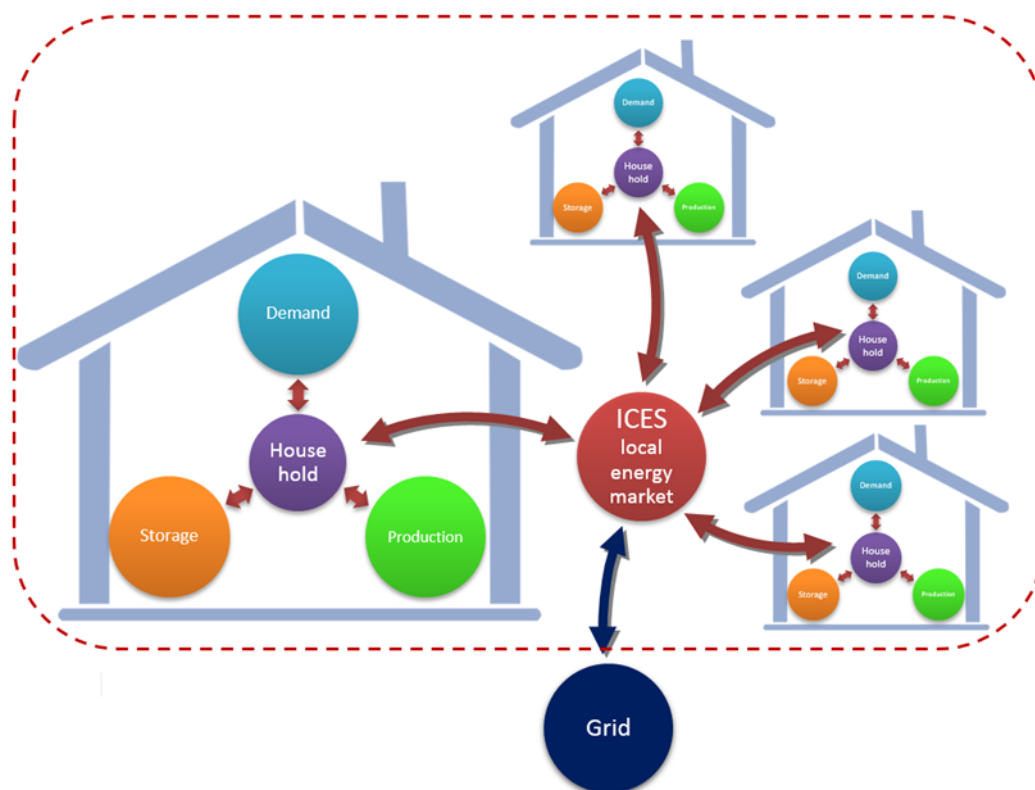


Multi-objective optimisation of Integrated Community Energy Systems and assessment of the impact on households

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Master of Science Thesis



Multi-objective optimisation of Integrated Community Energy Systems and assessment of the impact on households

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Preface

Writing a thesis is a process. A process of conceptual thinking, planning, discussing, learning, changing ideas, writing and re-writing. This report is outcome of my master thesis research project and is the penultimate step in completing my MSc programme Sustainable Energy Technology. This research is performed at the faculty of Technology Policy and Management (TPM), coordinated by the section Energy & Industry.

With the concerns about depleting fossil fuel reserves, greenhouse gas emission and climate change, the need for radical changes becomes more urgent. This issues are nowadays getting more attention, from all levels in society. It is clear we have to rethink the way energy is being exploited ever since the industrial revolution. However a tangible solution is yet to be found. This research looks into the possibilities of community energy systems and to what extent this concept may contributes in increasing the efficiency of energy systems and thereby reduce energy costs and CO₂ emission. I am graceful to have the opportunity to perform research in the field of renewable energy.

I was always interested in energy. I remember my first public speech at primary school. It was about electricity and how it is being generated and transported to the residential consumers. My father helped me to prepare my speech and collected samples of large power cables. That day I could never have imagined to write a master thesis on the same topic about two decades later. During my journey I was fortunate to come along many highlights, study related and in my personal life. After these years I can look back at an inspiring, enlightening and happy student life. Throughout the thesis project I extended my knowledge on subjects I studied in previous years and in particular I gained a broad and deep insight in community energy systems. Moreover I learned to further develop my analytical and writing skills without losing sight of the overall picture, while working on the intersection of different fields. Off course at times I got lost, but I experienced this to be an important part of the process. The journey. There is no journey without wandering. But after all 'Not all those who wander are lost.' (Tolkien, 1954).

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This thesis could not have been completed without the help of many experienced professionals. I would like to thank my daily supervisor Binod Koirala for sharing his expertise and his time to guide me through the whole process and for his numerous recommendations on my not-so-perfect drafts. Our weekly meetings were very useful to me and your keen eye for detail contributed to the quality of my research. I would also like to thank my supervisor Dr. Rudi Hakvoort for his guidance, inspiring thoughts and valuable comments during our meetings. Our meetings were very helpful in steering me in the right direction. I appreciate your sense of humour. I also want to express my gratitude to Eric Woittiez from Essent, for being part of the committee as well and for bringing in his point of view from practical experience. Furthermore I would like to thank Professor Paulien Herder and Dr. Daniel Scholten whom completed my thesis reviewing committee and provided me with useful feedback. Tim and Sierk, I would like to express my appreciation for your recommendations during the progress of my thesis.

I want to address special thanks to Charlotte, my family and friends for their love, patience and encouragements during my education, and especially during my master thesis project. I will definitely spend more time with you after graduation!

Executive summary

Sustainability has gained considerable interest at all levels in society during the last decades. Climate change has been a large contributor to this mentality change. As current energy systems are inefficient and contribute to climate change, a transition towards more efficient energy systems is sought. The share of local produced energy in the total energy mix increases, for example through small scale solar installations at household level. Integrated Community Energy Systems (ICES) is a community energy concept that looks into the optimal integration of distributed energy sources and engage local communities, as a solution to the drawbacks of the current energy system. These drawbacks include: notable transmission losses, significant carbon emission, flexibility limitations and a primarily one-dimensional structural design. ICES deals with these drawbacks and allows energy exchange between community members. This multi-source multi-product energy network framework is a broad and flexible concept that involves all facets of energy within a community. Within this research, focus lies on household level energy demand and production, although ICES is able to cover a wider variety of energy forms and carriers.

This research uses a bottom-up approach and analyses different demand profiles at household level and a selection of available energy generation technologies (with its typical production profiles). Thereby the flows of energy within ICES are studied and evaluated for different technology mixes, different community preferences and different community compositions.

The goal of this research is to determine to what extent ICES can contribute to energy autonomy and at the same time, to the reduction of CO₂ emission. Therefore a multi-objective optimisation of ICES is performed, in which the different available technologies, community preferences and community compositions are considered. The three optimisation preferences are: energy costs minimisation, CO₂ emission reduction and energy autonomy maximisation. The main focus lies on the impact this optimisation has on households. A literature study and a stakeholder analysis are performed to identify the most suitable technologies to implement. A state-of-the-art ICES model is designed in MATLAB, to provide founded outcomes and to underpin the answers to the research questions. With this tool, the optimal technology mix is determined, based on different community specific parameters, valued on their technical, economic and environmental impact. Model input parameters include: demand profiles, weather data, and production profiles.

The ICES model consists of two main parts. First a model on household level is designed, which is used to select the optimal technology mix for each type of household and for each optimisation preference. Different technologies are implemented to fulfil energy needs. Energy exchange with the electricity grid allows households to trade excess energy. The four types of households that are considered are: one adult household, two adult household, family household and pensioner household. Three performance indicators are mapped to quantify the performance of the technology mix at household level: energy price, CO₂ emission and energy autonomy. The optimisation process at household level results in twelve optimal technology mixes. These twelve sub-results are used in the ICES model. Results of the household level model are stored and loaded in the ICES level model.

With the ICES level model, the selected households with their optimal technology mix are combined to form an energy community. Stored household parameters are initialised (e.g. performance indicators, residual energy demand and excess energy profiles). An algorithm is developed, to distribute any excess energy among households that could not fulfil their own demand. Community ideology has a central role during the distribution of energy within ICES. Energy is imported from other community members at average levelised costs of energy production (LCOE). At each particular hour of the day, all households that import energy from ICES pay the same price per kWh for this energy. Households that export energy to ICES receive their full LCOE. Thereby they cover their investment costs, but are not stimulated to over-invest or over-produce. Energy is allocated to the demanding households in ratio to their demand. Energy exchanges within ICES is encouraged by this pricing mechanism. Energy that is being exported within ICES, is allocated to the exporting households in proportion of their total production in relation to the total ICES production. Exporting revenues and benefits from importing, thereby are equally distributed amongst contributing households. Energy that is not being used within ICES is exported to the grid at APX price. Demand that cannot be fulfilled within ICES is being supplied by the grid, at retail price.

The outcome of the household level optimisation shows, for a purely **financial optimisation** preference (over a lifetime of 20 years), a 10% energy costs reduction is possible. This also results in a 25% CO₂ reduction. With the use of ICES, energy costs and CO₂ emission both reduce by another 10%. There are slight variations between results from different community compositions (less than 5% variation). The initial optimisation preference is of higher influence than the community composition.

CO₂ emission optimisation shows a larger CO₂ emission reduction is possible, however energy costs increase quickly when opting for a large reduction of carbon emission. A 50% CO₂ reduction is conceivable at ICES level, however this will increase the energy costs by 60%. In the case of CO₂ reduction maximisation, almost all reduction is ascribed to the implemented technologies and ICES has little impact. This is also due to the fact that a low carbon intensive configuration exploits as much distributed generation as possible, implying a high energy autonomy at household level.

Energy autonomy optimization is expensive and inefficient at household level. The technology mix that is able to supply peak demand, is largely over dimensioned during low demand hours. This is expensive, since investment is made for the full capacity. It is inefficient because technologies operate most of the time far below their optimal operating point. Also low annual energy production in comparison with the installed capacity causes high LCOE.

Demand peaks will result in a technology mix that is able to supply the occasional occurring demand peaks, but essentially for the largest part of the time is over dimensioned. Without ICES, the export of excess energy is less profitable. Of all performance indicators, the largest contribution of ICES is observed in energy autonomy.

Besides the different community compositions and technology mixes, a selection of additional scenarios is analysed. The different scenarios that are studied are electric vehicle (EV) penetration, stationary storage penetration, carbon pricing, scale effect and non-energy-producing household implementation. The electricity exchange price exponentially increases at high EV penetration level. A low EV penetration level has no negative effect, as long as there is sufficient available excess energy within ICES. The first EV owners and the last households without EV will benefit the most from ICES. The time mismatch between EV charging hours and renewable peak production asks for a solution, such as load shifting or temporary storage of renewable energy that is not used at time of production. The effect of stationary storage at household level, strongly relates with the effect ICES has on the performance indicators at household level. A high penetration ratio of stationary storage increases households' individual performance, but this also means the contribution of ICES becomes less. When batteries are installed at all households, the total energy exchange within ICES reduces with 85%. Due to the (still) high capital costs of batteries, the total energy costs are lower when using ICES instead of batteries, while the overall performance is comparable. The financial effect of carbon pricing is relatively small, compared to the total annual energy costs and is calculated to be €150 on annual base at most. The effect of scale shows that an increased number of households slightly increases the carbon reduction and energy autonomy. Adding non-energy-producing households is possible without noticeably reducing performance indicators, up to a level of 20%.

This research shows ICES has potential to reduce carbon emission (with maximum 50%), increase energy autonomy (up to 100%) and reduce energy costs (with maximum 20%). The multi-objective optimum is found at 20% CO₂ emission reduction, 95% energy autonomy and 20% energy costs reduction. This shows ICES can be a promising solution in the trajectory towards a more efficient and low-carbon energy system. When the observed barriers are reduced and the right technology mix is used, ICES offers a valuable contribution to the reduction of CO₂ emission at affordable costs. It offers perspective to an energy system that emphasizes on community engagement and equity for its community members.

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Nomenclature

AC	Alternating current
APX	Amsterdam Power Exchange
CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
CRF	Capital recovery factor
D	Discount rate
DC	Direct current
DER	distributed energy resources
DG	Distributed generation
DSO	Distribution system operators
ESCs	Energy Sustainable Communities
ETS	Emissions trading systems
EU	European Union
EV	Electric Vehicle(s)
GDP	Gross Domestic Product
GoO	Guarantees of Origin
ICES	Integrated Community Energy Systems
ICT	Information and communications technology
kW	Kilowatt (10^3 watt)
kW _e	Kilowatt electric; 10^3 watt electric power
kWh	Kilowatt hour
MES	Multi-energy systems
MJ	Mega joule
MW	Megawatt (10^6 watt)
Nm ³	Normal cubic metre
O&M	Operations and Maintenance (costs)
ODE	' <i>Heffing Opslag Duurzame Energie</i> ', a Dutch stimulation program for renewable energy
PV	Photovoltaic
REB	' <i>Regulerende Energie Belasting</i> ', a Dutch energy tax per kWh.
SDE+	' <i>Stimulerende Duurzame Energieproductie</i> ', a Dutch Sustainable Energy Incentive Scheme
SEC	Smart Energy Collective (when used for SEC Heerhugowaard) or Sustainable Energy Community
SQL	Structured Query Language
TSO	Transmission system operator

This thesis is dedicated to my devoted parents, my dearest wife and our unborn child!

Chapter 1: Introduction

1.1. The changing energy landscape

Energy is a topic that touches everyone on earth. We are surrounded by energy. From the electromagnetic radiation we receive each day from the sun, to the energy it takes us to drive with our bicycle to university. From the energy content of the sandwiches we consume each day to the energy from the national electricity grid on which we become so much dependent in our daily activities. The latter example will be the start of our exploration through the energy landscape and the changes it is subjected to. With the term ‘energy landscape’ we refer to the all energy related activities within certain geographic boundaries, including its production, distribution and consumption. Figure 1.1 shows the three levels of the energy landscape. The arrows in this figure represent the possibility to exchange energy and information.



Figure 1.1: Three levels of the energy landscape (Adapted from Kroposki et al., 2012).

For example, in the Netherlands, changes in the energy mix are observed. Traditionally the electricity is being produced in large centralised coal, oil or gas-fired power plants. The last decades the energy sector experiences a tendency towards sustainability. **Renewable energy sources**, such as wind, solar and biomass, become more important in electricity generation. The trend in this development is shown in Figure 1.2. The increased share of renewables place different demands and stresses on the energy network. Hence network characteristics change, especially because a large share of the renewable electricity is produced decentral and is highly intermittent.

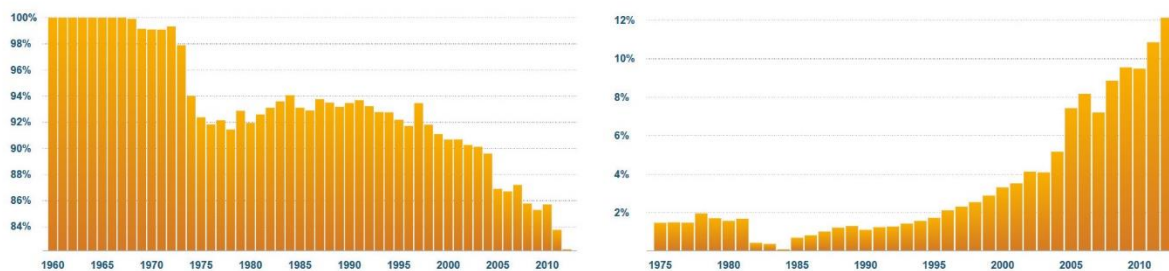


Figure 1.2: Electricity production from fossil sources (left) and renewable sources (right) in the Netherlands (Retrieved from HegiLibrary, 2015).

Renewable energy sources have grown quickly in many countries worldwide in the last decade. However, mainly due to their high direct costs and global increase in total energy consumption, the share of renewable sources in total generation-mix remain still small, and the cost competitiveness is still controversial (Borenstein, 2012; Reichelstein & Sahoo, 2015). The trend towards more sustainable energy production could be explained by a growing awareness of climate change related issues, the depletion of fossil fuel, concerns about energy security and the technological change. Technology has become one of the main drivers of economic and social development over the past decades, and also becomes more important in the trend towards more efficient energy systems (OECD, 1996).

Traditionally energy conversion was considered to be a **one-dimensional system**, where energy was converted from one form to another. Coal for example, is used predominantly to produce electricity and still is the largest source of energy for the generation of electricity worldwide (IEA, 2010). Heat was seen as a conversion by-product and was disregarded, and treated as waste. This nowadays is changing and heat recovery is more commonly applied, for example by the use of a waste heat recovery unit (WHRU). Also waste heat can be used for domestic space or water heating. This application is known as district heating and is often realised by use of a combined heat and power plant (CHP). The use of different energy sources and energy conversion technologies and the research into the different ways of integration, have potential benefits. These benefits include increased flexibility and more robust operation of energy systems (Hemmes et al., 2007).

During the past decades, the system for electricity and gas supply has gone through a process of **centralisation and scale magnification**. The liberalisation and privatisation of the energy market in the beginning of this century, caused many municipal and regional energy companies to merge into provincial power companies and shortly after they were incorporated by large international companies. Interestingly enough, parallel to the process of scale up and centralisation, more and more **local initiatives** have been started by consumers or small companies to take responsibility for a sustainable energy supply at a local level (Arentsen & Bellekom, 2014). Almost 500 local initiatives are existing in the Netherlands (van der Schoor & Scholtens, 2015). A couple examples include wind turbines at agricultural farms, solar panels on houses and the formation of larger consumer cooperatives that produce local energy, such as *TexelEnergie* or *Coöperatie Windunie* in the Netherlands. Consumers become prosumers and commence to fulfil a more ambiguous role in the energy system.

The energy landscape is changing rapidly. Geopolitical issues, fuel price volatility and strong market power of incumbent companies influence these changes. The emergence of decentral electricity production, a quick rise of intermittent renewable energy generation, but also the improved possibilities for storage and demand-side management are indicators of the energy landscape transformation. These developments can be seen as successes of energy policies (Slingerland et al., 2015), as they initiated and direct a radical transformation of energy systems.

1.2. Trajectory towards efficient and low-carbon energy systems

It is important to look into the drivers behind these changes and the supporting policies that demand higher energy efficiency. For example the European Union (EU) 2020 targets aims to encounter global climate change and to increase EU's energy efficiency and security. A 20% share of renewable energy sources, a greenhouse gas emission reduction of 20% and a **20% efficiency improvement** compared to the 1990 levels needs to be realised (Capros et al., 2011). Recently accepted climate and energy targets for 2030 are even more stringent and illustrate the ambitiousness of the EU and the apparent necessity to increase the efficiency of energy systems (EC, 2013).

To increase the efficiency of an energy system, source to sink efficiency must be increased. Electric power distribution & transmission losses in the Netherlands are around 4 % for the last forty years, but these losses could reach up to 30 % in developing countries like Cambodia (The World Bank, 2015). This indicates the potential efficiency gain is strongly dependent on local conditions.

The residential sector accounts for a significant share of the total national and global energy consumption. Nationally the residential sector is responsible for 16 - 50 % of the total energy consumption (Swan & Ugursal, 2009). The global average is approximately 30% whereas the built environment in the Netherlands accounts for 35% of the primary energy consumption (IEA, 2008). If we only look at the energy consumption of households, this accounts for 14% of the total national energy consumption (see Figure 1.3). When looking at communities as an agglomeration of households, it is good to keep these numbers in mind and put them in perspective of total energy consumption. Domestic energy demand has significant possibilities for improvements in efficiencies and therefore much of the recent research interest and effort has been focussed on this sector (Green, 2012).

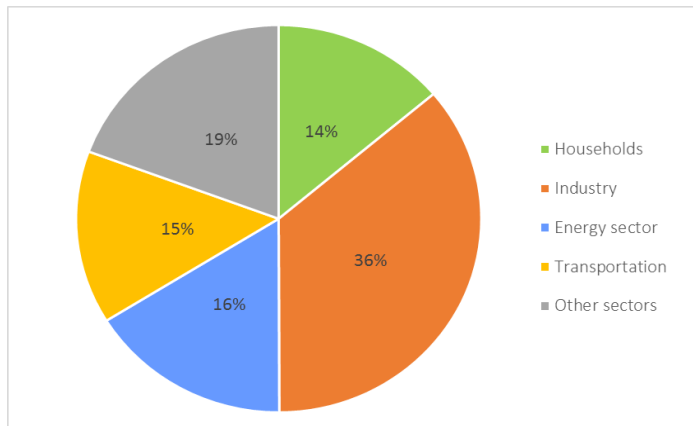


Figure 1.3: Energy consumption per sector in the Netherlands 2013 (data from CBS).

The decentralisation of energy production will increasingly compete with traditional centralised power plants. First of all the growing success of local initiatives may be accounted to the efficiency improvements of small-scale energy production. A cost reduction of these technologies makes them available to a larger group of consumers. Social factors such as the desire to make a contribution towards the establishment of a sustainable society, intensifies and accelerate this transition towards more efficient energy systems. Within the changing energy landscape it looks quite plausible to expect these distributed energy resources (DER) to continue to increase in the share of total energy production. The share of global electricity generation by DER increased from 15 to 24 % between the year 2000 and 2013 (Palazzi et al., 2014). DER is described as a combination of renewables (excluding big hydroelectric dams) and cogeneration of electricity and heat (e.g. CHP).

The changing of the energy system will require suites of interoperable technologies. Different technologies and technological developments need to complement each other in the most efficient way, to obtain maximum system efficiency. This applies to the transmission and distribution grids, where the industrial development of wind power technology must be kept up by the developments in the power grid. This also applies to the household level, where the rise of EV causes a substantial increase in electricity demand, requiring appropriate infrastructure for charging. These examples illustrate the importance of considering energy as an integrated system. Energy systems undergo a transition and the way we look at these systems changes. It is not self-evident that the current system is the only way we can organise our energy. Neither it is clear that it now provides the best solution for our energy demand, with respect to energy price, flexibility, environmental impact and diversification of energy sources. Will the need for more energy efficient systems push to more local, smaller energy systems or communities? At least community based energy systems offer a worthwhile alternative to the traditional fossil fuel based energy system (Hoffman & High-Pippert, 2005) and contribute to the reduction of energy consumption and carbon emissions.

1.3. Changing roles of actors in the energy landscape

The changes within the energy landscape bring about changes to all actors in the energy sector. This requires reconsidering roles and responsibilities, from end-users to grid operators and from energy supplying companies to policy makers. This chapter describes the major changes for the different actors within the energy landscape and how their role in future could evolve.

For a long time local **consumers** had no other role in the energy sector than using energy and paying their energy bills. This is changing as small scale local energy production becomes more common, more affordable and easier to install. The role of a **community** however is still unchanged and has in general no significant importance with respect to energy. This can change when local energy initiatives emerge within communities. Local energy initiatives are an outstanding example of the increased public influence through the direct involvement in planning, implementation and financing of energy systems. Globally there are possibly thousands of operational community renewable energy projects (Hicks & Ison, 2011). The emergence of more and more local initiatives indicate consumers are willing to move to the foreground and are prepared to actively take part in the energy system. Not only as individual consumers, but also as producers, investors and operators. This role is emphasised

by the increasing share of consumers that install sustainable energy technologies at household level or take part in any form of energy collective. The ownership of local energy systems can be arranged in different ways and can be one of the new roles of community and its community members. Community could be the total owner but co-ownership arrangements with private and public sector are also possible (Walker, 2008).

Along with this new role for consumers, the role of the traditional **energy supplying companies** and **network operators** has to be revised, to adapt to the new dynamics of increasing local production and changing demand profiles. If community energy systems will become more commonplace, and especially when they apply local balancing, demand response and energy storage, the role of DSO (distribution system operators) need to adapt. With many community energy systems operating on national scale, peak demand at the transmission or distribution level could be stabilised. **TSO** (Transmission system operators) and **DSO** obtain in that case more the role of balancing energy demand and supply among all connected communities. They are both responsible for the transport of energy from production site to demand side. As the flows of energy are no longer purely one-directional, different coordination and different infrastructural features are needed. Thereby increased (data) synchronisation between the different TSOs and DSOs is essential. **Aggregators** are responsible for the balancing of demand and supply between small customers. They can be seen as intermedator between electricity end-users and the system operators. To Price signals are used to motivate either demand or production adjustment. With an increasing share of DER and a growing number of local initiatives, the dynamics of the electricity network change. These changes need to initiate adjustments to the role of the aggregator. When energy is being organised at community level, new aggregation techniques need to be established (ETP, 2011).

Energy markets have been liberalised and online energy-trading spot markets develop, giving the consumer more flexibility to choose a specific energy supplier and energy contract. **Energy policy** has changed and will continue to be changed to accommodate market parties with guidelines on how to deal with consumers which also become (local) producers. Subjects that are being covered in energy policy are for example the issues related to energy tax restrictions and exemptions for local produced energy, renewable energy policy, responsibility for security of supply, pricing mechanisms to safeguard affordability for consumers and market coupling.

1.4. The gap and the need for ICES

Considering the changing energy landscape, the changing roles in the energy sector, the increased attention to energy efficiency and environmental concerns and the rising number of energy collectives, it is obvious the energy sector is undergoing a transition that is not likely to come to an end in the near future. Therefore it is useful to evaluate possible **future scenarios** and investigate the impact these scenarios could have on consumers. Local energy systems or **local energy communities** could be an answer to these transformations and changes within the energy landscape. However at present, there is little experience with the approach of energy communities in practice. A couple of examples of **local energy cooperatives** in the Netherlands are: *Coöperatie Windunie*, *TexelEnergie* and *Lochem energie*, but most collectives focus on the collective production or purchasing of (mostly renewable) energy by a group of consumers that not necessarily live in the same geographical area.

Other collectives focus on the smart-grid concept and use smart-meters and switchable appliances to manage and optimise energy consumption. However, most community based microgrids are still based on the old design paradigm, “you are either on the grid or you are on the backup” (Cartes et al., 2007, p. 4). Some collective also focus on the interaction between different types of energy. It is interesting to look into the combined ideas of integrated energy systems and local microgrid to Integrated Community Energy Systems (ICES). This provides insight in the contribution of ICES on the re-arrangement of future energy systems and especially the potential benefits for the participants of community energy systems. Existing energy system integration frameworks are recognised. Examples of new concepts are: virtual power plants (Morales et al., 2014), energy hubs (Orehounig et al., 2015) and micro-grids (Soshinskaya et al., 2014). These concepts focus on methods of complementing the centralised grid. These concepts, however, have their limitations when it comes to local community engagement. ICES has potential to this regard.

When local communities come together with the aim to manage their energy, the **roles of consumers within this community** will change. Consumers could have the option to trade their excess energy within the community. They become also energy traders which can decide to sell or buy energy from the community or from the national grid. A local (automated) marketplace is needed to facilitate energy trading among different community members. Various different strategies could be carried out, depending on the community energy system components and configuration. When there are multiple energy carriers, storage options and demand-response, this already gives the individual consumer (but also the community) a wide range of strategic options. The possibilities to exploit energy management within community are diverse. At present day this concept however is hindered by regulatory obstacles. It is for example not possible to operate your own grid, neither to obtain energy tax exemption.

Smart grid technology and energy management systems on community level need to function as some form of mediator between the local community and the central, national energy system (Arentsen & Bellekom, 2014). Insight in the energy potential within each community and the rate of demand predictability therefore will be essential. The development of a new mechanisms and institutional structures might be necessary to optimally integrate generation and demand at local level.

1.5. Research objective

Community based integrated energy systems offer significant potential benefits to both the national grid infrastructure and to the community itself (Cartes et al., 2007). These include grid performance improvements, and economic benefits for individual households. To what extent these benefits could realistically be utilised and attributed to households will be investigated.

We want to get insight in the parameters that are important for a community energy system. Important for a well-functioning community energy system, but also the parameters that are important for individuals that are part of the community. We want to find out what it means for the community members to be part of ICES. What is the contribution of different **generation technologies** and **demand profiles** at household level for the overall system performance? Do individual households for given **community preferences** experience different individual performance indicator outcomes? In other words: can certain consumer types have more benefits from being part of ICES than other consumer types? Community preferences can for example be financially or environmentally driven. We try to look further than purely financial benefits, because there could be other incentives that motivate people to become part of ICES. Does it thereby matter what technologies they install at their households or do their demand profiles have a larger impact on for example their total energy costs? Current trend show more and more renewable energy sources being implemented. Does this influence community performance in terms of costs and what does this mean for the individuals? The advent of EV also may influence the dynamics of ICES and possibly has a different effect on household within ICES than on households that are not part of ICES.

The idea of an **autarchic community** is often discussed and idealised. There are various reasons to be part of an energy autonomous community. There can be environmental or economic incentives or the remoteness of the village. Regardless of these incentives, we would look into the conditions under which an autarchic community can succeed. How much does it cost an individual to be part of it and what are the benefits?

This research uses a bottom-up approach and starts with the analysis of the different demand profiles, the available energy generation technologies and its typical production profiles. With these parameters the flows of energy within ICES can be studied to evaluate the impact of different technologies, different community preferences and different community compositions on ICES and households. An optimal solution set of technology mixes for the system is determined based on different community specific parameters, valued on their technical, economic and environmental impact. Such parameters are: the lowest costs, the smallest amount of energy import from the grid, flexibility provided to the national grid, or lowest CO₂ emission. Especially we are interested in the relation between those indicators for the community as a whole and for its individual households. We want to analyse how these indicators are related within ICES and how these can be used to optimize the system. Environmentally optimal is defined as having the lowest CO₂ equivalent life cycle emissions. Economical optimal is defined as having the lowest life cycle costs. Other cost aspects, such as capital investment and annual energy

costs, will be considered, since they might turn out to be obstacles for community members to actually become part of ICES.

These questions will be answered by developing a **model** in which different scenarios can be tested. Environmental and economic data serves as an input of the ICES model. We focus on data that is representative for the Netherlands, but the findings will be generally applicable to other countries as well. This analysis can be used for both conceptual systems and existing community systems. For example, to indicate if it is possible to reduce the amount of CO₂ emission, with minimal extra costs. In addition we want to analyse how costs and environmental impact relate to grid independency, reliability and flexibility to the grid. This will result in a selection of technology-mix which are optimal for given community composition and households demand profiles.

To study different performance indicators at two levels, a distinction is made between values for the total system and for the individual households. From this community overarching perspective we will focus on the individual households' performances. Therefore the **role of individual households within ICES** will be studied, as a renewing approach in looking at the dynamics of community energy systems. Past studies focus mainly at the role of the community as a whole and apply systems theory in which individuals all serve the higher goal of the system (e.g. Hemmes et al., 2007; Pelet et al., 2005). Thereby the **value distribution among community members** is being neglected. It might be true a certain community increases its GDP by energy related activities, but what happens to the distribution of the capital? An increase in the spread of the distribution of wealth in a community unavoidably leads to friction. As far as the author's knowledge, there is no analyses on the change of value distribution within communities, based on a specific technological mix in the open literature. Therefore this topic is an interesting research component and also relevant within the development and prospects of ICES.

1.6. Research scope

Since ICES multi-source multi-product energy systems, covers such a wide variety of different fields, the fields of research and the system boundaries must be determined precisely. To measure the value of a product, a service or a system, economic performance is always an important criteria. Corporations and individuals are interested in the costs and benefits of a product or service. Therefore an economic analyses will be part of the research into the household performance within ICES. Furthermore technology plays an important role in our society, and this is expected to increase even more with technological progress and digitalisation of society (Risto Linturi, 2000). To fulfil the energy needs of the households within ICES, different technology is available on the market. We will take into account a selective variety of these technologies. Another aspect that needs attention is the environmental impact. As described in paragraph 1.1 and 1.2, the awareness of climate change related issues is growing. We are therefore interested in the contribution a community has on the emission of CO₂, one of the major pollutants and contributors to anthropocentric climate change and global warming.

This thesis will focus on the economic, technological and environmental aspects of ICES although we will touch some other aspects, to describe how societal and institutional aspects contribute to the development in ICES.

The focus lies on the energy flows and balance within the ICES, where households play a central role. Only electricity and heat flows are considered and other types of energy are not taken into account. All costs associated with the energy use are analysed from the consumer perspective.

1.7. Research questions

This thesis project will be guided by the following main research question:

Given the present available set of technologies, to what extent may ICES contribute households to become energy autonomous and reduce their carbon footprint at affordable costs?

In which

- *ICES* comprehends the number and type of households, the demand profiles, the resource availability and the operation mode of ICES;
- *the available set of technologies* is used to select the best suited mix of distributed and local conventional and renewable technologies, which leads to optimization on costs, CO₂ reduction and energy autonomy.

In order to answer the main research question, three sub-questions have been formulated. These will support and give structure to the research project. Each sub-question is elaborated in detail.

1. What are the constituents, drivers and barriers of ICES?
 - i. What are technical, economic, social and institutional factors that are important for assessing ICES? (e.g. technologies, costs, CO₂ emissions, capacity and grid exchange.)
 - ii. What is the role of the different actors within ICES?
 - iii. What are the distinct community preferences for ICES?
 - iv. What are the available generation and energy management technologies for ICES and their corresponding techno-economic parameters?
 - v. What are the benefits of ICES for household consumers?
2. What is a suitable decision framework for determining an 'optimal' technology mix for given community preferences?
 - i. How to make a selection of technologies that should be considered during the assessment?
 - ii. With the selected technologies, how can a proper procedure be defined to optimally match demand with supply at specific community preferences?
3. Under what conditions and in which scenarios is it attractive for households to be part of ICES?
 - i. What is the impact of high RES penetration or CO₂ minimisation on households?
 - ii. What is the impact of high EV penetration or stationary storage on households?
 - iii. What are the effects of different household compositions within ICES on costs, emissions and energy autonomy for community and for households?
 - iv. Under what conditions can autarchic communities succeed?

1.8. Thesis outline and structure

This thesis is structured as follows. In **chapter 2** the research methodology is presented, including a literature review to identify knowledge gaps and to position the work described in this thesis, relative to the literature. The necessary background framework for ICES is provided in **Chapter 3**. Also this chapter looks deeper into the applications, drivers and barriers of ICES. The interactions within the community are being explored on economic, technological and environmental aspects. **Chapter 4** describes the model and the way it is applied to answer the research questions. With examples of optimal technology mix selection and household clustering the model structure and process is explained. The model scope and components are described. The performance of ICES (and households in particular), is illustrated in **Chapter 5** and is indicated for different optimisation conditions and different scenarios. **Chapter 6** elaborates on the model results that lead to the discussion section. In **chapter 7** the conclusions are formulated in answer to the research question. Also the recommendations for different actors, the assumptions and the academic relevance are described. The chapter concludes with recommendations for further work on ICES.

Chapter 2: Methodology

2.1. Modelling energy systems

Energy systems are complex systems, consisting of many elements that interact with each other. The different components are often interdependent on each other. To get a grasp on the implications of the interdependencies in these complex systems, energy models are a useful tools to provide valuable insights. From these insights conclusions can be drawn, with regard to the energy system and to its components. Future energy demand and supply can be influenced by energy models, which are used to stimulate policy and technology choices.

Energy models are most often used to project future energy demand and supply in an exploratory manner. Usually the developments of boundary conditions over time is being estimated or assumed in modelling future energy systems. These boundary conditions are for example: the development of economic activities, demographic development, energy prices on world markets, energy efficiency policies (Herbst et al., 2012) or the demand for more renewable energy sources. Every energy model is an abstract of reality, because of its assumptions and approximations. There is a trade-off between the level of detail and the level of deviation from reality, caused by approximations. A model needs to approach reality with enough detail to get the complexity of the required results. The level of detail in the model output should correspond with the degree of certainty about the input parameters. "Energy models ... at best provide a good approximation of today's reality" (Herbst et al., 2012).

A literature research has been performed to obtain information and data on community energy systems as well as on modelling energy systems. Since the scope of existing models differs to some extent from the created model, reports that describe other energy system models are used. The insights are adapted to fit the scope and purpose of the constructed model. Also data on household energy profiles, provided by Essent, is used to validate model results. Data on historical energy prices is retrieved from the APX Power NL exchange database (APX Power NL, 2015). This data is used to ensure realistic energy prices as model input. Also the deviation in the historical energy prices is used to analyse its impact on ICES performance. Other information was collected from TU Delft databases and scientific databases, such as Scencedirect and Scopus.

In order to answer the research questions, a quantitative model of an ICES is developed in MATLAB. The advantage of this tool is its ability to handle large sets of data and the option to perform complex calculations. Large datasets of all different production- and demand-profiles are easily handled by MATLAB. Because modelling is the basic research method, the largest part of the research is assigned to the different modelling steps. The modelling steps that are followed are: data collection and model conceptualization, model validation and testing, conduct experiments and analyse simulation results (Law, 2005).

Community energy systems models can be divided into two categories: "top-down" and "bottom-up". In the top-down approach, a larger system is divided into its underlying components, to gain insight into the compositional sub-systems. The bottom-up approach is constructed in the opposite way; combining sub-systems to build a more complex system. The bottom-up approach was developed to point out the contribution of each individual component (household) towards a larger system. This view improves the understanding of the details at household level (Swan & Ugursal, 2009). Therefore we choose to use the bottom-up approach to calculate the energy flows of individual households and then zoom out to community level and analyse its multi-perspective performance.

The analyses of different scenarios provides insight in the impact of different developments at community level on individual households within ICES. Thereby the ICES model considers scenarios such as the community composition of different types of households, the impact of high renewable penetration and the impact of EV penetration. These results provide valuable insights that can be used by policy makers, to create favourable conditions for the development of ICES.

2.2. Stakeholder analysis

A stakeholder analysis is performed to identify the key actors for ICES and to assess their knowledge, interests, positions, alliances and importance related to the development of ICES. It is a tool that provides the means to address the associated policy implications. The stakeholder analysis gives more insight in the actors, their interests and how they are affected by the implementation of community energy systems. The stakeholder analysis elaborates on the stakeholder mapping.

The methodology process (including modelling and stakeholder analyses) is illustrated in Figure 2.1. The literature research is concentrated at the start of the project, although it is an ongoing process throughout the research track.

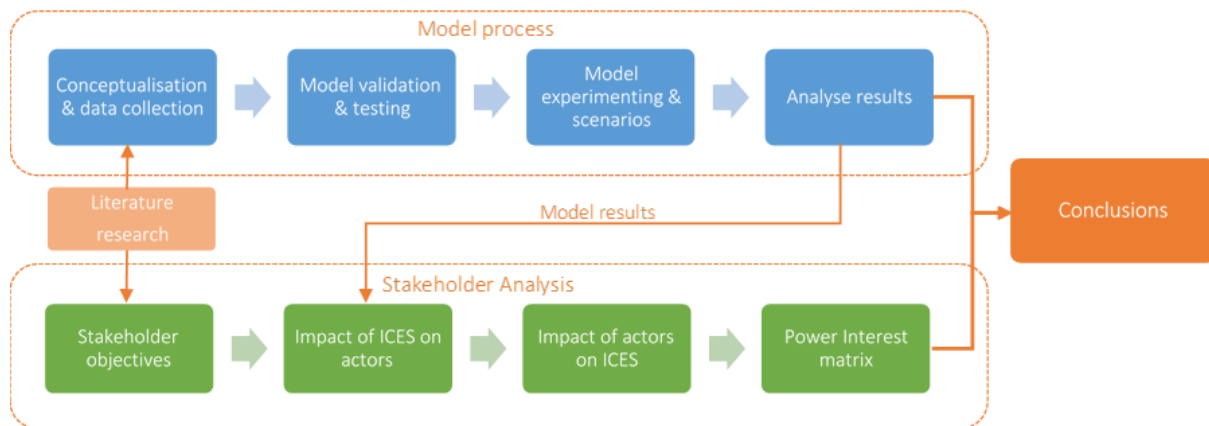


Figure 2.1: Research methodology process

The stakeholder analysis framework is derived and adapted from methods and literature on stakeholder analyses (Bryson, 2004; Enserink et al., 2010). Slight modifications are made to make the analysis more suitable for examining energy systems. The four steps of the stakeholder analysis are explained below.

Stakeholder objectives:

Objectives describe the directions in which stakeholder would like to move. Their general interests are described by more specific goals and interests. Objectives may change more quickly whereas objectives are relatively stable. Actors most of the time have clear objectives, and use these as a measure to judge the system performance. The main objectives are described for the actors that are used in the ICES analysis.

Impact of ICES on actors:

The impact ICES has on the different actors is examined. How would the actors respond to the emergence of ICES? To what extent may model results influence the position of actors? To answer these questions, results from the ICES model are used to conclude whether they would support or oppose the development of ICES.

Impact of actors on ICES:

The other way around, actors also have the power to affect the development of ICES. This influence can be constructive, but also actors can hinder the development of ICES. The impact actors have is dependent on their power to be able to influence ICES (resources, connections with other actor groups, public support) and on their interest in the emergence of ICES (for example to expand their market or improve their profit).

Power Interest matrix:

A power-interest matrix is used to present the results of the previously described steps in the stakeholder analyses. This helps comparing the different stakeholders and their position to influence the development of ICES. Above all, the matrix will support us to classify the stakeholders into the ones with significant importance and the ones that can be left out of account in the further assessment of ICES.

Chapter 3: Background framework

3.1. Integrated Community Energy Systems

3.1.1. Exploration of ICES concept

Integrated Community Energy Systems (ICES) is a broad and flexible concept of how to look at all facets of energy within a community. By means of its flexibility, ICES is able to accommodate energy technologies of the present day, but also the next generation energy technologies. This makes the concept of ICES very powerful for conceptualising or assessing future energy systems. ICES can be described as a development of the concepts of distributed generation and micro-grids combined. ICES tries to link those two concepts in a multifaceted approach, and aims to find an optimal utilization of the energy requirements of a local community. This optimum should be seen in the scope of energy efficiencies, economic, environmental and social aspects. The network approach of micro-grids is applied to connect all energy systems into an Integrated Community Energy System.

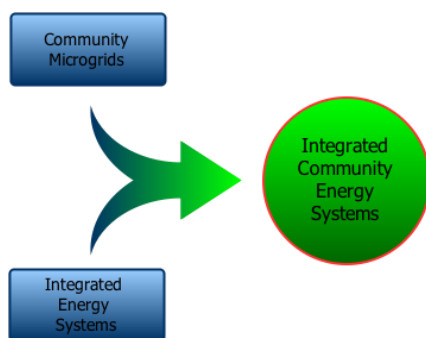


Figure 3.1: ICES as Integrated Energy Systems concept combined with a community micro-grid vision.

ICES emerge as a novel way to organize local energy systems, where besides the energy system integration also the engagement of communities at the local level is emphasized. A community is a group of households in the same local area, connected by an energy infrastructure such as the electricity grid.

The principle of Energy Systems Integration (or Integrated Energy Systems), is applied to analyse the interactions and interdependencies among the different energy flows at all scales; from national and regional level to communities and end users. Generally this energy flow consist of electricity, thermal and fuel services, but integration is increasing between other systems, such as data and information networks and water systems (Kroposki et al., 2012). ICES is more specific and restrains its scope to the energy system at community level

In principle ICES covers the complete package of energy streams in a community, which consists for example of electrical, mechanical and thermal energy. This is different from micro-grids, which do not cover the total energy needs of a community, but are typically limited to the field of electricity. Micro-grids can be seen as a small-scale power supply network, build with the purpose of providing electricity to a small community (Gupta & Gupta, 2015). A micro-grid technically can be described as a low-voltage electricity distribution network that is located at community level, downstream of a electricity distribution substation (Su & Wang, 2012). Examples of building integrated micro-grids are presented by Sechilariu et al. (2013). In most literature ICES is prescribed to manage electricity, heat and cold supply to small or medium sized communities. ICES provides electrical and (in addition to the micro-grid paradigm) thermal energy. The energy demand can be fulfilled with the supply from a wide range of renewable energy technologies, Combined Heat and Power (CHP) or Combined Cooling, Heat and Power (CCHP) complemented with innovative energy storage solutions (Mendes et al., 2011). In order to organise the energy flows within ICES, an energy management system is important. The energy management system is based on Information and Communication Technology (ICT). Control and coordination across the energy pathways is made possible by monitoring, control and the integration of data and information networks within the energy system (Kroposki et al., 2012).

ICES originated back from the late 1970s, when the energy crisis made clear that the energy system of those days was not functioning optimal. One of the first scientific researches on this topic dates back to the 1970s, when Holtz (1977) published his paper on the possibilities of grid connection of an ICES.

In ICES many different energy technologies can be combined for different implementations, covering energy generation, transformation, consumption and storage. ICES is able to complement energy sources, in balancing energy production with energy demand. Households become 'prosumers' instead of 'passive' consumers and start to play a more important role in the community energy landscape. Energy generation and storage opportunity at household level are examples of this transformation. Since the concept of ICES is not limited to any type of energy production nor any type of energy consuming service, this gives access to a large variety of different energy sources and consumers. The specific types and numbers of producing and consuming units will vary, depending on the needs and characteristic of the community. This gives a great flexibility, but increases the complexity of the system, since all components are interconnected and interrelated.

Lerohl (2012) described all different sectors, such as electricity, heat, transportation, waste, water and land use, that can be combined to ICES. In this research we focus mainly on energy supply and distribution (electricity, heating and cooling) and partially on transportation (electric vehicles). Looking at current trends, these types of energy integration in community are nowadays prevailing (St. Denis & Parker, 2009).

Moreover ICES is best seen as a whole system concept that includes multi-level knowledge, design, financing, analysis, construction and maintenance of the complete energy system. It incorporates the long term utilization of a community's energy needs (Cartes et al., 2007). ICES covers a wide variety of different fields, and operates at various physical, institutional and social levels. At least we can indicate ICES involves technological implementation, economic consideration and environmental issues. Furthermore these are all subject to social and institutional settings. This classification of ICES related issues among different areas is presented in Figure 3.2.

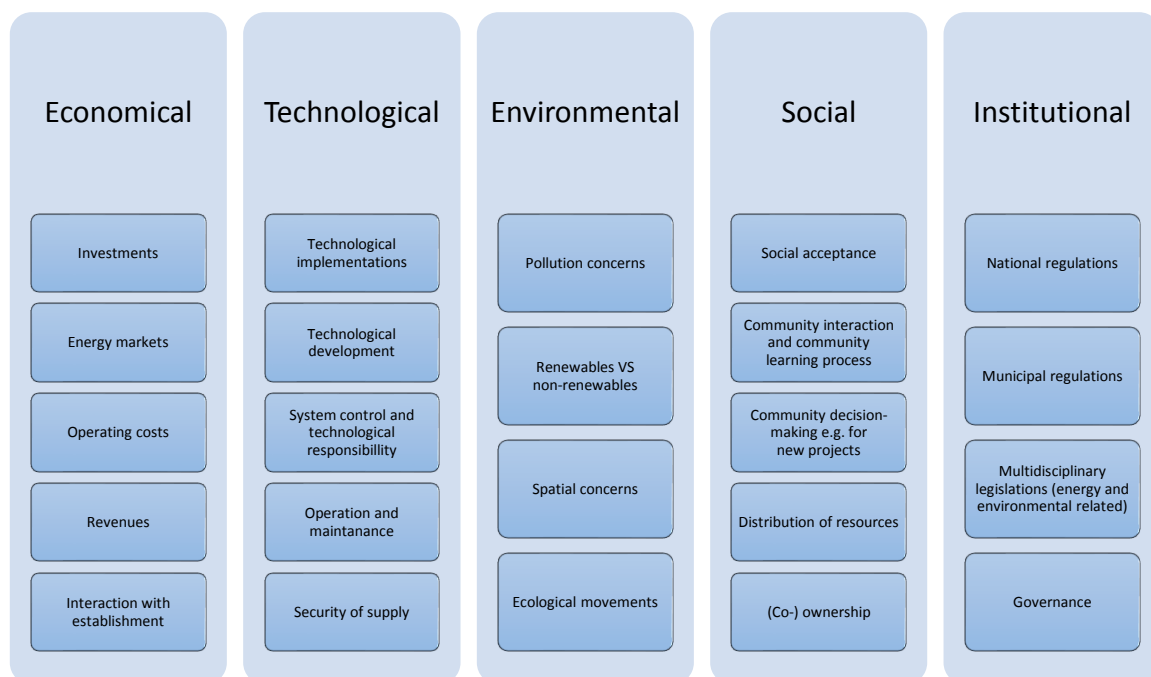


Figure 3.2: ICES related issues per sector

Because a variety of different fields is involved in ICES, there are also many actors and stakeholders engaged. This can lead to complications and difficulties, in the sense that a larger and more diverse group of stakeholders is more likely to have different opinions and interests. ICES may at first sight appear to be the ultimate solution in the local energy transition, however there are some problems that have to be solved first. Among these, ICES has

to deal with economic aspects, such as path dependency and lock-in effects. In many aspects ICES have to face tensions, controversies and institutional problems (Koirala et al., unpublished).

