mean value of 10 different runs, as is done for every KPI in every scenario and uncertain future development. The standard deviation of the different runs is also given. This table is an example to show how the values in the tables in appendix A are formed.

Note that the mean values of the CO_2 emission in the stable future development, the lower ICES capital costs, the lower APX electricity price and the higher natural gas price are slightly different. However, in the tables in appendix B, these values are given the same number because their difference can only be attributed to a difference in stochastic seed values. The difference between these results is not significant.

Scenario 1: None, Low, Low, None (Minimal ICES investments)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
CO_2 emission [Ton CO_2/year]	**Stable** Run 1: 8399 Run 2: 8411 Run 3: 8407 Run 4: 8470 Run 5: 8428 Run 6: 8417 Run 7: 8409 Run 8: 8396 Run 9: 8403 Run 10: 8402 *Mean: 8414* *Standard deviation: 21.69*	**30% lower:** Run 1: 6683 Run 2: 6660 Run 3: 6681 Run 4: 6677 Run 5: 6671 Run 6: 6695 Run 7: 6691 Run 8: 6703 Run 9: 6658 Run 10: 6730 *Mean: 6685*	**15% lower:** Run 1: 8431 Run 2: 8471 Run 3: 8433 Run 4: 8420 Run 5: 8418 Run 6: 8451 Run 7: 8393 Run 8: 8432 Run 9: 8474 Run 10: 8417 *Mean: 8434*	**30% lower:** Run 1: 8365 Run 2: 8377 Run 3: 8474 Run 4: 8399 Run 5: 8437 Run 6: 8395 Run 7: 8465 Run 8: 8416 Run 9: 8439 Run 10: 8426 *Mean: 8420*	**50% higher:** Run 1: 8406 Run 2: 8462 Run 3: 8431 Run 4: 8422 Run 5: 8480 Run 6: 8426 Run 7: 8425 Run 8: 8412 Run 9: 8440 Run 10: 8447 *Mean: 8435*
		30% higher: Run 1: 10,275 Run 2: 10,304 Run 3: 10,321 Run 4: 10,288 Run 5: 10,300 Run 6: 10,295 Run 7: 10,291 Run 8: 10,317 Run 9: 10,295 Run 10: 10,359 *Mean: 10,305*	**30% lower:** Run 1: 8401 Run 2: 8425 Run 3: 8449 Run 4: 8452 Run 5: 8391 Run 6: 8419 Run 7: 8434 Run 8: 8418 Run 9: 8428 Run 10: 8432 *Mean: 8425*		

Table B.1: CO_2 emission outputs for every run and the mean value of these runs of scenario 1.

Appendix C: Simulation output for the scenarios

The tables C.1 to C.10 give the full simulation outputs for the ten scenarios that have been simulated in the model study. Every table shows the results for one scenario. In the table, the numerical output for each key performance indicators is given for each of the uncertain future developments. The first column shows the output values when there is a 'stable future development' so neither the electricity demand, the ICES related capital costs, the APX electricity price or the natural gas price is different than the standard value that has been used in the simulation, so the value as it is today. The other columns show the numerical outputs in the scenario of the key performance, when one of the uncertain future developments takes one of the possible directions.