Besides these multi-level and multi-actor aspects, ICES distinguish themselves as units of the total (national) energy system. This was already mentioned by Holtz (1977) when he examined different grid connection options for ICES. Physically the grid connection is the ICES system boundary. This is the place where energy exchange with the electricity grid is possible. Grid connection however is not necessary for ICES to operate. Isolated systems are possible, for example in rural areas and remote communities, where no grid connection is available. The two different modes of operation of an ICES are called grid-connected and islanded mode.

3.1.2. Principles and examples

ICES describes local and community driven projects concerning the total energy system within the community. Where ICES have various connections with other systems, the main focus in this research lies on the interrelations among different energy sources and technologies within the community level of the energy system. These also contain the different producers within the community, the different types of end-users and the actors that are responsible for the distribution or storage of energy.

The idea of the integration of different technologies and different energy forms within a local and collectively organised energy system, is described in literature also with different terms than ICES. The used term is often dependent on the author, the region the system operates, or just the acceptance of a name for the system. Some examples are: Energy Sustainable Communities (ESCs) (Schweizer-Ries, 2008), self-organized energy community, community micro-grids, multi-energy systems (MES) (Mancarella, 2014) or the energy hub approach (Orehounig et al., 2015). Two examples of realised ICES are presented briefly.

The **Strathcona County Community Energy System (SCCES)** is an example of a realised ICES and has been operating since November of 2006. This ICES is set up in Sherwood Park, Strathcona County, Alberta, Canada (Lerohl, 2012). This project is the first Business Case of a collaborative network of organisations (gas and electric utilities, technology and infrastructure industries, public society groups, community leaders and researchers). SCCES provides both space heating and domestic hot water to ten community buildings. Natural gas is used as the fuel to heat the water. The focus of SCCES lies on efficiency gain by using a centralized heating system.

Feasibility challenges were indicated by (Lerohl, 2012):

1. Large capital investment associated with debt, challenging the likelihood of attaining cost recovery.
2. Policy approaches associated with establishing new customer connections to the system. The voluntary customer connection policy has left the SCCES with lower demand than expected and thereby reduced the financial viability of the project. Thereby the cost recovery extended from 15 to 22 years.

Another example of ICES is located in **Saint Paul, Minnesota, U.S.** and operates since 1983. (Kenneth W. Smith, 2010). This system serves heat, cooling and part of the electricity demand of 200 buildings. With 300 MW total installed thermal capacity and CHP electric capacity of 33 MW, this is North America's largest district heating system. The concept is shown in Figure 3.3.

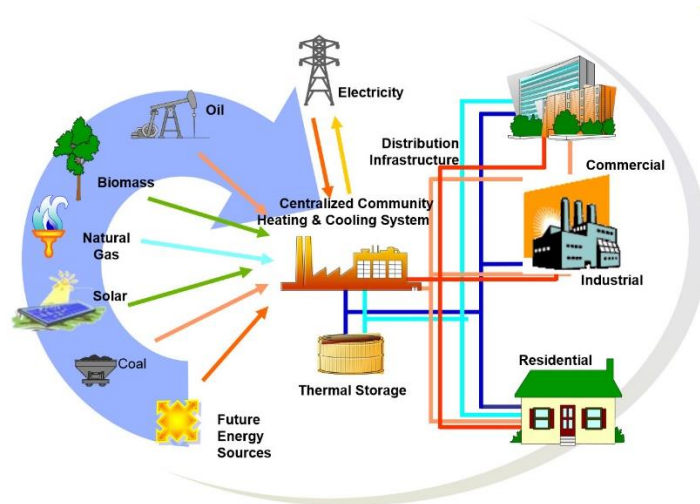


Figure 3.3: Saint Paul district energy (Retrieved from Burns, 2010).

The system is privately owned and provides energy security, stable costs and a carbon emissions reduction (Kenneth W. Smith & Rancone, 2014). Customers save 20 to 25 % on energy consumption (DESP, 2007)

Keys parameters to a successful energy project were described to be:

- Match production size with energy demand and fuel availability.
- Locate production facility near thermal load.
- Use CHP to maximize efficiency and generate extra revenue.
- Design the producing facility for high plant reliability and availability.
- Community engagement will help to smoothen the development process.

Feasibility challenges were indicated by (Kenneth W. Smith & Rancone, 2014):

1. Investment risk. This was initially transferred to customers through a lengthy agreement (30 years contract). A more attractive contract lead to a much better result and more participants.
2. Converting costs for existing systems. Helping customers to convert existing heating systems can be an important (marketing) incentive to sway customers, especially those who own older buildings.

3.1.3. Drivers and barriers

From the mentioned examples of ICES, **political leadership** and **community engagement** appear to be of great influence for an ICES to become successful. This concerns the question: “How to encourage community members to be part of ICES and what mechanisms can be used to engage them?”

Community engagement can be driven by different motivations. These motivations are: environmental concerns, disappointment with the current centralised system, a desire to become self-supporting and for economic reason. In common the initiatives emphasize a concern about the future and they share the ambition to make a difference by local action.

Also in both ICES example cases, the **capital investment** was experienced as a barrier to overcome. A solid business model, efficient production technologies, adequate project management as well as long term policy are needed to attract enough investors. Besides the barrier of high investment costs, insufficient policy support hinders the development of ICES. Further aspects that play a role are the government regulation (renewable energy targets) and industry standards, public opinion, energy price development, and carbon pricing.

3.2. Interactions, interdependencies and the role of individual households

Within complex systems such as ICES, where multiple energy products and sources are operating, interactions and interdependencies are inevitable. This thesis aims to get insight into these interactions and interdependencies. For a single household with a grid connection this is quite uncomplicated. When there is more energy consumed, the carbon emission increases proportional and the energy costs increases as well. The latter increment depends on the applied pricing structure, in which for example the distinction between fixed and variable costs. When multiple households form a community the interactions become more complex.

Interdependencies occur at all levels of the energy landscape. For ICES we focus on the interdependencies within community and its households. At community level for example, all community members with solar PV and solar thermal installed will experience less energy production from their installation during a day of low solar irradiance. Subsequently other energy sources need to increase their production. This affects the cost of energy production, the total carbon emission and the remaining flexibility options. Interdependencies also occur within multi-source energy production units, such as CHP or fuel cells. Each appliance has its typical efficiency, depending on the operating point and power-to-heat ratio. Changing either the thermal or electrical output power of a CHP or fuel cell will affect the efficiency. These are examples of interactions and interdependencies that should be considered when looking into the different components that are implemented in a community energy system.

Households that are part of a community energy system (such as ICES) have a different role and have different options for organising their energy compared to isolated households. Individual households can use energy storage, demand response and deploy their unused production capacity to support the community in its energy needs. This is only interesting if it also benefits themselves. The idea of community energy systems has been studied and examples of realised pilot projects are discussed in section 3.1.2. The ambiguous role of households in such a system however is not completely evident and needs further exploration. Besides the benefits of being part of a collective system, there must be individual benefits as well, before ICES can become successful.

3.3. Uncertainties

The drivers and barriers described are factors that influence the development of community energy systems. For many parameters it is uncertain how they will evolve, even in the near future. Fossil fuel prices, energy policies, technology breakthrough and consumer perception are hard to predict. The accelerated nuclear power phase out in Germany after the March 2011 Fukushima nuclear disaster, the immediate phase out in Japan but also the current considerations to restart nuclear power show strong and unpredictable dynamics (Times, 2015).

Also the current trend of individuals to be part of an energy corporative could be deflected in the near future. Will it still be attractive for individual end users to be part of a community integrated energy system? Or will the development of renewable energy technologies undermine the necessity to be part of a corporation to receive maximum benefits? Also the development of policies and community based paradigms is hard to foresee. An increase in individualism is observed in modern society, which seemingly contradicts with the community ideology. Yet, it is hard to predict which movement will dominate. In either way it is useful to explore the opportunities of community based energy system, as this will provide individuals with the details to argument for or against participating ICES.

3.4. Stakeholder mapping

Stakeholder mapping is useful to gain insight in stakeholders' influence. It gives a classification of the different stakeholders in matrix form. The power stakeholders hold is mapped to the level of interest they have in supporting or opposing developments. The matrix representation helps recognising stakeholder influences on the development of strategy and shows the relation between the following importance issues (Johnson et al., 2005):

- How much each stakeholder group is interested in the emergence of ICES.
- Whether or not stakeholders have the power to be able to influence ICES.

Within ICES the **community members** form the centre of the community. Within this research, they are the **problem owners**. Their role and interest is versatile and diverse, and depends on their preferences and interests. Within the context of the development of ICES, we assume that ICES formation is initiated from individual level. This could be attributed to different reasons, such as cost minimisation or emission reduction. The interest of households therefore is high. However, their influence as individuals is very low but when integrated in communities, their power increases. Within community various energy technologies can be incorporated. We'll distinguish and map these technologies from household perspective.

Consumers which operate **distributed generation**, such as solar and wind energy, have a good position to exercise power, on two levels. Firstly, the operators of these technologies run at low marginal costs, and offer strong competition to traditional supplying generators. Secondly, the local users of these technologies offer lowest carbon emission for communities. However, the power they can exercise is limited because of the intermittency of these energy sources and the fact that the financial performance fluctuates with strongly with the policy and subsidy changes. The power of CHP and fuel cell owners to influence the system is quite limited, because their share in the energy mix is small. Their interest in influencing the advance of ICES is also limited, because although their efficiencies are quite high, they still use mostly fossil fuels. When biogas or nitrogen use is applied, they might receive more influence on ICES, since the carbon emission will be reasonably lower.

Non-intermittent and large scale energy sources, such as hydro-energy and deep-geothermal energy are dependent on the geological location and are not suitable for each community. Their influential power and level of interest is relatively low, but this will change when more value is being given to renewables. **Biomass** is dependent on fuel supply and fuel prices but has a stable and controllable output, in common with hydro and geothermal. It has a better application perspective within communities and offers low carbon and reasonable controllable power. Their level of interest is moderate, but their power is not very strong since its carbon pollution is higher than the emission of solar and wind. The public opinion is not always in favour of biomass, as for example the discussion food crops versus energy crops is ongoing (Zhang et al., 2010). Although this source is more accessible than hydro and geothermal, local use of biomass for energy production at household level is rare.

Owners of **EV** have high interest in ICES when this provides them additional benefits with respect to the case when they are not connected to the community energy system. This benefits are mainly financial. Their power is still small as their total installed capacity is still low, although the individual installed capacity is relatively high. They can offer interesting functionalities to the community, such as demand response. This makes EV supplementing intermittent renewables also interesting for other actors, such system operators. This increases the power of EV.

The contribution of **fossil-fired power plants** to the global energy demand is decreasing, but their power is significant, since they are (still) responsible for the majority of the energy production (World Energy Council, 2013). Thereby their energy is reliable and the technology is mature and proven. Furthermore they have extended expertise and knowledge of the energy sector, large financial assets and extensive connections throughout the energy landscape. However, their power and interests are drifting, in response to public opinion (on environmental issues) and energy policy. In the near future, they will remain important for supplying energy during demand peaks and during hours of low intermittent renewable production. Their capability to affect the shaping of ICES and influential policy is considered medium to high.

Energy suppliers are getting more interested in the dynamics of community energy systems, as there lay options for smarter and innovative energy contracts. Also more and more energy suppliers engage in the energy management within households nowadays. To do so within communities is only one step further. Since these companies are the only participants in the energy market that have direct contact with the consumers, they have significant power to influence ICES development. Energy management service is also offered by independent **energy service companies** (ESCOs). ESCOs get engaged in energy reduction projects, to develop, design, construct and finance projects to reduce energy consumption and energy costs at household level. Their knowledge is valuable for ICES, since energy reduction management serves both cost reduction and carbon reduction.

The **system operators** (DSO and TSO) have significant power, since they are responsible to balance demand and supply at regional and national level. A change in the way energy distribution is managed locally will certainly influence the position and the role of the system operators. Thereby they have also large interest in influencing the way ICES are organised in such a way this will be beneficial for them as well. For the development of local energy communities DSO has more interest as long as the impact will remain at regional level. If the development also will influence the national level, this also becomes of interest of TSO.

When groups of consumers organise their energy as a collective, their net demand statistically becomes more predictable and the individual peaks are smoothed by the collective. An **aggregator** is an energy service providers between the utility and the consumers that is able to manage demand during peak hours by demand side management. The aggregator's objective is to shave the aggregated peak demand and to support the system operators in supplying steady power to end users (Babar et al., 2013). Within ICES the households give permission to the aggregator to manage their consumption patterns in the optimal way, to maximise the profits while respecting the constraints imposed by each individual household. The household does not change its behaviour, but let the aggregator optimise the load pattern of larger appliances, such as washing machines or EV. For ICES, the aggregator will fulfil a key-role between the community members and the system operators. Their interest is high, because they can seize an important position in the development of ICSE. Aggregators have already knowledge of managing demand patterns and can apply this expertise to ICES. If they manage to gain control of many communities nationally, they can be of great value to TSO, providing options for increasing network stability. The larger the amount of households and communities they serve, the larger their added value to the system and the larger their power.

The highest power belongs to the **government and policy makers**, that have the power to change legislation, directly or indirectly influencing the advantages or RES (e.g. by feed-in-tariffs). This has a large impact on the possibilities and potential of ICES. An example is the liberalisation of the energy market that offered the incumbents plenty of opportunities to expand beyond the borders of their former supply areas and opened the market for new players. Also CO₂ policy is a tool regulators make use of to steer development of energy systems. A favourable policy will attract more investors.

Ecological movements have low power, but they are able to influence public opinion. Their interest however are high, since they are supporting more efficient and more sustainable energy systems.

The different actors are mapped in the power-interest matrix in Figure 3.4 below.

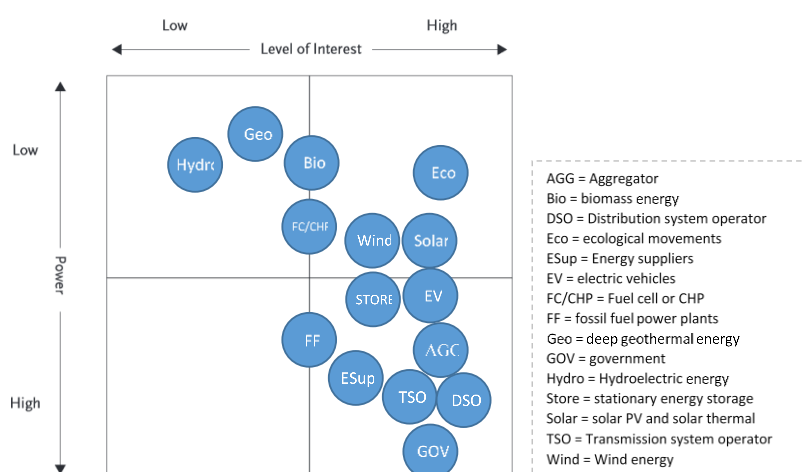


Figure 3.4: Mapping actor dependencies: power/interest matrix (Adopted from Enserink et al., 2010; Johnson et al., 2005).

3.5. ICES technological components

The selection of technologies that will be implemented in the ICES assessment are based on two criteria. Firstly we look at proven technologies that are already prevailing in domestic energy generation. Next we also look into the results of the stakeholder mapping. With these outcomes, a selection of different technologies that will be taken into account in the assessment of ICES is made. The selection is also based on technology diversity and energy efficiency. Thereby no highly similar components are implemented together and inefficient components will be excluded. Technologies that have a high level of interest in the power-interest matrix will be included. Also technologies that are able to increase or decrease their output in response to the actual energy demand are implemented, to provide flexibility at household level. Very site specific options like geothermal or hydro energy will not be implemented, to keep the research more suitable for generic communities. Components that will be considered are listed below and described into more detail in section 4.4.

Production technologies

- Wind turbine
- Solar PV
- Solar thermal
- CHP and FC

Energy storage components

- Solar thermal storage in boilers
- Electrical storage in batteries
- Electric vehicles

These technologies will be used to (partially) fulfil energy demand at household level. At community level, energy exchange between households is used to supply the amount of energy demand that could not be fulfilled within each household. Different demand profiles will be considered at household level, to represent different household compositions. Seasonal variation is considered by using four different seasonal demand profiles per household type. This will increase the level of detail of the ICES model results as well as it emphasises the effect of seasonal variation on renewable energy production. Hence it contributes to energy diversity within ICES.

Chapter 4: Implementation and application of the ICES model

4.1. Model scope

The ICES model analyses different indicators, such as energy costs, CO₂ emissions and energy autonomy, and focusses on the performance of households within ICES. The model boundary is set at the community border. Processes that take place outside the community are not considered in the ICES model, with only two exceptions. Electricity can be exchanged with the national grid and natural gas serves as fuel for household level central heating systems, fuel cells and CHP units. The model is easily adaptable to different fuel types, if for example local produced biogas becomes more abundant and also more economically attractive. The ICES model boundary is represented by the red dashed line in Figure 4.1. The energy exchange between different households within ICES is visualised.

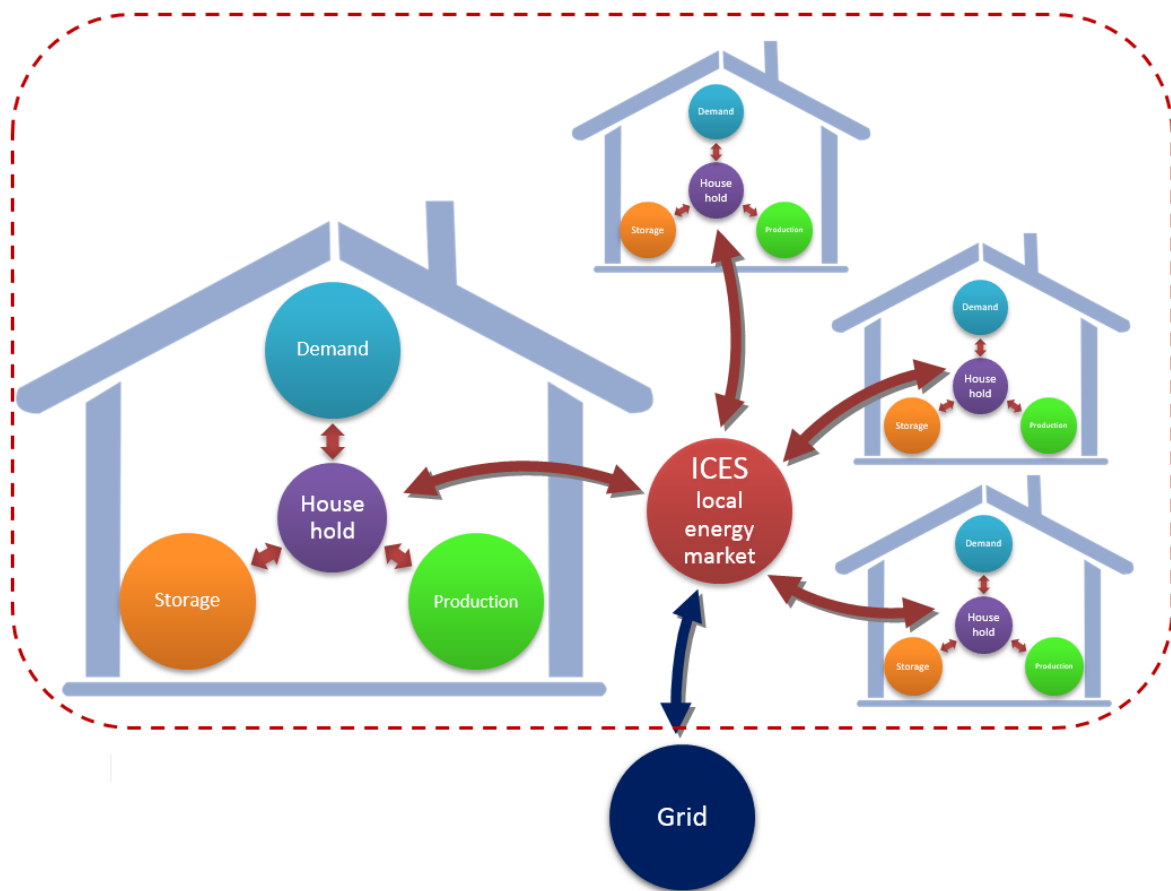


Figure 4.1: ICES model conceptualisation

Different production and storage technologies are implemented, with their specific techno-economic characteristics. Given the type of analyses, a particular level of detail is needed. The purpose of the ICES model however is not to analyse the performance of a specific component in the highest possible detail. A micro-system level model is used to get better understanding of the system effects of community energy systems. The ICES model gives a good and thorough estimation at household and community level, but detailed factors such as temperature dependent performance and the decrease of efficiency over lifetime are being neglected.

The ICES model can be used to obtain insight in the energy related performance of individual households as well as communities. For example in analysing economic efficiency and carbon emissions. The model of ICES, as a conceptual future energy system, gives quantitative analysis on the performance of such an energy system. This tool could also be used by real estate developers of residential areas, in cost-benefit calculations or in finding the

optimal community structure for becoming as low carbon intensive as possible. Even people who want to build their own house, can use this tool to analyse the effects of applying different local energy technologies.

4.1.1. Economic analyses using levelised cost of electricity

Economic parameters are used to calculate households' energy costs. Hourly varying input parameters are used and results are presented as annualised costs and revenues per household. Energy costs can either be expressed as cost per installed capacity (€/kW) or cost per unit of electricity generated (€/kWh). The latter is also referred to as levelised cost of electricity (LCOE). The LCOE is commonly used to compare the costs of electricity production from different sources. It is a measure of the average costs of electricity over the lifetime of a generating technology (DECC, 2013; Hearps & McConell, 2011; Parra et al., 2015). In addition this approach is easily understood by residential consumers (households), since their energy bill is commonly reported in costs per kWh. Therefore the economic performance of households (and the installed technologies) within ICES is accessed using the LCOE approach. Since the LCOE approach is widely used, literature can be used to validate the calculated levelised costs. The LCOE of a particular generation technology is the ratio of the total capital and operating costs of the production technology to the amount of electricity expected to be generated over the lifetime of the production technology (DECC, 2013). The LCOE approach involves three steps:

1. Determine life-cycle costs: including investment costs, operation and maintenance cost and fuel costs;
2. Estimation the total energy generated by the system over its economic lifetime;
3. Divide the life-cycle cost by the energy produced by the system.

$$LCOE = \frac{\sum \text{costs over lifetime}}{\sum \text{electricity produced over lifetime}} = \frac{\sum_{t=1}^n \frac{I_t + OM_t + F_t}{(1+D)^t}}{\sum_{t=1}^n \frac{E_t}{(1+D)^t}} \quad (\text{Eq. 4.1})$$

It is assumed the same amount of energy is being produced in each year during the lifetime of the technology and that this calculation does not include aspects such as financing issues, inflation effects or degradation costs. However since performing a life-cycle cost analyses, two aspects need to be taken into account:

1. The assessment of investment costs over the lifetime. This is done by using the capital recovery factor.
2. The time value of money for future cash flows. This is done by use of discounting.

To assess the investment costs of a technology over the lifetime of a project, the **capital recovery factor** (CRF) can be used. The CRF converts the present value of a technology into a collection of equal annual payments over the lifetime, at a specified discount rate or interest rate. The CRF is calculated by (Eq. 4.1).

$$CRF = \frac{D(1+D)^n}{(1+D)^n - 1} = \frac{0.03 \cdot (1+0.03)^{20}}{(1+0.03)^{20} - 1} = 0.067 \quad (\text{Eq. 4.2})$$

For example, an investment of € 1000 today is converted to 20 annual allocations of € 67, resulting in a total costs allocation of € 1344. However, since future allocation is discounted, the sum of this annual allocations in future value is equal to the NPV of this investment. Only when assessing a specific year, the CRF needs to be considered.

The **discount rate** (D) should represent the opportunity cost of a project relative to other investments and could be reflected by interest rates. Since interest rates are decreasing over the last years, in our analyses a lower discount rate is used than most older literature describes (Oxera, 2011). This is because the discount rate is strongly related to the interest rate, but reduced by the inflationary estimation losses over lifetime. The discount rate is estimated at 3% (Rushing et al., 2013) and a lifetime of 20 years is considered. The discount weight per year is given by (Eq. 4.3) and is calculated per year over a 20-year lifetime in Table 4.1.

$$d_t = \frac{1}{(1+D)^t} \quad (\text{Eq. 4.3})$$

With the determined discount rate and lifetime, the discount weight factors per year are elaborated. A cost or revenue of € 100 in year 10 is worth the same as a cost or revenue of € 77 at present day value. This shows to what extent the net present value of future revenues and costs will decrease over time.

Table 4.1: Weight factors per year

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Discount rate	1	0.97	0.94	0.92	0.89	0.86	0.84	0.81	0.79	0.77	0.74	0.72	0.7	0.68	0.66	0.64	0.62	0.61	0.59	0.57

O&M and fuel costs are discounted over the lifetime by theory of discounted cash flows, since future costs and benefits need have a lower value than costs and revenues in the present day. Discounting expresses costs and benefits that occur in future comparable by expressing their values in present terms. The net present value is the sum of the discounted present value of each year over the lifetime and is calculated as follows:

$$NPV = \sum_{t=1}^n DPV_t = \sum_{t=1}^n d_t \cdot (OM(fv)_t + F(fv)_t) = d_1 DPV_1 + d_2 DPV_2 + \dots + d_n DPV_n \quad (Eq. 4.4)$$

This results in the following LCOE formula, which considers total capital costs and discounted annualised O&M and fuel costs during the lifetime of the project.

$$LCOE = \frac{I_{TOT} + \sum_{t=1}^n DPV_t}{\sum_{t=1}^n E_t} \quad (Eq. 4.5)$$

Table 4.2: List of economic parameters

Symbol	description	units
I_t	Investment costs in year t	€
I_{TOT}	Total investment costs	€
OM_t	O&M costs in year t	€
F_t	Fuel costs in year t	€
E_t	Electricity generation in the year t	kWh
D	Discount rate	%
d	Discount weight factor per year	%
n	Expected lifetime of the system	years
t	Year to calculate cost in	years
fv	Future value	€
pv	Present value	€
DPV	Discounted present value of O&M and fuel costs	€

4.1.2. Carbon emission analyses

Environmental aspects are getting more and more attention at global as well as at local level. In the Netherlands, cities want to reduce their carbon footprint or even want to become energy-neutral. Almere (2022), Groningen (2035) Eindhoven (2045) Nijmegen (2045) have the target of being climate neutral, while Rotterdam wants to reduce their carbon emission by 50% in 2025, compared to the levels of 1990 (RCI, 2012). Since cities are formed by communities, action must be taken at community level if CO₂ emission reduction and energy efficiency improvements is to be achieved. Without doubt (new) communities in the near future will have stricter carbon emission restrictions.

The ICES model analyses the carbon emission per household and for community. Emission factors of fossil fuel are used. For renewable energy sources, lifecycle carbon emissions are used from literature. The average emission factor per kWh of the Dutch national grid is used for electricity imported from the national grid. Carbon emission is allocated at consumption side. This implies that when energy is exported or traded, also the corresponding carbon emission shifts from the producing household to the household that consumes the energy.

4.1.1. Energy autonomy

The energy autonomy of a household indicates the level of its ability to fulfil its own energy needs by local production. Although energy autonomy is a rather normative definition, it is more easily being quantified than its fundamental criteria. One of the underlying principles of energy autonomy is energy security, or security of supply.

This criteria is one of the three goals for energy policy (TFUE, 2007) and one of the main targets within the energy sector. Since the first oil crisis, energy security is gaining increasingly more awareness (Scheer, 2007). In a society which is becoming more and more dependent on energy, energy security (and thereby also energy autonomy) becomes more important. In this research we present the energy autonomy ratio as a factor between 0 (all energy is imported) and 1 (all energy is produced local). Even when a household produces more than it consumes, the energy autonomy is still considered to be 1, since all of its demand is produced locally. Table 4.3 illustrates the energy autonomy calculation per household.

Table 4.3: Energy autonomy example

	Demand	Local supply	Energy autonomy
Hour 1	10 kW	1 kW	10 %
Hour 2	2 kW	2 kW	100 %

Excess energy can however be stored, to increase energy autonomy if this energy is used at times the household has higher demand than local production. The second example illustrates the energy autonomy calculation with storage included (Table 4.4). In the calculation, two options were explored. First the energy autonomy was calculated at each hour of the day, and for a daily energy autonomy factor, the hourly energy autonomy value were averaged (Eq. 4.6). However, since the quantity of energy demand varies during the day, these calculation results diverge from the actual total energy autonomy ratio. The total energy autonomy calculation uses total demand and production numbers, and is expressed by (Eq. 4.7). This brief examples show the deviation is significant in cases where demand fluctuates.

$$\text{Energy autonomy (average calculation)} = \frac{100\% + 10\%}{2} = 55\% \quad (\text{Eq. 4.6})$$

$$\text{Energy autonomy (total demand calculation)} = \frac{1 \text{ kW} + 2 \text{ kW}}{10 \text{ kW} + 2 \text{ kW}} = 25\% \quad (\text{Eq. 4.7})$$

Therefore total energy production and demand are taken into account for daily and annual energy autonomy calculation, while hourly based energy autonomy will be used to analyse instantaneous performance. The annual energy autonomy be calculated using the sum of annual production and demand (Eq. 4.8).

$$\text{Annual energy autonomy} = \frac{\sum(\text{annual local production} - \text{annual export})}{\sum \text{annual local demand}} \quad (\text{Eq. 4.8})$$

Because we set the maximum value for energy autonomy to 1, we need to take into account the excess energy that is being stored. This is done on hourly basis, by using a positive value for battery contribution when energy is being stored, and using a negative value for battery contribution when energy is being extracted from the battery. On daily basis the battery contribution levels out when an equal amount of energy is being stored and extracted. The difference between hourly average method and total demand calculation is shown in (Eq. 4.8) and (Eq. 4.9).

Table 4.4: Energy autonomy example with storage

	Demand	Local supply	Storage contribution	Energy autonomy
Hour 1	5 kW	9 kW	+ 4kWh	100 %
Hour 2	10 kW	6 kW	- 4 kWh	80 %
Hour 4	10 kW	2 kW		20 %

$$\text{Energy autonomy (average calculation)} = \frac{100\% + 80\% + 20\%}{4} = 50\% \quad (\text{Eq. 4.9})$$

$$\text{Energy autonomy (total demand calc.)} = \frac{9 \text{ kW} + 6 \text{ kW} + 2 \text{ kW}}{5 \text{ kW} + 10 \text{ kW} + 10 \text{ kW} + (4 \text{ kW} - 4 \text{ kW})} = 68\% \quad (\text{Eq. 4.10})$$

The calculation method for energy autonomy in our model, considering battery storage, is expressed by (Eq. 4.11).

$$\text{Annual energy autonomy} = \frac{\sum(\text{annual local production} - \text{annual export})}{\sum \text{annual local demand} + \sum \text{storage contribution}} \quad (\text{Eq. 4.11})$$

4.2. Selected scenarios and indicators

The performance of households within ICES is examined using performance indicators such as: energy costs, total energy production, carbon emission, energy autonomy etc. With these performance indicators, the overall techno-economic performance of an ICES can be evaluated. The results can also be used to compare the performance of different communities.

Different communities have different characteristics and different views on how they value community performance. In order to analyse ICES performance, we look at different characteristics and scenarios in the light of the different community preferences. To make a benchmark comparison, we compare community performance with a base case scenario. The **base case scenario** is defined as the scenario in which the energy is being supplied from the national grid to the average Dutch households. Traditionally electricity is being supplied through the distribution network and heating is provided by a central heating system with a gas boiler. When mentioning central heating systems during this research, we refer to a household level heating system. Although district heating systems are also existing, they are not widely available. In the Netherlands, large scale district heating systems (*stadsverwarming*) and small scale district heating systems (*blokverwarming*) combined have a 7% heat connection market share on the total of 7 million gas connections for central heating (GasTerra, 2012).

Within the detailed information at household level, we are interested in the insights to be obtained from relations and dependencies of parameters that could play a role for communities. These parameters are: energy costs, environmental impact and energy autonomy. Assuming that individuals and communities act rational and pursue utility maximisation, financial incentives are always of importance. Environmental aspects are gaining more and more attention in society and thereby also within communities. These environmental incentives urge communities to reduce their carbon emissions. When carbon taxing or carbon pricing will get more expensive, these incentives might converge. This effect will be studied in one of the examined scenarios. Some communities also want to become energy independent and therefore strive after grid energy import minimisation. Other communities want to achieve the highest possible renewable energy penetration. This preference at first hand looks similar to the environmental incentive, but there are interesting differences that need to be examined. A high penetration level of wind and solar will generate sufficient energy for peak demand during the daytime. However, for fulfilling the energy needs during periods of low intermittent renewable energy availability, there need to be back-up capacity available that contribute substantial to overall carbon emission. Grid is often considered as back-up option. However, with high penetration of distributed energy resources, grid electricity prices could be very high during peak-demand. Smaller transmission line capacity would be needed, since less demand needs to be supplied by the grid. Grid capacity will reduce when assets are adapted to the increased utilisation of distributed generation technologies. This results in higher prices during peak-demand, since the grid supply reaches its limit sooner because of its reduced capacity.

The distinct **community preferences** are:

- Financial incentives: Minimise energy costs
- Environmental incentives: Minimise CO₂ emission. Highest goal: become climate neutral.
- Energy autonomy incentives: Minimise energy import. Highest goal: become autonomous.

Within the community, we will look at **different types of households** and take into account their different seasonal heat demand profiles. The implemented household types are:

- One adult
- Two adults
- Family
- One or two Pensioner or unemployed

Although an average household is difficult to find in reality, it is a useful concept in terms of analysing the energy performance for specific types of households. In addition the different household types will be used to study variations at community level. According to the current figures and the future perspectives of the Dutch household composition, **community compositions A and B** are defined. These represent the current situation and the outlook of the year 2045 (CBS, 2013, 2015). The forecast is that the number of households as well as the composition of different types of households will stabilise after 2045. That is why we choose this year, even though it is far ahead. The other reason is that data from earlier years (e.g. 2030) shows less deviation from present data, making results less interesting. To extend our research, composition C looks at a more extreme scenario and considers no stabilisation takes place after 2045. Instead, the forecasted trend of household composition within the Netherlands between 2015 and 2045 will continue. This assumes the large majority consists of one-person and retiree households. Composition D represents a uniform distribution of household compositions within a community. The four types of households and the community composition scenarios are presented in Table 4.5.

Table 4.5: Community composition scenarios

	One adults household	Two adults household	Family	Pensioner(s) or unemployed
Composition A (2015)	25 %	25 %	40 %	10 %
Composition B (2045)	30 %	20 %	20 %	30 %
Composition C (prolong B)	40 %	10 %	10 %	40 %
Composition D (uniform)	25 %	25 %	25 %	25 %

To increase the understanding of the impact of different factors on ICES performance, different scenarios are distinguished. These **scenarios** characterise a particular community and indicate for example the size and composition of a community. The following scenarios will be studied and compared with the base case scenario:

1. Community size to study scale effect
2. Distribution of different types of households
3. High or low EV penetration scenario
4. High or low stationary storage scenario
5. The impact of carbon pricing
6. The impact of non-producing households

The first two scenarios relate to the composition of households and community. The 3rd and 4th scenario relate to the implementation of two upcoming technologies. The 5th scenario looks into the impact of carbon pricing, which may become more influential in future. To extend the application of the ICES model, the impact of non-producing households is studied by the last scenario. Non-producing households could be represented by low-income households that do not have the financial resources to invest in distributed generation technologies. It is evident this list can be extended with numerous scenarios. A balance between the number of scenarios and the interpretability of results is sought-after. The selected scenarios will provide a comprehensive selection of results.

To monitor the performance of the different households within the community, different indicators need to be defined. These performance indicators will be used to analyse the impact of the described distinct community preferences. A good way to visualise the results will be the use of a matrix or table, which make interpretation of multiple indicators easier. For individual types of households, the following **indicators** are distinguished to quantify their performance:

- Energy costs and revenues
- Emission factor
- Energy self-sufficiency rate (or surplus deficit ratio)

The Energy self-sufficiency rate is defined as the ratio between energy output and energy consumption. This number is associated with the energy autonomy described in section 4.1.1 and is expressed as a percentage. The ratio may be calculated for each individual household or for the community in total. A rate over 100% indicates a production surplus in relation to demand, and therefore net energy export.

Furthermore grid capacity is not infinite and therefore other options to supply community energy needs should be considered. Additionally the relation between the energy price and carbon emission is interesting. When system components are not chosen optimally, this relation gives perspective for efficiency improvement without proportional additional costs. The most ideal set of solutions can be used to compare a system with other possible system configurations. This functionality can be used as a tool to show how a specific ICES performs in relation to the optimal set of system indicators, being optimized on multiple parameters. Thereby it is possible to indicate a certain system can be more carbon efficient with minor additional costs.

4.3. Model structure

While assessing the performance of households within ICES, the performance of each individual household needs to be evaluated first. Therefore the model uses of two step approach. Both steps will be explained in more detail.

1. Find optimal technology mix at household level, for the different household compositions.
2. Construct ICES from a set of optimised households and analyses results.

4.3.1. Household level

Whereas the ultimate goal is to assess the performance of households within ICES, one need to understand the flows of energy within one household first. The first step in the model, processes the different demand profiles of a household and combines different technologies to fulfil this demand as optimal as possible. This is done by combining a large number of technological assets and evaluating the model results. The different technologies are listed in section 3.5 and explained in more detail in section 4.4.2: Production components. The optimisation preferences are explained in section 4.2: Selected scenarios and indicators. With the variety of implemented technologies, approximately 800 unique combinations are possible per household. Performance indicators are mapped for each set of technological combinations. We only consider electricity exchange between community members and therefor heat demand should be sufficiently supplied at household level. For each system configuration, the output parameters are stored, to be used in the second step of the model. The output section of Figure 4.2 shows for example the relation between energy costs and carbon emission per produced kWh of a specific household, by applying different energy technologies. The red dot specifies the results for the base case scenario. With the model results, one could quantify the costs associated with a certain carbon reduction or an increase in energy autonomy. Each type of household (with its specific demand profile) will have an optimal technology composition for each optimisation preference. The different types of households are explained in section 4.2: Selected scenarios and indicators.

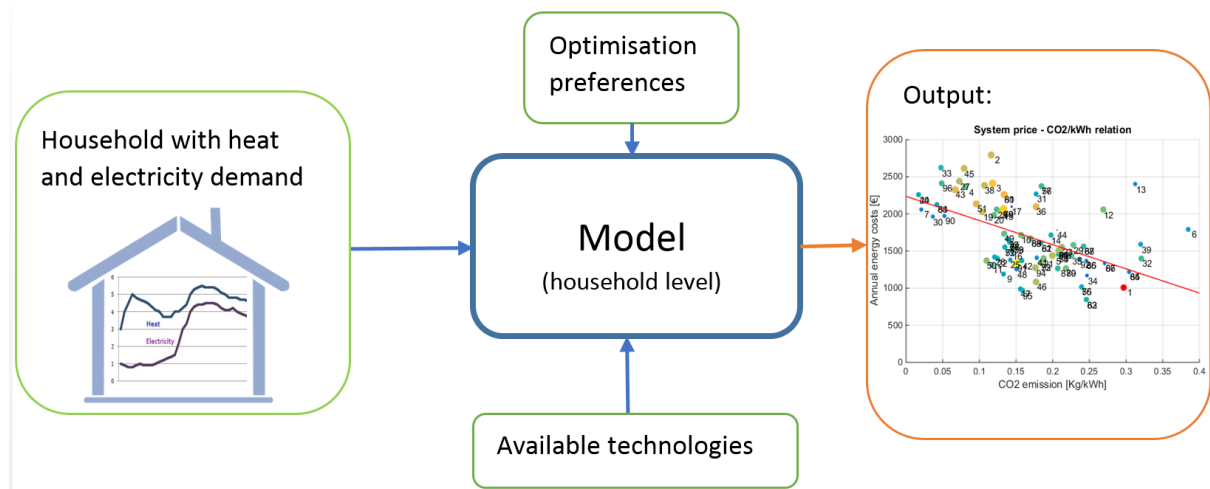


Figure 4.2: Model concept at household level

The model structure at household level is presented in Figure 4.2. Each time the model runs, a new system configuration is generated, containing the selected household type with its demand profile and a randomly generated technology mix. All generated configurations with its subsequent performance indicators are stored. The stored parameters are listed in Appendix A: System configuration vector - stored household parameters. After running the model for many times, a good indication of the impact of different technologies on the performance indicators can be made. From this results, the optimal set of technologies will be selected for each optimisation preference. These optimal configurations are used as input for the ICES level model. The successive steps of the model at household level are presented in Figure 4.3 below. To make optimal use of the available energy resources, the use of the selected technologies is performed in a fixed sequence. This sequence is embedded in the household level model step “Randomly combine different technologies” and is listed below:

- Utilise energy from renewable sources
- Charge EV (if EV is implemented)
- Locally store excess energy (heat and electricity)
- Use CHP or fuel cell to fulfil heat and electricity demand as much as possible
- Import energy deficit from grid and export excess energy to grid

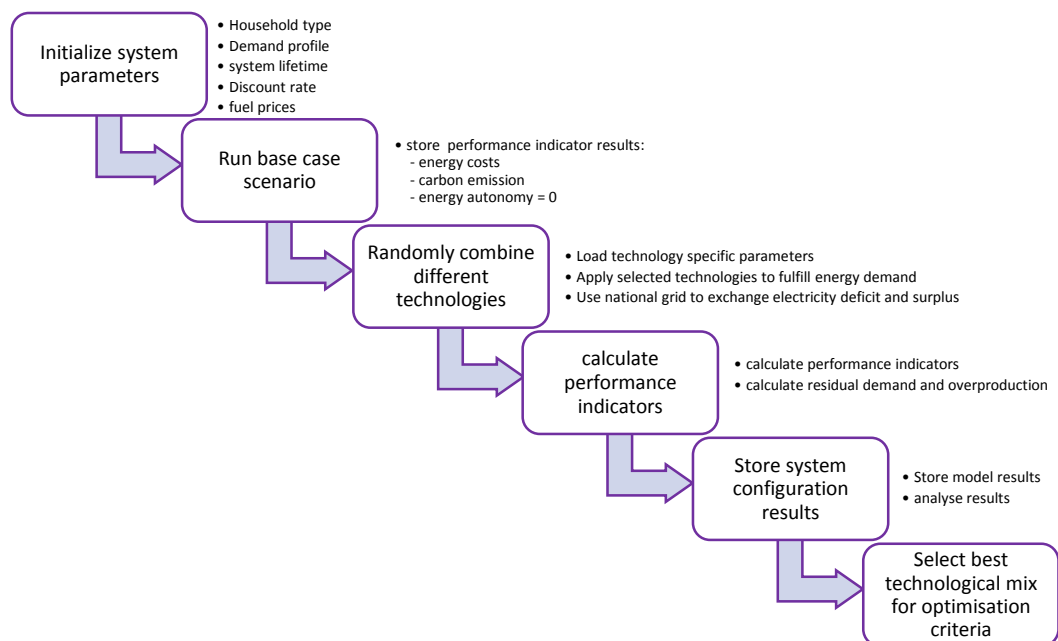


Figure 4.3: Model structure at household level

4.3.2. ICES level

After choosing the optimal combination of technologies for each type of household, these households will become the input for the sequenced model step. Now the focus shifts from household level to the community level of the energy landscape. The households with their optimally selected technological assets are combined to form an ICES. All stored household parameters are loaded into the ICES profile. This profile contains the residual demand and supply functions from each individual household. Residual demand is defined as household initial demand minus its local production. An example of household net energy results (residual demand and overproduction) for a selection of seven households is presented in Figure 4.4

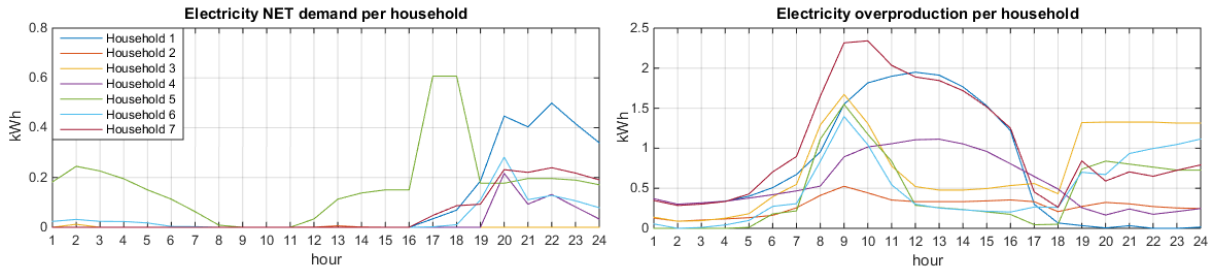


Figure 4.4: ICES net energy flows

ICES enables the use of excess energy, distributing it amongst the households that need it. This generates financial benefits and environmental gain for community members. The ICES energy exchange platform facilitates the distribution of energy among community members. The demand that could not be supplied locally (neither at household level nor in any of the other ICES households) needs to be imported from the national electricity grid. To analyse the different performance indicators, the stored parameters for costs, carbon emission and energy autonomy are loaded for each individual household. The model structure at ICES level is presented in Figure 4.5. Figure 4.6 shows the intersection of the two model parts in a simplified ICES model representation. For each household composition and system configuration (numbered from 1 to n), household level output parameters are input parameters for the ICES level model. The exchanged data between the two model parts consist of the residual electricity surplus and deficit as well as various performance indicators, such as energy costs, CO₂ emission and energy autonomy per household. To study the impact of ICES on households, ICES performance indicators after applying ICES will be compared with the initial performance indicator results.

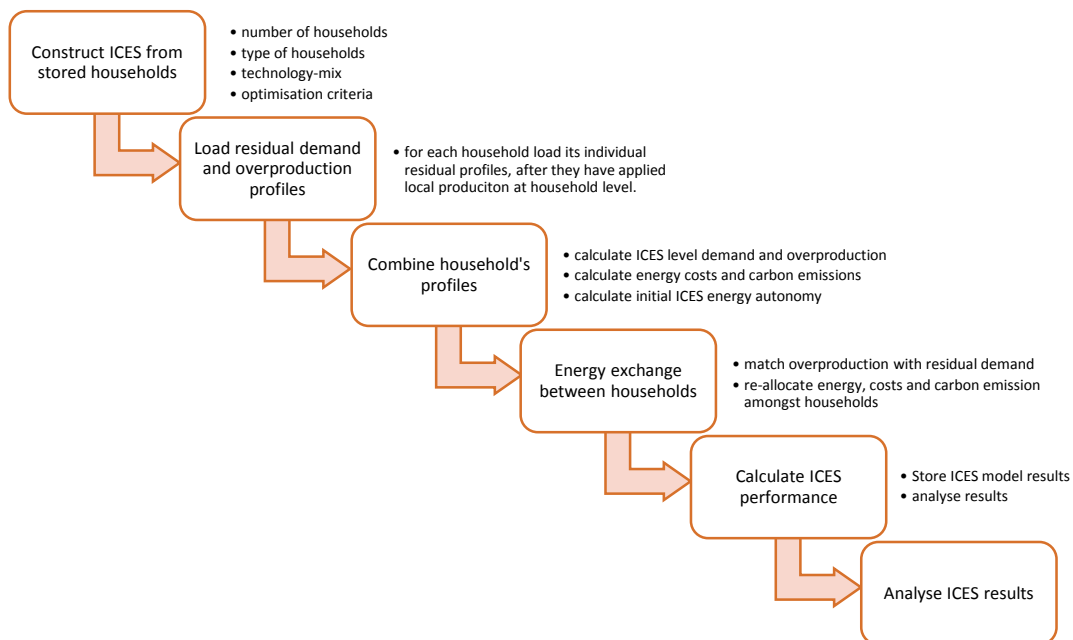


Figure 4.5: Model structure at ICES level

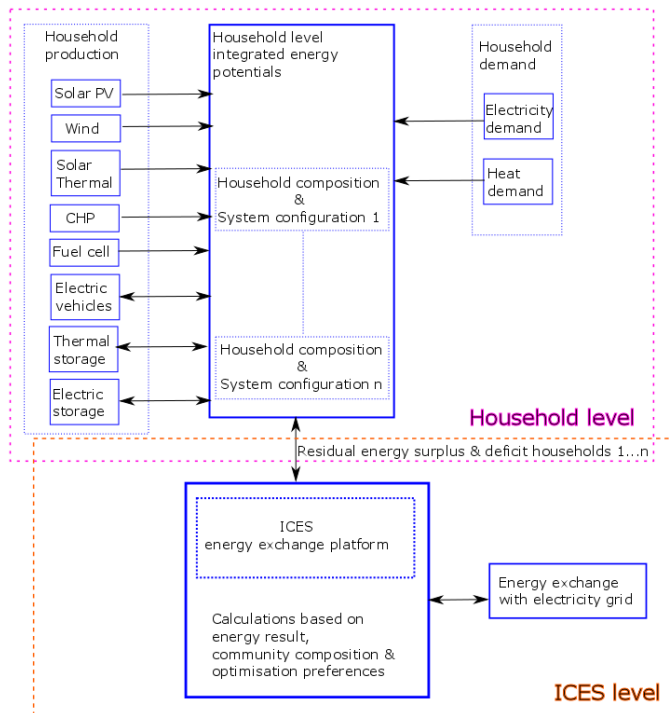


Figure 4.6: Complete model structure

4.4. Model components

4.4.1. Households' energy demand

In this research we focus on the energy consumption of households, the end users of the energy system, for both electricity and heat. Although we focus on household level of community members, the diversification among its underlying appliances will not be mapped. Energy demand is defined as the sum of respectively heat and electricity demand and covers all energy-using activities in a household, including space and water heating, cooling, lighting and the use of electronic appliances. Heat demand consists of the sum of all heat demanding possibilities. No distinction between the different heat demand characteristics is considered. This means the energy from all heat producing components can be used to supply heat demand at any time.