Scenario 1: None, Low, Low, None (Minimum ICES investments)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO_2 emission [Ton CO_2/year]	**8403**	30% lower: **6656**	15% lower: **8403**	30% lower: **8403**	50% higher: **8403**
		30% higher: **10,320**	30% lower: **8403**		
2. Self-sufficiency [%]	**18.00**	30% lower: **18.31**	15% lower: **18.00**	30% lower: **18.00**	50% higher: **18.00**
		30% higher: **16.82**	30% lower: **18.00**		
3. Total energy demand per household [GJ/household/year]	**27.76**	30% lower: **24.42**	15% lower: **27.76**	30% lower: **27.76**	50% higher: **27.76**
		30% higher: **31.19**	30% lower: **27.76**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**695**	30% lower: **514**	15% lower: **695**	30% lower: **699**	50% higher: **842**
		30% higher: **890**	30% lower: **695**		
5. Total renewable energy exported to the central grid [GJ/year]	**935**	30% lower: **2436**	15% lower: **935**	30% lower: **935**	50% higher: **935**
		30% higher: **379**	30% lower: **935**		
6. Self-consumption [%]	**95.06**	30% lower: **87.30**	15% lower: **95.06**	30% lower: **95.06**	50% higher: **95.06**
		30% higher: **97.91**	30% lower: **95.06**		
7. Maximum line capacity flow [kWh]	**4246**	30% lower: **2654**	15% lower: **4246**	30% lower: **4246**	50% higher: **4246**
		30% higher: **6151**	30% lower: **4246**		
8. Capital costs of the ICES components [€]	**6,430,000**	30% lower: **6,430,000**	15% lower: **5,465,500**	30% lower: **6,430,000**	50% higher: **6,430,000**
		30% higher: **6,430,000**	30% lower: **4,501,000**		
9. Payback time of ICES related capital costs [Years]	**4.67**	30% lower: **3.06**	15% lower: **4.03**	30% lower: **4.75**	50% higher: **8.1477**
		30% higher: **10.76**	30% lower: **3.26**		

Table C.1: Numerical output of scenario 1.

Scenario 2: Full, High, High, Full (Maximum ICES investments)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO₂ emission [Ton CO₂/year]	**749**	30% lower: **388**	15% lower: **749**	30% lower: **749**	50% higher: **749**
		30% higher: **1244**	30% lower: **749**		
2. Self-sufficiency [%]	**86.32**	30% lower: **89.03**	15% lower: **86.32**	30% lower: **86.32**	50% higher: **86.32**
		30% higher: **83.06**	30% lower: **86.32**		
3. Total energy demand per household [GJ/household/year]	**8.68**	30% lower: **6.06**	15% lower: **8.68**	30% lower: **8.68**	50% higher: **8.68**
		30% higher: **11.27**	30% lower: **8.68**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**29**	30% lower: **-37**	15% lower: **29**	30% lower: **98**	50% higher: **29**
		30% higher: **105**	30% lower: **29**		
5. Total renewable energy exported to the central grid [GJ/year]	**46,500**	30% lower: **54,515**	15% lower: **46,500**	30% lower: **46,500**	50% higher: **46,500**
		30% higher: **39,614**	30% lower: **46,500**		
6. Self-consumption [%]	**38.92**	30% lower: **28.48**	15% lower: **38.92**	30% lower: **38.92**	50% higher: **38.92**
		30% higher: **48.05**	30% lower: **38.92**		
7. Maximum line capacity flow [kWh]	**8385**	30% lower: **8533**	15% lower: **8385**	30% lower: **8385**	50% higher: **8385**
		30% higher: **8095**	30% lower: **8385**		
8. Capital costs of the ICES components [€]	**81,720,000**	30% lower: **81,720,000**	15% lower: **69,462,000**	30% lower: **81,720,000**	50% higher: **81,720,000**
		30% higher: **81,720,000**	30% lower: **57,204,000**		
9. Payback time of ICES related capital costs [Years]	**20.23**	30% lower: **18.97**	15% lower: **17.23**	30% lower: **21.70**	50% higher: **20.23**
		30% higher: **21.88**	30% lower: **14.16**		

Table C.2: Numerical output of scenario 2.