The different types of consumers that will be researched are representative for the most common compositions of households in the Netherlands (CBS, 2013, 2015). These different household types are: one adult, two adults, a family and a household with one or two pensioners or unemployed.

Four types of consumers will be considered and seasonal variations will be taken into account. Figure 4.7 illustrates considerable seasonal divergence in heat demand profiles and also in total energy demand. Electricity demand profiles show little seasonal variation for each respective household composition, as illustrated in Figure 4.8. Data is being used from a demand profile generator, that generates electricity and heat demand profiles (Strathclyde, 2015). The units are in kWh in both seasonal demand plots. Distinction is made between summer days, winter days and spring/autumn days, considering spring and autumn have relatively similar demand profiles.

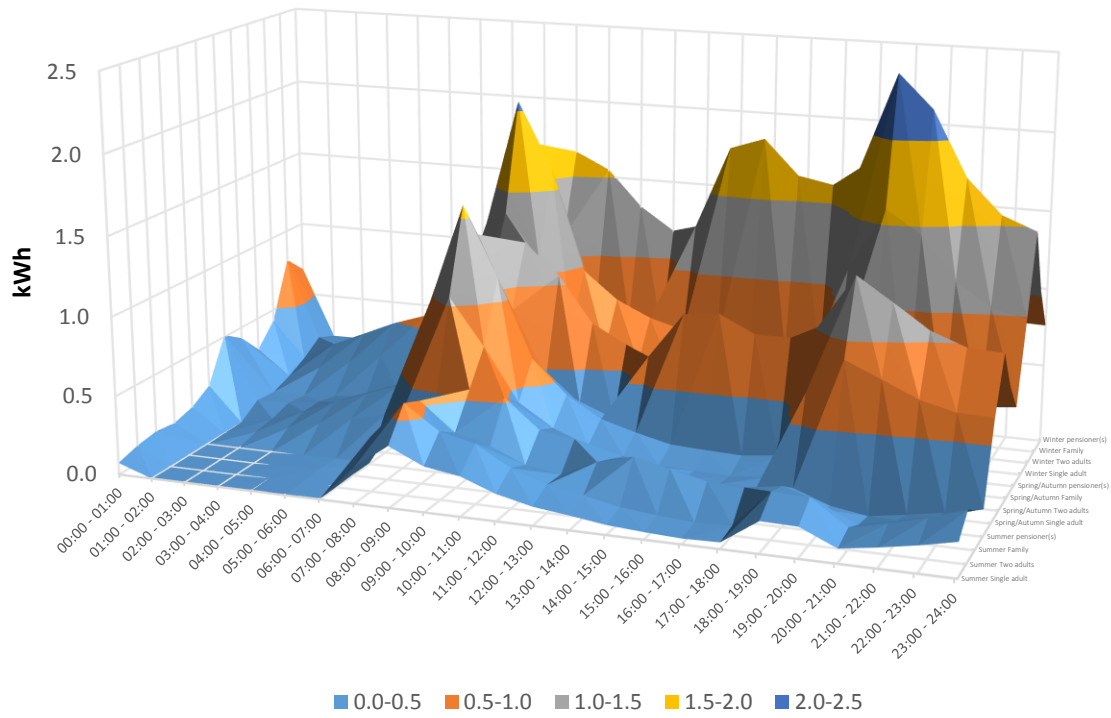


Figure 4.7: Seasonal heat demand by household composition

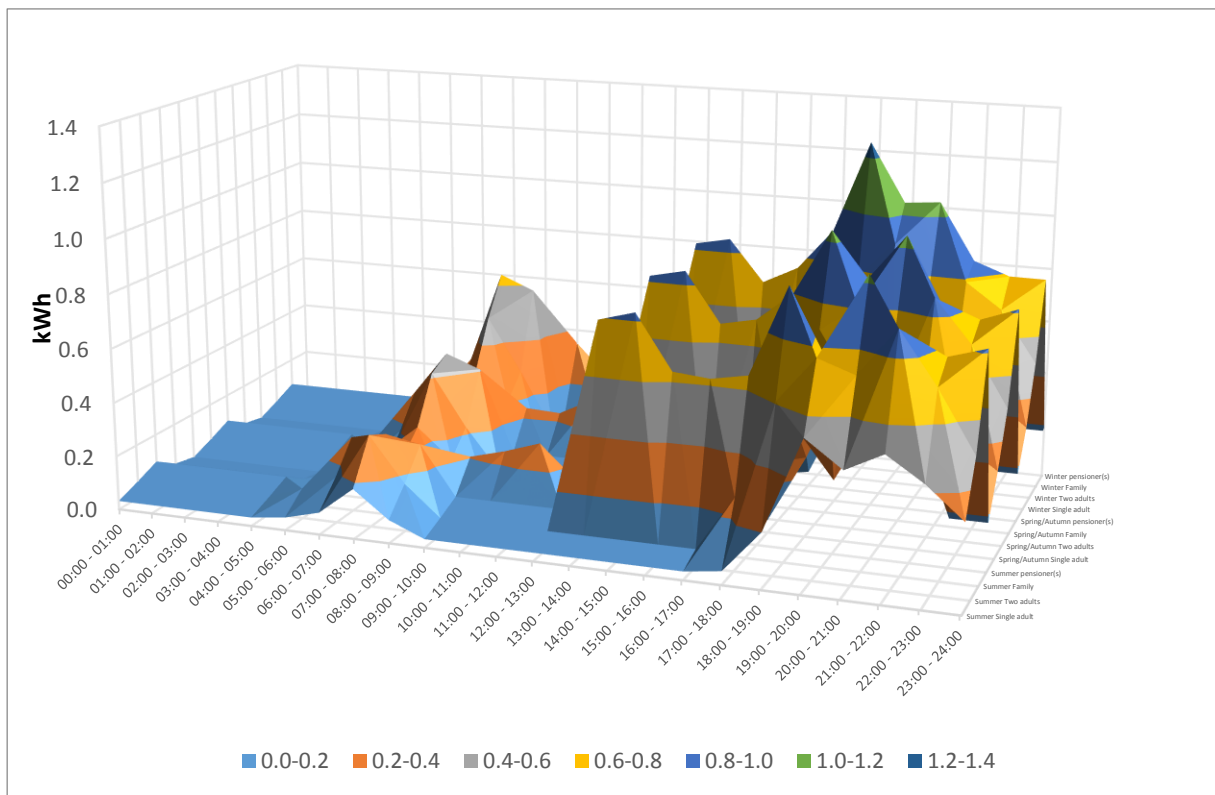


Figure 4.8: Seasonal electricity demand by household composition

Additionally, some households are equipped with electric vehicles (EV) that induce a supplementary electricity demand and change the dynamics of the system. On community level, the penetration level of EV will be analysed, since its demand is significant with respect to the domestic electricity demand.

Another relevant aspect that influence the demand profiles of end users is demand side management. This needs a decent mechanisms to trigger consumers' incentive to shift demand. The impact on consumers and how they are affected by load shifting is also considered.

4.4.2. Production components

A selection of energy production technologies to consider in the assessment of ICES is made in section 3.5:

1. Wind
2. Solar PV
3. Solar thermal
4. CHP
5. Fuel cell
6. National grid

The first three components are considered to be renewable energy sources, that dependent on weather conditions and are able to produce energy at zero marginal costs. Since the solar irradiance and wind availability are strongly site specific, the region in which ICES will be assessed needs to be specified. Considering the good accessibility of weather data for the Netherlands, we will use this country in the analysis of ICES.

4.4.2.1. Wind energy

For the generation of electricity from wind energy, several 'urban wind turbines' are available. For this research, we choose a relatively large urban wind turbine: the **Fortis Montana**. This three-bladed wind turbine has a rated output power of 5 kW. This seems a suitable turbine to implement, because of its high output power, low cut in wind speed (2.5 m/s), low investment costs per kW (€ 3000) and an estimated kWh price of € 0.18 (WINEUR, 2006). Another research, this one performed in the Netherlands, tested this turbine over a period of four years and calculated the price per kWh to be € 0.35 (Mertens, 2012). In comparison with other (smaller) turbines, the Fortis Montana has higher output power, also at low wind speed. The wind speed to power curve of the wind turbine is presented in Figure 4.9, and will be used during the assessment.

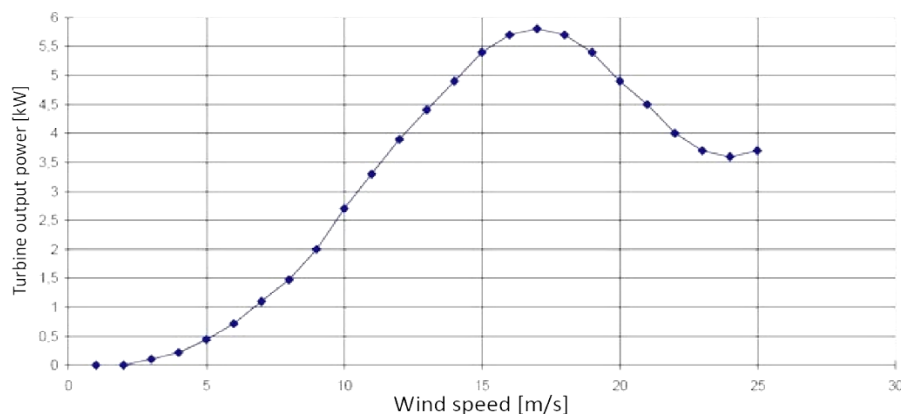


Figure 4.9: Fortis Montana - Wind speed to power curve (adapted from Fortis, 2012))

4.4.2.2. Solar PV

Solar energy is the most abundant permanent source of energy on earth. Every hour the sun provides earth with more than enough energy to fulfil global annual energy needs (National Geographic Society, 2015). Photovoltaic panels are used to convert the energy from radiation to electricity. The output power is proportional to the solar irradiance and depends on the solar cell efficiency and the performance ratio.

The performance ratio is the ratio of actual energy output to theoretically possible energy outputs. It includes inverter losses, cable losses, shading losses, thermal losses and snow losses as well as energy consumption for operating the solar system. The performance ratio (PR) is calculated as follows:

$$PR = \frac{\text{Actual produced energy in kWh}}{\text{Theoretical energy output in kWh}} \quad (\text{Eq. 4.12})$$

The maximum theoretical energy output power is dependent on the solar panel efficiency and can be calculated:

$$\text{Theoretical output [kWh]} = \text{Solar irradiation} \left[\frac{\text{kW}}{\text{m}^2} \right] \times \text{Solarpanel area [m}^2] \times \text{module efficiency} \quad (\text{Eq. 4.13})$$

The amount of residential solar systems have grown exponentially over the last years (Adaramola, 2015). Since solar systems are easily scalable, they are suitable for the implementation at different households, with different available rooftop areas. Nowadays monocrystalline and polycrystalline solar modules are the most popular types. Monocrystalline solar panels are commercially available at efficiencies of 13-18% and at prices less than € 1, - per Wp (World Energy Council, 2013). A LG 300 Watt Peak solar panel will be used in this research, since it has a high efficiency (18%) and a high maximum output power. The datasheet of this module is presented in Appendix E: LG Mono X Datasheet.

Besides the costs for the solar panels (€ 300, - each), a power inverter needs to be installed. The costs of the inverter are mainly determined by the maximum power it is able to convert. Three different inverters are selected and sized to the PV installed capacity.

Table 4.6: Selected solar PV systems (data from: Solar Online, 2015; Wholesale Solar, 2015; Zonnepanelen-Weetjes, 2015)

Installed capacity	Size inverter	Type inverter	Price inverter	Installation costs	Total costs
0 – 1000 Wp	1000 Watt	Sunny Boy 1100	€ 550	€ 350	€ 900
1000 – 2000 Wp	2000 Watt	Sunny Boy 2000HF	€ 1000	€ 600	€ 500
2000 – 5000 Wp	5000 Watt	Sunny Boy 5000TL	€ 2500	€ 1000	€ 2500
5000 – 10000 Wp	10000 Watt	Sunny Boy 10000TL	€ 3500	€ 1500	€ 5000

4.4.2.3. Solar thermal

While solar PV accounts for the generation of electricity, a solar thermal system generates useful heat from solar radiation. Solar thermal collectors harvest energy from the sun and uses this to heat a liquid. Solar thermal systems are able to reach a total system efficiency of 70% - 80% (Lozanova, 2011). A boiler is used to store the heated liquid, to provide heat when there is demand. Four different system configurations will be implemented. The presented system price for solar thermal systems includes the installation costs.

Table 4.7: Selected solar thermal systems (data obtained from: Zonnepanelen-Weetjes, 2015)

Installed capacity	Boiler size	System price
1600 Wp	100 litre	€ 2200
2500 Wp	100 litre	€ 3000
3500 Wp	200 litre	€ 3500
5000 Wp	300 litre	€ 5000

4.4.2.4. CHP and FC

A household needs to have the option to fulfil its energy demand at any time. Besides the intermittent energy sources, a controllable energy source will give the flexibility to increase energy production when demand is larger than the energy provided by the intermittent renewable energy sources. At household level, a few technologies are available that generate electricity and/or heat. Since both electricity and heat are needed, we look into technologies that are able to produce both at the same time: fuel cells and (micro) combined heat and power.

Fuel cell

A fuel cell converts chemical energy that is stored in a fuel into electrical energy. The energy conversion is driven by a chemical reaction. This exothermic chemical reaction generates heat. When this heat is used (and not wasted), this increases the overall efficiency of the fuel cell. The BlueGen fuel cell will be implemented in our analysis. First of all, because this is one of the few commercially available domestic fuel cell systems. It has a high efficiency, excellent partial load behaviour and it holds the world record for conversion of natural gas to electricity (Föger, 2013). Furthermore this device is already implemented in the SEC Heerhugowaard pilot project (described in section 4.8), and therefore it is interesting to compare its performance with the results from this research. The BlueGen has an electrical maximum output power of 2 kW and a maximum thermal output power of 1 kW. The BlueGen domestic fuel cell can be purchased from € 28000 (FuelCellToday, 2012). The typical electrical efficiency as a function of AC export power is shown in Figure 4.10. The resultant thermal power is shown in the same plot.

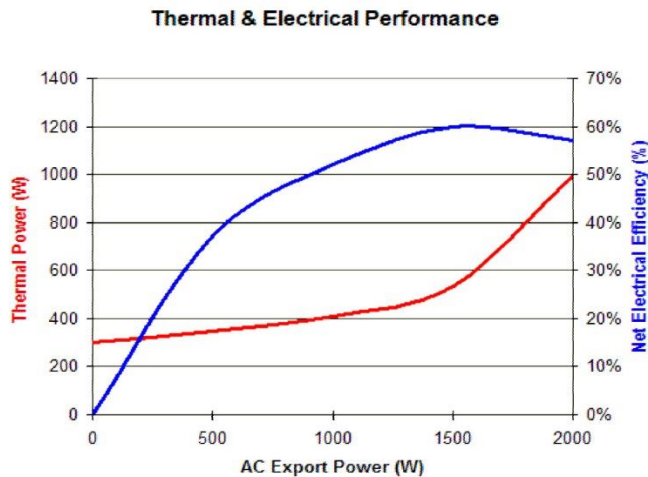


Figure 4.10: Thermal and electrical performance of the BlueGen fuel cell (Retrieved from Payne et al., 2011)

CHP

Like Fuel cells, combined heat and power (CHP) also generates heat and electricity simultaneously. In the industrial sector, CHP has been used since the oil crisis in the 1970s and has recently become more popular due to its high overall efficiency and low carbon emissions. Since it is able to produce local electricity and heat, it is a technology to consider at household level, by means of a low carbon intensive energy source.

In contrast to fuel cells, a (micro)-CHP produces heat as main output, and the generated electricity is a useful bi-product. This makes the comparison between fuel cells and CHP in the analysis also more interesting. Different households with different demand profiles could require one or the other technology to optimally fulfil its heat and electricity demand.

CHP capital costs could be expressed in the price per kW maximum output. These costs (including installation) are varying in the literature from € 10000 (Brooks et al., 2013) to € 13000 (Nguyen et al., 2014). The Baxi Ecogen, a 1kW_e Micro CHP is available for € 10000,- (Yougen, 2015). In this research we will use therefore € 10000 per kW_e as design parameter for our different CHP systems. Economies of scale are taken into account for the largest systems. Future CHP prices have potential for cost reductions through industry scale-up and learning by doing. Projections of CHP price targets show that prices of € 3000 per kW are realistic by 2020 (Staffell & Green, 2013).

Table 4.8: Selected CHP systems

CHP max output (kW _{thermal})	CHP max output (kW _{electrical})	CHP price
2	1	€ 10000
5	2.5	€ 25000
10	5	€ 45000
20	10	€ 85000

4.4.3. Energy storage components

The energy generation from renewable, intermittent source, is limited to the maximum energy that is being provided by the wind or the sun at a specific time. Since energy is a strongly time-limited product, supply and demand need to be continuously in balance. Traditionally the production side is controlled such that demand is being fulfilled at any time of the day. With a higher penetration of intermittent renewable energy sources, energy production becomes less controllable. This will give problems when peak demand is not aligned with peak production, as this leads to energy shortage at household level or even at community level. The two options to tackle this are storage and demand side management. Energy storage can be used to absorb the fluctuations in wind power and solar power, while demand side management schemes increase the flexibility of the energy system and reduces peak demand (Mateo, 2011).

4.4.3.1. Heat storage

Solar thermal systems come with a storage boiler, to store the heated liquid to be used at times there is heat demand. The size of the boiler determines the maximum amount of stored heat. Three commonly used boiler sizes are implemented: 100 litre, 200 litre and 300 litre. The selection is made such that a larger solar thermal collector will be combined with a larger thermal storage boiler, to facilitate adequate heat storage. Two methods of heat recovery from the storage boiler are implemented (Figure 4.11). The stored heat from renewable production can be used directly after it is being stored (left plot) or can be used to supply at times of peak demand (right plot). The green area indicates the energy that is being stored when renewable heat production is higher than heat demand. The blue area represents the thermal energy that is being extracted from the storage boiler.

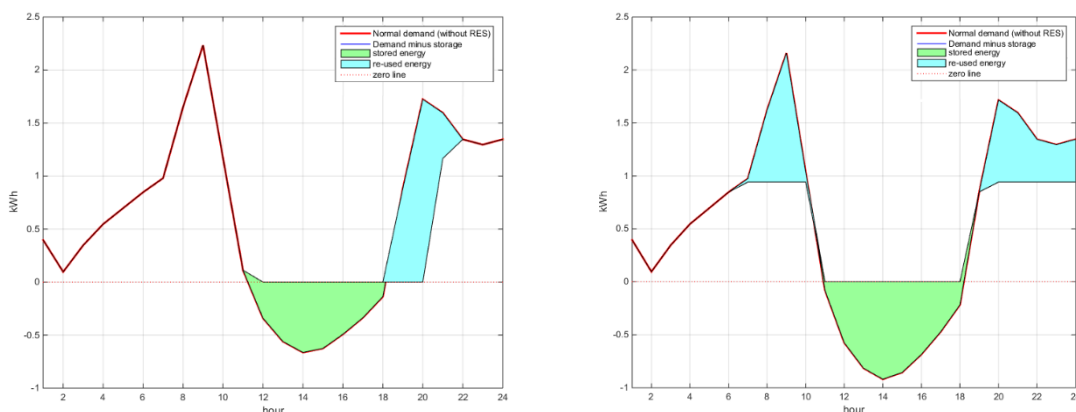


Figure 4.11: Heat storage: heat recovery options

4.4.3.2. Electricity storage in batteries

Batteries are stationary energy storage units that are able to store electricity and provide the option to use this energy at times when it is needed the most. Batteries convert stored chemical energy into electrical energy. Ions are exchanged between two electrodes, the anode and the cathode, which induces a current. There exists various different types of batteries, with each their own characteristics, benefits, drawbacks and applications. For application as energy buffer at household level, the battery need to be rechargeable. In this type of batteries, the composition of the electrodes is restored by the reverse (charging) current. Three common types will be discussed to make a selection for the battery to be implemented in ICES at household level.

Lead acid batteries: For many years lead-acid batteries have been used to store energy from residential solar electric systems, to increase system efficiency and flexibility. The technology is mature and these batteries have low maintenance requirements and cost. However the round-trip efficiency is only 75% (Rydh et al., 2005). Lead acid batteries are able to supply large surge-currents.

Nickel–metal hydride batteries: Nickel-metal hydride (Ni-MH) batteries are characterised by a higher energy density than lead acid batteries (Rydh et al., 2005), but they are more expensive. Their main application is small

rechargeable batteries, but also some EV are supplied with Ni-MH batteries. Ni-MH batteries cannot handle overcharging very well, since this cause hydrogen build-up inside the battery that can rupture the cell.

Sodium sulphur batteries: Sodium sulphur batteries use a molten-salt as electrolyte and offer high energy density and high power density. With an efficiency of 90%, it offers better performance than lead acid batteries. These type of batteries have been used to store electricity from wind power (Scientific American, 2008), but due to its high operating temperature (above 300 °C), these batteries are more suitable for large-scale applications rather than for household implementation.

Lithium ion batteries: Recently lithium-ion batteries become more attractive for residential stationary storage, because of its rapid decreasing price and increasing power density. Lithium-ion batteries are used in cell phones and laptops. However this technology is less mature, the performance of lithium-ion batteries is high and the efficiency almost reaches 95% (Wang et al., 2013). Their performance is more or less comparable with Ni-MH batteries. Since costs of Li-ion batteries went down quite dramatically this year, and it is expected the costs for Li-ion battery packs will fall by up to 35% by 2025 (Beetz, 2015), we use this type of battery in our analysis.

To provide stationary electricity storage at household level, we will use the **Tesla Powerwall**, a 10 kWh rechargeable lithium-ion battery. This battery is designed specific for household application and provides the option for load shifting and auxiliary power supply. The device can be connected to the grid, to store additional energy from the grid, for example at times the electricity price is low (Greentechmedia, 2015). A 10 kWh energy storage pack that includes batteries, thermal management, and software costs € 3500 (Tesla Motors, 2015). The installation costs are quoted around € 500 and depend on individual factors such as cable length, type of cut-off switch etc. The Tesla Powerwall specifications are presented in Table 4.9.

Table 4.9: Tesla Powerwall specifications (data retrieved from Tesla Motors, 2015)

Powerwall specs:	
Mounting:	Wall Mounted Indoor/Outdoor
Inverter:	Pairs with growing list of inverters
Energy:	7 kWh or 10 kWh
Continuous Power:	2 kW
Peak Power:	3.3 kW
Round Trip Efficiency:	>92%
Operating Temperature Range:	-20 °C to 43 °C
Warranty:	10 years
Dimensions:	H: 1300mm W: 860mm D:180mm
Price:	€3000 (7 kWh) € 3500 (10 kWh)

4.4.3.3. Electric vehicles

Electric vehicles (EV) gain increased interest in the last decade, due to environmental awareness of the fossil-fuel based transportation sector and to peak oil concerns (Eberle & von Helmolt, 2010). Electric vehicles have a carbon footprint that depends on its manufacturing emissions, but even stronger on emission caused by the process of electricity generation. Within this process, the type of fuel and the type and efficiency of the generator are important parameters that determine a large share of carbon emission. Compared with combustion engine powered vehicles, they emit less carbon per driven km (Wilson, 2013). Therefore they can be considered as an option to make ICES more sustainable, especially when local produced electricity is used to power EV.

Despite its benefits, EVs have challenges, such as the limited driving range, the recharge time and the expensive battery packs that might need to be replaced multiple times. Promising improvements are being made on all these challenges, resulting in an increasing EV penetration rate in the transportation sector. The energy use of average present-day electric vehicles is between 0.17 and 0.21 kWh per km (Green Emotion, 2013). In our research and model, a typical EV is used, characterised by data from EV types that are currently available on the market (ChargePoint, 2015). These characteristics are specified in Table 4.10.

Table 4.10: EV specifications (data adapted from: ChargePoint, 2015; Green Emotion, 2013)

EV characteristics:	
Battery size:	25 kWh
Maximum charging rate:	3.3 kW
Maximum charge level battery:	90 %
Maximum discharge level battery:	20 %
kWh use per km:	0.20
Range :	125 km

To analyse the impact of different EV penetration levels within ICES, we use different scenarios, based on predictions found in literature. The Dutch government forecasted EV penetration will eventually saturate at 75% of all passenger vehicles around the year 2040 (Ministry of Transport, 2009). The forecasted trajectory is visualised in Figure 4.12. Although this are early predictions, the actual EV penetration in the first few years is higher than the government's forecast from 2009. Currently there are almost 60.000 EV's on the Dutch road, representing less than one percent of the total number of passenger vehicles (RVO, 2015).

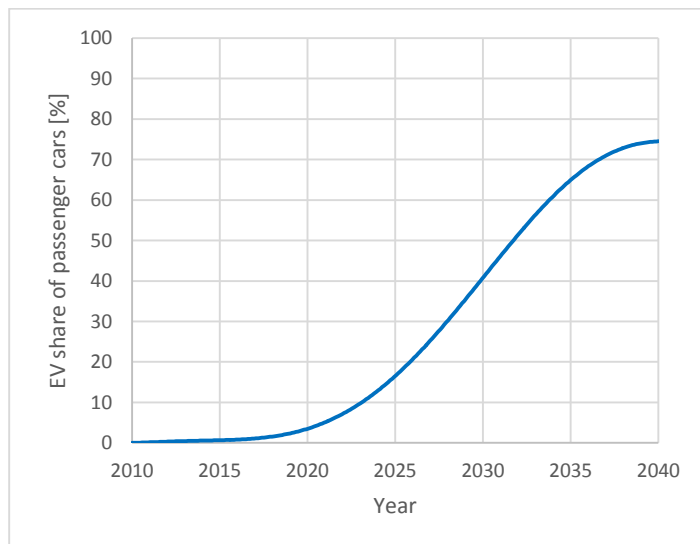


Figure 4.12: EV penetration forecast by Dutch government. (Adapted from Ministry of Transport, 2009)

Hassett et al. (2011) examined EV uptake scenario's for various EU counties and concluded the percentage of EV's is strongly country dependent. In the most optimistic case the EV penetration ratio for Germany in 2030 will be 25%, while this number for Portugal will be less than 3% in the most pessimistic scenario. These numbers illustrate a large disagreement amongst different researchers and the vision of the Dutch Ministry of Transport.

Within the Netherlands there are almost 1.2 automobiles per household (KiM, 2013). When the penetration of EV will continue the trend as forecasted by the Dutch government, this results in 90 EVs per 100 household within a community. The used scenarios for this research are presented in Table 4.11 below.

Table 4.11: EV penetration scenarios

Scenario	EV percentage with respect to total number of vehicles	Percentage of households with EV
Base case without EV	0 %	0 %
Minor EV penetration	5 %	6 %
Dutch government forecast for 2027 and (Hassett et al.) forecast for Germany 2030	25 %	30 %
Dutch government forecast for 2040	75 %	85 %

To include EV demand at household level in the ICES model, there are two options to consider:

1. Demand for EV is already included in the household demand profiles. In that case the EV demand needs to be considered as a certain amount of flexible electricity demand with respect to households' total electricity demand. This does not require extra resources to operate EV for households. In the comparison between households with EV and households with traditional cars, this seems reasonable when looking at total transportation costs. However, when interested in the dynamics of the electricity and heat consumption of different types of households within ICES this becomes less practical. The introduction of EV will change the demand profile of households significant (in quantity as well as in the specific time this demand occurs).
2. Demand for EV is seen as separate, additional demand. This means households with EV have an increased demand level compared to households that own a petrol-fuelled car, since the petrol energy flows are out of the model's scope. This leads to the situation that EV owners appear to have higher electricity consumption and thereby higher energy costs. However this is only because of the model boundaries do not contain alternative fuel costs for the petrol-fuelled vehicles. Since we are not making a comparison between EV and traditional transportation, but are interested in the impact of EV within ICES, EV demand is modelled separately as additional electricity demand at household level.

We consider electric vehicles are not at home during office hours, and therefore they only can be charged during the evening, night and early morning. Energy from intermittent renewable energy sources has priority for charging the EV. At hours the EV is at home, it will always be charged by RES until the maximum recommended charge level of the battery is reached. Furthermore the desired driving distance of the day is taken into account, to determine additional charging is needed. Lithium-ion batteries are charged below 90% of their maximum capacity, to increase lifetime performance (Teslarati, 2014). Figure 4.13 shows a typical daily pattern of the EV that is being used between 9.00 A.M. and 17.00 P.M. and recharged partially by renewables (between 05.00 A.M. and 09.00 A.M. and between 17.00 P.M. and 18.00 P.M.) and the grid in the evening. The blue line represents the renewable energy potential, the orange line represents the part of renewable energy potential that is actually being used to charge the EV. The dashed orange line indicates the part of the renewable energy that stays unused, and should be exported to other households within ICES or the grid. The purple line indicates the actual battery charge level.

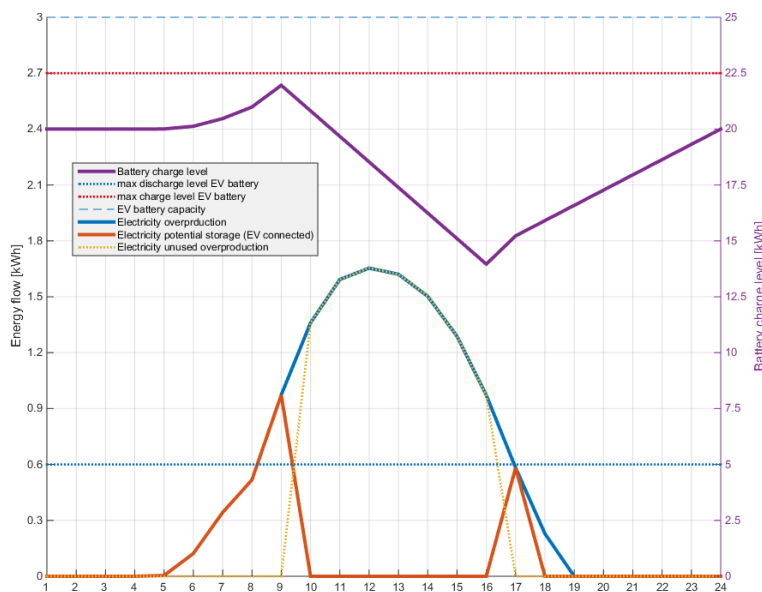


Figure 4.13: EV energy flows and battery charge level

4.5. Base case scenario

In order to compare the performance indicators of households participating in ICES with households that organise their energy in a traditional way, a base case scenario is designed. The base case scenario will act as a benchmark

in the assessment of different technologies at household level and quantify of the advantage or disadvantage ICES has to offer.

The base case scenario is based on the way energy is organised for the large majority of the Dutch households. Electricity is supplied by the national electricity grid and bought from retail energy suppliers and heat is supplied by a central heating system, fuelled by natural gas. Input parameters for the base case scenario are: energy prices, the price of the central heating system, carbon emissions, maximum line capacity and maximum heat supply rate.

4.5.1. National electricity grid

At times local demand cannot be fulfilled by local production, energy needs to be imported. The concept of ICES gives the option to import energy from other community members, but also to import energy from the national grid. On the other hand, it also creates the opportunity to export excess energy to the grid at times there is local overproduction. Electricity from the Dutch national grid has an carbon emission of 0.48 kg per kWh (Essent, 2015).

Energy prices from the electricity grid are determined by the type of contract consumers have with their energy supplier. Traditionally these contracts have a fixed price, but some suppliers offer contracts with varying tariffs per hourly or per 15 minutes, based on APX prices fluctuation. A contract with hourly energy prices however is still rare in the Dutch energy sector. However, as smart meters are increasingly becoming common, hourly electricity prices might be realistic in future. The price consumers pay for each kWh they use is made up of the APX price, the energy supplier surplus, taxes and levies. For 2014, about 40% of the electricity tariff accounts for taxes and levies (Eurostat, 2015). The average retail electricity price for 2015 gives us the data to estimate the energy supplier surplus (Milieu Centraal, 2015a). The different components of the electricity retail price are presented in Table 4.12. This example calculations shows the price composition at an APX price of € 42/MWh.

Table 4.12: Electricity tariff composition (data retrieved from Belastingdienst, 2015)

Tariff component	Price [€/MWh]	Price [€/kWh]
APX price	€ 42	€ 0.042
Energy supplier surplus	€ 8	€ 0.008
REB*	€ 119.60	€ 0.1196
ODE**	€ 3.60	€ 0.0036
VAT (21%)	€ 36.37	€ 0.0364
Retail price	€ 210	€ 0.21

* REB stands for 'Regulerende Energie Belasting' and is an energy tax per kWh. This value is applied for electricity use up to 10.000 kWh per year. At higher usage, the REB per kWh decreases.

** ODE stands for 'Heffing opslag duurzame energie' and is an energy tax per kWh, intended to finance a Dutch stimulation program for renewable energy (SDE+). This value is applied up to 10.000 kWh per year.

All tariff components are used to generate hourly varying retail prices for consumers. The APX price and the standard deviation of the annual APX data is presented in Figure 4.14, together with the calculated retail price. Seasonal variations of APX data is studied and the results are illustrated in Figure 4.15. This shows the highest deviation takes place around six o'clock in the afternoon, where the price peaks in winter season but not in summer season. The seasonal deviation from the annual average value is considered too small to make the implementation of seasonal APX pricing worthwhile, since the daily patterns are to a large extent equivalent. The annual APX data is used to calculate revenues from exporting electricity outside the community, whereas the costs for importing electricity are quantified by the electricity retail price.

Local renewable energy production is supported by different policy mechanisms, designed to stimulate and accelerate the investment and implementation of renewable energy technologies. Two common types are feed-in-tariffs and net-metering, which both will be briefly explained.

In the Netherlands, the **SDE+** is available to encourage the production of renewable energy. SDE, 'Stimuleren Duurzame Energieproductie' in Dutch, stands for Sustainable Energy Incentive Scheme Plus and is a **feed-in-tariff** subsidy. This scheme was introduced in 2011, as a follow-up to the SDE (RVO, 2010). Producers receive financial

compensation for the renewable energy they generate, for a fixed number of years. The subsidy is equal to the difference between the market price of regular energy and the production price of renewable energy. The price producers receive from their energy supplier is increased by SDE+ subsidy to a predetermined level. The level of the SDE contribution is dependent on energy-price developments (NLAGengy, 2012). The SDE+ is meant for companies, whereas households cannot apply for this subsidy. After 2011 the focus was shifted from private producers to corporate producers and economic efficiency improvements. The SDE+ is mainly funded by the ODE.

Another options to encourage private investment in renewable energy is the implementation of **net metering**. In the Netherlands this energy policy is called '*saldereen*'. Net metering allows consumers to compensate their local generated electricity with their imported energy during the (usually annual) billing period. If more energy is generated than is used during the year, the energy company is obliged to pay for the difference by a 'reasonable compensation' (Electriciteitswet, 1998). It allows customers to sell excess generated energy to their energy supplier. Customers receive the same price (retail price) for exported energy, as they pay for the energy they receive from the energy supplier, up to the amount of annual imported electricity (RVO, 2014). Unlike a feed-in-tariff, net metering can be implemented solely as an accounting procedure.

Renewable energy supporting policies vary by country, but are all intended to support investment in renewable energy production during period of technological immaturity. As DG technologies become more developed, net metering policies and renewable supporting structures should be updated and possibly will completely be phased out. We are aware of the currently available schemes, but will not use them in our analyses, since in future these supporting schemes might be altered radically and even phased out completely.

The same figures are used for the electricity retail price and APX price at the household model, to calculate respectively the costs and the revenues from imported and exported electricity. Likewise this is done for the ICES model, to calculate the cash flows of energy that is being imported or exported at community level.

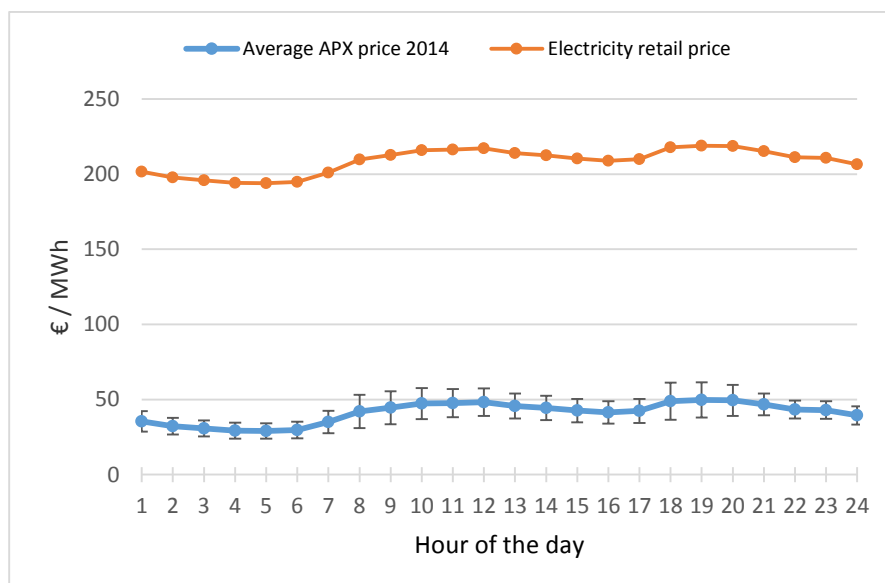


Figure 4.14: 2014 daily average APX-endex and retail prices (Data from <https://www.apxgroup.com>)

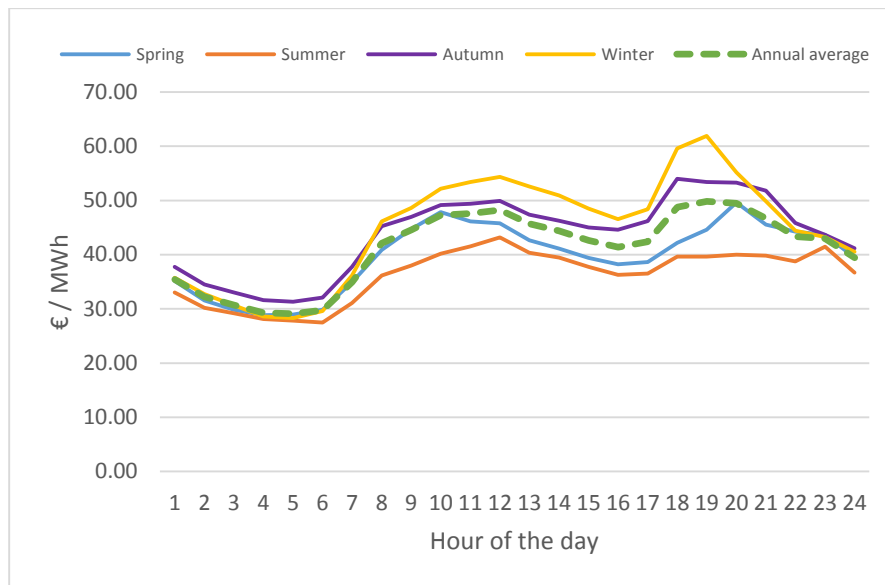


Figure 4.15: 2014 seasonal average APX-endex price (Data from <https://www.apxgroup.com>)

4.5.2. Household central heating system

To fulfil household's heat demand, a residential central heating system is used. Water is heated by burning natural gas. In the Netherlands, around 85 % of the households is equipped with a central heating system, and this number is increasing (NEN, 2014). The large majority of the central heating kettles are high-efficiency kettles (HR). In the base case scenario analyses we will use this type of heating in order to supply heat demand at household level.

The average price of a complete central heating system (including installation) is between € 6000 and € 11000 (Allesoverhuisentuin.nl, 2015; Cvketel-Weetjes, 2015). In our base case assessment a price of € 8000 is used. Remember that this price is also paid for if you live in a house that already has a central heating system installed, since these costs are basically included in the price you pay for the house or in the rent payments.

The average gas price for Dutch households in 2015 is € 0.62 per m³ (Milieu Centraal, 2015a). This number will be used as input parameter in the ICES model, for all technologies that use natural gas.

For heating by burning natural gas in a household's central heating system, we account an emission factor of 1.79 kg CO₂ per m³, based on the lower heating value of 31.65 MJ/Nm³ of Groningen natural gas (TNO, 2006). To make the comparison between different energy sources more transparent, this number is converted to the equivalent in kWh. Using the standardised net caloric value of natural gas (9.77 kWh/Nm³), the CO₂ emission of a central heating system is 0.18 kg per kWh. Considering the average annual efficiency of 80% (Inoxcon, 2015), CO₂ emission of a central heating system for the base case scenario is estimated at 0.23 kg per kWh.

4.6. Climate data

In this project, the local weather pattern is obtained from the Royal Netherlands Meteorological Institute (KNMI). The KNMI provides us with relevant data in the Netherlands for the period 2011 to 2015. The standard deviation for wind speed and solar irradiance shows a large spread for each hour of the day (Figure 4.16). Therefore, seasonal influences for wind availability and solar irradiance are considered (Figure 4.17). Hourly wind speed and solar irradiance is obtained from seasonal average data over the years 2011 to 2015 for the city Rotterdam.

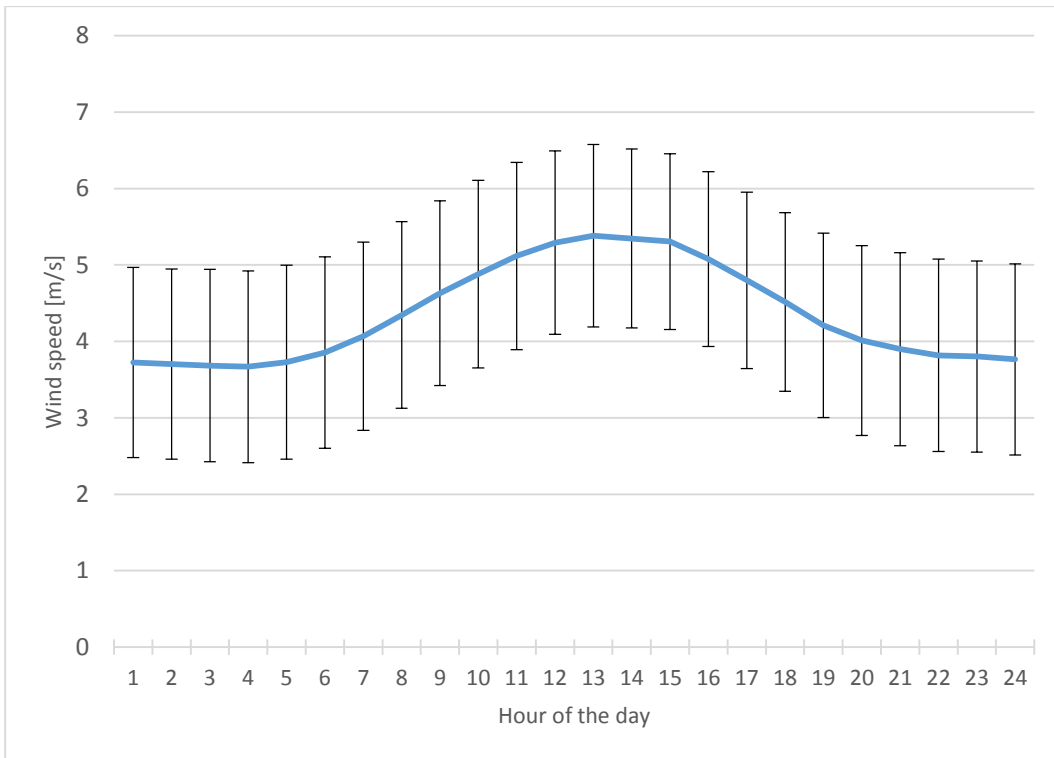


Figure 4.16: Average daily wind speed and std. deviation in Rotterdam between 2011 & 2015. Data obtained from: www.knmi.nl

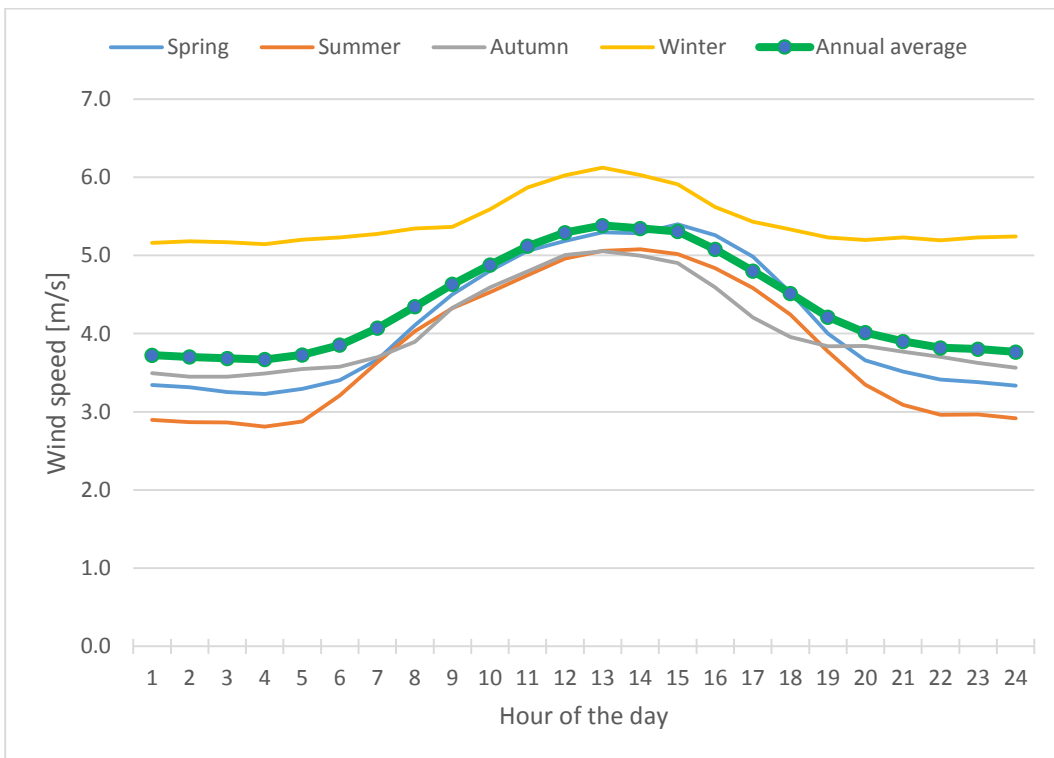


Figure 4.17: Seasonal daily average wind speed in Rotterdam between 2011 & 2015. Data obtained from: www.knmi.nl

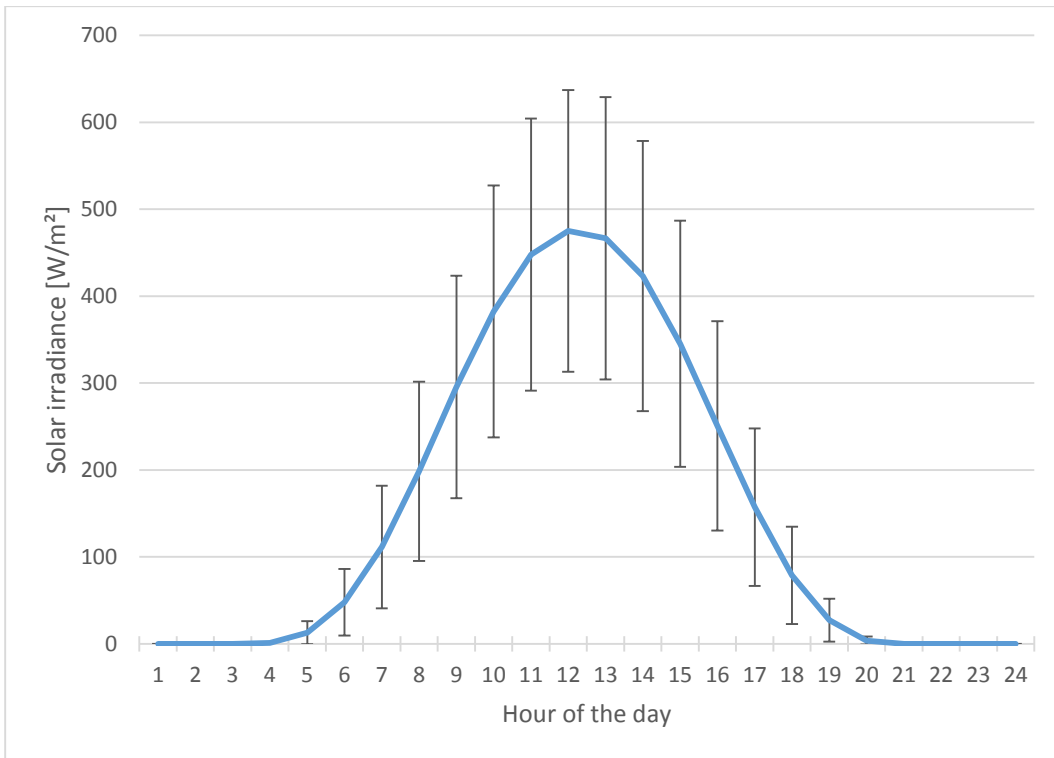


Figure 4.18: Average daily solar irradiance and standard deviation in Rotterdam between 2011 & 2015. Data from www.knmi.nl

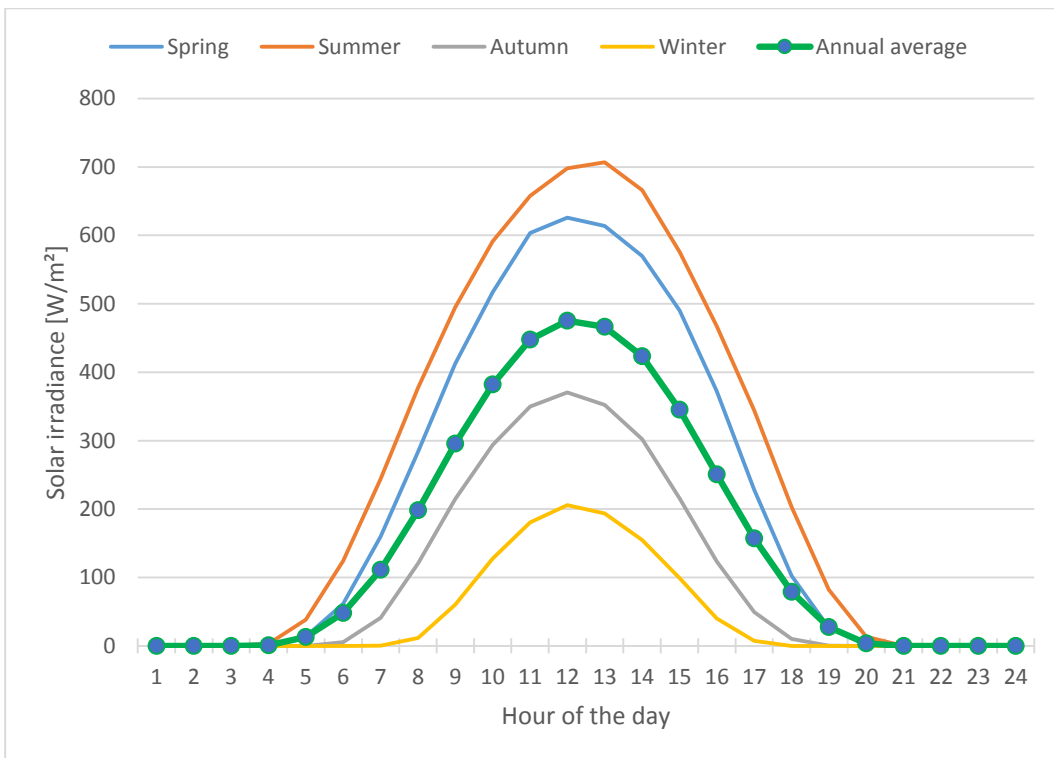


Figure 4.19: Average seasonal solar irradiance for Rotterdam between 2011 & 2015. Data obtained from www.knmi.nl

4.7. Selecting the optimal technological mix

4.7.1. Optimisation at household level

To optimise the energy means for a community, we first look at individual households and their preferences within community. At first the optimisation at household level is carried out. The combination of different household compositions and preferences, leads to 12 different system configurations that are optimal for the separate optimisation parameters, illustrated in Table 4.13. The optimal system configuration for each household type and for all distinct optimisation preferences is presented in Appendix B: Individual household optimal system configurations.

The **household preferences** from which individual optimal system configurations will be derived are:

- Financial incentives: Minimise energy costs
- Environmental incentives: Minimise CO₂ emission. Highest goal: become climate neutral.
- Energy autonomy incentives: Minimise energy import. Highest goal: become autonomous.

Four types of households with their specific demand profiles are distinguished and listed below. In the following sections, these types will be elaborated and the optimal technology mix will be selected.

- One adult
- Two adults
- Family
- One or two Pensioner or unemployed

Table 4.13: Households optimisation matrix

Household	One adults household	Two adults household	Family	Pensioner(s) or unemployed
Autonomy maximisation:	System 1A	System 2A	System 3A	System 4A
Carbon reduction:	System 1C	System 2C	System 3C	System 4C
Financial optimisation	System 1F	System 2F	System 3F	System 4F

4.7.1.1. One adult household

For a one adult household the process of selecting the optimal technology mix with respect to the household optimisation preferences, is described in more detail. The selection of technology mixes for the other household compositions is performed in the same way, except the different demand profiles.

For energy costs minimisation and carbon reduction incentives, all generated technology mixes are evaluated based on the annualised energy price and the carbon emission per kWh. The annualised energy price is calculated by life cycle analyses. The carbon emission is expressed in emission per produced kWh, because this deals with the fact that some households produce more than they consume. This excess energy at ICES level will be exported to other community members or to the national grid. Thereby also the corresponding carbon emission shift to the household who uses the energy. To make an unbiased comparison between the carbon intensity performances of households, the average CO₂ emission per kWh is used. Figure 4.20 shows a graphical representation of the performance of all tested technology mixes. The red dot (system number 1) indicates the base case scenario and the red dotted line represents the approximated curve-fitting Pareto distribution. The marker size indicates the amount of energy production. The colour range of the dots indicate the energy autonomy of heat; yellow indicates a high energy autonomy and blue indicates this configuration is not heat autonomous at all. Since heat cannot be exchanged, this value should be close to 100% and thus represented by a yellow marker in the plot. When optimising on costs, we are particularly interested in the configurations within the green dashed area, whereas looking for energy cost minimisation, the configurations within the blue dashed area are of our interest.

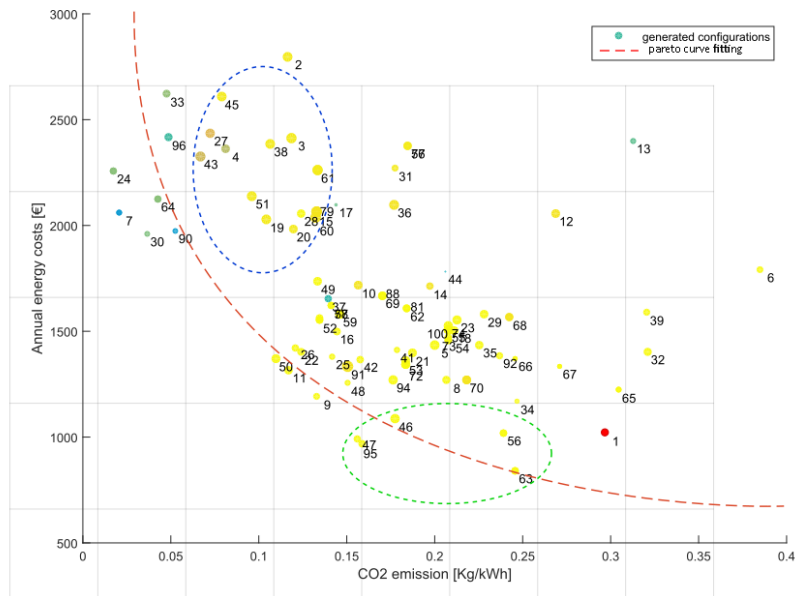


Figure 4.20: Annualised energy costs - CO₂ relation (one adult household)

The selected configuration for energy **cost minimisation** is system 63, since this configuration ends up with the lowest annual energy costs for a one person household. The selected configuration for **carbon emission reduction** is system 45, since this configuration offers low carbon emission (0.094 kg/kWh) and has a high heat autonomy.

Figure 4.21 shows the configurations for **energy autonomy** exploration. The colour scale again is used to indicate the heat energy autonomy. The horizontal axis show the total energy autonomy. The technological mix of the system with the highest energy autonomy is represented by system 56. This system is 100% energy autonomous for both electricity and heat, at lowest annual energy costs.

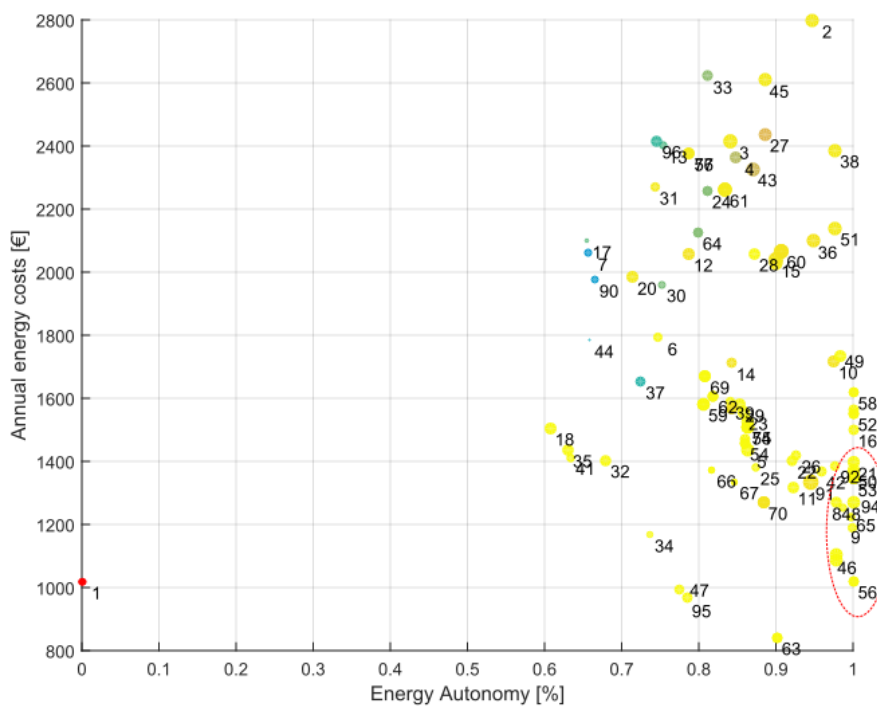


Figure 4.21: Annualised energy costs - Energy Autonomy relation (one adult household)

Figure 4.22 gives a 3D visualises of the model results for a one adult household. The three axes represent the results of the three performance indicators. The results for all four household types are visualised in Appendix C: Model details: all generated system characteristics.

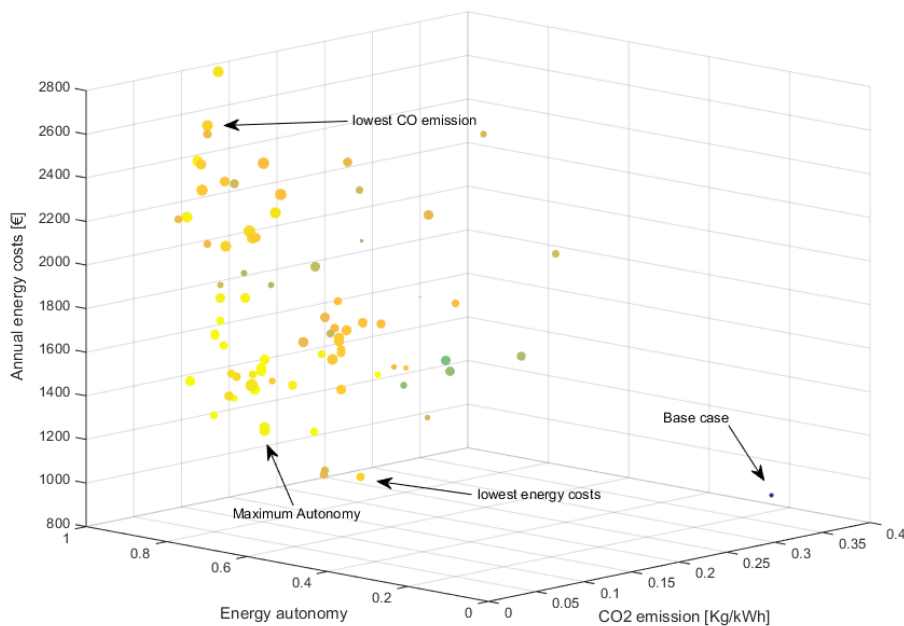


Figure 4.22: Annualised energy costs - Energy Autonomy - CO2 emission relation (one adult household)

With this routine the three system configurations for a one person household are determined, as proposed in Table 4.13. This results are presented in Table 4.14. The one adult household financial optimisation case (1F) will be explained in more detail below.

Table 4.14: Selected household configurations - one adult household

One adult household	Base case	Energy autonomy optimisation	CO ₂ reduction	Financial optimisation
System configuration number	1	56	45	63
System code	1B	1A	1C	1F
Capital investment costs (€)	€ 8000	€ 20600	€ 51400	€ 17100
Annual energy revenues (€)	€ 0	€ 937	€ 1366	€ 998
Net annual energy costs (€)	€ 1019	€ 1038	€ 2609	€ 859
CO ₂ emission (kg per kWh)	0.289	0.239	0.094	0.244
Energy self-sufficiency rate	0%	100%	89%	90%

Example 1: System 1F: One adult – Financial optimisation

A one adult household that has costs reduction as its main objective, is served best by a technological mix of a 3.6 kW solar PV and a 2 kW micro CHP. Heat supply by a CHP is driven by heat demand, which makes sure heat demand is fulfilled at each hour of the day, at all four seasons (Figure 4.23). Figure 4.24 shows electricity demand and supply. A large electricity surplus is caused by the combination of solar production and heat supply by the CHP, and will be exported to other community members or to the national grid. Figure 4.25 illustrates the local electricity balance, showing the export and import electricity values. Figure 4.26 shows the energy autonomy for heat and electricity for each hour of the day. In winter the one adult household is 100% energy autonomous as the CHP need to produce more heat, resulting in higher electricity production.

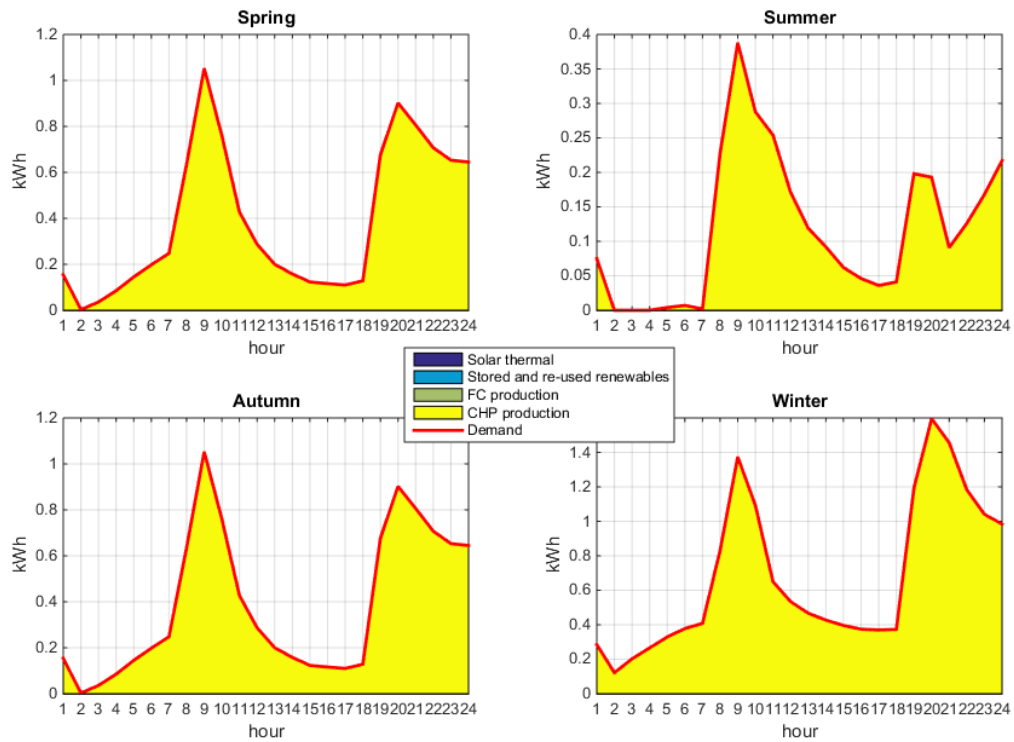


Figure 4.23: Seasonal heat demand and supply for a one adult household – cost minimisation.

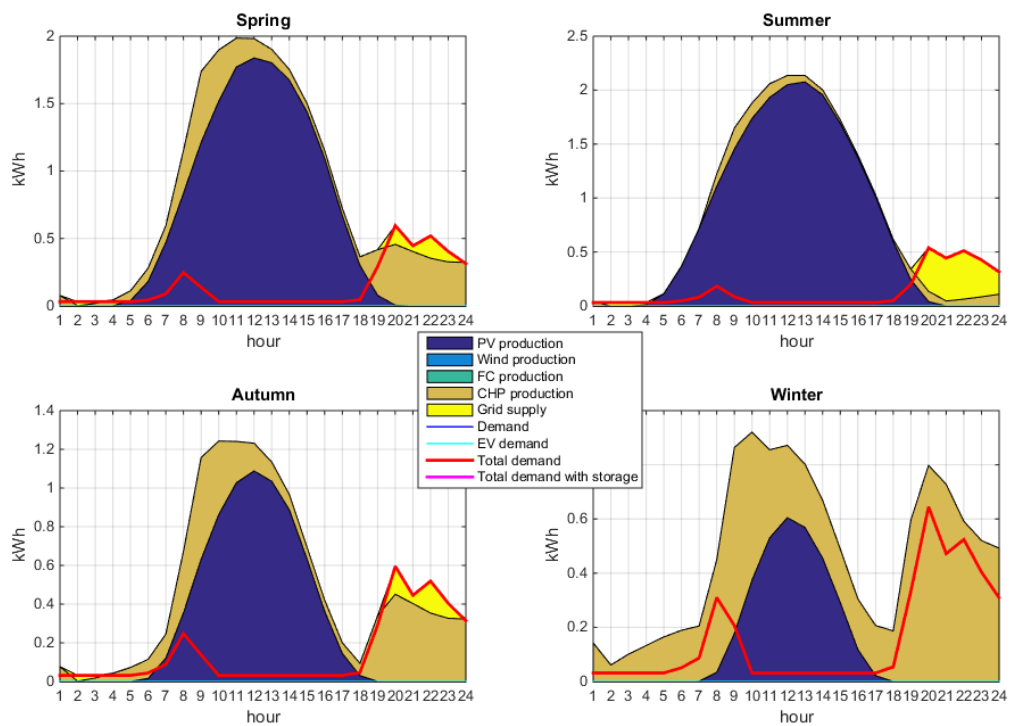


Figure 4.24: Seasonal electricity demand and supply for a one adult household – cost minimisation.

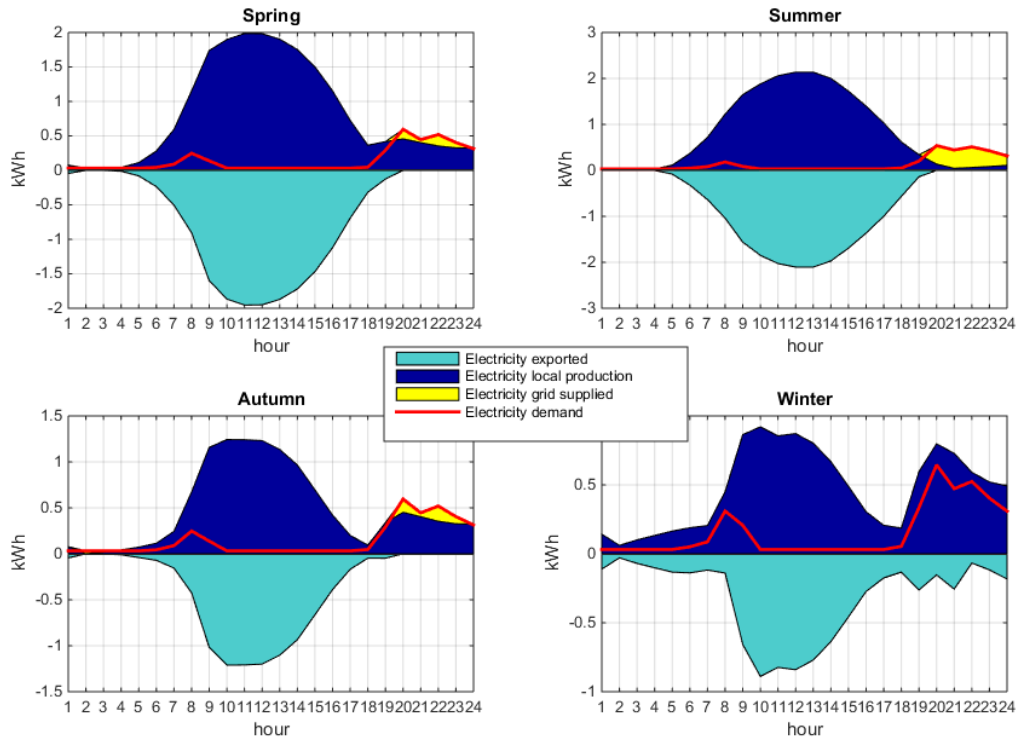


Figure 4.25: Seasonal electricity local energy balance for a one adult household – cost minimisation.

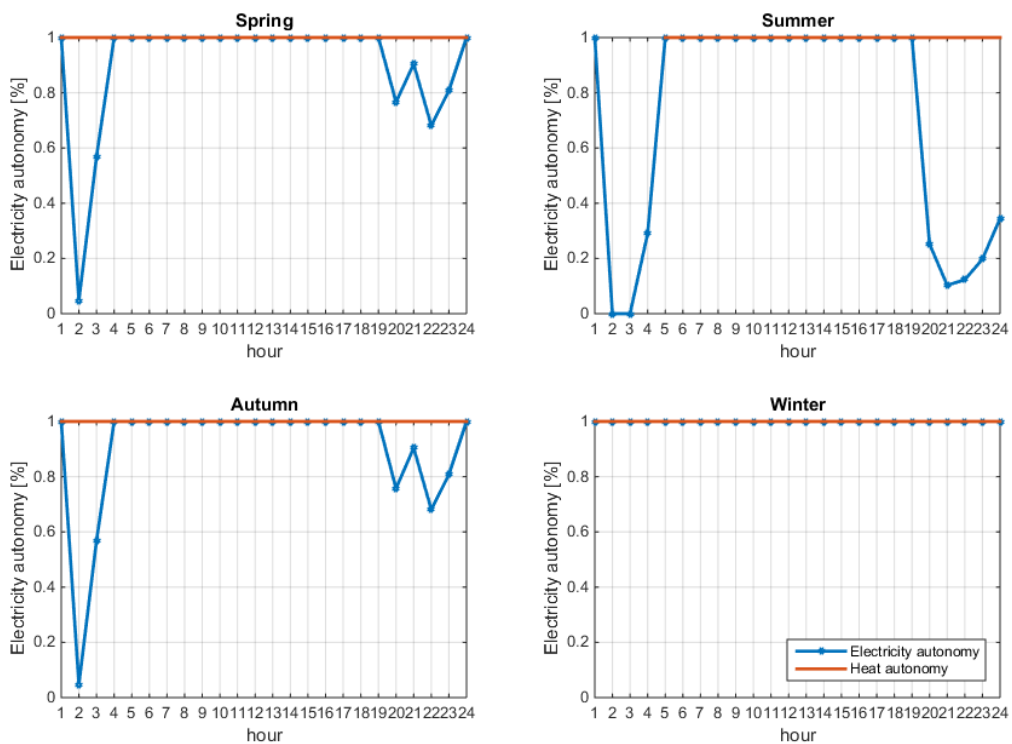


Figure 4.26: Seasonal energy Autonomy for a one adult household – cost minimisation.

4.7.1.2. Two adult household

The procedure of selecting the optimal technology mix for a two adult household is similar to the method applied to a one adult type household, described in the previews section. The demand profile, and in particular the heat

demand profile, shows two large peaks during the day. This leads to the exclusion of the smallest CHP configuration and the FC, which respectively have a maximum heat output power of 2 kW and 1 kW. If heat demand could be smoothed over the day, this would definitely open up more technological possibilities, and offering better financial performance.

Figure 4.27 shows all generated technology combinations for a two adult household. The red dot represents the base case scenario. The blue area indicates technology mixes that have lowest CO₂ emission, given the prerequisite of heat autonomous (yellow marker). It is clear that it is not possible to reduce energy costs for this type of household, mainly because the explained heat demand peaks above 2 kW per hour. This results in a fairly over dimensioned system, when installing a 5 kW CHP system. The green area indicate a configuration that has comparable annualised energy costs with the base case, and less CO₂ emission. However, this system is less autonomous. This household (119) is used for cost reduction analyses. CO₂ reduction is possible, nevertheless at considerable costs. Household 162 is used to represent a household which wants to minimise its CO₂ emission. A fair compromise between costs and carbon emission is made by the system within the red area (125). For maximum energy autonomy, household 124 is used, as this offers 100% energy autonomy for the least energy costs (Figure 4.28).

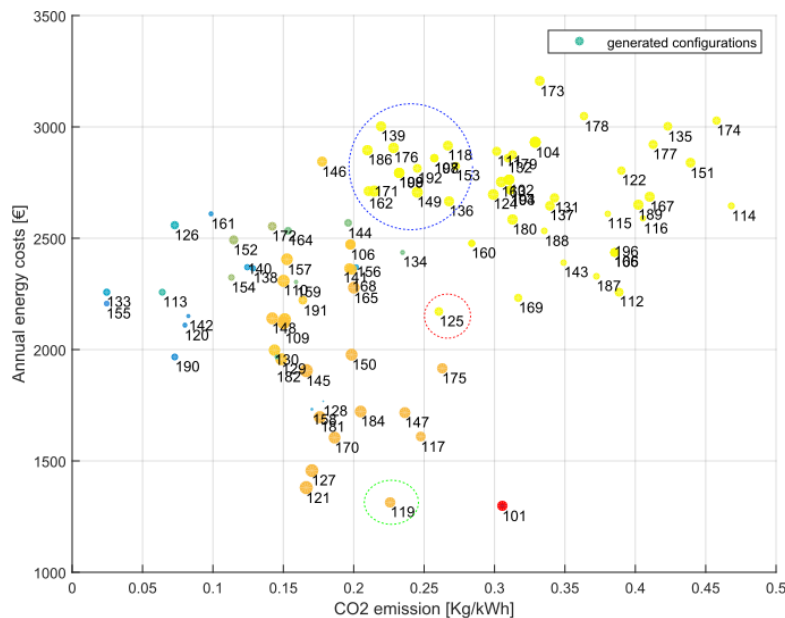


Figure 4.27: Energy costs versus CO₂ emission – 2 adult household.

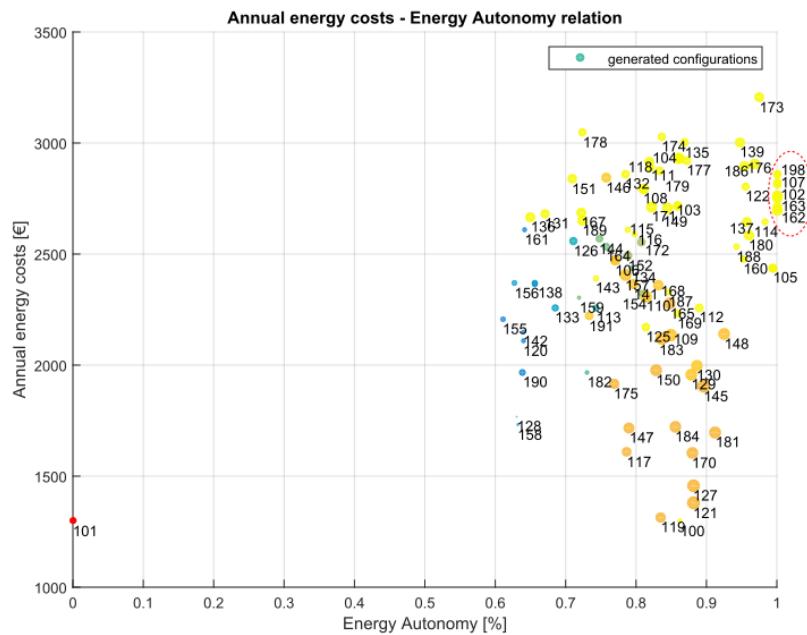


Figure 4.28: Energy costs versus Energy autonomy – 2 adult household.

Table 4.15: Selected household configurations - two adult household

Two adult household	Base case	Energy autonomy optimisation	CO ₂ reduction	Financial optimisation
Household number	101	124	162	119
System code	2B	2A	2C	2F
Capital investment costs (€)	€ 8000	€ 50600	€ 52400	€ 31100
Annual energy revenues (€)	€ 0	€ 1619	€ 1440	€ 1714
Net annual energy costs (€)	€ 1297	€ 2699	€ 2711	€ 1315
CO ₂ emission (kg per kWh)	0.297	0.295	0.224	0.226
Energy self-sufficiency rate	0%	100%	100%	84 %

Example 2 - System 2C: Two adults – CO₂ minimisation

Aiming at the lowest CO₂ emission, the technology mix needs to contain a large share of renewable energy sources. Model results confirm this presumption. The lowest carbon emission can be achieved by a combination of a 2.4 kW solar PV, a 2500 Wp solar thermal collector with a 100 litre thermal boiler for heat storage, an urban wind turbine and a 5 kW CHP. Mark the large annual energy costs for this configuration in Table 4.15. The results for demand and supply of this household are presented in Figure 4.29 (heat) and Figure 4.30 (electricity). The electricity balance and local energy autonomy are illustrated in Figure 4.31 and Figure 4.32. Thermal storage is applied and the daily storage pattern during a spring day is represented by Figure 4.33.

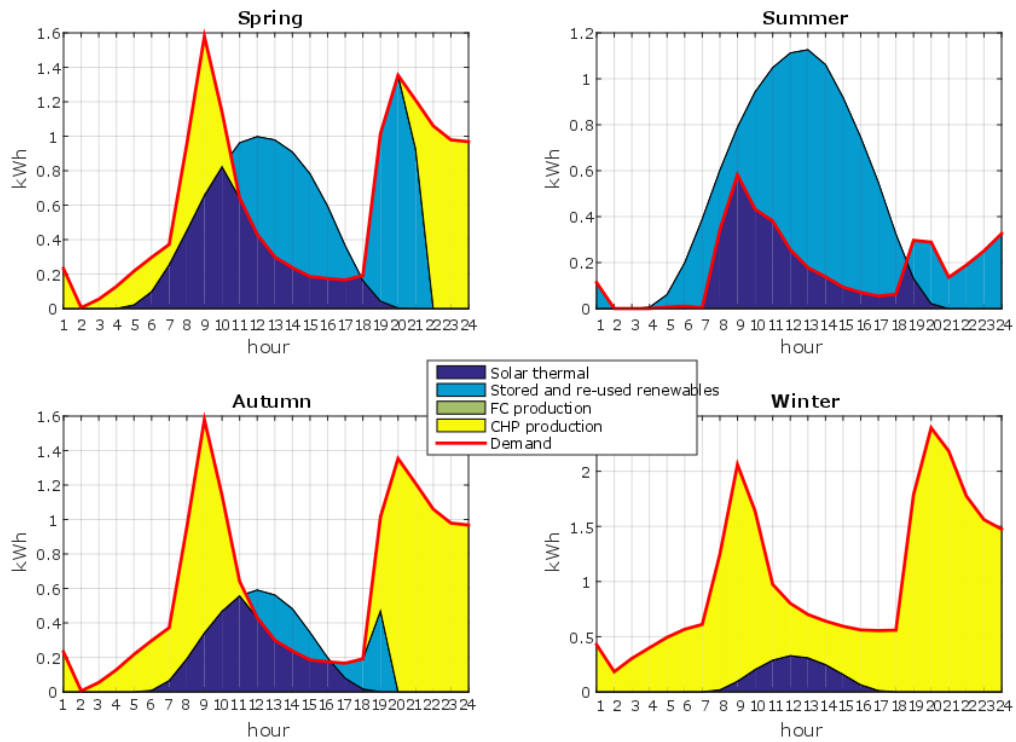


Figure 4.29: Seasonal heat demand and supply for a two adult household – maximum CO₂ reduction

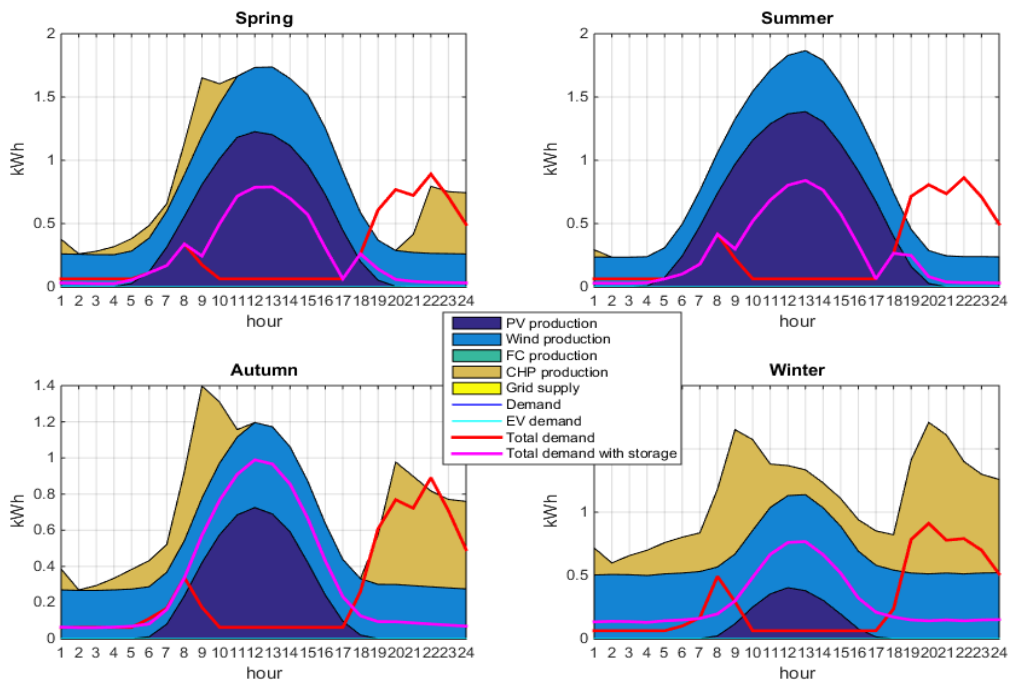


Figure 4.30: Seasonal electricity demand and supply for a two adult household – maximum CO₂ reduction

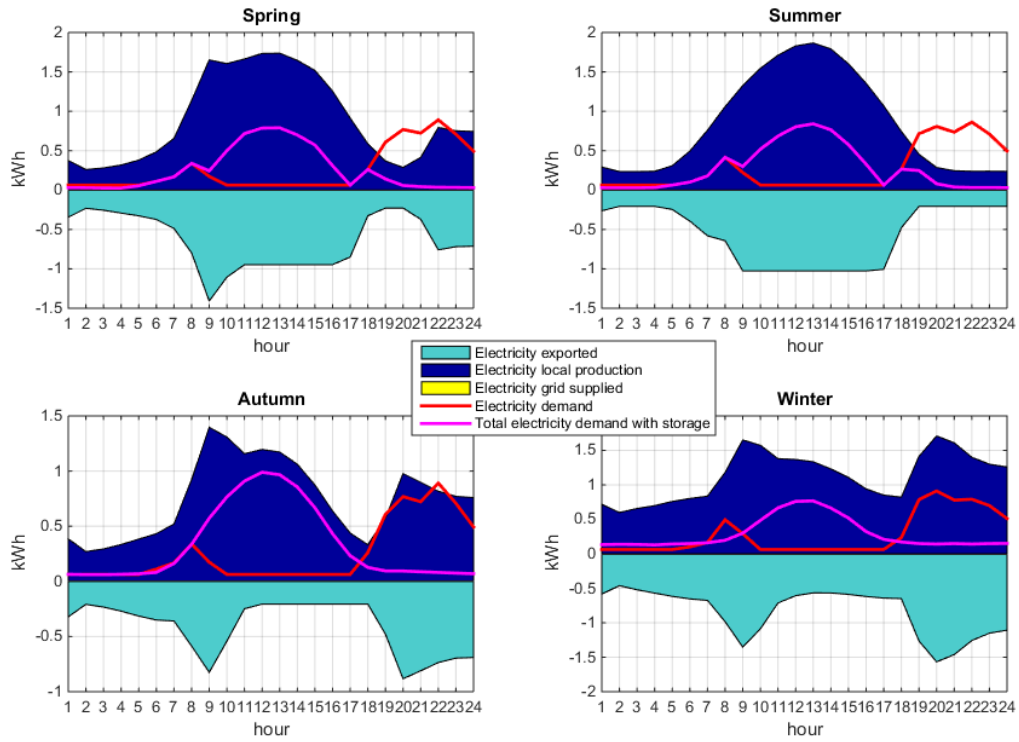


Figure 4.31: Seasonal electricity local energy balance for a two adult household – Maximum CO₂ reduction.

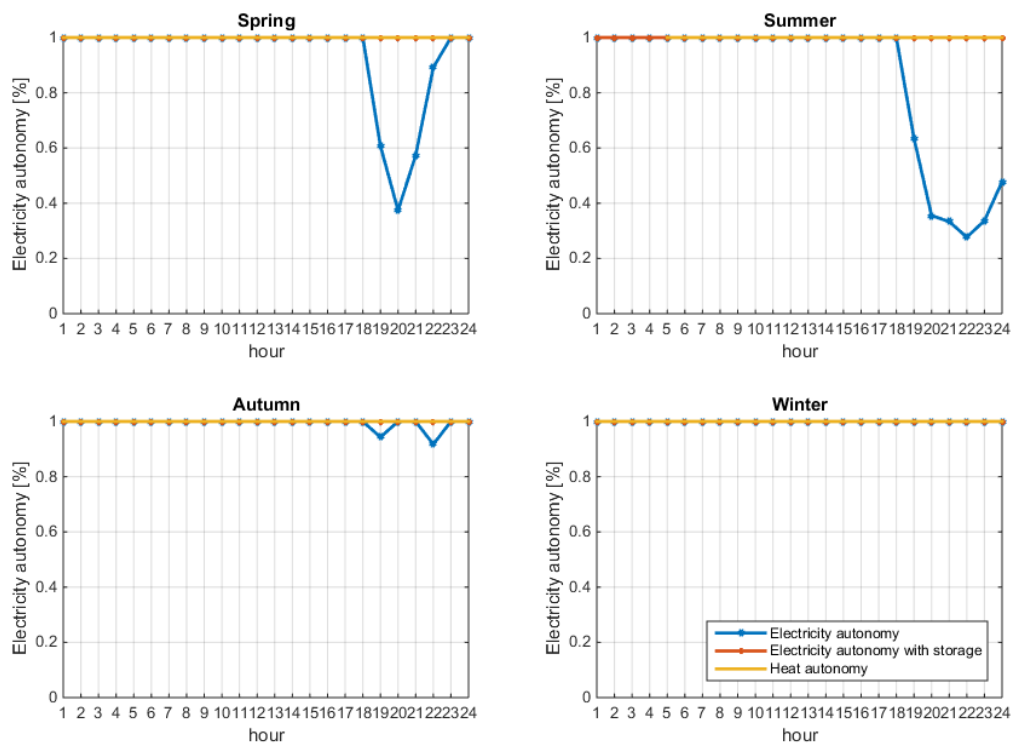


Figure 4.32: Seasonal energy Autonomy for a two adult household – Maximum CO₂ reduction.

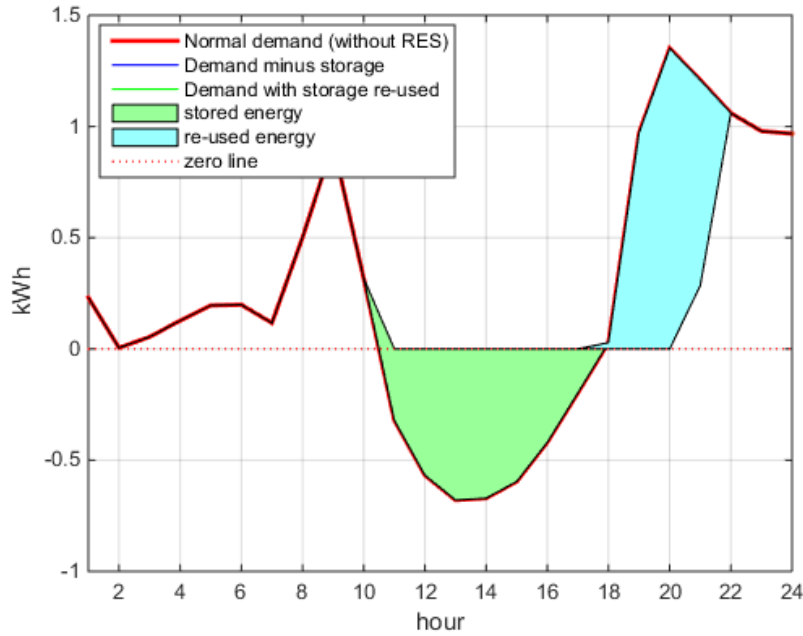


Figure 4.33: Thermal storage during a spring day for two adult household – maximum CO₂ reduction.

4.7.1.3. Family household

The spread of the configurations of family households shows strong similarities with the spread of the configurations of the one person household (Figure 4.34 and Figure 4.35). The systems with low heat autonomy are located approximately at the same position as they were for the one adult household. Note the marks are on average at a higher vertical position, indicating higher annualised energy costs. This corresponds with a higher energy demand. Configurations are selected the same way as this is done for the earlier described systems. The results are summarised in Table 4.16.

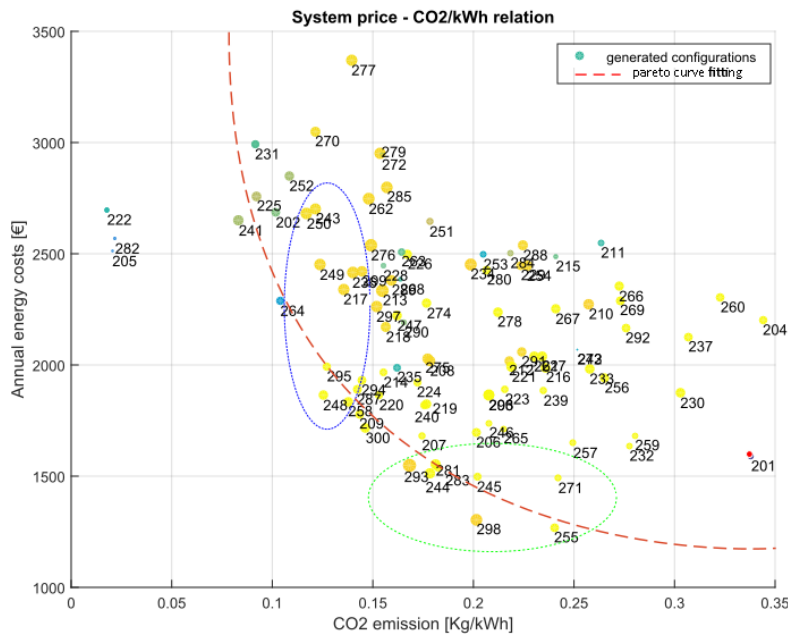


Figure 4.34 Annualised energy costs - CO₂ relation (family household)

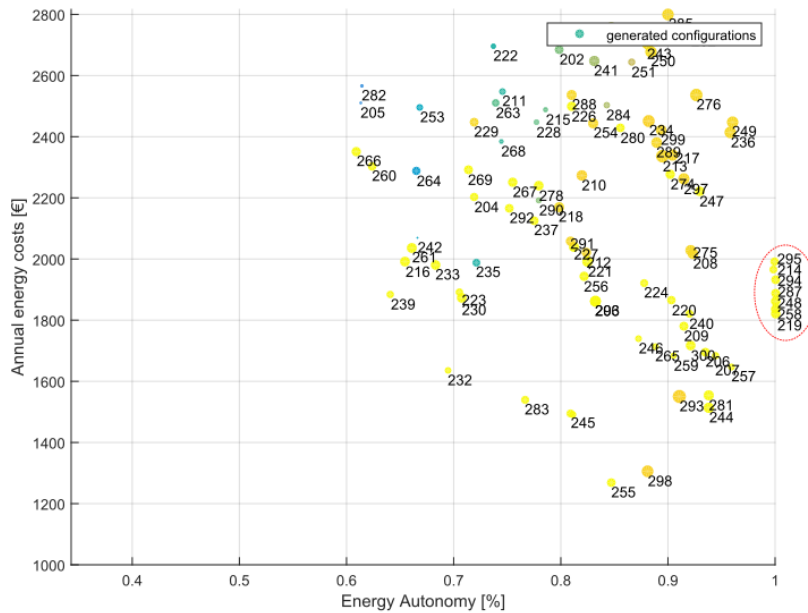


Figure 4.35: Annualised energy costs – Energy autonomy relation (family household)

Table 4.16: Selected household configurations - family household

Family household	Base case	Energy autonomy optimisation	CO ₂ reduction	Financial optimisation
Household number	201	219	248	255
System code	3B	3A	3C	3F
Capital investment costs (€)	€ 8000	€ 34700	€ 38000	€ 17100
Annual energy revenues (€)	€ 0	€ 1043	€ 924	€ 811
Net annual energy costs (€)	€ 1590	€ 1822	€ 1863	€ 1269
CO ₂ emission (kg per kWh)	0.333	0.176	0.132	0.239
Energy self-sufficiency rate	0 %	100 %	100 %	85 %

Example 3 - System 3A: Family household - Energy autonomy maximisation

A family that wants to become energy autonomous is best served by a combination of 2.7 kW solar PV and an urban wind turbine to provide electricity. A battery is used for temporary storage and a 2kW CHP system supplies electricity at times there is no renewable production and when battery level is low. The CHP also supplies the required heat demand. The battery is used in peak shaving mode. Figure 4.40 shows the battery impact on local demand. When demand is negative, this means there is more electricity being produced than needed. This part is stored (green marked area), for later use when demand peaks (blue marked area). The battery facilitates this household can be 100% autarkic during the year (Figure 4.38). The fact that this household wants to be self-sufficient, results in a significant amount of produced excess energy. While solar and wind energy combined are capable of supplying already more energy than needed, the CHP even increases the excess amount of electricity because it needs to produce in order to fulfil heat demand. Figure 4.36 shows the seasonal variation in both electricity demand and production, resulting in the local energy balance presented in Figure 4.37. The energy autonomy is presented in Figure 4.38 and shows a 100% autonomy during all seasons, with the use of batteries in peak shaving mode (Figure 4.40).