Scenario 3: Med, Med, Med, Med (Medium ICES investments)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO$_2$ emission [Ton CO$_2$/year]	**3795**	30% lower: **2784**	15% lower: **3795**	30% lower: **3795**	50% higher: **3795**
		30% higher: **5092**	30% lower: **3795**		
2. Self-sufficiency [%]	**46.31**	30% lower: **44.40**	15% lower: **46.31**	30% lower: **46.31**	50% higher: **46.31**
		30% higher: **45.48**	30% lower: **46.31**		
3. Total energy demand per household [GJ/household/year]	**18.06**	30% lower: **24.42**	15% lower: **18.06**	30% lower: **18.06**	50% higher: **18.06**
		30% higher: **21.54**	30% lower: **18.06**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**378**	30% lower: **252**	15% lower: **378**	30% lower: **407**	50% higher: **436**
		30% higher: **527**	30% lower: **378**		
5. Total renewable energy exported to the central grid [GJ/year]	**15,539**	30% lower: **22,454**	15% lower: **15,539**	30% lower: **15,539**	50% higher: **15,539**
		30% higher: **10,577**	30% lower: **15,539**		
6. Self-consumption [%]	**67.29**	30% lower: **52.92**	15% lower: **67.29**	30% lower: **67.29**	50% higher: **67.29**
		30% higher: **77.74**	30% lower: **67.29**		
7. Maximum line capacity flow [kWh]	**4720**	30% lower: **5053**	15% lower: **4720**	30% lower: **4720**	50% higher: **4720**
		30% higher: **5229**	30% lower: **4720**		
8. Capital costs of the ICES components [€]	**44,075,000**	30% lower: **44,075,000**	15% lower: **37,463,750**	30% lower: **44,075,000**	50% higher: **44,075,000**
		30% higher: **44,075,000**	30% lower: **30,852,500**		
9. Payback time of ICES related capital costs [Years]	**16.67**	30% lower: **13.99**	15% lower: **14.17**	30% lower: **17.44**	50% higher: **18.28**
		30% higher: **21.51**	30% lower: **11.67**		

Table C.3: Numerical output of scenario 3.

Scenario 4: Full, High, High, None (Maximum RES investments and full energy efficient buildings)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO_2 emission [Ton CO_2/year]	**3143**	30% lower: **2959**	15% lower: **3143**	30% lower: **3143**	50% higher: **3143**
		30% higher: **3438**	30% lower: **3143**		
2. Self-sufficiency [%]	**35.92**	30% lower: **29.13**	15% lower: **35.92**	30% lower: **35.92**	50% higher: **35.92**
		30% higher: **40.50**	30% lower: **35.92**		
3. Total energy demand per household [GJ/household/year]	**16.64**	30% lower: **14.71**	15% lower: **16.64**	30% lower: **16.64**	50% higher: **16.64**
		30% higher: **18.68**	30% lower: **16.64**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**59**	30% lower: **15**	15% lower: **59**	30% lower: **135**	50% higher: **148**
		30% higher: **111**	30% lower: **59**		
5. Total renewable energy exported to the central grid [GJ/year]	**52,214**	30% lower: **58,841**	15% lower: **52,214**	30% lower: **52,214**	50% higher: **52,214**
		30% higher: **46,172**	30% lower: **52,214**		
6. Self-consumption [%]	**31.30**	30% lower: **22.56**	15% lower: **31.30**	30% lower: **31.30**	50% higher: **31.30**
		30% higher: **39.32**	30% lower: **31.30**		
7. Maximum line capacity flow [kWh]	**8443**	30% lower: **8311**	15% lower: **8443**	30% lower: **8443**	50% higher: **8443**
		30% higher: **8306**	30% lower: **8443**		
8. Capital costs of the ICES components [€]	**45,720,000**	30% lower: **45,720,000**	15% lower: **38,862,000**	30% lower: **45,720,000**	50% higher: **45,720,000**
		30% higher: **45,720,000**	30% lower: **32,004,000**		
9. Payback time of ICES related capital costs [Years]	**11.67**	30% lower: **11.16**	15% lower: **9.93**	30% lower: **12.64**	50% higher: **12.83**
		30% higher: **12.32**	30% lower: **8.17**		

Table C.4: Numerical output of scenario 4.