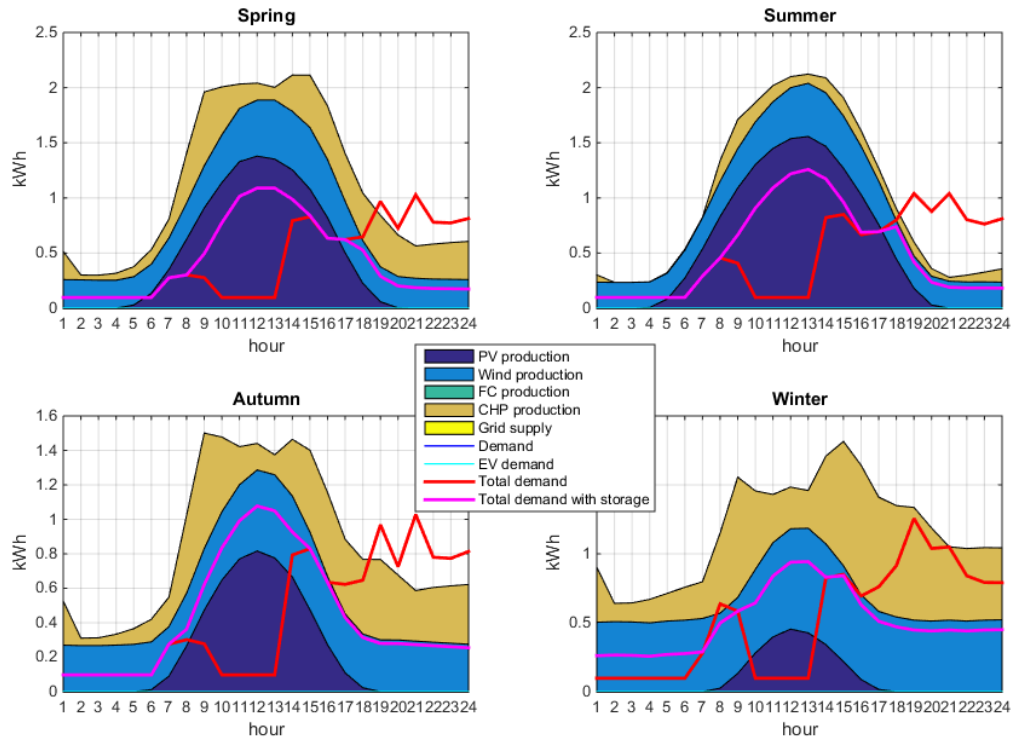


Figure 4.36: Seasonal electricity demand and production for a family household – energy autonomy maximisation.

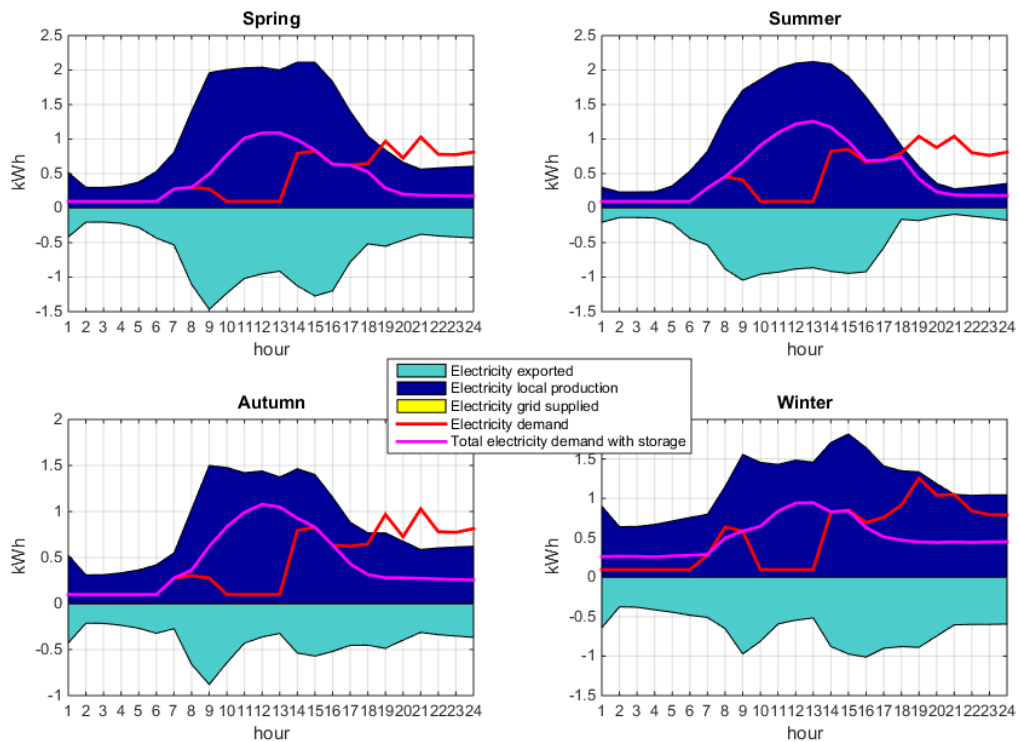


Figure 4.37: Seasonal electricity local energy balance for a family household - energy autonomy optimisation.

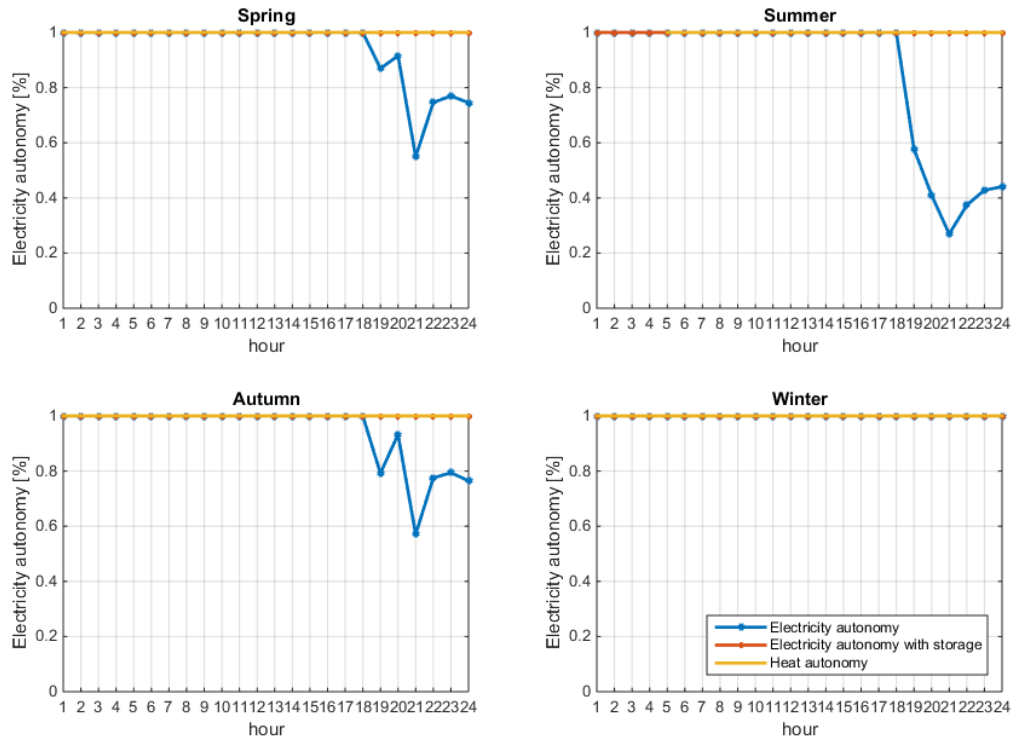


Figure 4.38: Seasonal energy autonomy for a family household – energy autonomy maximisation.

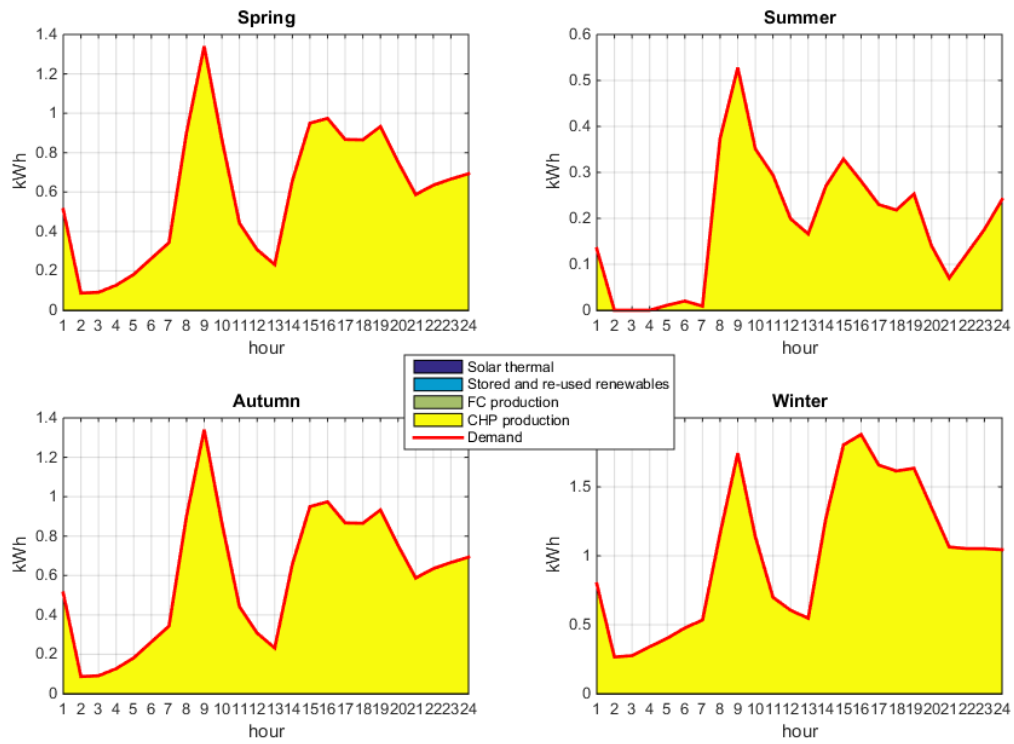


Figure 4.39: Seasonal heat demand and supply for family household – energy autonomy maximisation

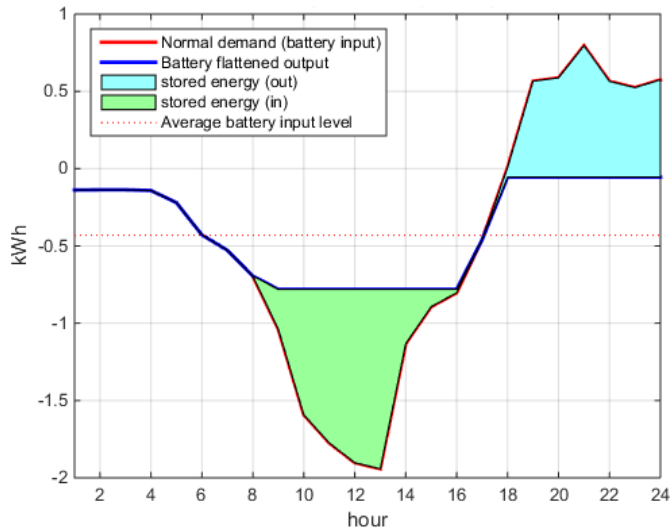


Figure 4.40: Battery peak shaving mode during summer for a family household – energy autonomy maximisation.

4.7.1.4. Pensioner(s) household

The demand profiles for pensioners’ households are flatter than the other demand profiles, since this group of occupants is more often at home. Although total energy demand is comparable with a two adult household, fewer and lower demand peaks occur. This has a positive effect on the energy demand-supply match. Although the base case is only slightly cheaper for the pensioners household, all three optimal system configurations show significant lower annualised energy costs. Less carbon emission per kWh is realised for all optimal technology mixes. This is because the higher demand peaks in two adult and family households cause over dimensioned configurations. Once again the results are visualised by the energy costs – CO₂ relation (Figure 4.41) and the energy costs – energy autonomy relation (Figure 4.42). All selected optimal configurations are presented in Table 4.17. From all examined household types, the pensioner household shows the least divergence in annualised energy costs.

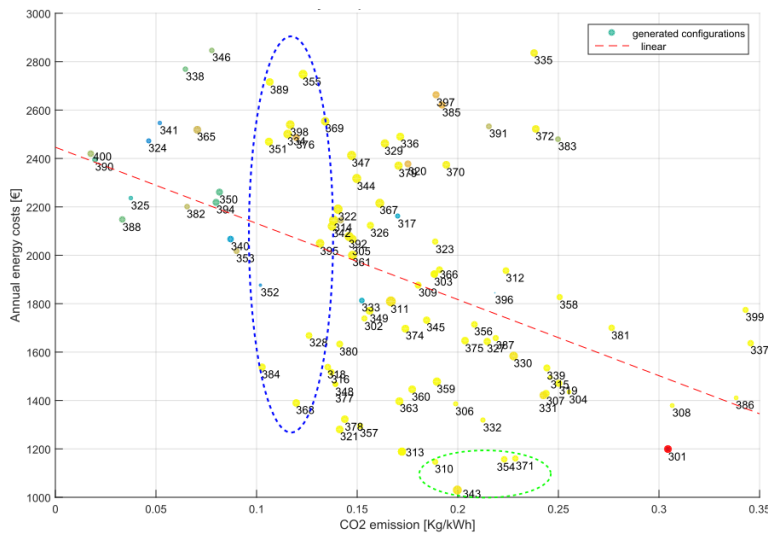


Figure 4.41: Annualised energy costs - CO₂ relation (pensioner(s) household)

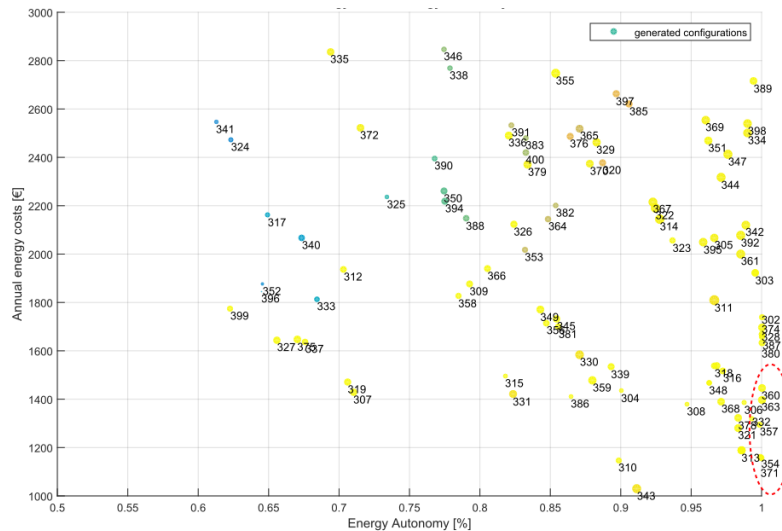


Figure 4.42: Annualised energy costs – Energy autonomy relation (pensioner household)

Table 4.17: Selected household configurations - pensioner household

Pensioner household	Base case	Energy autonomy optimisation	CO ₂ reduction	Financial optimisation
Household number	301	371	384	310
System code	4B	4E	4C	4F
Capital investment costs (€)	€ 8000	€ 20300	€ 32800	€ 19200
Annual energy revenues (€)	€ 0	€ 838	€ 841	€ 610
Net annual energy costs (€)	€ 1198	€ 1160	€ 1418	€ 1148
CO ₂ emission (kg per kWh)	0.297	0.229	0.107	0.191
Energy self-sufficiency rate	0 %	100	97 %	90 %

4.7.2. Clustering households into ICES

After we selected the optimal technological mixes for the different household compositions and optimisation preferences, these households will be clustered to form an ICES. This section illustrates the model process of clustering households and describes a number of examples to explain the principle of ICES. At ICES level, electricity will be exchanged between the different households. As explained in section 4.1.2, carbon emission is also exchanged in proportion to the exchanged energy. Therefore the CO₂ impact at household level will be part of the ICES analyses. The CO₂ emission from the optimal technology mixes varies from 0.09 kg/kWh to 0.23 kg/kWh.

Energy exchange within ICES will affect the energy autonomy of individual households. This effect is analysed to find out to what extent ICES contributes to the increase in energy autonomy of a community. The energy autonomy of individual households before energy exchange with ICES varies between 81% and 100%.

In the performance calculations for each individual household, excess energy is exported from household level to ICES. The LCOE price for the different household optimisation preferences varies from € 0.13 per kWh to € 0.24 per kWh. The exporting household will receive their average LCOE price for the exported energy within ICES. This ensures them to get their production costs covered, but does not give them an incentive to over-invest. This is a strong advantage over the schemes that are currently being used. The Netherlands uses a net-metering scheme called 'salderen', as explained in section 4.5.1. According to the Dutch Electricity Act art. 31-C (Electriciteitswet, 1998), energy taxes only apply to the net electricity consumption (the difference between electricity imported from the grid and exported to the grid). This tax benefit is limited to a fed-in quantity that is equal to the electricity received from the grid per year. Additional energy can only be sold at a tariff set by the energy supplier. This does not guarantee levelised production costs are earned back. Within ICES, excess energy that is used locally will at least make sure the LCOE is covered at production side. Therefore the use of ICES will increase the financial benefits of households that export locally produced energy. Energy that is not used within community is exported

to the national grid for APX price. The energy that could not be produced locally is supplied by the grid for retail prices.

When optimising at community level, the energy that is being imported from ICES is bought at average levelised energy price. This price is the hourly based average LCOE of all households that have excess energy. The exporting households receive LCOE for the electricity that is being exported to a community member. The part that cannot be used within ICES is exported to the grid at APX price. This process is visualised in Figure 4.43, for a random hour of the day. Households 1, 2 and 3 are exporting for LCOE and receive production costs for electricity that is being exported within ICES. Household 4 pays the average LCOE price to the ICES local energy market. The 10 kWh that Household 4 receives from ICES is allocated to the supplying households in ratio to their available excess energy. This serves the community ideology, as revenues thereby are equally being distributed amongst contributing households. Household 1 supplies in this example 5 kWh to household 4 and receives € 1.00 (5 kWh x € 0.20/kWh). The remaining 5 kWh from household 1 is exported to the grid at € 0.04 / kWh. This encourages to exchange within ICES, since exporting households receive a considerably higher price for their export to ICES members while importing households pay a considerably lower price when importing from ICES.

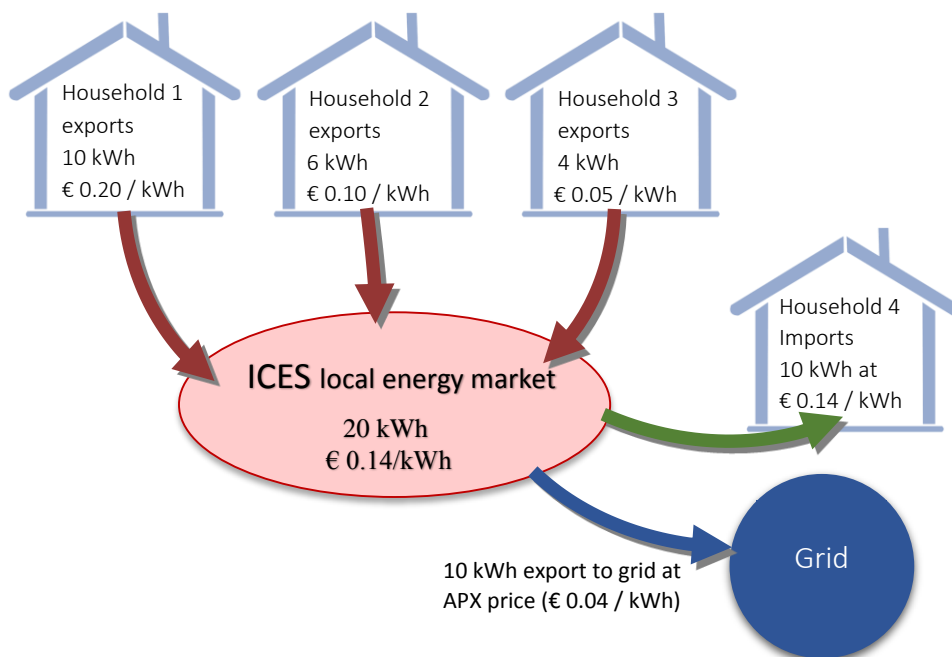


Figure 4.43: ICES energy exchange concept example

For the electricity that is being exported to the grid, households receive the same rate as when they are not participating in ICES; the APX price. This excess electricity is produced within the household, either by renewable sources or as a side-product from FC or CHP heat production. Thereby any additional revenue for this electricity surplus is considered as extra income, even when LCOE might not fully be covered. This energy surplus is produced anyway, so to receive at least some revenues is better than to discard it.

For the total energy costs calculations we need to take into account the initially by grid arranged uptake of excess energy and its supply of energy deficiencies. The extra revenues for household 1 in the above described example are: 5 kWh x (ICES export price – APX grid price) = € 0.30. For the ICES energy costs calculation we need to subtract the financial contribution of the energy that was being exchanged with the grid in the base case scenario, since this now is arranged locally within ICES. The price per kWh when using ICES is calculated as follows:

$$kWh_{price_{new}} = \frac{kWh_{price_{old}} \cdot (local\ production - export) + ICES\ import \cdot (kWh_{price_{import}} - kWh_{price_{grid}})}{local\ production - export + import} \quad (Eq. 4.14)$$

The explained principle of financial allocation can also be applied to CO₂ emission allocation. From the description of the allocation method, we will now look into the implementation of these methods and the practical application.

Model steps and outcomes for community composition A are explained and discussed in more detail in this section. (See Table 4.5 for all community compositions). We focus on the performance indicators to analyse the performance of households within ICES. First we analyse the energy transportation from overproducing households to households that have residual demand. Figure 4.44 and Figure 4.45 show the effect of ICES on each household's net electricity demand and overproduction, for a random community composition. After the excess electricity is redistributed, all households have their demand fulfilled. This illustrates the concept of ICES and the approach of the ICES level model. The remaining large overproduction is directly noticed, and is largely caused by the over dimensioned households 3 and 4 (two adult households). As mentioned earlier, this is due to the mismatch between the maximum heat peak demand and the selection of an optimal CHP size. To make use of this excess energy within ICES, we will explore the option of adding households that have no local production facilities.

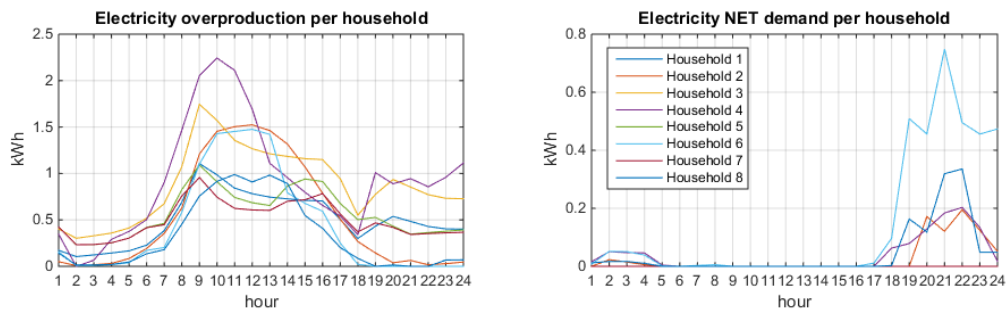


Figure 4.44: ICES overproduction and residual demand per household – before applying ICES

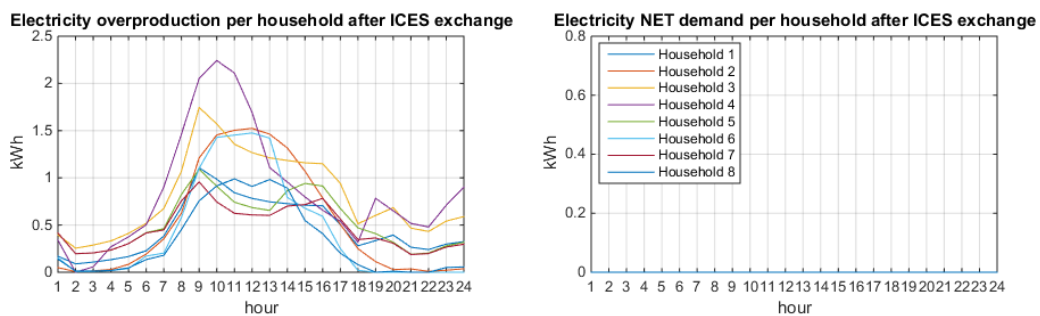


Figure 4.45: ICES overproduction and residual demand per household – after applying ICES

At first we discuss the economic impact of households for being part of ICES. The benefits for households is twofold. In the first place, the exported energy generates revenues. The net profit equals the difference between the price received from ICES and the opportunity costs of selling to the grid. In the second place, the import of energy is done at LCOE of the producing household. When this price is lower than the retail electricity price from the grid, additional profit is made. Both aspects are analysed and presented in Figure 4.46. All households have economic benefit from being a participant in ICES, however not to the same extent. In this case the one adult households (household 3 and 4) receive the most income from energy export within ICES. Compared to the total annual energy costs (Figure 4.47), however there is only minor impact noticeable.

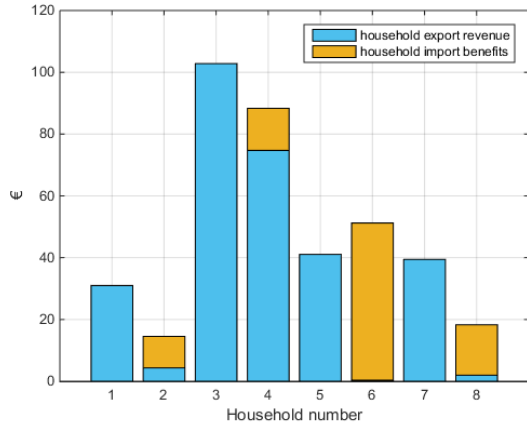


Figure 4.46: ICES annual electricity financial benefits

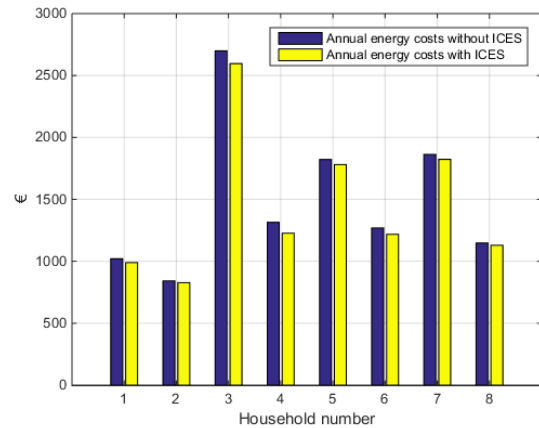
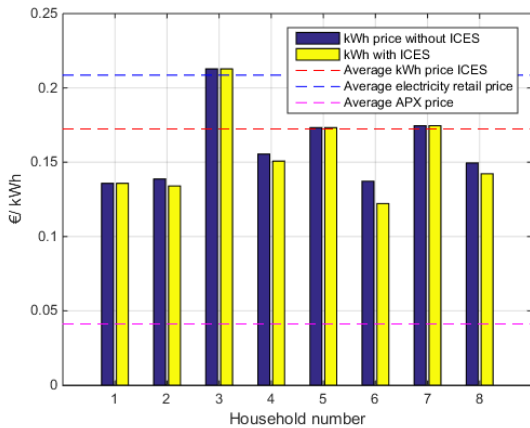


Figure 4.47: ICES electricity kWh price implication and annual energy costs consequence

The impact of ICES on annual CO₂ emission shows similarities with the ICES impact on annual energy costs. This is reasonable, because both are a function of the amount of exchanged energy. Note that the largest contribution in carbon reduction already was made by the switch from traditional (fossil-fuel based) energy sources to local production at household level. The average household CO₂ emission in the Netherlands for example was 4045 kg in 2013 for natural gas and electricity (ECN, 2014). This is as much as the emission of the largest CO₂ contributor in our ICES. Household 6 (family household) has the largest CO₂ reduction, because this household is responsible for the largest electricity import from ICES. Furthermore it should be noted that the exchange of electricity does not influence the CO₂ contribution of heat. The plots show households total annual CO₂ emissions.

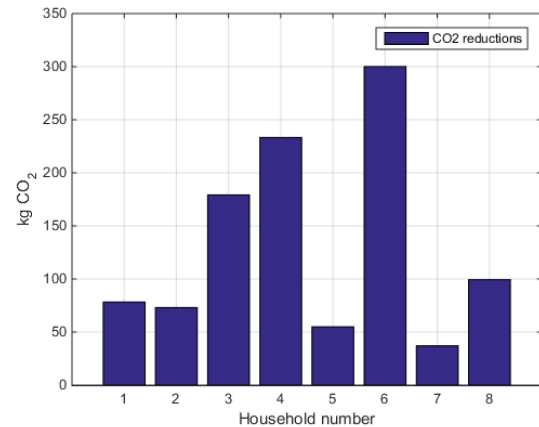
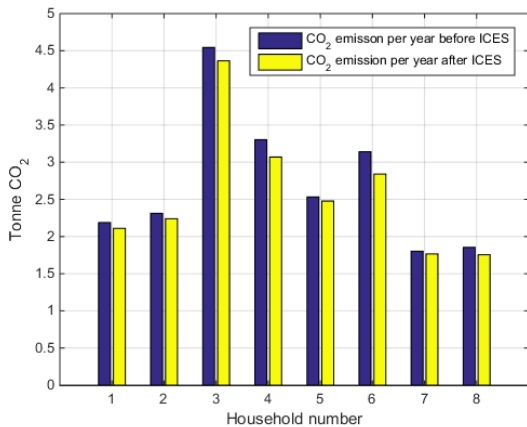


Figure 4.48: ICES annual CO₂ emission and CO₂ reduction per household

The most visible influence of ICES could be ascribed on the energy autonomy performance of households. Figure 4.49 clearly shows that all households within this community become 100% autonomous, after exchanging energy

within ICES. All electricity is being produced locally within the community. Household 6 has the highest increase in autonomy, because this household has the largest energy import from community level.

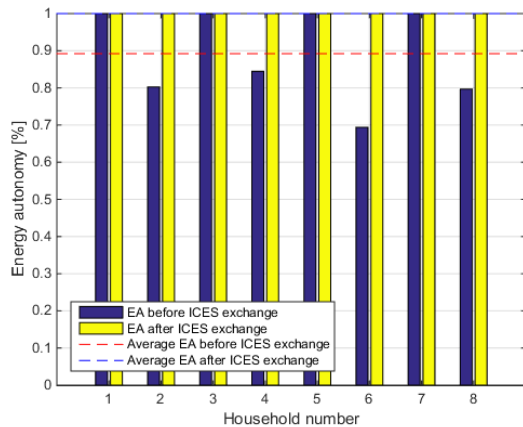


Figure 4.49: Electricity autonomy per household

4.8. SEC Heerhugowaard case study

For the ICES model, data from SEC Heerhugowaard is used to validate demand profiles and model outcomes. SEC stands for Smart Energy Collective. SEC Heerhugowaard is a pilot project in which national and international companies formed an alliance to obtain knowledge on the development of a Universal Smart Energy Framework. SEC focusses on the smart grid development and aims to accelerate innovations in smart energy. Although the SEC approach is not the same as the one of ICES, the data being measured in in SEC Heerhugowaard is useful for the ICES assessment. This collected data is processed to be of use for the ICES model results verification. Therefore Microsoft Access is used to create several SQL views that allow us to combine the provided datasets and to make proper data selections that are of particular interest in this research. For around 110 households data is provided, however not all data is useful. This is because the pilot is still in the early phase and data is not perfectly recorded for all households yet. Meter readings from the first day of each month are used to calculate the monthly export and import of electricity per household. The annualised electricity import and export for each household is represented in Figure 4.50 and shows a wide variety in the quantity of energy import and export per household. The extrapolated, annualised average electricity import is 996 kWh and the average electricity export is 424 kWh.

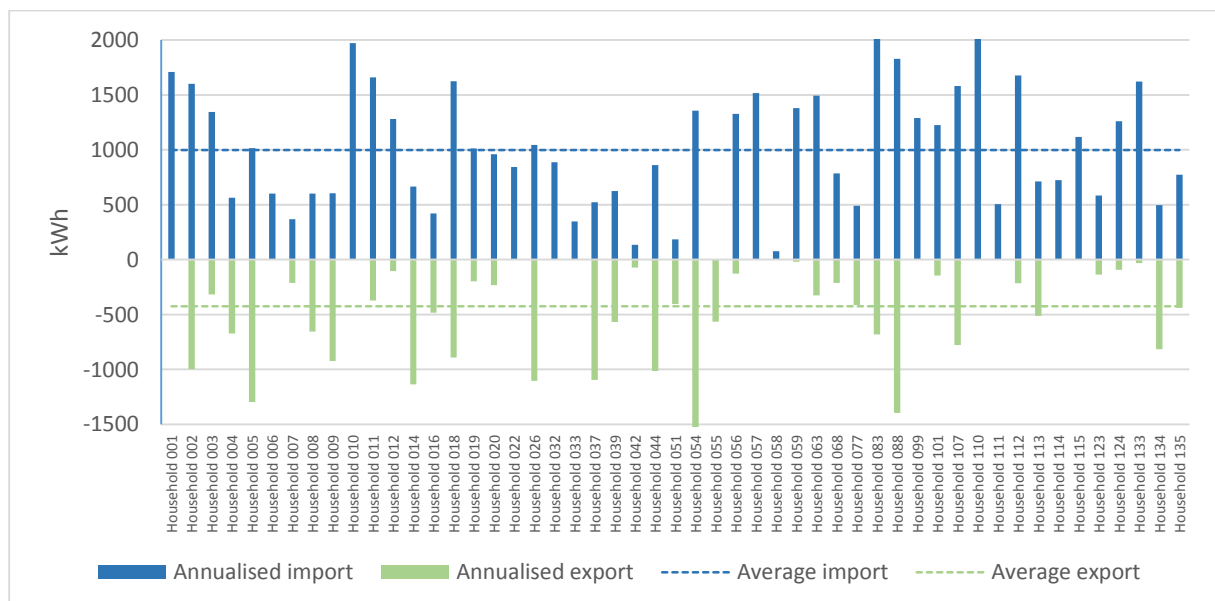


Figure 4.50: SEC Heerhugowaard annualised electricity import and export per household

Unfortunately some data errors and data gaps need to be corrected. Considering the large dataset, manually testing all data for every single household is a time consuming process. Table 4.18 shows an indication of the missing data analyses on monthly energy usage for a selection of households. For example when the meter readings of June 1 are missing (e.g. for Household 119), the demand in May appears to be negative when subtracting the meter reading of June 1 from the meter reading of May 1.

Table 4.18: SEC Heerhugowaard monthly usage – data errors analysis

	Household 001	Household 110	Household 111	Household 114	Household 115	Household 119	Household 135
March - Export low tariff	0	3393	1609	0	0	0	0
April - Export low tariff	0	442	-1392	2665	222	1653	42
May - Export low tariff	1	425	173	191	162	-1653	68
March - Export normal tariff	0	0	0	0	0	0	0
April - Export normal tariff	0	0	0	0	234	219	0
May - Export normal tariff	0	0	0	0	345	406	0
March - Import low tariff	164	2023	3009	0	0	0	0
April - Import low tariff	-164	78	-2847	3031	72	1213	93
May - Import low tariff	427	62	45	69	55	-1213	53
March - Import normal tariff	0	1427	688	0	0	0	0
April - Import normal tariff	0	159	-622	1198	74	689	10
May - Import normal tariff	0	262	81	112	78	-689	37

It is necessary to exclude all individual households, or at least the parts of the data, that have missing data. This makes the process of analysing, correcting and excluding some parts of the data, in order to result with a piece of meaningful validation material, a time-consuming practice. We excluded questionably high and low values and use the average value over all households for the test period between 3 February 2015 and 1 June 2015. With the corrected data, we look only at average energy import and export values for all households combined. The results of this exercise are presented in Figure 4.51.

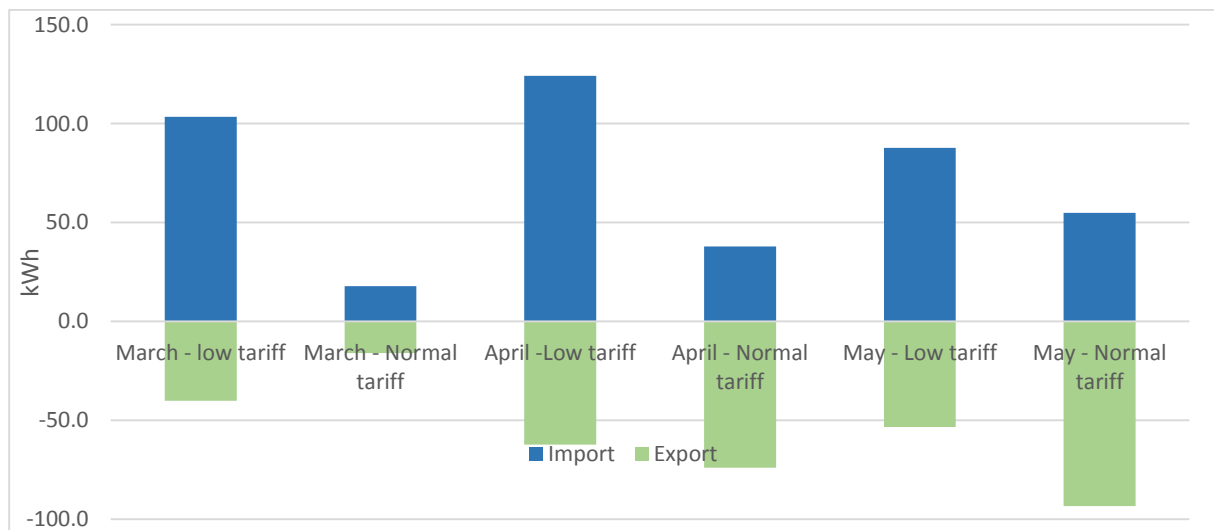


Figure 4.51: Average electricity import and export - SEC Heerhugowaard

To obtain annual values, the numbers of the test period are extrapolated. This results in an average annual energy import of 1700 kWh per household and an annual energy export of 1350 kWh. If we take into account the annual extrapolated average CHP contribution of 320 kWh (measured over 20 households) and the solar PV production of 1830 kWh (measured over 63 households and represented by Figure 4.52), this results in a total electricity demand of 2500 kWh (Eq. 4.15). The average annual electricity demand used in the ICES model is 2400 kWh. The large electricity export and the small contribution of the fuel cell is interesting and needs further research. Nevertheless, the data shows that the values used for electricity demand profiles in the model are very reasonable.

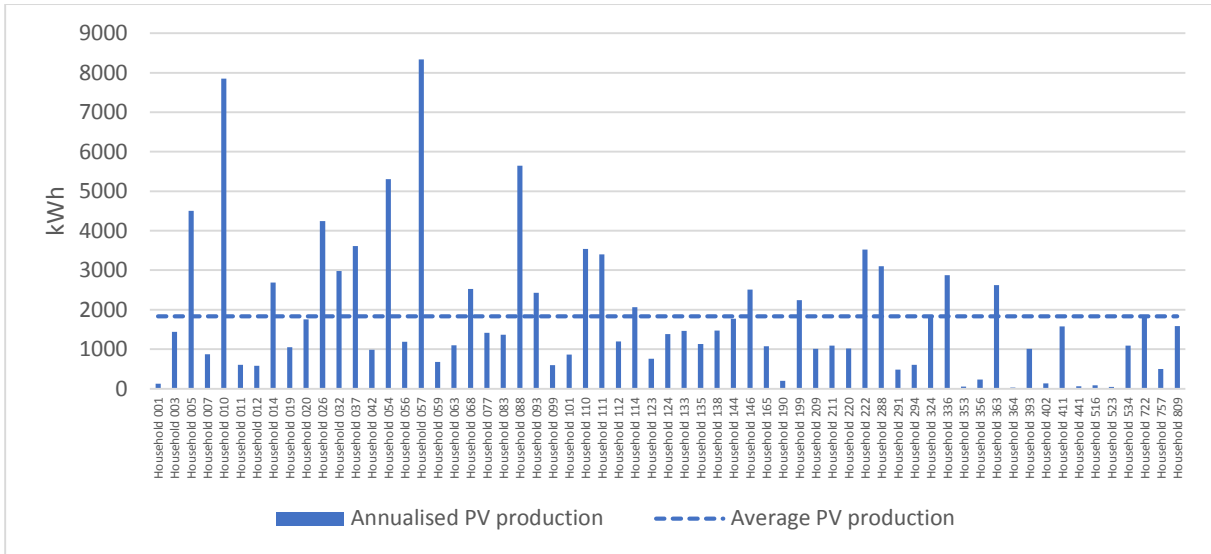


Figure 4.52: SEC Heerhugowaard annualised PV production per household

Hence a large deviation between the individual households is observed, it makes sense to look at the agglomerated demand and production numbers. Annualised local energy demand (and consumption) is described by (Eq. 4.15).

$$electricity\ demand = import - export + solar\ PV\ production + FC\ production \quad (Eq. 4.15)$$

Chapter 5: ICES performance under different scenarios

The previous chapter mainly focussed on the performance of individual households and the optimisation process to obtain the best results based on the desired optimisation preference. This chapter describes the process of combining households to form a community. Firstly we will look into the optimisation process that is used to utilise ICES in order to reduce energy costs, lower CO₂ emission and to increase the energy autonomy. Thereafter different scenarios will be studied, to analyse the impact on the distinct performance indicators on household level and on ICES level.

5.1. Community optimisation preferences

The individual households are assessed by their individual preferences of optimisation, described in section 4.2. For each optimisation parameter (costs, carbon emission and energy autonomy), an ICES is constructed with the in section 4.7.1 determined optimal household configurations. These households correspond to the selected optimisation preferences. The impact of different optimisation preferences is analysed at community level. The performance indicators are used to value and compare the community performance under different optimisation parameters and different community compositions, as presented before in Table 4.5.

5.1.1. Financial optimisation

Table 5.1: Community composition - financial optimisation

Household	One adult household	Two adults household	Family	Pensioner(s) or unemployed
Financial optimisation	System 1F (63)	System 2F (119)	System 3F (255)	System 4F (310)
Composition A (2015)	3	3	5	1
Composition B (2045)	4	2	2	4
Composition C (prolong B)	5	1	1	5
Composition D (uniform)	3	3	3	3

A selection of households that have their technology mix selected on energy costs reduction is combined, according the determined community compositions. A 12 households ICES is constructed according Table 5.1. The numbers in the table indicate the number of households that are implemented for each scenario. Composition A has three one adult households (of which the household number from the household level model is 63). In the subsequent performance indicator plots, the household order of the table is always followed. For community composition A, the first three households are one adult households, households 4, 5 and 6 are two adult households, the 7th to 11th households are family households and the 12th household is a pensioners household.

For community **composition A**, the results are visualised. The results show the largest gain in energy costs reduction (Figure 5.1 & Figure 5.2), and carbon emission (Figure 5.3) is to achieve by the 2 adult households, albeit the increase in energy autonomy is lowest for this type of consumer (Figure 5.4). This is because the technological mix of 2 adult household is over-dimensioned (explained in section 4.7.1.2), resulting in a significant amount of energy that is available for export to other community members. The capital costs of family households is the largest of all household types. The large amount of excess energy creates for this household type the best perspective to earn back investment costs. The family households are the largest energy importers within ICES.

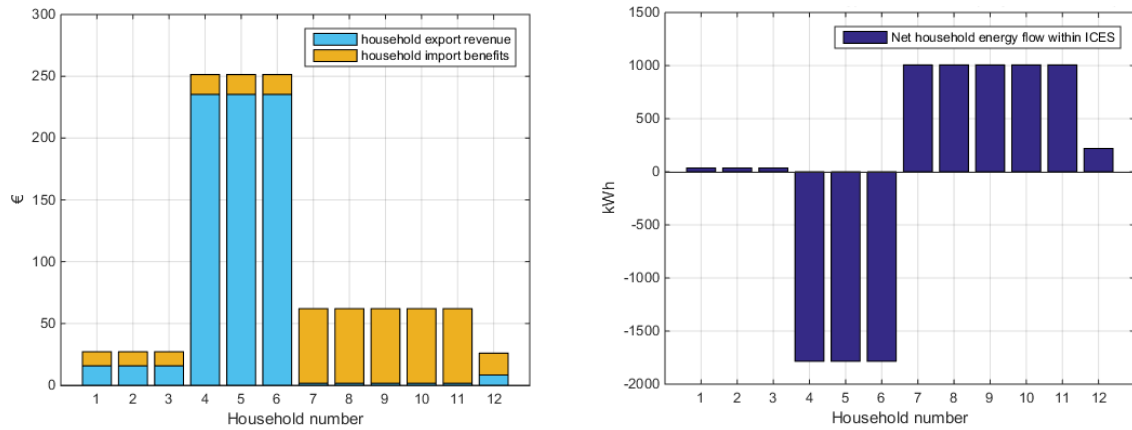


Figure 5.1: ICES annualised financial implications and net household energy flow within ICES (negative = exporting to ICES). Household number 1, 2, 3 = one adult, 4, 5, 6 = two adults, 7, 8, 9, 10, 11 = family, 12 = pensioners

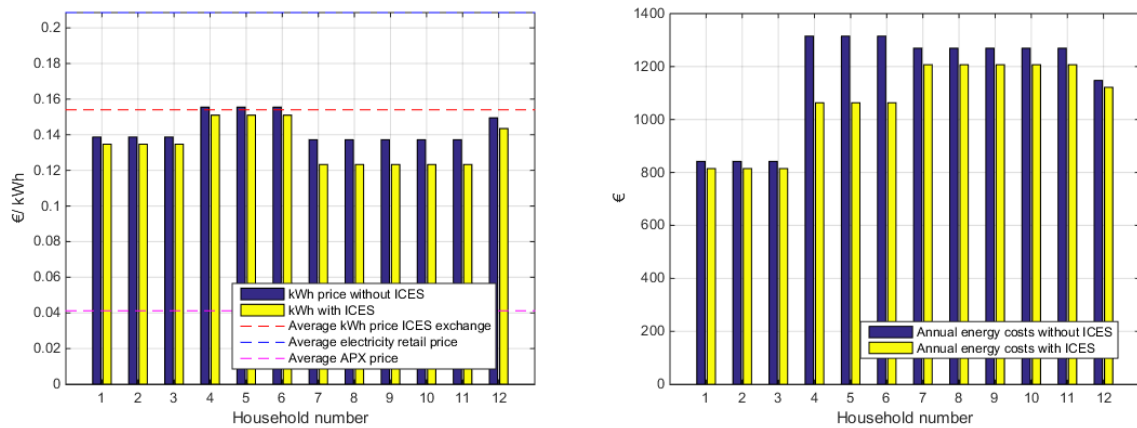


Figure 5.2: ICES electricity kWh price implication and annual energy costs consequence - financial optimisation

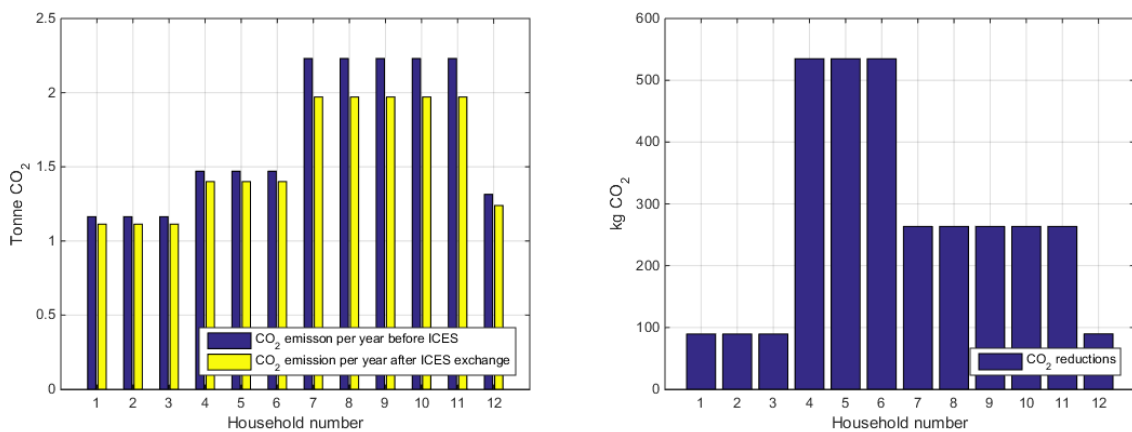


Figure 5.3: ICES annual CO₂ emission and CO₂ reduction per household - financial optimisation

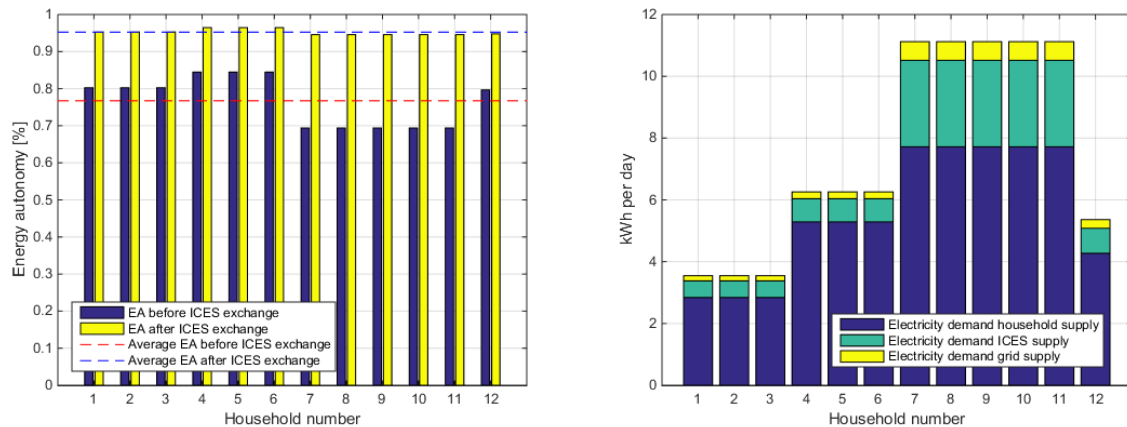


Figure 5.4: Electricity autonomy & electricity supply source per household – financial optimisation

For the four different community compositions, the results are presented in Table 5.2. The trend in community compositions (from composition A to B to C, as described in section 4.2) does not look in favour of the development of ICES in the case households optimised their portfolio on financial growth. The positive contribution of ICES reduces, however a significant benefit remains. Financial benefits from participating in ICES decreases from € 0.008 per kWh to € 0.006 per kWh when the projected trend in household composition will be followed until 2045 (composition B). Also the increase in energy autonomy and the CO₂ reduction decreases for composition B. Composition A has the largest benefits from joining ICES, for all three performance indicators.

Table 5.2: ICES results financial optimisation per community composition

	Composition A	Composition B	Composition C	Composition D
kWh price before ICES [€/kWh]	0.143	0.145	0.144	0.145
kWh price after ICES [€/kWh]	0.135	0.139	0.140	0.138
Price difference [€/kWh]	0.8	0.6	0.4	0.7
Annual CO ₂ emission before ICES [tonnes]	34.4	26.9	27.3	31.8
Annual CO ₂ emission after ICES [tonnes]	31.1	27.4	25.9	29.0
CO₂ reduction [kg]	3280	2118	1402	2799
Energy autonomy before ICES [%]	76.7	78.9	79.5	78.4
Energy autonomy after ICES [%]	95.2	94.6	91.4	96.8
Energy autonomy increase [%]	18.5	15.7	11.9	18.4

Looking at the impact of the use of renewable technologies with respect to the impact of applying ICES, the impact of ICES is never larger than the impact of the selection of the optimal technology mix. A 10% energy costs reduction is possible at household level, and at ICES level another 10% cost reduction can be realised. However in most cases, the efficiency gain of ICES is less than 10%, while the benefits of the local generation technologies often exceeds 10%. For the CO₂ emission reduction, the contribution of ICES is smaller than the contribution of the optimal technology mix. In the financial optimisation scenario the benefits from local renewable energy generation is about 25% CO₂ reduction while the reduction from ICES is an additional 11%. There are slight variations observed between the results from different community compositions (less than 5% variation). It is noticed that the initial optimisation preference is of higher influence than the community composition.

5.1.2. CO₂ reduction

Table 5.3: Community composition – CO₂ reduction

Household	One adults household	Two adults household	Family	Pensioner(s) or unemployed
Carbon reduction:	System 1C (45)	System 2C (162)	System 3C (248)	System 4C (384)
Composition A (2015)	3	3	5	1
Composition B (2045)	4	2	2	4
Composition C (prolong B)	5	1	1	5
Composition D (uniform)	3	3	3	3

Again a 12 households ICES is constructed. For the CO₂ reduction scenario, this is done according the data presented in Table 5.3. The numbers in this table indicate the amount of households that are implemented in each scenario. For community **composition A**, the ICES results are visualised and elaborated below.

The results show significantly lower financial benefits from participating ICES, compared to the financial optimisation (Figure 5.5 and Figure 5.6). This is because each household is equipped with a technology mix that offers the lowest CO₂ emission. Figure 5.7 shows the CO₂ emission per household is much lower than the emission in the financial optimisation scenario. Little extra CO₂ reduction is added by ICES. The households are equipped with a large share of decentral renewable technologies. This results in highly energy autonomous households (Figure 5.8). As a consequence, little energy is being exchanged within ICES. The one adult households and the pensioner’s household benefit the most from ICES, since they are the only types of households that import energy from other community members.

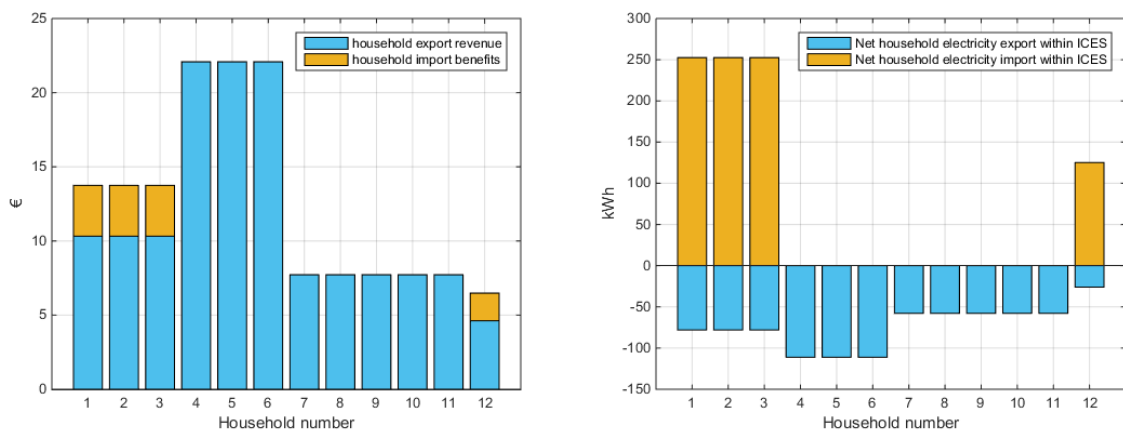


Figure 5.5 ICES annualised financial implications and net household energy flow within ICES (negative = exporting to ICES). Household number 1, 2, 3 = one adult, 4, 5, 6 = two adults, 7, 8, 9, 10, 11 = family, 12= pensioners

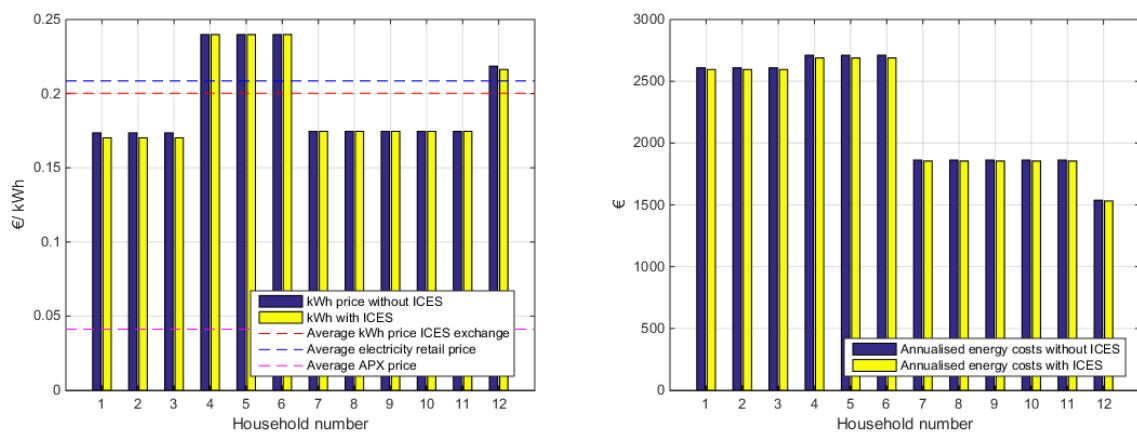


Figure 5.6 ICES electricity kWh price implication and annual energy costs consequence - CO₂ minimisation.

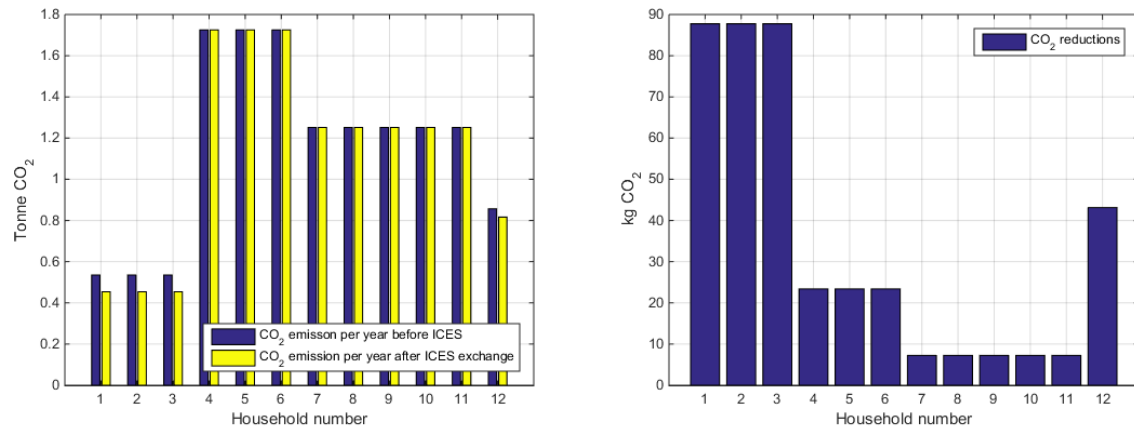


Figure 5.7: ICES annualised CO₂ emission and CO₂ reduction per household - CO₂ emission reduction

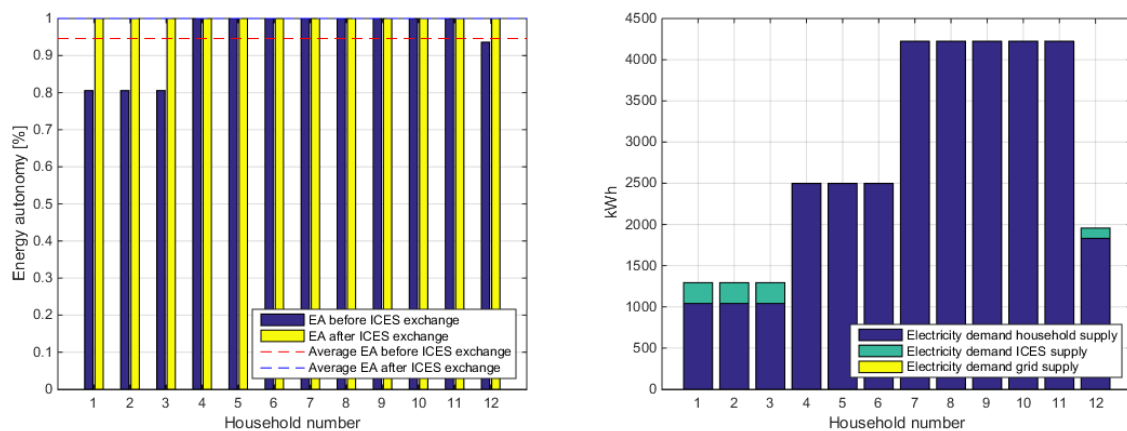


Figure 5.8: Electricity autonomy & electricity supply source per household - CO₂ emission reduction

Results are presented in Table 5.4 for the four different community compositions. A 100% energy autonomous community is realised for all community compositions. The observed energy price differences are marginal, partially because the small contribution of energy exchange within ICES as the two adult and family households were already 100% autonomous before participating in ICES (Figure 5.8). The other reason that the financial benefits are small, is that the average ICES energy exchange price is only slightly lower than the electricity retail price (Figure 5.6). This makes importing electricity from other community members only slightly cheaper than importing from the grid. Although the carbon emission already was reduced at household level, ICES also contributes to a further CO₂ reduction. Community composition B and C have a larger energy autonomy increase due to the energy exchange within ICES, because these compositions contain fewer two adult and family households. These household types are 100% energy autonomous in this scenario. Fewer two adult and family households will decrease the overall ICES energy autonomy.

Table 5.4: ICES results CO₂ emission reduction per community composition

	Composition A	Composition B	Composition C	Composition D
kWh price before ICES [€/kWh]	0.194	0.200	0.198	0.202
kWh price after ICES [€/kWh]	0.193	0.198	0.195	0.200
Price difference [€/kWh]	0.1	0.2	0.3	0.2
Annual CO ₂ emission before ICES [tonnes]	22.0	18.6	16.3	21.0
Annual CO ₂ emission after ICES [tonnes]	21.6	17.9	15.4	20.4
Total CO₂ reduction [kg]	413	706	892	528
Energy autonomy before ICES [%]	94.6	91.4	89.2	93.5
Energy autonomy after ICES [%]	100	100	100	100
Energy autonomy increase [%]	4.5	8.6	10.8	6.5

5.1.3. Energy autonomy maximisation

Once again a 12 households ICES is constructed. For the energy autonomy maximisation scenario, this is done according to the data presented in Table 5.5. The numbers in this table indicate the amount of households that are implemented in each scenario. For community **composition A**, the ICES results are presented below.

Table 5.5: Community composition – energy autonomy maximisation

Household	One adults household	Two adults household	Family	Pensioner(s) or unemployed
Autonomy maximisation:	System 1A (56)	System 2A (124)	System 3A (219)	System 4A (371)
Composition A (2015)	3	3	5	1
Composition B (2045)	4	2	2	4
Composition C (prolong B)	5	1	1	5
Composition D (uniform)	3	3	3	3

The results show the selected households are already energy autonomous and therefore no energy exchange takes place (Figure 5.9, Figure 5.10 and Figure 5.11). The average ICES electricity price is almost € 0.03 cheaper than the average electricity retail price (Figure 5.9). When maximising the energy autonomy at household level, ICES has no additional value to the households. The community composition results are presented in

Table 5.6.

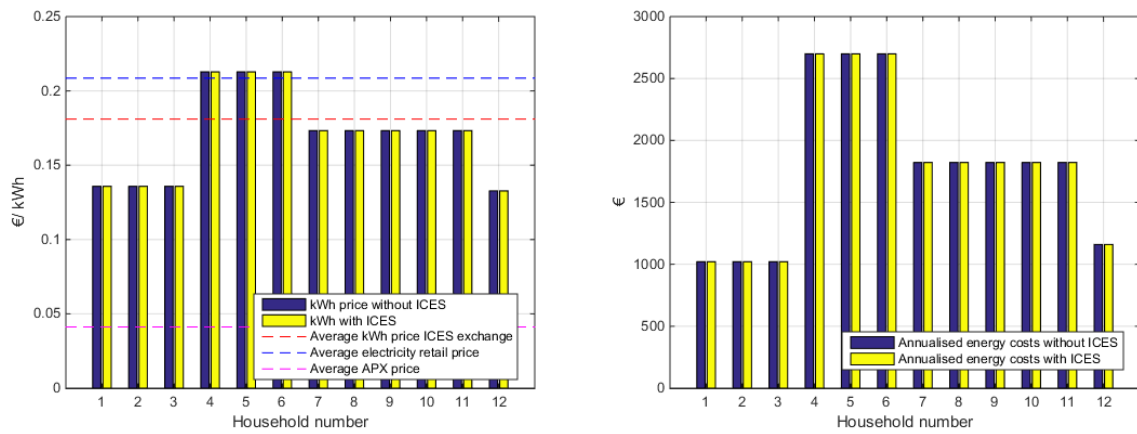


Figure 5.9: ICES electricity kWh price implications & annual energy costs – Energy autonomy maximisation. Household number 1, 2, 3 = one adult, 4, 5, 6 = two adults, 7, 8, 9, 10, 11 = family, 12 = pensioners

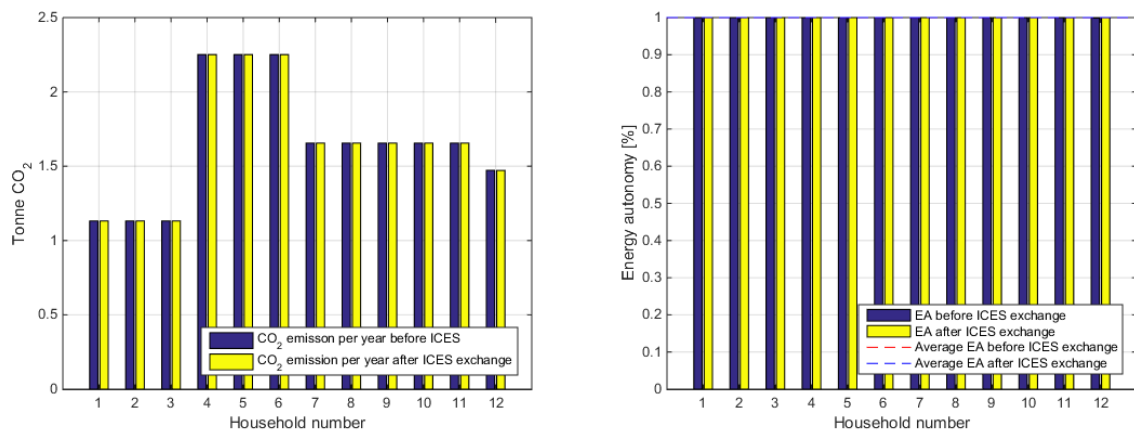


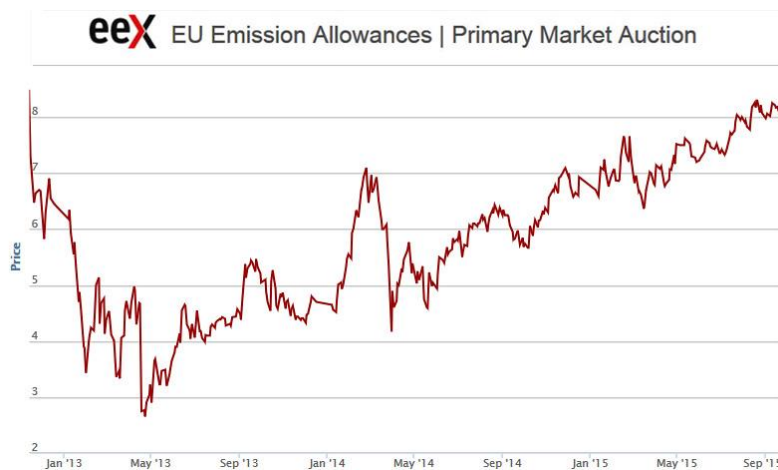
Figure 5.10: ICES annualised CO₂ emission and energy autonomy per household – Energy autonomy maximisation

Table 5.6: ICES results energy autonomy maximisation per community composition

	Composition A	Composition B	Composition C	Composition D
kWh price before ICES [€/kWh]	0.170	0.154	0.144	0.164
kWh price after ICES [€/kWh]	0.170	0.154	0.144	0.164
Price difference [€/kWh]	0	0	0	0
Annual CO ₂ emission before ICES [tonnes]	35.2	32.4	29.9	34.9
Annual CO ₂ emission after ICES [tonnes]	35.2	32.4	29.9	34.9
Total CO₂ reduction [kg]	2	6	8	5
Energy autonomy before ICES [%]	100	99.9	99.9	100
Energy autonomy after ICES [%]	100	100	100	100
Energy autonomy increase [%]	0	0.1	0.1	0.1

5.2. Carbon pricing and carbon emissions projections

Carbon pricing has the potential to become more influential as a driver for ICES. Two main types of carbon pricing can be distinguished: emissions trading systems (ETS), a cap-and-trade system, and carbon taxes. Stricter energy policy targets will limit the options of CO₂ emitting without financial consequences. Therefore the price of emitting CO₂, 'the carbon price', is expected to rise in the near future and will thereby become more important in the choice for investments in different energy sources and possibly also in the way energy systems are being organised. Carbon prices in the EU are fluctuating around €7 per tonne CO₂, as shown in Figure 5.11. Mid Augusts 2015 the price reached a peak of € 8.2 per tonne, after a strong price increase of almost 5% in one week (Energieia, 2015).

Figure 5.11: European environmental CO₂ exchange auction prices (Retrieved from European Energy Exchange AG, 2015).

Different future carbon price scenarios are possible, dependent on the implemented policies of governments. (Luckow et al., 2014). These scenarios are illustrated in Figure 5.12.

- In the **low case scenario** regulatory or legislative policies exist but are not very stringent.
- The **mid case scenario** forecast represents a scenario in which policies are implemented with significant but reasonably achievable goals.
- The **high case scenario** is consistent with the occurrence of one or more factors that have the effect of raising carbon prices. These factors could be more aggressive emissions reduction targets; restricted availability or high cost of technological alternatives; more aggressive international actions; or higher baseline emissions.

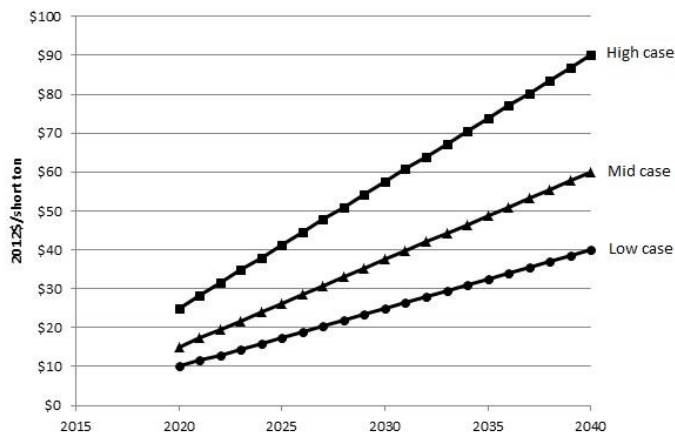


Figure 5.12: CO₂ price trajectories (Retrieved from Luckow et al., 2014)

This shows us the carbon price could reach ten times its actual value within a few decades, giving it significant importance. In our research we will look into the effects of carbon price from ICES perspectives. It is important to define a proper method of CO₂ allocation. Carbon emission can be allocated to the energy producer or to the end user. In literature this is referred to as production-based or consumption-based allocation (Davis & Caldeira, 2010). The advantage of consumption-based allocation is that it takes into account the import and export of energy. This is particularly interesting in the case of community energy systems, where energy exchange with community members is one of the main pillars to success. Therefore consumption-based allocation is used.

When households export energy to the grid, this also shifts the CO₂ allocation from the producing household to the grid, changing the average grid CO₂ emission. For one household this contribution is negligible, but when the number of households that export energy to the grid increases, this will change the emission level of the grid more notably. Exchanging local produced energy within ICES reduces the total CO₂ emission at the producing household and increases the CO₂ emission at importing consumer's household. The value of ICES in the reduction of carbon emission is the contribution to local energy exchange that reduces the need for energy import from more carbon intensive energy sources. For the CO₂ allocation of exported energy, the average household CO₂ emission per kWh is considered. Therefore the export does not change households' CO₂ emission per kWh.

Additionally, an interesting implementation of a functioning carbon market could be the sales or trade of excess carbon rights from community level. This could be particularly interesting when carbon credits become scarce.

5.3. Scenario results

5.3.1. Electric vehicle penetration

The electric vehicle penetration within ICES is studied. Section 4.4.3.3 explains the perspectives for the EV acceptance and labels the implementation scenarios. Also the choices for the EV penetration scenarios are underpinned by data from the Dutch Ministry of Transport and the Netherlands Enterprise Agency. Within our model, besides the base case scenario without EV, three scenarios are analysed. An EV penetration of 6%, 30% and 85% within community is studied. These numbers are approximated for a 12 household community by 1, 4 and 10 EVs. We use the presented scenarios of section 5.1.1 to compare ICES performance at different EV penetration percentages. EVs are distributed among the different household types within community according to the numbers in Table 5.7 below.

Table 5.7: EV distribution within ICES for different scenarios

Number of EVs	Household numbers without EV	Household numbers with EV
0	1,2,3,4,5,6,7,8,9,10,11,12	
1	1,2,3,4,5,6,8,9,10,11,12	7
4	2,3,5,6,8,9,10,11	1,4,7,12
10	6,11	1,2,3,4,5,7,8,9,10,12

The energy costs for households without EV slightly reduce for each added EV, as these households export within ICES increases due to the larger residual demand from households with EV. This effect is the largest for the first EV and decreases for each subsequent EV. This is caused by the increasing import from the electricity grid, as community cannot fulfil demand at the high EV penetration scenario. Households that export to ICES benefit from the presence of EV. This effect reverses when the implemented EV imports electricity that otherwise would have been imported by a household without EV. While more and more ICES electricity is being allocated to households with EV, the other households need to import more electricity from the grid, usually at a higher price. However the effects are small, as shown in Figure 5.13. From 30% EV penetration, the grid becomes the main supplier for the energy deficit for the households that have an EV and when EV penetration reached 90% also the majority of the energy deficit for households that do not have EV's is being supplied by the grid. This is shown in Figure 5.14. ICES can no longer fulfil electricity demand and its contribution to energy autonomy decreases. This is largely contributed to the mismatch between EV charging hours and the time that renewable energy production (and especially solar energy) is available.

In all subsequent plots, the household numbers of households that possess an EV are marked by a red circle.

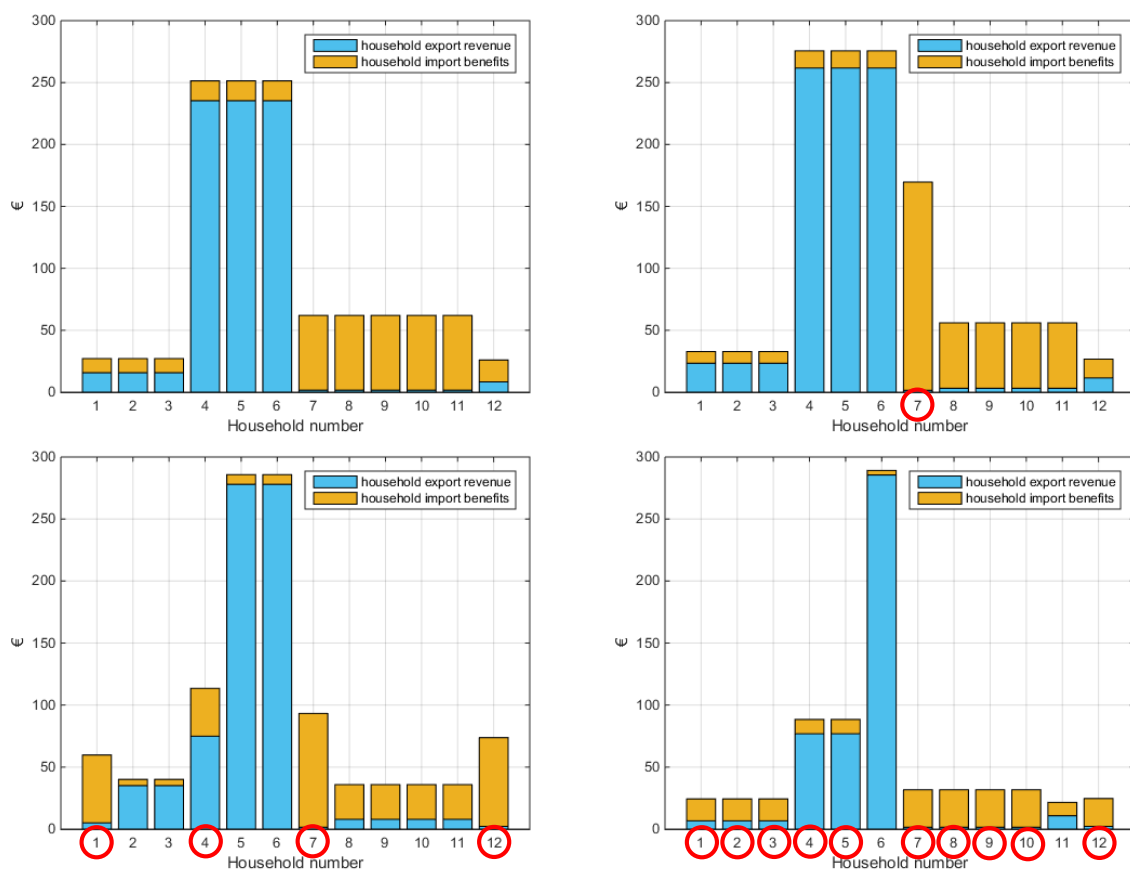


Figure 5.13 EV penetration impact on export revenues and import benefits. 0 (top left), 1 (top right), 4 (b.left) & 10 (b.right) EVs.

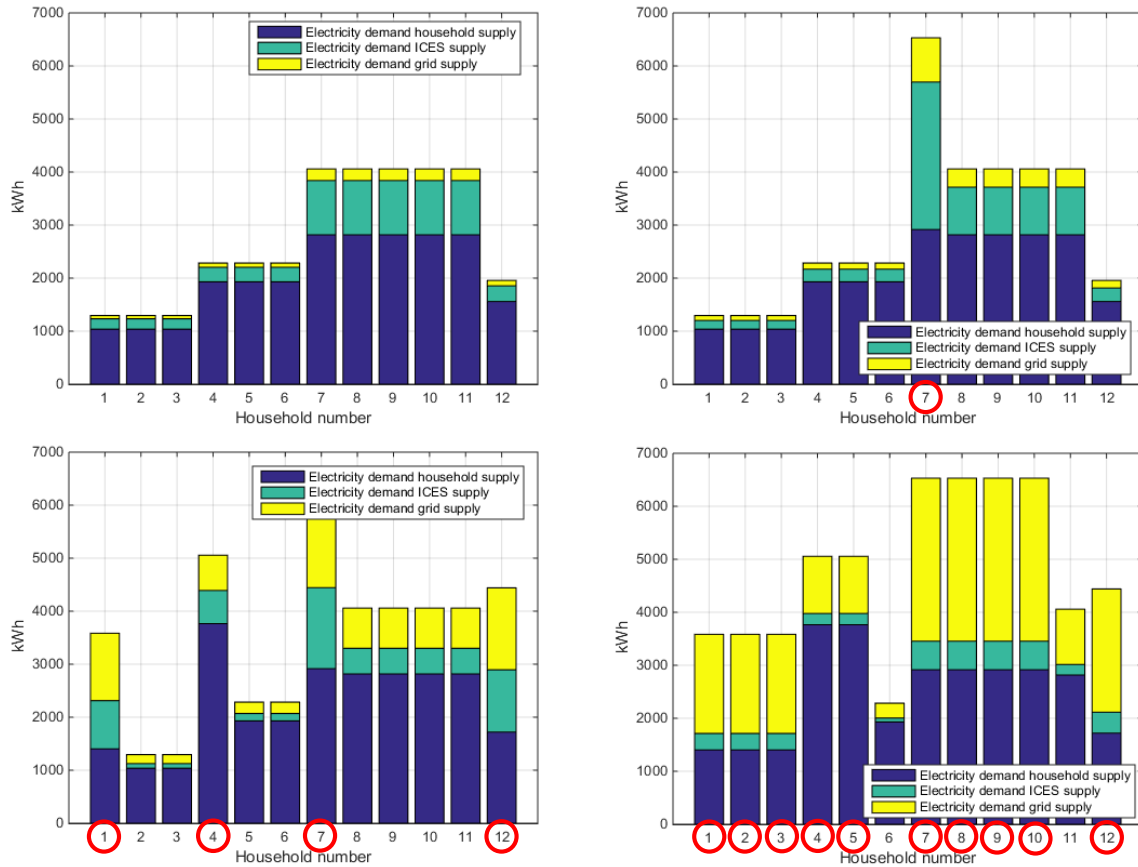


Figure 5.14: EV penetration impact on electricity supply. 0 (top left), 1 (top right), 4 (bottom left) & 10 (bottom right) EVs.

The results of the performance indicators for different EV penetration scenarios is presented in Table 5.8. The price at which electricity is being exchanged within ICES increases when the EV penetration increases. This effect increases when more EVs are implemented. The effect initially is still small, since the needed energy for charging the EV is available within ICES. At higher EV penetration levels, this is not the case anymore and other households need to reduce their ICES import since there is not enough available for all consumers. There is no priority given to types of consumers and the allocation and exchange of available energy within ICES is done at ratio of household residual demand, as explained in section 4.7.2. The CO₂ emission reduction decreases when more EVs are implemented, since although more energy is being exchanged within ICES, even more electricity needs to be imported from the grid. This leads to a lower energy autonomy. Also the contribution of ICES on energy autonomy decreases. The households with EV, export less energy since they use a larger part of their locally produced supply energy.

To receive maximum benefit from being part of ICES, it is recommended to be one of the first movers or to remain one of the few households without EV. The first mover has the advantage of importing a large share of ICES excess energy at low costs and low carbon emission. The last remaining households without EV have the advantage of exporting a large share of their excess energy to community members with EV, for a reasonable price.

With this results, load shifting at household level, in response to community signals, is strongly recommended to improve the performance of ICES under high EV penetration ratios. Currently charging EV is not adjusted to the hours where large overproduction occurs within ICES. The mismatch between EV charging hours and the renewable energy production peak hours increases the drawback of large scale EV implementation within ICES. Load shifting could partially solve this issue, although the mismatch in time is one of the permanent EV characteristics. This needs another type of solution, for example interchangeable batteries that can be charged during the daytime.

Table 5.8: ICES performance indicator results for EV penetration scenarios

	0 EV	1 EV	4 EVs	10 EVs
kWh price before ICES [€/kWh]	0.143	0.145	0.148	0.156
kWh price after ICES [€/kWh]	0.135	0.136	0.140	0.151
Price difference [€/kWh]	0.8	0.9	0.8	0.5
Annual CO ₂ emission before ICES [tonnes]	34.4	35.5	38.0	43.7
Annual CO ₂ emission after ICES [tonnes]	31.1	31.8	34.8	41.7
Total CO₂ reduction [kg]	3280	3772	3207	2030
Energy autonomy before ICES [%]	76.7	74.7	67.0	53.1
Energy autonomy after ICES [%]	95.2	92.4	80.4	60.2
Energy autonomy increase [%]	18.5	17.7	13.4	7.1

5.3.2. Adding households without production

As described in section 4.7.2, after the excess energy from all households is distributed among other households within ICES, still some energy is available. This is usually exported to the electricity grid. To make use of this excess energy within ICES, we investigate the option of adding households that have no local production facilities. Due to the fact that within our model set-up only electricity exchange is possible, this households needs to have an alternative heat source. This could be a conventional heating system or a more sustainable option such as the use of geothermal heat. Our purpose is to illustrate to what extent ICES is able to supply non-producing households with electricity from local overproduction. Using the same input parameters as used for the example presented in section 4.7.2, overproduction after combining eight households to an ICES is shown in Figure 5.15. These households are all producers and consumers. Figure 5.16 and Figure 5.17 show the overproduction and residual demand for ICES and per household. These plots show demand is practically fulfilled for all households within ICES. Moreover it illustrates the principle of distributing energy equally among community members, in proportion to their total residual demand. If the residual demand cannot be fulfilled completely, households with higher demand receive more electricity but still remain with a higher final demand.

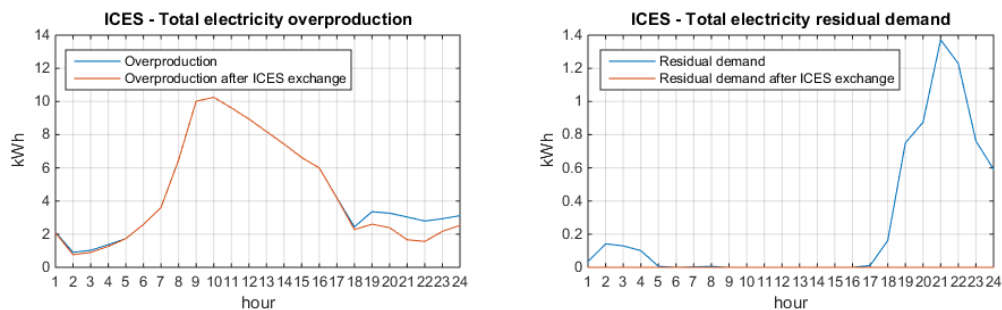


Figure 5.15: ICES overproduction and residual demand

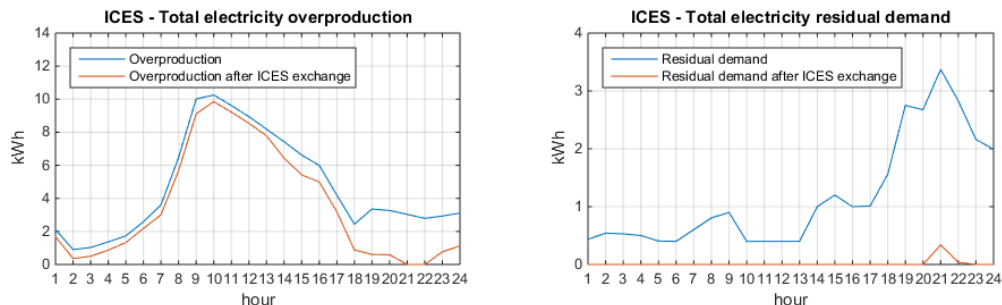


Figure 5.16: ICES total overproduction and residual demand after adding 2 households without own production

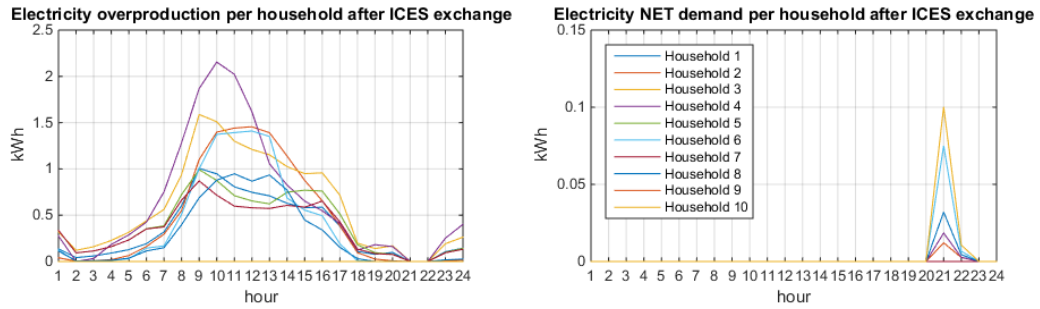


Figure 5.17: ICES overproduction and residual demand per household after adding 2 households without own production

The electricity overproduction is used to fulfil the electricity demand of two additional households that have no electricity production implemented at household level. Model results show that adding two households does not compromise the energy autonomy of ICES (Figure 5.18). The households without own production have the largest benefit from participating ICES, since they did not participate in the optimising process at household level. Whenever the ICES electricity price is lower than the electricity retail price, this households will profit most. The additional households without local production are indicated by a red circle around the household number.

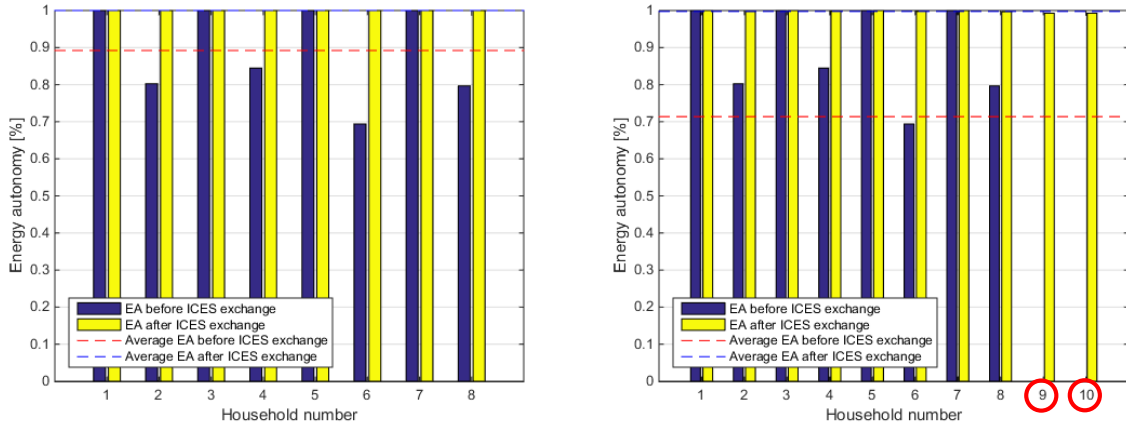


Figure 5.18: Electricity autonomy per household before (left plot) and after (right plot) adding two additional households.

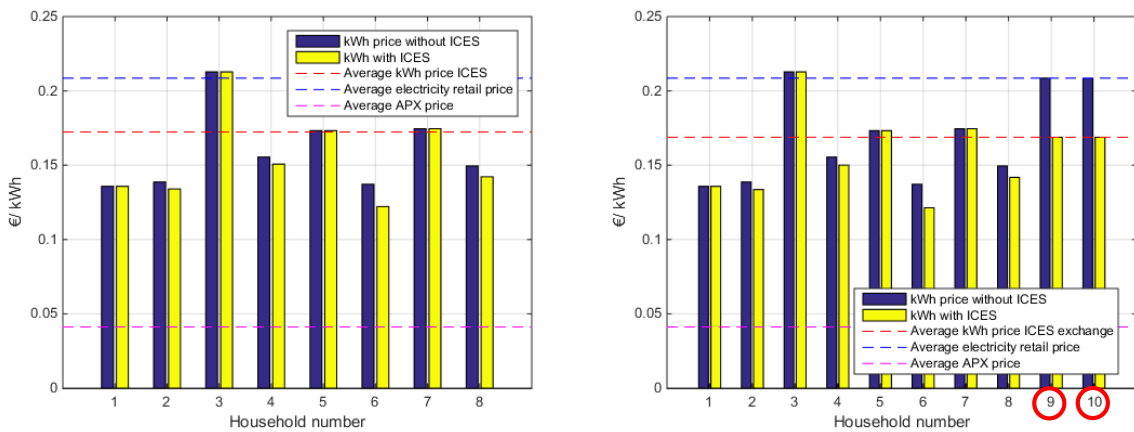


Figure 5.19: kWh price per household before (left plot) and after (right plot) adding two households without own production

5.3.3. Scale effect

To study the effects of scale on ICES, community composition A with household financial optimisation preference is used. We want to determine if a larger community exposes different dynamics or if it leads to different performance indicator results. The results from section 5.1.1 are used to benchmark the results that are obtained by expanding the community to 120 households. To model this large community, ten households are implemented for each household in a twelve-household community. The community composition is presented in Table 5.9.

Table 5.9: Community composition - financial optimisation - scale effect analysis

Household	One adult household	Two adults household	Family	Pensioner(s) or unemployed
Financial optimisation	System 1F (63)	System 2F (119)	System 3F (255)	System 4F (310)
Composition A (2015)	30	30	50	10

When the ratio of different household types does not change, we observe equal results on performance indicators. Community size does not affect ICES performance when households are being ‘copied’ to increase the number of households within ICES. Figure 5.20 and Figure 5.21 illustrate the effect of scale on electricity import and export volume and price. Other performance indicators show exactly the same trend, and show no deviation from the initial twelve-household ICES.

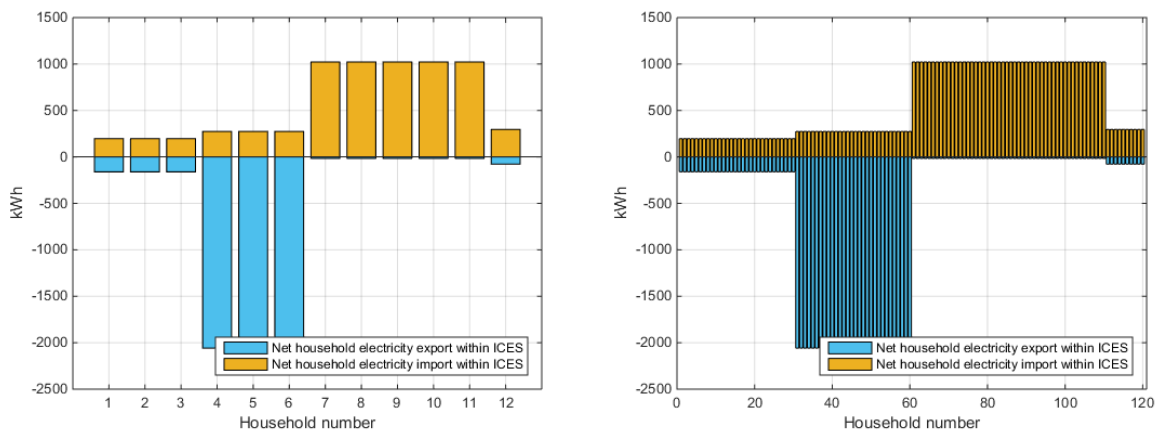


Figure 5.20: ICES scale effect analysis - export and import comparison between a 10 (left) and 120 (right) household ICES.

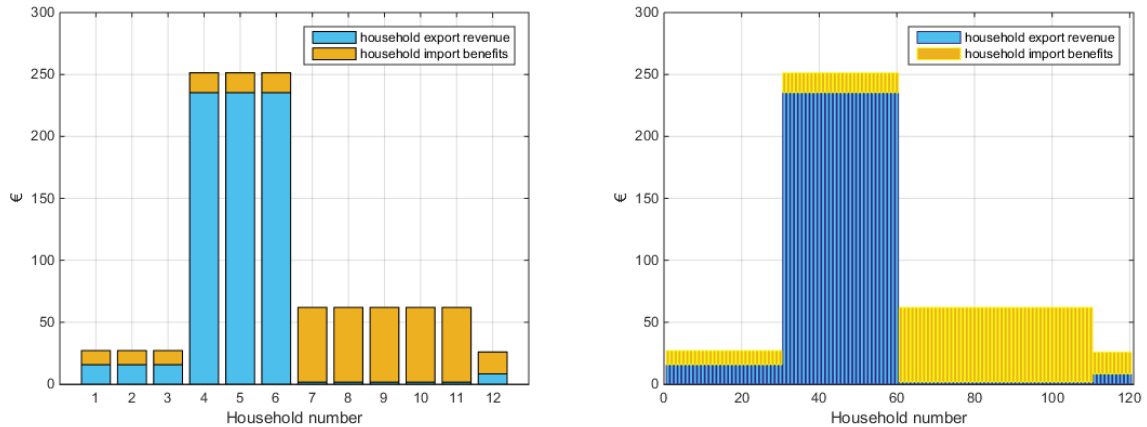


Figure 5.21: ICES scale effect analysis - export and import revenues for a 10 (left) and 120 (right) household ICES

To make the 120 household ICES more realistic, we now select our households not only from the ones that were used in the twelve household ICES, but we’ll use a wider variety instead. This is done by selecting households from inside and closely around the green dashed areas in Figure 4.20, Figure 4.27 and Figure 4.28. These figures specify the relation between energy costs and CO₂ emission for a range of households with different technology mixes. We select households that show indicator results in close range of the optimal selected households. These added households have slight deviations in performance, because they have slightly different technologies installed, or they use a different storage strategy. Since the number of modelled households is limited, each type of household is selected 3 or 5 sequential times in the ICES simulation. This also increases the readability of the plots. The results of this wide-ranged 120 household ICES are a lot more dynamic. Household numbers 1 - 30 consist of one-adult households, numbers 31- 60 consist of two-adult households, number 61 - 110 are family households and numbers 110 - 120 are pensioners. Figure 5.22 shows two-adult households are generally net exporters, while most family households are net importers. For one adult and pensioners households, the results varies per selected household.

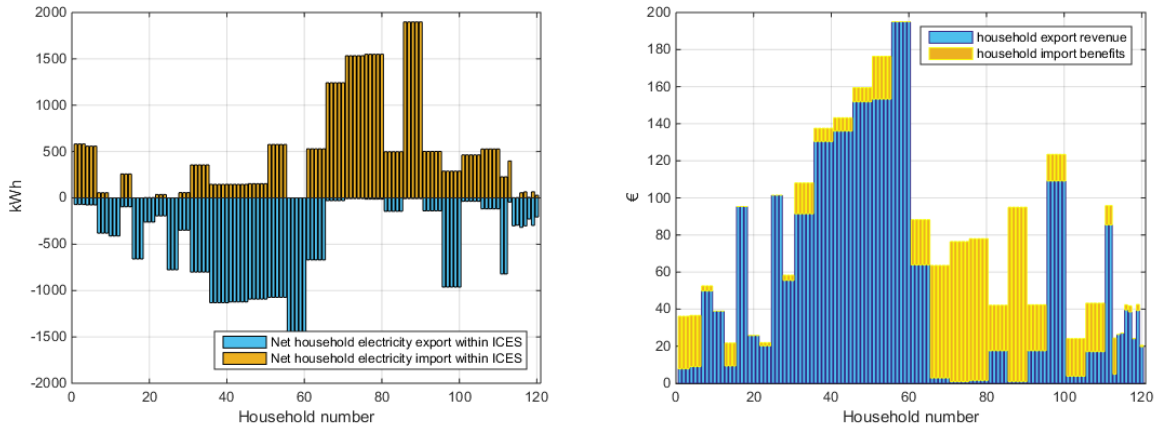


Figure 5.22: ICES scale effect analysis - net export and import (left) and revenues (right) - wide-ranging 120 household ICES

Financial benefits vary from household to household, but family households tend to have the largest energy price reduction, followed by two adult households (Figure 5.23). This is caused by the fact that the largest ICES import is accounted to these two types of households, and especially to the family households (Figure 5.24). Family households also have the largest CO₂ emission reduction. The wide variation in households' demand profiles is visualised by the overproduction and residual demand curves in Figure 5.25. The different colours represent the different households. ICES is able to fulfil all energy demand. The excess energy can be used to supply additional households without production, as described in the previous section. We added 25 non-producing households, which could easily be supplied by the excess energy from the producing 120 ICES households (Figure 5.26).