Scenario 5: None, High, High, Full (Maximum RES and full heat pump investments)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO₂ emission [Ton CO₂/year]	**2053**	30% lower: **1007**	15% lower: **2053**	30% lower: **2053**	50% higher: **2053**
		30% higher: **3450**	30% lower: **2053**		
2. Self-sufficiency [%]	**78.49**	30% lower: **84.45**	15% lower: **78.49**	30% lower: **78.49**	50% higher: **78.49**
		30% higher: **72.37**	30% lower: **78.49**		
3. Total energy demand per household [GJ/household/year]	**14.46**	30% lower: **10.12**	15% lower: **14,46**	30% lower: **14,46**	50% higher: **14,46**
		30% higher: **18.83**	30% lower: **14,46**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**215**	30% lower: **71**	15% lower: **215**	30% lower: **268**	50% higher: **215**
		30% higher: **385**	30% lower: **215**		
5. Total renewable energy exported to the central grid [GJ/year]	**32,278**	30% lower: **42,506**	15% lower: **32,278**	30% lower: **32,278**	50% higher: **32,278**
		30% higher: **24,385**	30% lower: **32,278**		
6. Self-consumption [%]	**57.59**	30% lower: **44.16**	15% lower: **57.59**	30% lower: **57.59**	50% higher: **57.59**
		30% higher: **68.19**	30% lower: **57.59**		
7. Maximum line capacity flow [kWh]	**8123**	30% lower: **8123**	15% lower: **8123**	30% lower: **8123**	50% higher: **8123**
		30% higher: **7305**	30% lower: **8123**		
8. Capital costs of the ICES components [€]	**61,720,000**	30% lower: **61,720,000**	15% lower: **52.462.000**	30% lower: **61,720,000**	50% higher: **61,720,000**
		30% higher: **61,720,000**	30% lower: **43.040.000**		
9. Payback time of ICES related capital costs [Years]	**18.71**	30% lower: **15.93**	15% lower: **15.96**	30% lower: **20.00**	50% higher: **18.71**
		30% higher: **23.60**	30% lower: **13.12**		

Table C.5: Numerical output of scenario 5.

Scenario 6: None, High, High, None (Maximum RES investments)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO_2 emission [Ton CO_2/year]	**5728**	30% lower: **5102**	15% lower: **5728**	30% lower: **5728**	50% higher: **5728**
		30% higher: **6556**	30% lower: **5728**		
2. Self-sufficiency [%]	**33.62**	30% lower: **28.12**	15% lower: **33.62**	30% lower: **33.62**	50% higher: **33.62**
		30% higher: **36.84**	30% lower: **33.62**		
3. Total energy demand per household [GJ/household/year]	**27.81**	30% lower: **24.38**	15% lower: **27.81**	30% lower: **27.81**	50% higher: **27.81**
		30% higher: **31.21**	30% lower: **27.81**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**306**	30% lower: **207**	15% lower: **306**	30% lower: **367**	50% higher: **453**
		30% higher: **419**	30% lower: **306**		
5. Total renewable energy exported to the central grid [GJ/year]	**39,542**	30% lower: **48,897**	15% lower: **39,542**	30% lower: **39,542**	50% higher: **39,542**
		30% higher: **31,549**	30% lower: **39,542**		
6. Self-consumption [%]	**48.07**	30% lower: **35.82**	15% lower: **48.07**	30% lower: **48.07**	50% higher: **48.07**
		30% higher: **58.26**	30% lower: **48.07**		
7. Maximum line capacity flow [kWh]	**8037**	30% lower: **8251**	15% lower: **8037**	30% lower: **8037**	50% higher: **8037**
		30% higher: **8217**	30% lower: **8037**		
8. Capital costs of the ICES components [€]	**25,720,000**	30% lower: **25,720,000**	15% lower: **21,862,000**	30% lower: **25,720,000**	50% higher: **25,720,000**
		30% higher: **25,720,000**	30% lower: **18,004,000**		
9. Payback time of ICES related capital costs [Years]	**8.72**	30% lower: **7.73**	15% lower: **7.47**	30% lower: **9.56**	50% higher: **10.96**
		30% higher: **10.37**	30% lower: **6,15**		

Table C.6: Numerical output of scenario 6.