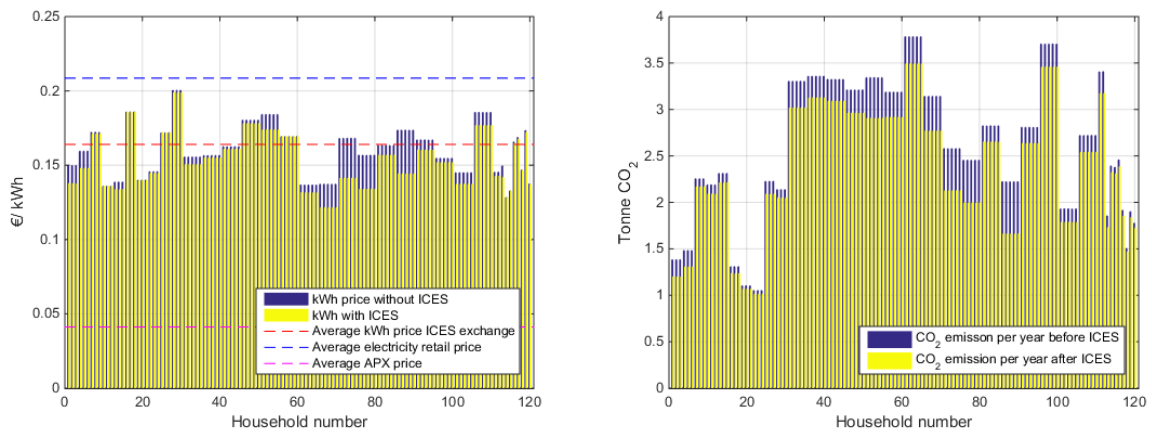


Figure 5.23: ICES scale effect analysis – energy price (left) and CO₂ emission (right) - wide-ranging 120 household ICES

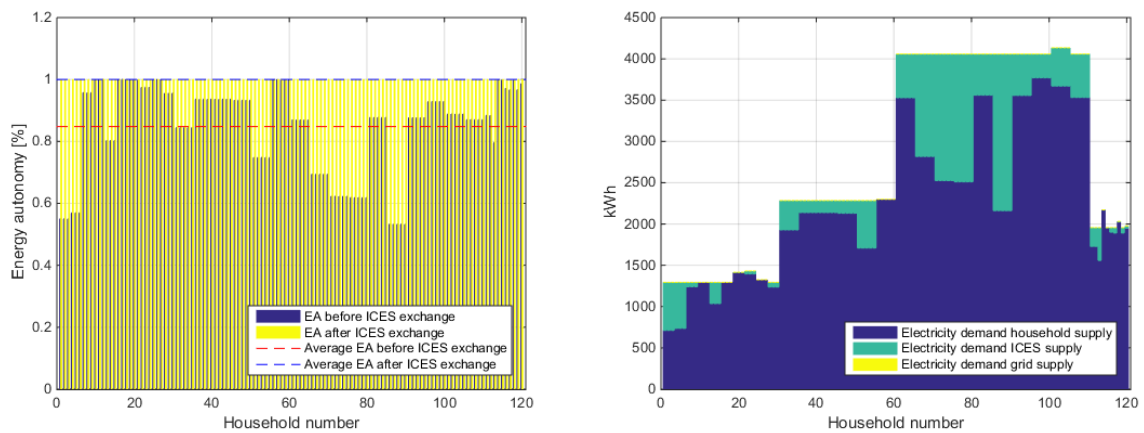


Figure 5.24: ICES scale effect analysis – autonomy (left) electricity supply (right) - wide-ranging 120 household ICES

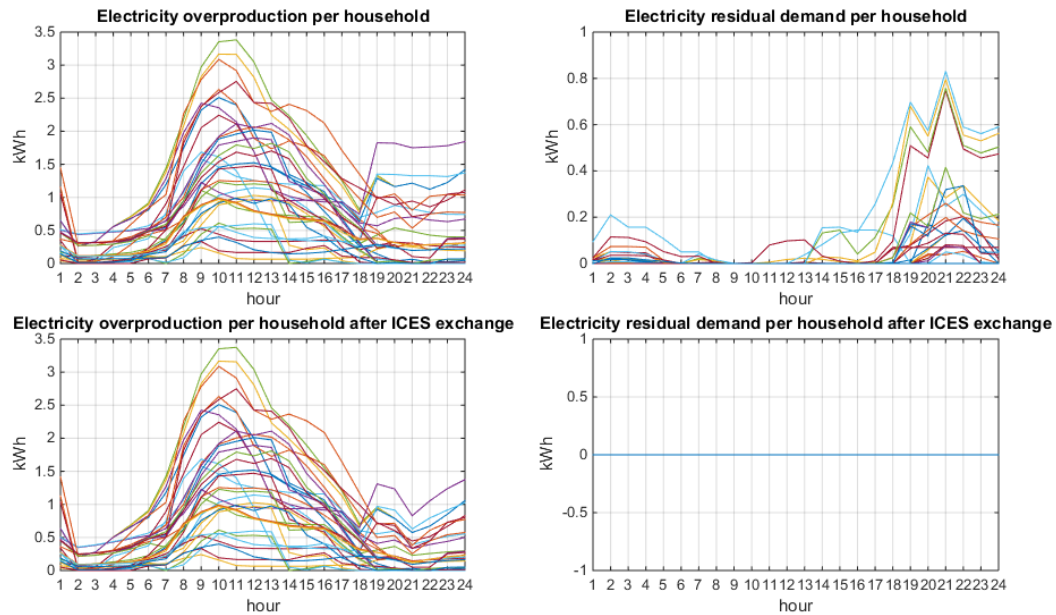


Figure 5.25 ICES scale effect analysis- electricity overproduction and residual demand - wide-ranging 120 household ICES

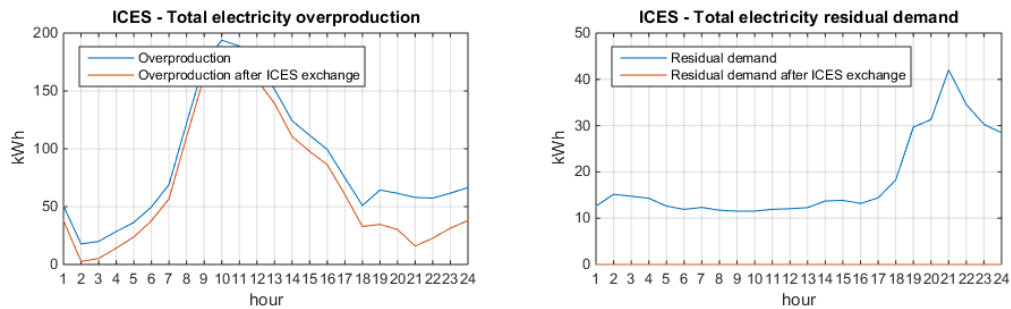


Figure 5.26: ICES scale effect analysis- total electricity overproduction and residual demand - wide-ranging 120 household ICES + 25 non-producing households

An overview of the results from the 12 household ICES and both 120 households ICES is presented in Table 5.10. It is evident that the original 12 household ICES that was optimised on cost reduction, has the lowest energy price per kWh. The 120 household ICES that is constructed by copying the households from the original ICES has the same results, since no new dynamic elements are being added in the scenario. This changes for the 120 household ICES where a wide-range of different households is introduced. Albeit the increasing dynamics, the energy price did not end up lower than the original price. CO₂ emission was slightly reduced while energy autonomy increased in comparison with the 120 'copied' households' scenario. However, the average community performance already was slightly better on this performance indicators before applying ICES. This is due to the fact that the originally selected households were optimised on energy price, and have slightly worse performance on CO₂ emission and energy autonomy. Selecting households that have slightly lower price performance, score slightly better on the other two performance indicators.

Table 5.10: ICES results scale effect analyses

	Composition A 12 households	Composition A 120 copied households	Composition A 120 varied households	Composition A 120 varied households + 25 non-producing households
kWh price before ICES [€/kWh]	0.143	0.143	0.161	0.169
kWh price after ICES [€/kWh]	0.135	0.135	0.153	0.141
Price difference [€/kWh]	0.8	0.8	0.8	2.8
Annual CO ₂ emission before ICES [tonnes]	34.4	344.1	314.7	314.7
Annual CO ₂ emission after ICES [tonnes]	31.1	311.3	287.0	238.1
CO₂ reduction [tonnes]	3.3	32.8	27.8	76.6
Energy autonomy before ICES [%]	76.7	76.7	84.8	72.0
Energy autonomy after ICES [%]	95.2	95.2	100	100
Energy autonomy increase [%]	18.5	18.5	15.2	28.0

5.3.4. Carbon pricing

In the analyses of the carbon pricing effect (explained in section 5.2) a price of € 60 per tonne CO₂ is used. This are the projections of the mid-case scenario for the year 2045. This is also the year for which one of the community composition scenarios (community composition B) is analysed, as explained in section 4.2. Although this is thirty years ahead of us, it is good to perform the analyses over a longer period of time, since community composition and carbon prices tend to be subjected to gradual changes over time.

Prior the carbon pricing impact on ICES and its households, it is good to refer to the numbers of carbon emission in reality. For Dutch households the average CO₂ emission is 3.5 tonne (Milieu Centraal, 2015b). Carbon emission is modelled for the three community optimisation preferences (described in sections 5.1.1, 5.1.2 and 5.1.3). Model results show the average CO₂ emission per household is 2.2 tonne per year. This imposes an average energy cost increase of 2.2 tonne x € 60 per tonne = € 132 per year. The difference between the Dutch average CO₂ emission and the model results, are ascribed to the use of renewable technologies at household level and to the fact that energy is being exchanged within ICES. Also a part of this difference can be explained by the fact that the used demand profiles in our model might deviate to some extend from demand profiles in reality. This model outcome however is sensible and ranges within the scope of the expectations, as carbon emission were expected to be lower than the annual emission numbers from literature.

The impact of a carbon price of € 60 per tonne is studied for community composition B, for all three optimisation preferences. Figure 5.27, Figure 5.28 and Figure 5.29 respectively show the impact on the scenario of financial optimisation, carbon emission reduction and energy autonomy maximisation. We are especially interested in the results for the four types of households within ICES under certain optimisation preferences, compared to the base case scenario results. Therefore start by giving an overview of ICES performance under the three different optimisation preferences.

The scenario where costs minimisation is main priority, has a larger share of higher CO₂ emitting technologies implemented than the households that focus on CO₂ minimisation. Therefore carbon pricing has a larger effect on annualised energy costs for financial optimised communities. The effect of carbon pricing (in increasing the annual energy costs) is larger than the effect ICES has on the energy price reduction, in all cases except for a two adult household with cost reduction incentives (household number 5 and 6 in Figure 5.27). This household type exports a lot of its excess energy within ICES, thereby significantly reducing its own carbon footprint.

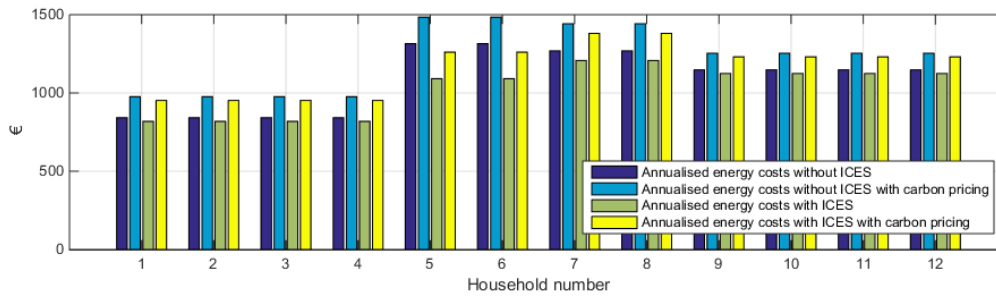


Figure 5.27: Carbon pricing impact - financial optimisation

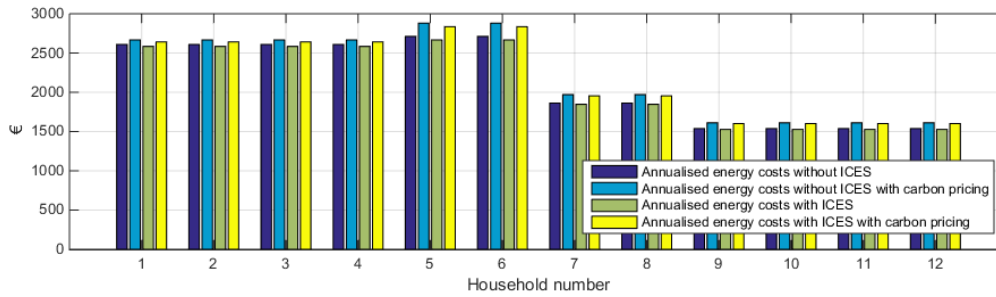
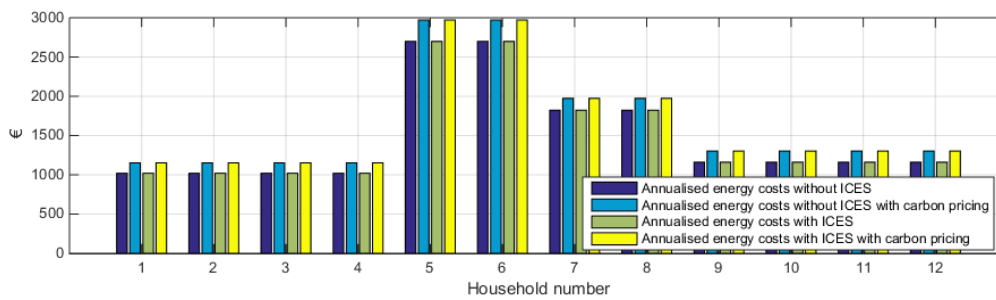
Figure 5.28: Carbon pricing impact - CO₂ minimisation

Figure 5.29: Carbon pricing impact - Energy autonomy optimisation

The average annualised additional costs per household for the three different scenarios is € 52 for a one adult household, € 94 for a two adult household, € 48 for a family household and € 36 for a pensioner's household. Family households and pensioners' households have the largest deviation from the base case scenario and thereby have the lowest cost increase due to a carbon tax. The two adult household in the energy autonomy scenario experiences the smallest CO₂ reduction from participating ICES, mainly because this household has a 30% higher CO₂ emission content per produced kWh (Appendix B: Individual household optimal system configurations). CO₂ emission per household type is presented in Table 5.11. The resulting price implication is presented in Table 5.12. The CO₂ minimisation optimisation preference results in the lowest carbon emission for each type of household and thereby also has the largest financial benefits from carbon pricing, compared to all other scenarios.

Table 5.11: Carbon pricing results – CO₂ emission (in tonnes) for community composition B

	Base case	Financial optimisation	CO ₂ minimisation	Energy autonomy maximisation
One adult household	1.4	1.1	0.5	1
Two adults household	2.3	1.4	1.1	2.2
Family household	3.1	0.9	0.6	0.9
Pensioner(s) household	2	0.5	0.4	0.9

Table 5.12 Carbon pricing results – additional costs for CO₂ emission for community composition B

	Base case	Financial optimisation	CO ₂ minimisation	Energy autonomy maximisation
One adult household	84	66	30	60
Two adults household	138	84	66	132
Family household	186	54	36	54
Pensioner(s) household	120	30	24	54
Average	132	59	39	74

The additional energy costs in the form of carbon tax, make the exploitation of renewables within community more attractive in comparison with the base case scenario. The financial impact however is relatively small, compared to the total annual energy costs, even with a relatively high energy tax of 60 € per tonne CO₂.

The impact of carbon pricing is not limited to electricity and heat consumption. The largest share of total carbon emission at household level is related to indirect carbon emission (BuildDesk Benelux B.V., 2011). These include the CO₂ allocation due to the construction (and eventually the deconstruction) of the house, the production of clothing, production and transportation of food, personal care, holidays and leisure time and traveling. Therefore the electricity and heat share in the total financial impact on households due to the effect of carbon pricing, is only a fraction of the total impact a carbon pricing scheme would impose. This is out of the scope of this research. In our study the effect of more local production and the use of ICES, reduces the annual CO₂ emission costs by a factor 1.8 (focus on energy autonomy) to 3.4 (focus on CO₂ minimisation).

5.3.5. Stationary storage penetration

Recently domestic electricity storage options in batteries gain more interest due to increased performance and as a result of price reduction of these technologies. Section 4.4.3.2 describes the characteristics of the applied stationary battery storage in the ICES model. Because of its increasing performance and reducing costs, a future scenario with a high penetration level of batteries at household level is imaginable. The effect of a 100% penetration level is studied, to find out to what extent this changes the results of the performance indicators on household level and at community level. To test this effect, community composition A with household financial optimisation preference is used. A comparison is made between the original technology mix for all households within this community, and the same technology mix supplemented by a battery for each individual household. The battery is configured to reduce the electricity load during peak hours, when electricity demand and energy price are high.

The impact of a 100% battery implementation on the total electricity overproduction of a twelve household ICES is shown in Figure 5.30. Excess energy is being stored during renewable peak production hours. The financially optimised ICES has its renewable production exclusively being supplied by solar energy, due to the current economic advantage of this technology. The production peak of total community electricity overproduction around noon is reduced by around 25%. This stored electricity is used later that day, almost completely flattening the total residual demand peak in the afternoon. As a result, each individual household's electricity autonomy increases to almost 100% before even exchanging energy with ICES (Figure 5.31).

The electricity export within ICES reduces with 85%. For two adult households the export reduces even by 93% (Figure 5.32), since this household had a large amount of overproduction that (with the use of a battery) could largely be used to fulfil its own demand. For all household types the electricity import reduces, because they fulfil a larger share of their own demand by the use of stored energy. Figure 5.33 shows the effect of stationary storage on the electricity supply, before and after implementing batteries. Especially for family households the effect is significant. The former 25% of demand that was supplied by ICES, will with the use of batteries almost completely be supplied at household level.

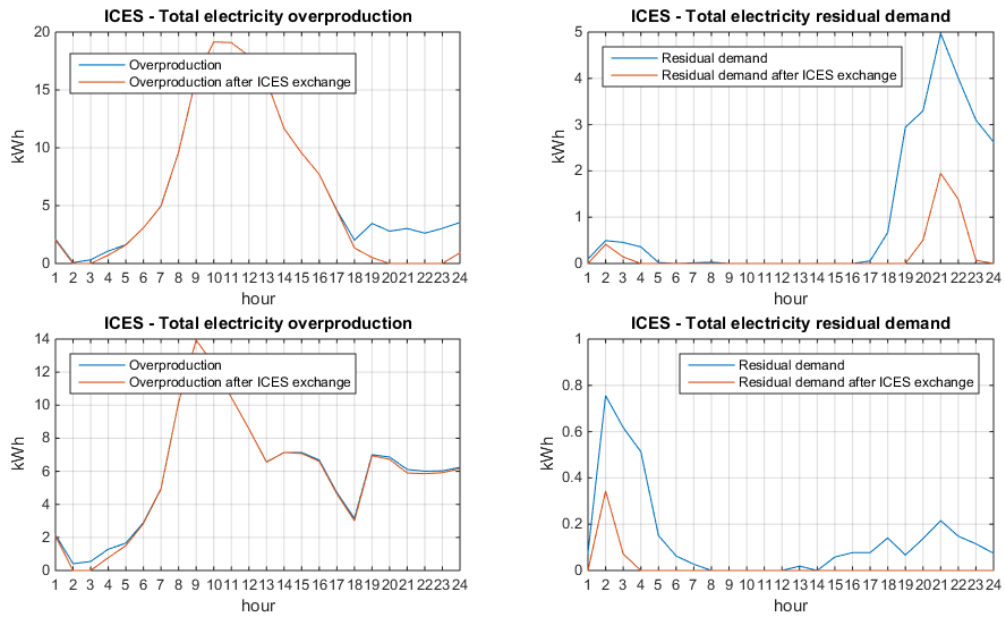


Figure 5.30: ICES total overproduction and residual demand without batteries (top) and with batteries (bottom).

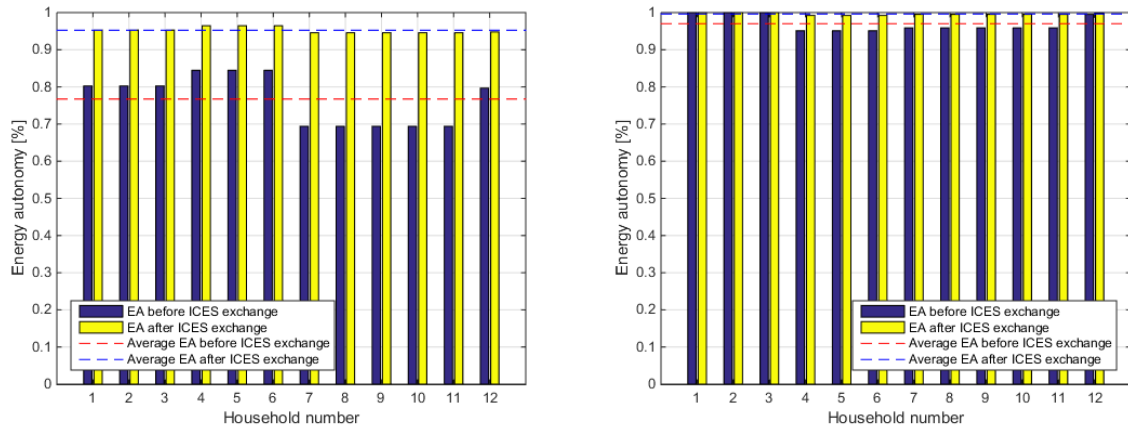


Figure 5.31: ICES Energy autonomy analyses without batteries (left) and with batteries (right) at household level.

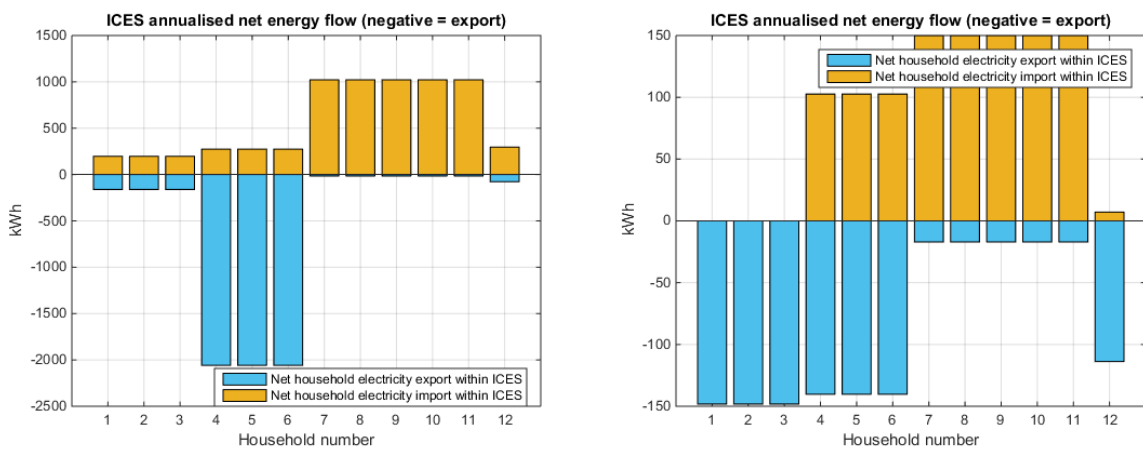


Figure 5.32: ICES energy flow analyses without batteries (left) and with batteries (right) at household level.

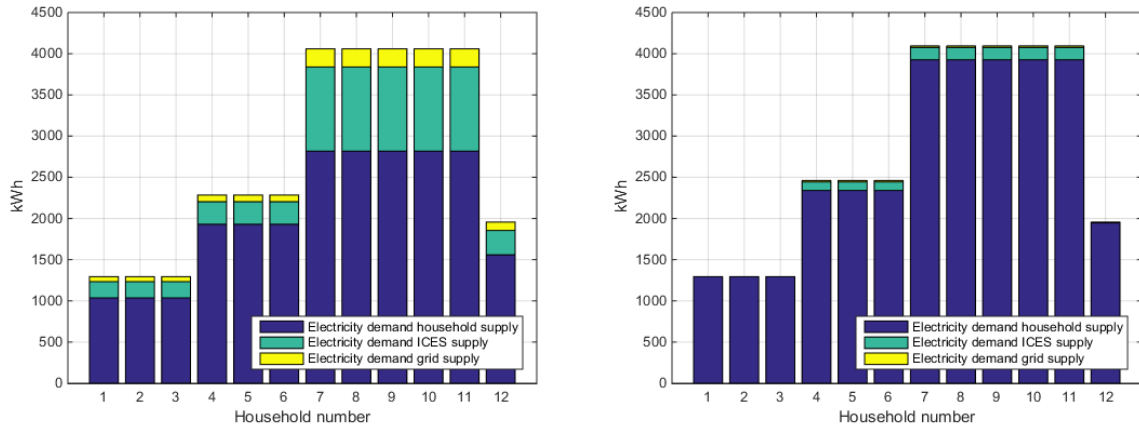


Figure 5.33: ICES electricity supply per household without (left) and with batteries (right) at household level.

Although the use of batteries reduces the average price per kWh for energy exchange within ICES (Figure 5.34), the actual weighted price per kWh per household does not change noticeable. Actually it turns out the application of batteries has more or less the same effect ICES has on household level: energy is being exchanged, which results in a lower energy price per kWh. Total annual energy costs however increase due to the use of batteries, as shown in Figure 5.35. This is caused by the (still) high capital costs of this technology. The same effect holds for CO₂ emission reduction, as the use of batteries reduces carbon emission at household level, already before ICES energy exchange is being applied (Figure 5.36). This results in less contribution to ICES energy exchange and thereby less carbon reduction ascribed to the ICES contribution (Figure 5.37).

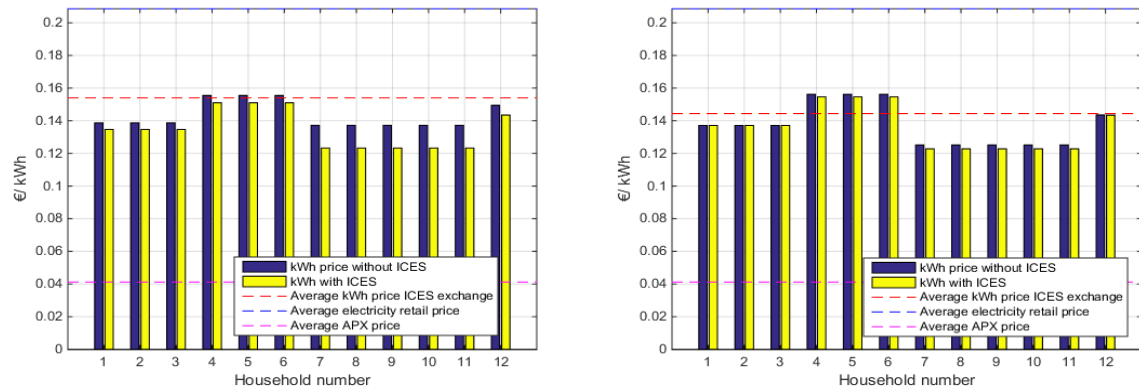


Figure 5.34: ICES electricity kWh price development without batteries (left) and with batteries (right) at household level.

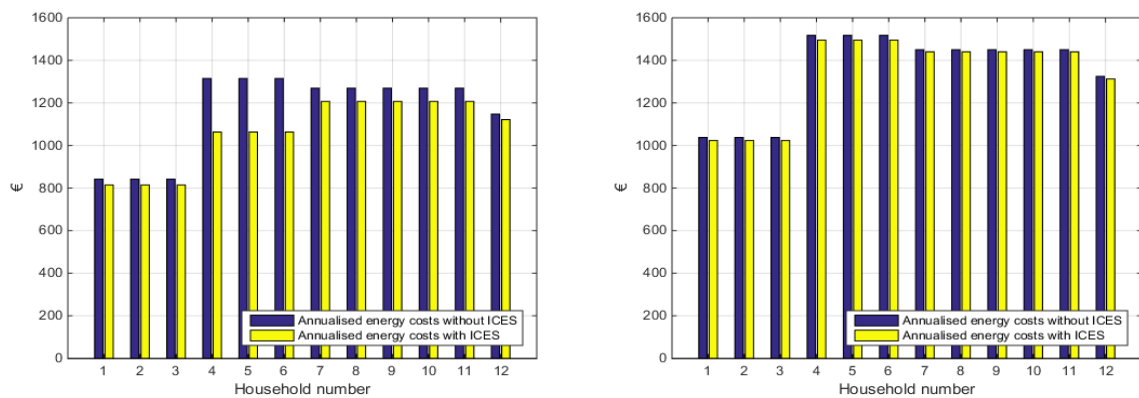


Figure 5.35: ICES total energy costs development without batteries (left) and with batteries (right) at household level.

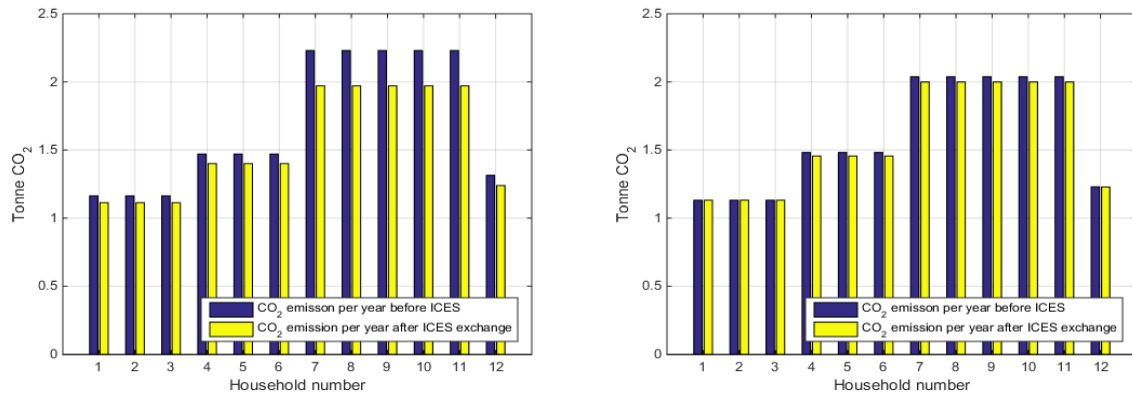


Figure 5.36: ICES CO₂ emission per household without batteries (left) and with batteries (right) at household level.

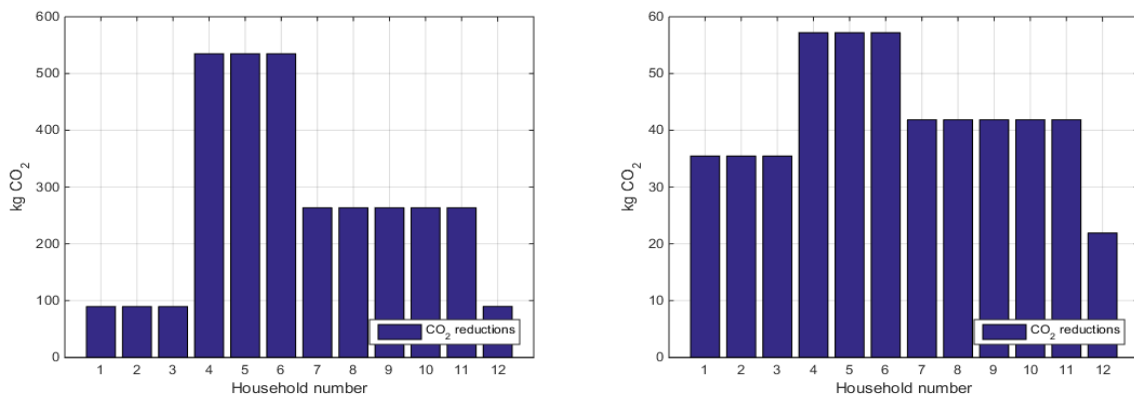


Figure 5.37: ICES CO₂ reduction per household without batteries (left) and with batteries (right) at household level.

After having looked at the individual household performance, we will look into the effect on performance indicators at ICES level. The results of this exercise are presented in Table 5.13. As mentioned before, the effect of adding batteries at household level is comparable with the effect ICES has on the performance indicators. Due to the energy exchange, the price per kWh and the CO₂ emission reduces and the energy autonomy increases. CO₂ emission and energy autonomy performance is increased by the use of batteries. Final performance indicator results for battery implemented systems give slightly better results than ICES without batteries. Note the effect of batteries is comparable for other battery configurations. However the scale of this effect depends on the size of the installed battery (and the battery penetration ratio).

For the tested scenario, the energy price per kWh remains more or less constant, while the annual energy costs increase by around 20%, due to the cost of a battery system.

Table 5.13: Battery impact on ICES performance

	Without Batteries	With batteries
kWh price before ICES [€/kWh]	0.143	0.137
kWh price after ICES [€/kWh]	0.135	0.136
Price difference [€/kWh]	0.8	0.1
Annual CO ₂ emission before ICES [tonnes]	34.4	30.9
Annual CO ₂ emission after ICES [tonnes]	31.1	30.4
Total CO₂ reduction [kg]	3280	509
Energy autonomy before ICES [%]	76.7	97.0
Energy autonomy after ICES [%]	95.2	99.6
Energy autonomy increase [%]	18.5	2.6

Chapter 6: Discussion

The results derived from the ICES modelling and analysis at different optimisation preferences and scenarios, shows the potential of ICES. The added value of ICES to the overall community performance changes during the different test scenarios. This implies not all technologies, users and actors experience the same benefits from ICES.

6.1. Household's implications

With the current energy system, households know in advance what their energy price per kWh will be for the next year. Their total energy costs per year are purely a function of the amount of energy used. Consumers pay a monthly fee to the energy supplier and once a year the customer will receive an annual energy bill. The energy supplier also charges the grid operation costs and taxes to the customer, and forward these cash flows to the grid operators and public authorities. Consumers are fairly used to this idea and to the energy tariff structure. With the use of ICES, this changes. It becomes much harder to inform households within ICES on their exact energy-tariffs. When applying ICES this process has the risk of becoming less transparent, since in advance it is not clear what the energy price will be for the next year. The energy price within ICES is dependent on the amount of renewable energy production at household level, the ratio between local produced energy and imported energy (from ICES and from the grid) and the price of the energy that is being exchanged within ICES. A large uncertainty develops, for example because all community members experience more or less the same solar irradiance and wind power. A year with low renewable energy production will effect whole community and poses a greater stress on conventional technologies and import from grid. There should be enough back-up capacity to ensure security of supply and prevent black-outs. Since large investment cost are observed at household level, uncertainty about energy prices and revenues are a large disadvantage. In the best case, these prices can be estimated by looking at historical data, as is done for the developed ICES model.

With the rollout of smart meters, consumers already can obtain experience with the possibilities of variable energy pricing. These technologies are necessary to provide precise insight in demand profiles at household level and could be a step towards even more flexible energy systems, such as ICES. When consumers get more involved in energy, they can become more interested in alternative ways of organising their energy, especially if this will be beneficial. Smart meters can be used as tool to get more insight in hourly energy patterns at household level, providing important information to make accurate estimations of households' performance within ICES.

Besides the uncertain costs and benefits in future, the large investment costs are an obstacle for implementing ICES. To counter this argument, smart financing options should be considered. Subsidy on renewable technologies or a loan with low interest rate could be options, but it would be more interesting to look for a community based solution. This could be a construction under which the investment costs for a certain household are partly covered by other community members. These community members in return will receive energy from the household they invest in, as a payback of their investment over a pre-determined period of time.

The ease of use offered by current energy system should not be compromised and consumers might not accept energy usage limitations or time restrictions. This becomes more of an issue when demand response is applied from community level perspective, changing household level performance. For example by Influencing demand profiles or changing local storage patterns at household level in stationary storage or EV. An intelligent solution will be needed to coordinate all energy flows and to consider all community members preferences. Households might opt for different EV charging strategies, and even might want to change their strategy during the day. ICES is a flexible concept that is able to incorporate different technologies, preferences and strategies. It should be questioned to what extend individual preferences can be tolerated in ICES, since the benefits of organising energy at community level should create benefits for all its participants. As seen in the analysis of EV or battery penetration, the individual performance influences the community performance. Therefore the right balance between flexibility and ease of use at household level on the one hand, and transparency of impact on community level on the other should be pursued. This in combination with appropriate financial and procedural support.

6.2. Households' strategic choices

The business model of **energy storage** for own use is not beneficial, as can be concluded from simulation results. Large upfront capital costs and limited profits per kWh make it necessary to intensively charge and discharge the battery to earn back the investment costs. This will reduce the life expectancy of the battery. A rough calculation indicates the perspectives for households to use battery storage as energy trading facility within community. As a pricing benchmark the APX price is used for this calculation. It is assumed that energy prices within community reflect production costs and that energy price fluctuations reflect the level of demand, as this is (ideally) the case for the domestic energy market. With a price difference of € 0.02 per kWh, at least 150000 kWh needs to be traded, to break even € 3000 investment costs. When looking at the APX price development of an average day, the battery is charging approximately 1/3 of the time, it discharges another 1/3 of the time and will be idle the remaining 1/3 of the time. Charging (or discharging) at peak charging rate of 3.3 kW per hour means roughly 26 kWh per day is being traded and 15 years are needed to earn back the investment costs of the battery. Only when energy prices become more volatile, it would be an interesting strategic option to implement batteries just for energy trading purposes within ICES. With the current configurations, the implementation of batteries within ICES mainly contributes to the reduction of CO₂ and the energy autonomy on household level. When future carbon pricing schemes will make fossil fuel based energy less attractive, storage of local produced renewable energy gets more value. The battery does not make a physical distinction between electricity from different sources. Therefore the allocation of stored renewable energy should be considered purely as an administrative business. Battery lifecycle emission should be considered to make an unbiased comparison. Within ICES a large share of renewable energy cannot be used locally due to a time mismatch with demand. Storage becomes more interesting and can be considered as a strategic option to increase the benefits of ICES when carbon prices increase.

From model results it becomes clear that not all households have the same benefits from being part of ICES. In most of the test cases, two adult households benefit the most. This indicates that it is rewarding for households to adjust their **demand profiles**. An ideal demand profile for a specific household will generate the highest benefit from being part of ICES. This research did not look at the benefits from this optimisation, although from household perspective the benefits for different types of households is quantified. This not only applies to demand profiles, but the same counts for the production profiles. Households can alter their production profiles in respect to ICES residual demand. When they can produce additional energy at lower costs, they increase the performance of ICES and thereby also increase their own revenues.

With the recommended pricing system, **over-investment** is not encouraged, as energy exported within ICES only guarantees the recovery of LCOE. However households still can decide to install larger capacity, and this usually results in a reduction of LCOE due to economies of scale. A larger investment however is required, making this an interesting strategic investment choice for wealthy community members.

The effect **EV** has on ICES energy price increases with its penetration level. The first EV owners will benefit from being part of ICES, because low carbon intensive, affordable energy can be used to charge the vehicle. Therefore if community members consider the purchase of an EV, their benefits are highest when they are one of the first users within ICES. This allows lower energy costs for charging, but also ensures the energy price within ICES does not increase. The higher the EV penetration ratio within ICES, the higher the energy costs for charging will become. In contrast, the price of EV is expected to reduce in future, as nowadays EV are still in the early-adapters phase.

Interruptible contracts are used by energy suppliers to curtail certain demand, when production capacity is not sufficient. Some power companies also offer incentives to consumers to produce additional energy by running their back-up power, and export this during peak load periods. However today distributed generation is primarily used to fulfil residential energy needs. The local production is not well integrated in the day-to-day planning and operational needs of the national energy system. ICES could facilitate the role of **aggregator** of back-up power from all its individual households. With the right incentives, households could strategically supply energy during peak load periods, to gain additional revenues and help to balance the national grid. This means households can exploit their flexibility strategically.

6.3. Policy networks and actor behaviour

Public policies can be generated within networks in which multiple actors are interrelated quite systematically (Klijn, 1997). This also accounts for energy policy, which include legislation, international treaties, energy efficiency and energy conservation policy, taxation mechanisms and other public policy issues on energy development. Corporate business within the energy sector, but also public corporations and environmental activist groups, lobby with policy makers and attempt to alter policy decisions in a way which favours them most. To explain policy changes, one need to look further than policy networks alone, and complement the analysis with an evaluation at a lower level. Hence we need to look at actor properties. Three basic dimensions are described by Mitroff (1983) and Jobert (1989) to explain actor behaviour: perceptions (how actors look at the world around them), values (provide the directions in which actors would like to move and describe their internal motivation and are related to preferences), and resources (the things the actor is interested in and over which he has control). Resources are linked to power and influence (Enserink et al., 2010). The understanding of these conceptual dimensions helps to understand the behaviour of the actors in policy processes. It also gives insight in the drivers of changes in the energy landscape and the perspectives this gives for the development of community energy systems, such as ICES. Several methods are available to support actor analysis, from which the approaches for stakeholder analyses are mostly used. These method are easily being applied to a wide range of situations (Enserink et al., 2010). The elaboration on the stakeholder analysis and stakeholder mapping is presented in the following section.

6.4. Alternative ICES exchange pricing options

A households possibly does not earn back its LCOE at a specific hour, both with or without participating in ICES. In section 4.7.2 this is addressed, by pointing out that revenues from grid exported electricity can be lower than LCOE. This can be solve by increasing the price at which electricity is being sold within ICES, to such a level that it compensates for the financial loss caused by the export to the grid. This is explained by an example, illustrated in Figure 6.1. Assume the LCOE of this household is € 0.20 per kWh, its total production over a random period of time is 100 kWh and the APX price is € 0.05 per kWh. Local used energy (60 kWh) and energy exported to other community members within ICES (30 kWh) do not cause a deviation from the LCOE revenues, only the electricity that is being exported to the electricity grid does (10 kWh). This households 'losses' in total $(€ 0.20 - € 0.05) \times 10 \text{ kWh} = € 1.5$. This can be compensated by increasing the price at which electricity is being exported within ICES. This is described by (Eq. 6.1). As a result, total grid export revenues needs to increase by € 1.5, which is equal to $€ 1.5 / 30 \text{ kWh} = € 0.05 \text{ €/ kWh}$. The new costs for exporting within ICES becomes € 0.25 per kWh.

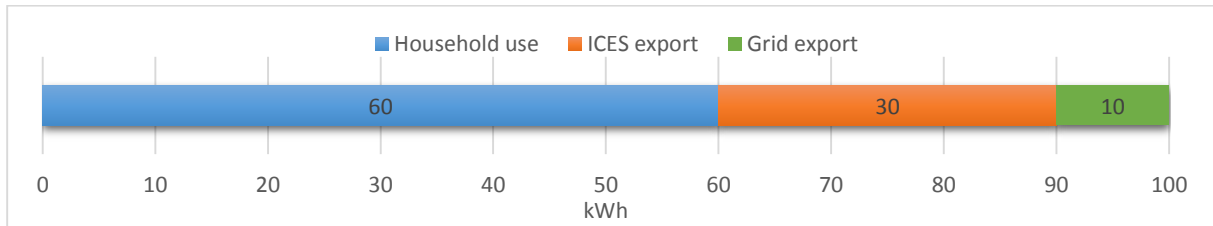


Figure 6.1: Example ICES LCOE compensation for grid export losses

$$ICES \text{ energy exchange price} = LCOE + \frac{(LCOE - APX \text{ price}) \cdot \text{Grid export volume}}{ICES \text{ export volume}} \quad (\text{Eq. 6.1})$$

This method has one large disadvantage. The retail electricity price, at which households compete when selling electricity to other households, in general is only slightly higher than the LCOE of ICES households. This means increasing the ICES export price artificially, this rapidly pushed the local energy out of the market, hindering the optimal exploitation of ICES. With increasing grid export, the ICES export price consequentially rises, making local use of electricity more challenging. Because of this disadvantage, we will not use this compensation method and strive to use the local energy within ICES as much as possible. However in future research, this aspect can be studied in more detail, to explore the impact of this phenomena on household and community performance.

6.5. Risk factors and uncertainties

This research attempts to quantify the results from organising energy from community perspective, taking into account the changes that are noticed within our energy system. Besides the energy system, external factors influence the development and perspective of community energy systems. A number of factors is elaborated, to emphasize the changing forces that are present and affect the results from this study.

Future energy prices

The financial value ICES has to offer depends on a selection of energy prices. Electricity and gas retail prices are important benchmarks for community members in the consideration of either importing or exporting energy, since it determines a substantial share of their costs and revenues. Future energy prices affect the business model of ICES and its individual households. A large deviation from current energy prices changes the pay-back time of investments and thereby changes the incentive to invest in local energy technology. When the energy retail price increase, this makes investment in local generation more attractive. It is hard to predict future energy prices, as they depend on unpredictable dynamics at macro-economic scale. In addition, price volatility of electricity and gas prices makes it more challenging for investors to manage investment risk. Small scale local energy technologies have the advantage over large power plants when it comes to risk of investment. However these risks will be judged differently because of the distinction between corporate investment and private investment.

Carbon price levels and volatility

In section 5.3.4, different carbon pricing scenarios are presented. These generate a wide range of possible future carbon prices, resulting in a substantial uncertainty on this aspect and its impact on ICES. The precise direction however is uncertain and sensitive to speculation. Since carbon emission credits can become scarce, speculative bubbles might arise and drive the carbon price to unrealistic values. A high carbon price directs towards more renewable energy production technologies instead of fossil fuel based power. Having less fossil fuel power plants (that traditionally supply a large share of base load power), might affect energy prices and volatility as well.

Discount rate and interest rate

Another uncertainty in the valuation of future costs and benefits is the discount rate. Discounting is used during this assessment to evaluate the future value of cash flows, albeit in literature there is a lot of discussion about the exact value of the discount rate. A used reference point is the interest rate. For a period of 20 years it is hard to make the correct estimation, since slight variations in the discount rate will significantly change results after many years. The same accounts for the interest rate, which fluctuated significantly over the last years.

Subsidy schemes and energy policy

As discussed in section 4.5.1 there are various subsidy schemes and supporting policies for specific technologies and for renewables in general. These subsidies are granted for a certain period of time and it is unsure for how long one could apply for a particular subsidy. In the Netherlands for example, subsidy schemes for renewable technologies at household level, as well as the benefits on additional tax liability for hybrid company cars have been reduced recently (Rijksoverheid, 2015a). The reduction or phase-out of subsidies for specific technologies will affect the development and adoption of these technologies. Also this changes the benefits for individuals that currently use these technologies. Because of this uncertainties, we did not apply any subsidy in our analysis. In general the uncertainty on future (long term) energy policy direction and sustainability targets has a significant impact the risk perceptions.

Electricity demand

Even a straightforward aspect as energy demand, cannot be predicted at 100% certainty. After many years of increasing demand in the Netherlands, the 2008 recession resulted in a demand reduction. The adoption of energy-saving and efficiency improvement of household appliances could result in a demand reduction, but the increase of digital appliances and EV could cancel this effect. The adoption of demand-side management at community level and an increased use of storage have its impact on the household level demand profiles. The aforementioned changes in demand could also have an impact on the retail prices and price volatility.

Public perception

Public opinion and perception is characterised by high changeability and unpredictability. Will the community ideology be stronger than individualism and will the public perception converge regarding the way energy is organised? The power of the public increases and with the use of social media, opinions are more easily being shared with the 'digital community'. In addition public opinion could substantial influence government's (energy) policy (Burstein, 2003). This aspect should not be underestimated in the development of community energy systems.

Chapter 7: Conclusion and recommendations

Due to changing roles and dynamics within the energy landscape, the way energy is organised changes. The effect on future energy systems and its participating household level consumers is yet uncertain. Integrated Community Energy Systems (ICES) emerge as a novel way to organise local energy systems. This flexible concept entangles all facets of energy within a community. Besides the energy system integration of different energy types and technologies also the engagement of communities at local level is emphasized. Within this research, the performance of households within ICES was tested for different scenarios by modelling a community energy system. The system was examined from the perspectives of individual households and at community level. The research showed that ICES can be a viable way of organising energy, deflecting the traditional energy system by bringing consumers and producers together at local level.

This final chapter summarises the main research results and the obtained insights, guided by the research question and underlying sub-questions. Assumptions and limitations of the research are also described and this chapter concludes with recommendations for further research.

7.1. Conclusions and answers to the research question

The research question as presented in section 0 reads:

Given the present available set of technologies, to what extent may ICES contribute households to become energy autonomous and reduce their carbon footprint at affordable costs?