Scenario 7: Full, Low, Low, Full (Full heat pumps and energy efficient buildings, low RES)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO₂ emission [Ton CO₂/year]	**2581**	30% lower: **1386**	15% lower: **2581**	30% lower: **2581**	50% higher: **2581**
		30% higher: **3951**	30% lower: **2581**		
2. Self-sufficiency [%]	**53.61**	30% lower: **65.26**	15% lower: **53.61**	30% lower: **53.61**	50% higher: **53.61**
		30% higher: **44.70**	30% lower: **53.61**		
3. Total energy demand per household [GJ/household/year]	**8.72**	30% lower: **6.10**	15% lower: **8.72**	30% lower: **8.72**	50% higher: **8.72**
		30% higher: **11.27**	30% lower: **8.72**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**357**	30% lower: **229**	15% lower: **357**	30% lower: **363**	50% higher: **357**
		30% higher: **498**	30% lower: **357**		
5. Total renewable energy exported to the central grid [GJ/year]	**1,990**	30% lower: **4,100**	15% lower: **1,990**	30% lower: **1,990**	50% higher: **1,990**
		30% higher: **972**	30% lower: **1,990**		
6. Self-consumption [%]	**89.63**	30% lower: **78.22**	15% lower: **89.63**	30% lower: **89.63**	50% higher: **89.63**
		30% higher: **95.01**	30% lower: **89.63**		
7. Maximum line capacity flow [kWh]	**3089**	30% lower: **2414**	15% lower: **3089**	30% lower: **3089**	50% higher: **3089**
		30% higher: **4130**	30% lower: **3089**		
8. Capital costs of the ICES components [€]	**62,430,000**	30% lower: **62,430,000**	15% lower: **53,065,500**	30% lower: **62,430,000**	50% higher: **62,430,000**
		30% higher: **62,430,000**	30% lower: **43,701,000**		
9. Payback time of ICES related capital costs [Years]	**22.97**	30% lower: **19.26**	15% lower: **19.43**	30% lower: **23.07**	50% higher: **22.97**
		30% higher: **28.86**	30% lower: **16.04**		

Table C.7: Numerical output of scenario 7.

Scenario 8: Full, High, Low, High (Maximum ICES investments, but low community RES)

Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO$_2$ emission [Ton CO$_2$/year]	**1913**	30% lower: **1035**	15% lower: **1913**	30% lower: **1913**	50% higher: **1913**
		30% higher: **2961**	30% lower: **1913**		
2. Self-sufficiency [%]	**65.30**	30% lower: **73.40**	15% lower: **65.30**	30% lower: **65.30**	50% higher: **65.30**
		30% higher: **58.48**	30% lower: **65.30**		
3. Total energy demand per household [GJ/household/year]	**8.67**	30% lower: **6.08**	15% lower: **8.67**	30% lower: **8.67**	50% higher: **8.67**
		30% higher: **11.27**	30% lower: **8.67**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**245**	30% lower: **140**	15% lower: **245**	30% lower: **271**	50% higher: **245**
		30% higher: **362**	30% lower: **245**		
5. Total renewable energy exported to the central grid [GJ/year]	**15,672**	30% lower: **20,033**	15% lower: **15,672**	30% lower: **15,672**	50% higher: **15,672**
		30% higher: **12,462**	30% lower: **15,672**		
6. Self-consumption [%]	**58.03**	30% lower: **46.30**	15% lower: **58.03**	30% lower: **58.03**	50% higher: **58.03**
		30% higher: **66.88**	30% lower: **58.03**		
7. Maximum line capacity flow [kWh]	**4942**	30% lower: **4942**	15% lower: **4942**	30% lower: **4942**	50% higher: **4942**
		30% higher: **4578**	30% lower: **4942**		
8. Capital costs of the ICES components [€]	**73,044,000**	30% lower: **73,044,000**	15% lower: **62,087,400**	30% lower: **73,044,000**	50% higher: **73,044,000**
		30% higher: **73,044,000**	30% lower: **51,130,800**		
9. Payback time of ICES related capital costs [Years]	**23.00**	30% lower: **20.31**	15% lower: **19.58**	30% lower: **23.77**	50% higher: **23.00**
		30% higher: **26.97**	30% lower: **16.09**		

Table C.8: Numerical output of scenario 8.

Scenario 9: Full, Low, High, Full (Maximum ICES investments, but low household RES)					
Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO_2 emission [Ton CO_2/year]	**1042**	30% lower: **538**	15% lower: **1042**	30% lower: **1042**	50% higher: **1042**
		30% higher: **1746**	30% lower: **1042**		
2. Self-sufficiency [%]	**81.05**	30% lower: **85.30**	15% lower: **81.05**	30% lower: **81.05**	50% higher: **81.05**
		30% higher: **76.18**	30% lower: **81.05**		
3. Total energy demand per household [GJ/household/year]	**8.71**	30% lower: **6.09**	15% lower: **8.71**	30% lower: **8.71**	50% higher: **8.71**
		30% higher: **11.32**	30% lower: **8.71**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**114**	30% lower: **37**	15% lower: **114**	30% lower: **158**	50% higher: **114**
		30% higher: **206**	30% lower: **114**		
5. Total renewable energy exported to the central grid [GJ/year]	**30,146**	30% lower: **37,141**	15% lower: **30,146**	30% lower: **30,146**	50% higher: **30,146**
		30% higher: **24,500**	30% lower: **30,146**		
6. Self-consumption [%]	**47.68**	30% lower: **35.72**	15% lower: **47.68**	30% lower: **47.68**	50% higher: **47.68**
		30% higher: **57.55**	30% lower: **47.68**		
7. Maximum line capacity flow [kWh]	**6284**	30% lower: **6526**	15% lower: **6284**	30% lower: **6284**	50% higher: **6284**
		30% higher: **6059**	30% lower: **6284**		
8. Capital costs of the ICES components [€]	**71,106,000**	30% lower: **71,106,000**	15% lower: **60,440,100**	30% lower: **71,106,000**	50% higher: **71,106,000**
		30% higher: **71,106,000**	30% lower: **49,774,200**		
9. Payback time of ICES related capital costs [Years]	**19.22**	30% lower: **17.73**	15% lower: **16.34**	30% lower: **20.17**	50% higher: **19.21**
		30% higher: **21.34**	30% lower: **13.47**		

Table C.9: Numerical output of scenario 9.

Scenario 10: Full, High, High, Med (Maximum ICES investments, but medium heat pump investments)

Key Performance Indicator	Stable future development	Electricity demand	ICES capital costs	APX electricity price	Natural gas price
1. CO₂ emission [Ton CO₂/year]	**1944**	30% lower: **1665**	15% lower: **1944**	30% lower: **1944**	50% higher: **1944**
		30% higher: **2337**	30% lower: **1944**		
2. Self-sufficiency [%]	**53.17**	30% lower: **46.61**	15% lower: **53.17**	30% lower: **53.17**	50% higher: **53.17**
		30% higher: **56.62**	30% lower: **53.17**		
3. Total energy demand per household [GJ/household/year]	**12.69**	30% lower: **10.38**	15% lower: **12.69**	30% lower: **12.69**	50% higher: **12.69**
		30% higher: **15.01**	30% lower: **12.69**		
4. Yearly cost of operation of the ICES of Buiksloterham per household [€/household/year]	**92**	30% lower: **36**	15% lower: **92**	30% lower: **163**	50% higher: **121.79**
		30% higher: **141**	30% lower: **92**		
5. Total renewable energy exported to the central grid [GJ/year]	**49,272**	30% lower: **56,625**	15% lower: **49,272**	30% lower: **49,272**	50% higher: **49,272**
		30% higher: **42,704**	30% lower: **49,272**		
6. Self-consumption [%]	**35.24**	30% lower: **25.58**	15% lower: **35.24**	30% lower: **35.24**	50% higher: **35.24**
		30% higher: **43.87**	30% lower: **35.24**		
7. Maximum line capacity flow [kWh]	**8286**	30% lower: **8396**	15% lower: **8286**	30% lower: **8286**	50% higher: **8286**
		30% higher: **8224**	30% lower: **8286**		
8. Capital costs of the ICES components [€]	**63,720,000**	30% lower: **63,720,000**	15% lower: **60,440,100**	30% lower: **63,720,000**	50% higher: **63,720,000**
		30% higher: **63,720,000**	30% lower: **54,162,000**		
9. Payback time of ICES related capital costs [Years]	**16.62**	30% lower: **15.88**	15% lower: **16.34**	30% lower: **18.17**	50% higher: **17.46**
		30% higher: **17.81**	30% lower: **11.81**		

Table C.10: Numerical output of scenario 10.