A selection of available technologies is implemented in the ICES model. Model results from optimising on energy cost, CO₂ emission or energy autonomy, are compared with a base-case scenario. These results, described in section 5.1, show ICES has the potential to increase energy autonomy at household level to 100%, if used in combination with local production. The use of batteries increase the achievability of becoming energy autonomous, although at higher costs. The largest contribution of ICES is observed when combining households with local production with households without local production. Section 5.3.2 shows within ICES a 20% share of non-producing households is being supplied, without compromise on performance. ICES helps to reduce the carbon footprint of individual households. However the largest contribution to CO₂ reduction is attributed to the renewable energy technologies. Selecting households with an optimal technology mix increases energy autonomy and reduces carbon emission, at lower energy costs compared to the base case scenario. At community level 35% CO₂ reduction and 20% annual energy cost reduction is achievable, at an energy autonomy of 95%. Energy cost rise rapidly when larger CO₂ reductions and higher energy autonomy results are desired. The detailed numbers of this effect are summarised in Table 7.1. At household level the benefits vary and depend strongly on the demand profile (peaks), the implemented technologies and the residual demand of other households within ICES. The selection of technologies and the use of ICES both contribute to performance increase at household level. The impact of the technology mix at household level on the performance indicators, is larger than the contribution of ICES. It is advised to make a concession when optimising on CO₂ reduction or energy autonomy, in order to obtain an acceptable performance increase at affordable costs. Very acceptable results on all performance indicators are obtained when focussing on costs reduction.

Table 7.1: Final model results per optimisation preference

Optimisation preference	Annual energy costs	CO ₂ emission	Energy Autonomy
Energy costs reduction	-20%	-35%	95%
Energy autonomy	+30%	-30%	100%
CO ₂ reduction	+60%	-50%	100%

The three sub-questions are answered and elaborated in detail below.

1. What are the constituents, drivers and barriers of ICES?

The success or failure of community energy systems can be ascribed to a small number of conditions. A solid business model, efficient production technologies, adequate project management as well as long term policy are needed to attract enough investors to initiate ICES. Besides the barrier of high investment costs, insufficient policy support hinders the development of ICES. Further aspects that are of importance for the emergence of ICES are government regulation (renewable energy targets) and industry standards, public opinion, energy price development, and carbon pricing.

i. What are technical, economic, social and institutional factors that are important for assessing ICES?

Technological factors that are important for the assessment of ICES are characterised by the different energy generation and storage technologies, described in section 4.4. Distributed (renewable) energy technologies form the starting point of our research. The selection of the right technologies is of great importance, as it facilitates the various optimisation preferences. Also the interactions between different technologies within ICES is considered. Within this research the energy exchange within ICES is restricted to electricity, as this is easier to implement in existing communities. Technological progress creates favourable conditions for some technologies. Economic factors that play a role are described by energy costs. A distinction between investment costs and operational costs is made. From realised community energy systems, capital investment was experienced a considerable barrier. Financing issues and financial obligation to community (leasing of community technologies) need to be considered. The discount rate plays an important role in assessing future costs and benefits. Carbon pricing plays a less significant role. Also the development of energy market prices affects the success of local production. Social factors are described to be of significant importance as well. In the examined existing community energy systems, the lack of community engagement hinders these systems to become successful. Community engagement can be driven by environmental concerns, disappointment with the current centralised system, a desire to become self-supporting or a strong social cohesion. Commonly the studied initiatives emphasize a concern about the future and they share the ambition to make a difference by local action. Institutional factors that are of influence for the success of ICES are the development of (renewable) energy policies, such as tax schemes or subsidy assistance programmes for certain energy technologies. Political leadership is described to be of great influence for an ICES to become successful. The main indicators used in the assessment of ICES are energy costs, CO₂ emission and energy autonomy.

ii. What is the role of the different actors within ICES?

Different actors are distinguished within ICES. These are the existing market parties from the energy sector, supplemented by new players. Stakeholder mapping is used to identify the key-players that have the power and interest to influence the development of ICES and to analyse their role in a future energy system. Community members form the centre of ICES and become more important as their role changes from consumer to prosumer, especially if they join together and form a collective. They become partial energy supplier and are able to provide flexibility to the transmission network and support network balancing. In community energy systems, energy suppliers will get a more diverse role as well. They will have to communicate in more detail with community and its members. They can contract ICES to adjust its consumption patterns during hours of peak demand and exploit the storage capacity of ICES. The role of the network operators is to guarantee the quality of the network and ensure energy can be transported efficiently and reliably. The development of ICES will change the dynamics of energy networks, since a larger share of the energy demand is fulfilled locally. The different renewable energy technologies are characterised by low marginal costs and provide households with local, low carbon intensive energy. Producers of these technologies are interested in the development of ICES, as this will increase the demand for renewable technologies. Owners of electric vehicles provide ICES

- with additional electricity storage capacity, but also increase peak demand during the end of the day when they are plugged-in for charging. Smart charging strategies increase the value of EV within ICES.
- iii. **What are the distinct community preferences for ICES?** Different communities have different preferences that are used to optimise the energy system. These preferences are classified in three categories: financial incentives (minimise energy costs), environmental incentives (minimise CO₂ emission) and energy autonomy incentives (minimise energy import). These incentives are used to frame the community preferences that will be used in the selection of energy technologies. The extent to which community preferences are being satisfied, is measured by the related performance indicators: energy costs, CO₂ emission and energy autonomy,
 - iv. **What are the available generation and energy management technologies for ICES and their corresponding techno-economic parameters?** From all available technologies, a selection is made from proven and easily applicable technologies. The selection is based on energy efficiency, costs, environmental impact, user friendliness and the outcome of the stakeholder mapping (see section 4.4.2 and 4.4.3). This results in the implementation of wind energy, solar energy (PV and thermal), CHP, fuel cells, thermal storage boilers, stationary electricity storage (batteries) and electric vehicles. Solar energy and wind energy are in this exercise the only genuine renewable energy sources. The energy generation of these sources is dependent on weather conditions. Within a community renewable energy is favoured in all three optimisation community preferences, due to its low marginal costs, low CO₂ emission and its reasonable contribution to the energy autonomy. Lower costs per kWh makes solar energy favourable. CHP and fuel cell both are controllable energy technologies, generating heat and electricity at the same time. The fuel cell's main output is electricity, while the CHP produces more heat. Due to the higher heat demand, the CHP output is matched with the heat demand. For fuel cells the output can be matched with the electricity demand or with the heat demand. Energy storage is realised in heat boilers (thermal storage) and in batteries and electric vehicles (both electricity storage). Energy management technologies are used to make better use of the available energy. Smart grid concepts with increasing ICT implementation and smart meters are useful technologies to monitor and distribute energy more efficient. Storage and demand response increases the flexibility of these systems. Within ICES a smart decision framework should be used to manage energy and power flows. The use of demand response seems an interesting option to fulfil residual demand peaks.
 - v. **What are the benefits of ICES for household consumers?** The trend of a growing number of (energy) cooperatives emphasises a desire to be part of a community or group, but cannot be described to social coherence exclusively. The main benefit for households are the attractive energy exchange conditions within ICES. The ICES energy exchange algorithm ensures LCOE is always received for energy exported within ICES. A large difference between the LCOE and the price received from the energy supplier (APX price) can be observed. In addition, the households' excess energy is distributed more equally amongst the community members thanks to ICES. This has the effect of levelling energy prices within ICES. Organising energy in ICES is more efficient than how energy systems traditionally are organised, resulting in lower energy costs and lower carbon emissions. At last, communities have a stronger bargaining position on technologies and service contracts than solitary households, which leads to further cost reduction.

2. What is a suitable decision framework for determining an 'optimal' technology mix for given community preferences?

A two-step approach is used. Firstly at household level, the 'optimal' technology mix is selected for all different optimisation preferences. Demand and supply must be in balance at all times. This criteria guides through the technology selection process. A wide range of technology combinations is tested and the performance indicator results reveal the most suitable technology mix (for each optimisation preference). Subsequently, the optimised households are combined to form a community. Lastly the community performance is calculated and evaluated.

- i. **How to make a selection of technologies that should be considered during the assessment?** We looked at currently available technologies to implement at household level. Besides the technologies should be able to fulfil energy demand, they should also be able to support in fulfilling the distinct community preferences. Conventional distributed generation technologies are used to increase the energy autonomy of households. Renewable distributed generation technologies are used to reduce the CO₂ emission. The selection of technologies is made based on technology diversification, the outcome of the stakeholder mapping, performance and costs. For energy generation, this led to the selection of a modular solar PV system with 300 WP monocrystalline solar panels and four sizes of inverters, four different sizes of solar thermal systems, a 5 kW micro-wind turbine, a fuel cell and four different sized CHPs. Heat and electricity storage respectively can be utilised in three different size thermal storage boilers and in a 10 kW battery. Since EV become more common, an average EV is implemented in the analyses.
- ii. **With the selected technologies, how can a proper procedure be defined to optimally match demand with supply at specific community preferences?** Selecting the optimal technology mix at household level is accomplished by randomly combining from available technologies. This results in a large set of technology combinations for all four household types, as shown in Appendix C. All performance indicators of each generated technology mix are stored, together with a range of other important parameters (Appendix A). These results are being analysed, to make the optimal selection for each demand profile and for each optimisation preference. This leads to a set of 12 different technology mixes, which produce the most suitable outcome (Appendix B). Pre-defined conditions are used to exclude households with undesirable performance indicator results. Since in our analyses heat is not being exchanged within ICES, each household that cannot fulfil its own heat demand is being excluded. The strength of this procedure is that it is flexible, new technologies or improved technical specifications can be easily implemented. Also this procedure visualises the model results, allow the comparison of many different technology mixes. After a household with suitable performance indicator results is found, details on the specific technology mix can be extracted from the model. After this exercise, an ICES is being constructed from households with optimal technology mixes.

3. Under what conditions and in which scenarios is it attractive for households to be part of ICES?

Largest CO₂ reduction is expensive. Higher EV penetration ratio increases the ICES energy exchange price. The first EV movers and the last households that do not use EV have the highest benefits from being part of ICES. Battery owners can offer flexibility to the community, but it is more beneficial for them to use the stored energy for themselves. Batteries offer the same kind of functionality as ICES, but at higher costs. The community composition is of less importance than the proper selection of generation technologies. Different optimisation preferences give diverse performance indicator results. Household level optimisation (for all three optimisation preferences), leads to significant improvement of all performance indicators. The accepted trade-of level between the different indicators determines to what extent it is attractive for households to be part of ICES.

- i. **What is the impact of high RES penetration or CO₂ minimisation on households?** Within the ICES model, CO₂ emission is recorded at household level and at ICES level. It is used as an indication of the RES penetration level. At household level CO₂ emission can be reduced by 54 % on average, at 75% annual energy cost increase (Appendix B). There is large variation in CO₂ reduction and the associated energy costs increase, among the different types of households. For two adult households the CO₂ reduction comes with the highest increase in energy costs with respect to the realised carbon reduction (100% price increase for 25% CO₂ reduction), while families and pensioners only increasing their cost by less than 20% for a CO₂ reduction of 60%. This differences are caused by the different demand profiles and the implemented technologies. When combining households to an ICES these large differences are important to consider, especially if is looking for the cheapest option to reduce carbon emission. Another implication of a high RES penetration is the largely overlapping production

profiles from RES at community level, as weather parameters are identical for all households in our model. When storage options are available or energy export is possible at beneficial conditions (at least LCOE is recovered), this is not necessarily a drawback of high RES penetration. The impact of a carbon tax is studied and although this increases the value of ICES, its effects are marginal, compared to the total annual energy costs.

- ii. **What is the impact of high EV penetration or stationary storage on households?** When the penetration level of electric vehicles (EV) increases within ICES, the price at which electricity is being exchanged increases exponentially (section 5.3.1). Therefore the first movers experience the largest benefits from being part of ICES. At low EV penetration level, ICES is able to supply the required energy for charging EV without reducing the energy exchange to other households. At higher EV penetration, the excess energy within ICES is no longer sufficient and more energy needs to be imported from outside ICES. This increases the average energy price, since locally produced energy turns out to be cheaper. The few remaining households without EV have the guarantee they can sell a large share of their excess energy within ICES. A higher EV penetration increases the average CO₂ emission per kWh and reduces the ICES energy autonomy, due to additional energy import from the electricity grid. Energy exchange within ICES is reduced when the majority of households have EV installed. This is caused by the fact that these households will export less energy and use a larger part of their locally produced energy themselves. The barrier for large scale EV implementation within ICES increases due to the mismatch between the EV charging hours (non-office hours) and the renewable energy production peak hours (during daytime). Demand response by load shifting, energy storage in stationary batteries or interchangeable EV battery packs could reduce this drawback and increase high EV penetration perspective. The effect of stationary storage (batteries) at household level is comparable with the effect ICES has on the household level performance indicators (section 5.3.5). Batteries are used to store excess energy and to extract energy from at times of high demand. This is comparable with the role of ICES: excess energy can be exported to community members and energy can be imported when local demand is higher than local production. A high battery penetration ratio increases households' individual performance, but this on the other hand reduces the additional value of ICES. With batteries installed at all households, the total energy exchange within ICES reduces with 85%. The use of batteries at household level, within ICES, slightly increases the final results of performance indicators, after energy is being exchanged with ICES. The total annual costs however increase up to 20% due to the (still) high capital costs of this technology. If the use of ICES comes without additional (participation) costs, this would result in equal performance as the use of local batteries, but at lower costs.
- iii. **What are the effects of different household compositions within ICES on costs, emissions and energy autonomy for community and for households?** Four different household types and four different community compositions are examined (section 4.2). Financial optimisation gives the best results for a community composition that is comparable with the current household composition distribution in the Netherlands (Composition A). Not only the energy costs at household level (before applying ICES) are lowest, but also ICES has the highest added value for this scenario. For all community compositions, the electricity price is lowest for community composition A, when optimised at cost reduction: € 0.135 per kWh. The results of all performance indicators, as well as the added value of ICES, is lower for the other community compositions. When focusing on energy costs reduction, the energy autonomy never reaches 100%. It is economically efficient to import a few percent from the electricity grid and save on investment costs on generation technology. Maximum CO₂ reduction comes at a price, up to 2.5 times the base case scenario annual energy costs (section 5.1.2). The CO₂ emission is reduced by 50% on average. The largest contribution to CO₂ reduction is made by the implementation of renewable technologies at household level and not by the use of ICES. The expected trend in community composition has a positive effect on CO₂ reduction, as community composition C has the lowest emission and the largest ICES reduction contribution. Optimising ICES on CO₂ reduction leads in all examined community compositions to 100% autonomy. Community can

become energy autonomous at affordable costs. However a two adult households doubles its annual energy costs. This is due to high demand peaks, resulting in an over-dimensioned system to be able to fulfil demand at all times. Since all households supply their own demand completely, there is no energy exchange within ICES, making the community needless. The different community compositions have slightly different results regarding energy costs and carbon emission. Again community composition C has the most promising results, having the lowest price per kWh and the lowest CO₂ emission. However this is purely because the individual household technologies match the household demand perfectly and no energy is being exchanged within ICES. From ICES perspective, the energy autonomy optimisation at household level is thereby not an interesting scenario. Energy autonomy at community level is a more interesting parameter to monitor. The other two optimisation preferences generate good results on community energy autonomy. Very small communities can use the energy autonomy preference to become energy autonomous. This is because smaller communities in general have less energy exchange, making it more difficult to become 100% energy autonomous. For energy autonomy, no optimum community size is found. This optimum rather is a function of the different demand- and production profiles. The ICES energy autonomy increase depends purely on the available excess energy and the residual demand of the households. Essentially this is equal to the difference between the demand- and production profiles of the individual households.

Within ICES, there are slight variations observed in the ICES model results from different community compositions (less than 5% variation). It turns out the selection of the right technology mix, in accord with the optimisation preference, is of greater importance and of higher influence on the performance indicators than the community composition. Also the household demand profiles are of great importance when looking at absolute results. Therefore also the relative benefits per household are mapped, in respect to the base case scenario. The largest difference is observed between a two adult household and a family household. The first cannot reduce their energy costs within ICES while the latter can reduce costs by 20%.

- iv. **Under what conditions can autarchic communities succeed?** Communities that fulfil their own energy demand need larger capital investments than communities that do not fulfil their demand locally. Community results show that the investment at household level on average is almost four times higher than the investment costs in the base case scenario. This optimisation scenario is not recommended to take as a starting point. Financial optimisation preferences lead to energy autonomy between 91% and 97% on community level for the different community compositions. For financial optimisation, capital investment (considered as an obstacle to success) is 'only' 2.5 times higher than the base case scenario. However, due to lower operational costs, the annualised energy costs remain comparable. Hence, it is costly to become fully autonomous (autarchic). All households within an autarchic community use solar PV (different sizes). 75% has a wind turbine installed and 75% has batteries installed. Half of the households have solar thermal with a thermal storage boiler.

The right mix of producing households and households without production can help to further reduce energy costs. A 20% share of non-producing households within ICES gives promising results. A high stationary storage penetration at household level reduces the need for ICES, as households can balance their energy themselves. Besides the technical conditions, the social and institutional factors have impact on the success of autarchic communities. Current energy systems fail to offer competitive prices for exported energy, as they do not cover full LCOE in general. Energy policy need to make it feasible to exchange energy within a community without additional costs. This will reduce the cost for imported energy and makes the business model of ICES stronger.

7.2. Recommendations and reflections

7.2.1. Recommendations to energy policy makers

Since it is evident that emission reduction will continue to be part of global and national energy targets, policy makers need to think of energy policies that work towards the realisation of these emission reductions. Since this research shows ICES can contribute to the reduction of CO₂ emission, it is recommended that energy policy will be reformed to encourage the energy exchange within ICES. A suggestion to the policy makers is to exclude local generated energy that is being exchanged within ICES, from energy tax and levies. This will stimulate the emergence of ICES, as it improves the business case for local consumers, and also contributes to CO₂ reduction.

In the Netherlands, natural gas that is used for electricity generation in CHP (with an electric power greater than 60 kW and efficiency higher than 30%) receives exemption on energy tax. To utilise the possibilities and advantages ICES has to offer, it is recommended to exempt also smaller CHP units, to allow households to participate in the contribution to a less carbon intensive energy system.

Another important aspect policy makers need to address is proper regulation concerning the rights of ownership and responsibility, the design of a local energy market as well as privacy related issues in ICES. Furthermore consumers need to stay protected against extremely high energy prices, as they are currently being protected by ACM regulations (De Krom et al., 2009). These factors might easily be overlooked when designing these energy systems, but they are of importance and have influence on the success or failure of ICES. Without a proper functioning local energy market and the right regulatory mechanisms that ensure households will not be able to develop market power (to manipulate energy prices within ICES), the success of local energy system is uncertain.

R&D should be promoted, to realise further cost reduction and technical improvement on (sustainable) distributed generation technologies and on local energy management systems.

7.2.2. Recommendations for further research

Model results show that ICES is able to reduce CO₂ emission and increase energy autonomy at affordable costs. The extent to which the performance indicators change, is very sensitive to variations in the demand profiles and technology mix. This is partly explained by the fact that only four different types of households (with equal demand profiles and installed technologies) are used to construct a 12 household ICES. A change in community composition thereby has per definition a stronger effect on the community level energy flows. It is recommended to implement a statistical deviation between the demand profiles of the identical households. This would make the analysis more realistic, and probably giving better results. Certainly the change that energy can be exchanged with another household increases, due to a deviation in demand and overproduction.

In line with the previous recommendation, the effect of deviations from the used data is essential for a realistic forecast. The ICES model uses historical data, but a realistic forecast of RES production and demand could increase the value of the analysis. Detailed weather data studies, which takes into account the probability distributions and forecast errors, will increase the value of model results. This will provide more accurate outcomes, within defined and founded boundaries of certainty. Therefore a more advanced optimisation process is needed, which increases the complexity of data processing.

It is also recommended to quantify the benefits that can be made from demand response at community level. This will need an intelligent decision algorithm with advanced demand and production forecasts. This algorithm needs to take into account the distinct community preferences. Also it needs to base its decision on forecasted demand, energy production and energy prices. At present, the ICES model works mainly in one direction, from household level to ICES level. Demand response at ICES level works in two directions; exploiting storage and production options at household level to increase the community performance to a larger extent. Applying demand response at community level, can be a new business case for energy suppliers or aggregators.

For the majority of the used parameters, seasonal variation is considered. To increase the flexibility of the model it is recommended to analyse the impact of seasonal variations in energy prices. For electricity this effect is not too noticeable, however for heat this effect can be of greater influence, since heat demand is characterised by strong seasonal variations.

Within our framework, we only looked at household level technologies. The implementation of community level technologies will be a next step of the research. A large wind turbine at ICES level can fulfil a large share of the demand of the community members. The efficiency of a large wind turbine is higher than the efficiency of a micro-wind turbine. However financing issues might arise and a decent funding scheme should be developed to tackle this. It needs to be clear who is the owner of the technology and under what conditions community members can join or leave the community. A non-profit community cooperation can be created to perform the central role of linking investors with community members. Although one could also opt for commercial parties to exploit community level technologies (and remove the financing obstacle), this might contradict with the community ideology if no influence can be exerted by community members upon this commercial entity.

To generate more sensible and interpretable outcomes, the model currently is set with fixed values for rooftop area (determines maximum solar capacity), rooftop orientation, EV type, daily traveling distance and charging profile of EV. In future work, more of the implemented physical parameters could be varied. Changing these parameters too, will diversify the production- and demand profiles. This might increase the value of ICES, as a larger diversification of individual household profiles, leads to the more energy exchange possibilities.

7.2.3. Outstanding remarks and findings for ICES development

The large capital costs remain an issue, in many tested scenarios. An investment of € 50.000 (to become totally energy autonomous and reduce CO₂ emission to its maximum) is a huge capital investment, equal to 23% of the price of an average Dutch household (Vereniging eigen huis, 2015). This cost could be implemented in the mortgage of the house and spread over the lifetime of the technology. Then the interest rate also should be taken into account, while assessing the performance and pay-back time. Another issue to be solved concerns members that are moving in or out of the community. The value of technology assets needs to be evaluated at some point. Nowadays this is already common with solar panels. Interestingly, solar panels turn out to increase the value of a house by more than their own value, and thereby turn out to be a profitable investment (ABN-Amro, 2015; Dekker, 2013). However, selling your house that is part of ICES might attract different buyers. For house owners within ICES, it is good to look into the options and perspectives there are for selling their house, and how this differs from houses that have their energy organised in a traditional way.

Privacy issues should be considered. In the way energy is organised currently, this is covered by the energy regulations, set by the authorities. Regarding smart meters, TSO and energy suppliers are only allowed to obtain meter readings at specific moments and the security of data needs to be guaranteed (Rijksoverheid, 2015b). However, a high resistance to smart meters is observed, expressing the lack of public acceptance and a distrust in the correct handling of privacy concerning data. When introducing ICES these issues should be kept in mind and public acceptance should not be presumed. Community data on energy usage should be securely stored and the controlling entity should be able to guarantee the community members' privacy, without compromising on performance and transparency.

In ICES, community members are connected to the ICES local energy market, or energy exchange hub. This unit decides whether the energy is being exchanged with community members, or when energy needs to be imported from the grid. This results in only one central connection to the grid, at community level. Thereby it is (with the current energy regulation, technical and quality standards) not possible for each household to select its own energy supplier. Each consumer within the EU, however, has the right to choose its own energy supplier from the moment energy markets were liberalised. The solution can be sought in two different directions. One could accept there is no freedom of choice of energy supplier within ICES. This is nowadays also the case within district heating systems. In that case, community members certainly need to be protected against excessively high energy prices. This could be done by legislation and government supervision. The other option is to technically allow the ICES

connection to the grid to have multiple active energy suppliers. Within the ICES exchange hub, the distribution of energy among the different households is being measured, and the allocation to the energy supplier is carried out.

Community energy systems are emerging in different forms, from small pilot project to commercialised district heating networks. For ICES to become successful, social acceptance and community engagement are important factors. A project that is not being supported by its end users, is without perspective. It is important to understand how to encourage community members to be part of ICES and what mechanisms can be used to engage them. In the scope of this research, these questions are only partially answered.

Within the energy sector three main targets are pursued: sustainability, security of supply and affordability. The importance that is being assigned to these three values differs for the actors and changes over time. ICES proves to be able to give the flexibility to adjust according to the requirements of its participants. For future developments the arrangement of energy within ICES can provide a flexible solution for the organisation of energy at households.

7.2.4. Reflections on methodology

The stakeholder analyses and mapping proved to be useful tools for selecting the right technologies. These methods also increased the insight in the relations between the different actors in the energy landscape. The weakness of these methods is that they are vulnerable to subjectivity. Furthermore the use of these methods will not give the guarantee that all important stakeholders are covered.

Reflecting on the modelling method, a quantitative, bottom-up model, proves to be a decent tool to answer the research questions. The difficulty with modelling is the dependency on good datasets. With the use of a bottom-up approach (and testing each model step and temporary output parameter), inaccuracies are restricted to a minimum, since possible errors are detected in an early stage. However, since not all real input data was available, a limited inaccuracy is inevitable. At best, a decent approximation of reality is attained. One final drawback of modelling is that it is a rather time-consuming process. However, to obtain detailed insights in these complex systems, the developed ICES model is a powerful tool to assess ICES.

In addition to the used methods, a survey amongst different types of households could provide more profound information on community preferences and thereby underpin optimisation preferences. Also real energy demand profiles over a full year (in combination with socio-economic parameters of the households) would contribute to the accuracy and usefulness of the ICES model results.

7.3. Elaboration on stakeholder analysis

Different stakeholders are identified in the stakeholder mapping, as described in section 3.4. The model results are used to elaborate on the stakeholder analyses, in order to provide insight in the interests of the different stakeholders in the development of ICES. The stakeholder mapping mainly describes the interests and power of the stakeholders. Now the impact of the emergence of ICES on the different stakeholders is analysed. The impact of ICES on actors is discussed by the observed model results, from which a number of conclusions can be drawn.

The impact of ICES on households depends strongly on households' initial demand profile, the implemented technologies and the community composition. Households will get more insight in their energy and energy costs at household level will reduce. However in contrast, the transparency of energy prices will likely decrease.

Regardless of the optimisation preference, solar PV is always being selected in the optimal technology mix by the model. This proven technology offers low-carbon intensive electricity at low costs and turns out to be very suitable for implementation in ICES. The result of the rollout of ICES will induce an increasing demand for solar systems. This might further speed up the technology process of this technology. By capturing a stronger position on the renewable energy market, it might also hinder the technology progress of other technologies. Since solar production has a typical production profile which peaks around noon, other technologies to supplement energy production during these hours will be needed.

In respond to emission restrictions and carbon pricing scenarios, it is likely that electric utilities will adjust their generation mixes. Over time these adjustments will change, following the developments in carbon pricing policy. (Rushing et al., 2013). This means also the resulting carbon emission will change over time as it is influenced by the carbon pricing policy. Stricter emission targets and higher carbon prices will force the utilities to reduce their emissions and invest in more renewable solutions. This is an inspiring development that contributes to carbon reduction in the whole energy sector. It reduces the difference between the carbon emissions from the grid and ICES, reducing the contribution of ICES on CO₂ emission reduction. Energy prices from local generated energy, low carbon emission and other advantages, such as local balancing options, need to ensure the benefits of ICES.

However a large share of 'green' labelled electricity is not as renewable as it pretends to be. It is being produced by conventional power plants and afterwards it is 'greenwashed' by the purchase of cheap Guarantees of Origin (GoOs) from foreign countries (Down to Earth, 2014). Dutch energy suppliers buy cheap hydropower GoOs from Scandinavian countries on large scale, where the investment in local generation lags behind. The excess energy from ICES can be used by energy suppliers to increase the share of local renewable energy in their portfolio.

The role of system operator need to be fulfilled by an independent entity. This local system operator needs to secure the quality and security of the network within the community. Thereby this system operator needs to collect all data from household level and process this to ensure demand is being fulfilled at all times. Furthermore the allocation of CO₂ emission and the revenue streams need to be tracked.

7.4. Assumptions and limitations

During any research process, it is inevitable to make assumptions. This not only is true for a scientific assessment, but it accounts for many things in our lives. While making assumptions it is good to be aware of the fact that we simplified reality and recognise the impact the assumptions have on outcomes and results. Without assumptions, it would not be possible to perform research, however we should be aware of the probability these assumptions might not be correct and what this would imply to the outcomes of our research. The main assumptions made during the research are listed below.

- The differentiation of demand in four seasons is a realistic approximation of the fluctuations within seasonal demand variations and is accurate enough to represent the annual energy demand profile.
- Four household types are classified to represent different household compositions. In reality occupant behaviour varies widely affecting demand profiles in an unpredictable way. It is difficult to predict or even estimate behaviour, but it is assumed the used data (verified with SEC Heerhugowaard) is representative.
- Due to the limitations of the demand profile generators, household demand profiles are identical at all days of the week. With more realistic data it would be interesting to distinguish different profiles for week- and weekend days.
- EV are implemented as additional electricity demand and recharge in the hours after it has been used. No strategic charging schemes are used for EV. Charging only occurs outside office hours and only at the associated household.
- The energy technologies are operational twenty-four seven, without failure.
- Batteries have two strategic options to charge and discharge. Direct use of stored energy or peak shaving to reduce the demand peaks. No hybrid or varying strategy is considered.
- The order in which energy technologies are being applied in the model is assumed to be an appropriate representation of reality: renewable production, storage, FC/CHP generation, grid exchange.
- The APX price, the 2014 average gas price and the obtained demand profiles are realistic representations of the energy price and energy demand profiles, also for the assessment of upcoming years.
- The used discount rate is 3% per year.
- Perfect state of electricity is assumed and the model describes electricity by its power. Voltage, ampère and derivative units are not taken into account in the analyses.
- Within ICES it assumed no additional conversion is needed to transport the energy within the community. This transformation is outside the scope of the energy system.

- For the electricity from the national grid, the average CO₂ emission value is used. It is possible to opt for 'green electricity', which has a significantly lower emission level. The author is aware of the fact this changes the contribution of ICES. Yet one need to distinguish green energy from 'greenwashed' energy.
- The households can exchange energy amongst themselves. Households are considered to be rational agents and they invest in new technologies with the principle of utility maximization.

7.5. Academic and social relevance of the research project

Research indicates the need for more efficient energy generation and distribution systems, driven by a desire to reduce the amount of CO₂ emission from energy related activities. The current energy system is largely centralised and mainly based on large fossil fuel power plants. In contrast to this centralised architecture, local community energy systems are emerging. The knowledge on these systems, however, is limited and immature. This underlines the significance of a study on the opportunities of community energy systems in comparison to the performance of the current energy systems.

Within energy systems, the role of individuals (households) is often neglected. This changes when more local generation is used and consumers become prosumers. The current system is not optimally designed and households could benefit more from their (renewable) distributed generation technologies than they do now. As a new approach in looking at energy systems, this research not looks further than community level performance. Also the benefits and drawbacks for households to be part of ICES are assessed.

A model is developed during this research, to increase the understanding of energy flows and performance indicator results at household level. This model is an important tool for obtaining scientifically relevant data. It helped to quantify the effects of different community compositions, demand profiles, energy technologies and scenarios. The results give direction on how to optimally design ICES under different community preferences. In combination with the performed stakeholder analyses, model results indicate the important elements or actors that need to be taken into account while constructing ICES. For example, Solar PV is always selected by the model as it offers low carbon intensive energy at affordable costs, and at the same time increases energy autonomy.

This research shows households can benefit from being part of a community, but that benefits are not always guaranteed. The level of the benefits varies, and depend on installed technologies, community composition and EV penetration. The ICES model shows it is not necessarily beneficial to be part of ICES. It also shows that the selection of the right technology mix at household level is more important than the additional benefit ICES offers. A financial concept is developed on how to allocate costs and benefits among the different community members.

This research use a multi-objective optimisation approach and looks into the impact on three performance indicators (costs, CO₂ and energy autonomy). In addition to existing research, the value distribution among community members is covered. Model results show that not all household types equally benefit from being part of ICES, measured on the three performance indicators. An interesting insight is that a high level of EV penetration increases the energy price of the community members without EV.

The results of this research are contributing science in the increased understanding of community energy systems. Although the contribution of ICES in the transition towards more efficient energy systems should not be overestimated, it has definitely potential to reduce carbon emission at community level at affordable costs.

7.6. Further work

During this research project it was necessary to make certain assumptions or to exclude some aspects from our analyses. Throughout the progress also new ideas and insights were developed from literature study and model results. This leads to the following recommendations for future work.

- Distinct different demand profiles for days of the week and weekend days and holidays.
- Run model at household level multiple times for each household (when community residual demand and overproduction is assessed), to fully exploit the local storage and production options.

- The exchange of electricity within ICES is being studied and modelled. For heat the demand and production are being matched at household level. To increase the value and flexibility of the research, the implementation of a heat exchange option at community level would be very interesting.
- A framework should be developed to stimulate community engagement. Also a structure should be established to make pricing more transparent to the consumers, in order to make the comparison with existing energy systems more tangible. With historical data it is possible to perform an analysis on the impact on energy costs, however this is not a guarantee for the energy costs of next years. A sensitivity analysis can be used to present model outcomes within a certain level of certainty, giving possible ICES participants a better indication on energy costs.
- Investigate the value of ICES and its implication on households, for a scenario in which ICES is allowed to trade in balancing market, flexibility market or provide ancillary services to grid operators.
- Investigate the options for the sales or trade of excess carbon rights from community level and its value.
- Different charging and trading strategies can be implemented for EV, to increase the realistic value of ICES.

Bibliography

- ABN-Amro. (2015). Zonnepanelen verhogen de waarde van uw woning (Solar panels increase house value). Retrieved 2015-08-27, from <https://www.abnamro.nl/nl/prime/hypotheeken/wonen/huis-bezitten/met-zonnepanelen-is-uw-woning-meer-waard.html>
- Adaramola, M. S. (2015). Techno-economic analysis of a 2.1 kW rooftop photovoltaic-grid-tied system based on actual performance. *Energy Conversion and Management*, 101, 85-93. doi: <http://dx.doi.org/10.1016/j.enconman.2015.05.038>
- Allesoverhuisentuin.nl. (2015). CV Installatie Installeren Kosten - Informatie en prijs. Retrieved 2015-08-06, from <http://www.allesoverhuisentuin.nl/idee/cv-installatie-aanleggen-kosten/2849>
- APX Power NL. (2015). APX Power Spot Exchange Database Netherlands. Retrieved 2015-08-12, from <https://www.apxgroup.com>
- Arentsen, M., & Bellekom, S. (2014). Power to the people: local energy initiatives as seedbeds of innovation? *Energy, sustainability and society*, 4(2).
- Babar, M., Taj, T. A., Ahamed, T. P. I., & Al-Ammar, E. A. (2013). The conception of the aggregator in demand side management for domestic consumers. *International Journal of Smart Grid and Clean Energy*, vol. 2, no. 3(371–375).
- Beetz, B. (2015). Stationary storage costs to remain high, despite predictions of \$172/kWh Li-ion battery costs. *pv magazine*. Retrieved 2015-07-30, from <http://www.pv-magazine.com/news/details/beitrag/stationary-storage-costs-to-remain-high--despite-predictions-of-172-kwh-li-ion-battery-costs-100019507/>
- Belastingdienst. (2015). Tabellen tarieven milieubelastingen. Retrieved 2015-08-06, from http://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/belastingdienst/zakelijk/overige_belastingen/belastingen_op_milieugrondslag/tarieven_milieubelastingen/tabellen_tarieven_milieubelastingen?projectid=6750bae7-383b-4c97-bc7a-802790bd1110
- Borenstein, S. (2012). The Private and Public Economics of Renewable Electricity Generation. *Journal of Economic Perspectives*, 26(1), 67-92. doi: doi: 10.1257/jep.26.1.67
- Brooks, K., Makhmalbaf, A., Anderson, D., Amaya, J., Pilli, S., Srivastava, V., & Upton, J. (2013). Business Case for a Micro-Combined Heat and Power Fuel-Cell System in Commercial Applications Springfield, U.S.: PACIFIC NORTHWEST NATIONAL LABORATORY
- Bryson, J. M. (2004). What to do when stakeholders matter: stakeholder identification and analysis techniques. *Public Management Review* 6, 21-53.
- BuildDesk Benelux B.V. (2011). Indirect energiegebruik en broeikasgassenuitstoot van huishoudens In S. van Broekhoven, R. Jharap, S. Hardenbol, G. Lappee, & J. Remmers (Eds.), *Planstudie Innovatieprogramma Klimaatneutrale Steden voor Amsterdam, Lochem en Wageningen*. Delft: BuildDesk.
- Burns, M. (2010). Greening Saint Paul by using clean, urban wood residue and CHP to heat and cool downtown buildings.
- Burstein, P. (2003). The Impact of Public Opinion on Public Policy: A Review and an Agenda. *Political Research Quarterly*, 56(1), 29-40. doi: 10.1177/106591290305600103
- Capros, P., Mantzos, L., Parousos, L., Tasios, N., Klaassen, G., & Van Ierland, T. (2011). Analysis of the EU policy package on climate change and renewables. *Energy Policy*, 39(3), 1476-1485. doi: <http://dx.doi.org/10.1016/j.enpol.2010.12.020>
- Cartes, D., Ordonez, J., Harrington, J., Cox, D., & Meeker, R. (2007). Novel Integrated Energy Systems and Control Methods with Economic Analysis for Integrated Community Based Energy Systems. *Proc. IEEE Power Engineering Society General Meeting*, p. 1-6.
- CBS. (2013). Huishoudens naar type, 2011-2060 Retrieved 11-06-2015, from <http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=80986NED&D1=a&D2=0%2c112-114&D3=0&D4=0%2c14%2c34%2c&HDR=T&STB=G2%2cG3%2cG1&VW=T>

- CBS. (2015). CBS StatLine - Households; size, composition, position in the household. Retrieved 11-06-2015, from <http://statline.cbs.nl/Statweb/publication/?DM=SELEN&PA=82905eng&D1=0-65&D2=8-19&LA=EN&VW=T>
- ChargePoint. (2015). EV Models - ChargePoint. *There's an EV for Everyone*. Retrieved 2015-07-30, from <http://www.chargepoint.com/evs>
- Cvketel-Weetjes. (2015). Kosten centrale verwarming per onderdeel. Retrieved 2015-08-06, from <http://www.cvketel-weetjes.nl/centrale-verwarming/centrale-verwarming-kosten/>
- Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences*, 107(12), 5687-5692. doi: 10.1073/pnas.0906974107
- De Krom, H., Van Leeuwen, E. T. W. M., & Schaap, A. R. (2009). Consumentenbescherming in het energierecht (Consumerprotectin in energy legislation). *Nederlands Tijdschrift voor Energierecht*, 2009 nr. 3/4.
- DECC. (2013). DECC Electricity Generation Costs (Vol. URN 12D/383). London DECC (Department of Energy & Climate Change).
- Dekker, V. (2013, 2013-08-07). Huis nog niet verkocht? Zet er zonnepanelen op! *Trouw*. Retrieved from <http://www.trouw.nl/tr/nl/5151/Vincent-wil-zon/article/detail/3488550/2013/08/07/Huis-nog-niet-verkocht-Zet-er-zonnepanelen-op.dhtml>
- DESP. (2007). DISTRICT ENERGY ST. PAUL - Achieving Energy Independence.
- Down to Earth. (2014). Kan groene stroom uit IJsland vliegen? (Does green electricity from Iceland fly?). *Down To Earth Magazine*, 2014-08-22(Energy & Climate).
- Eberle, D. U., & von Helmolt, D. R. (2010). Sustainable transportation based on electric vehicle concepts: a brief overview. *Energy & Environmental Science*, 3(6), 689-699. doi: 10.1039/C001674H
- EC. (2013). Green Paper. A 2030 framework for climate and energy policies. *European Commission*.
- ECN. (2014). Energietrends 2014. In ECN, Energie-Nederland, & N. Nederland (Eds.).
- Electriciteitswet 1998 art. 31-C, Dutch Electricity Act art. 31-C § BWBR0009755 (1998).
- Energieia. (2015). 'Prijs CO2-emissierechten in de lift'. Retrieved 2015-08-13, from <http://energieia.nl/nieuws/103575-1508/stemming-prijs-co2-emissierechten-in-de-lift>
- Enserink, B., Hermans, L., Kwakkel, J., Thissen, W., Koppenjan, J., & Bots, P. (2010). *Policy Analysis of Multi-Actor Systems*. The Hague: Lemma.
- Essent. (2015). CO2-waarden: verklein uw voetafdruk. Retrieved 2015-08-04, from <https://www.essent.nl/content/grootzakelijk/duurzaam/CO2-prestatieladder/co2-waarden.html>
- ETP. (2011). Energy retailers perspective on the deployment of Smart Grids in Europe (2011). In E. T. Platform. (Ed.), *Working Group Document: European Technology Platform*.
- European Energy Exchange AG. (2015). European Emission Allowances (EUA). from <https://www.eex.com/en/market-data/emission-allowances/auction-market/european-emission-allowances-auction#!/2015/09/24>
- Eurostat. (2015, May 2015). Electricity and natural gas price statistics - Statistics Explained. Retrieved 28-07-2015, from http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_natural_gas_price_statistics
- Föger, K. (2013). The Technology of Ceramic Fuel Cells. In K. Föger (Ed.), *Ceramic Fuel Cells Limited: Electrical Developments*.
- Fortis. (2012). FORTIS Wind Turbine Systems Montana 5kW - Datasheet. Haren, The Netherlands: FORTIS Wind Energy.
- FuelCellToday. (2012, 2012-08-17). BlueGen Domestic Fuel Cell Available for Under £20,000 in the UK. Retrieved 27-07-2015, from <http://www.fuelcelltoday.com/news-archive/2012/august/bluegen-domestic-fuel-cell-available-for-under-%C2%A320,000-in-the-uk>
- GasTerra. (2012). Warmte in de woonomgeving. In P. Friedel, P. Oostendorp, & P. Wagener (Eds.), *De wereld van aardgas - bronnen en systemen*. Groningen, The Netherlands: GasTerra / Castel International Publishers.

- Green Emotion. (2013). The Economics of Electric Vehicles. In D. Newbery (Ed.), *The Economics of Electric Vehicles*. Electricity Policy Research Group: University of Cambridge.
- Green, R. (2012). The Future of Electricity Demand: Customers, Citizens and Loads. *ENERGY JOURNAL*, 33, 219-222.
- Greentechmedia. (2015, 2015-05-01). Tesla Battery Bottom Line: \$3,500 for a 10-Kilowatt-Hour Storage System : Greentech Media. Retrieved 2015-07-30, from <http://www.greentechmedia.com/articles/read/Reporting-Live-From-the-Tesla-Mystery-Product-Unveiling>
- Gupta, R. A., & Gupta, N. K. (2015). A robust optimization based approach for microgrid operation in deregulated environment. *Energy Conversion and Management*, 93(0), 121-131. doi: <http://dx.doi.org/10.1016/j.enconman.2015.01.008>
- Hassett, B., Bower, E., & Alexander, M. (2011). Merge. Mobile Energy Resources in Grids of Electricity.
- Hearps, P., & McConell, D. (2011). Renewable Energy Technology Cost Review *Technical paper series*. Melbourne: University of Melbourne.
- HegiLibrary. (2015). *Electricity Production in the Netherlands*. Retrieved from: <http://www.heliglibrary.com/indicators/index/electricity-production-from-renewable-sources/netherlands>
- Hemmes, K., Zachariah-Wolf, J. L., Geidl, M., & Andersson, G. (2007). Towards multi-source multi-product energy systems. *International Journal of Hydrogen Energy*, 32(10–11), 1332-1338. doi: <http://dx.doi.org/10.1016/j.ijhydene.2006.10.013>
- Herbst, A., Toro, F. A., Reitze, F., & Jochem, E. (2012). Introduction to Energy Systems Modelling. *Swiss Journal of Economics and Statistics (SJES)*, 148(II), 111-135.
- Hicks, J., & Ison, N. (2011). Community-owned renewable energy (CRE): Opportunities for rural Australia. *Rural Society*, 20(3), 244-255. doi: 10.5172/rsj.20.3.244
- Hoffman, S. M., & High-Pippert, A. (2005). Community Energy: A Social Architecture for an Alternative Energy Future. *Bulletin of Science,, Technology & Society October 2005 25*, 387-401. doi: <http://dx.doi.org/10.1177/0270467605278880>
- Holtz, R. E. (1977). On the grid connection of an integrated community energy system. *Energy Conversion*, 17(1), 41-44. doi: [http://dx.doi.org/10.1016/0013-7480\(77\)90056-0](http://dx.doi.org/10.1016/0013-7480(77)90056-0)
- IEA. (2008). Energy Policies of IEA Countries: The Netherlands. *International Energy Agency(2008 Review)*.
- IEA. (2010). Power Generation from Coal - Measuring and Reporting Efficiency Performance and CO2 Emissions. *IEA Coal Industry Advisory Board (CIAB)*.
- Inoxcon. (2015). Frequently Asked Questions on central heating boilers. in Dutch: 'FAQ CV-ketel'. Retrieved 2015-08-24, from <http://www.inoxcon.nl/fag/ik-wil-mijn-cv-ketel-op-gas-ervangen-voor-een-elektrische-cv-ketel-waar-moet-ik-rekening-mee-houden>
- Jobert, B. (1989). The Normative Frameworks of Public Policy. *Political Studies*, 37(3), 376-386. doi: 10.1111/j.1467-9248.1989.tb00277.x
- Johnson, G., Scholes, K., & Whittington, R. (2005). *Exploring corporate strategy* (Eighth Ed.): Essex: Prentice Hall/Financial Times.
- KiM. (2013). Mobility research of the Netherlands 2013. *Tweede Kamer der Staten-Generaal, Mobiliteitsonderzoek Nederland(kst-31305-206)*.
- Klijn, E. H. (1997). *Policy Networks: An Overview*. In W. J. M. Kickert, E. H. Klijn & J. F. M. Koppenjan (Eds.), *Managing Complex Networks. Strategies for the Public Sector* (pp. 14-34). Thousand Oaks: Sage Publications.
- Koirala, B. P., Koliu, E., Friege, J., Hakvoort, R., & Herder, P. (unpublished). *Community as an Energy Plant: Review of the Key Issues and Trend in Integrated Community Energy Systems*.
- Kroposki, B., Garrett, B., Macmillian, S., Rice, B., Komomua, C., O'Malley, M., & Zimmerle, D. (2012). Energy Systems Integration; A Convergence of Ideas. *ENREL, National Renewable Energy Laboratory*.
- Law, A. M. (2005). *How to build valid and credible simulation models*. Paper presented at the Proceedings of the 37th conference on Winter simulation, Orlando, Florida.

- Lerohl, C. (2012). Integrated Community Energy System Business Case Study Strathcona County Community Energy System.
- Lozanova, S. (2011, 2011-04-06). 4 Things to Consider Before Going Solar Thermal. Retrieved 2015-09-24, from <http://www.triplepundit.com/2011/04/4-things-to-consider-before-going-solar-thermal/>
- Luckow, P., Stanton, E. A., Biewald, B., Fields, S., Jackson, S., Fisher, J., & Ackerman, F. (2014). CO2 Price Report, Spring 2014. *Synapse Energy Economics, Inc.*
- Mancarella, P. (2014). MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, 65(0), 1-17. doi: <http://dx.doi.org/10.1016/j.energy.2013.10.041>
- Mateo, Á. R. (2011). *Assessment of the contribution of storage and demand side management to power system flexibility*. (Master of Philosophy), The University of Manchester Manchester, UK Retrieved from http://www.ee.washington.edu/research/real/Library/Thesis/Angel_ROSSO.pdf
- Mendes, G., Ioakimidis, C., & Ferrão, P. (2011). On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools. *Renewable and Sustainable Energy Reviews*, 15(9), 4836-4854. doi: <http://dx.doi.org/10.1016/j.rser.2011.07.067>
- Mertens, S. (2012). Resultaten testveld kleine windturbines Schoondijke: Project Groep Schoondijke. Milieu Centraal. (2015a). Energieprijzen prijspeil 2015/2016. Retrieved 2015-08-06, from <http://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/energieprijzen/>
- Milieu Centraal. (2015b). Total annual CO₂ emission per average household. *Totale CO2 uitstoot per jaar van een gemiddeld huishouden (2,2 personen)*. Retrieved 2015-08-22, from <http://www.milieucentraal.nl/klimaat-en-aarde/klimaatverandering/bereken-je-co2-uitstoot/>
- Ministry of Transport, P. W. a. W. M. (2009). Elektrisch Rijden in de versnelling Plan van Aanpak 2011-2015
- Mitroff, I. I. (1983). *Stakeholders of the organizational mind*. San Francisco: Jossey-Bass.
- Morales, J. M., Conejo, A. J., Madsen, H., Pinson, P., & Zugno, M. (2014). Virtual power plants virtual power plant *Integrating Renewables in Electricity Markets* (pp. 243-287): Springer US.
- National Geographic Society. (2015). Solar Power Energy Information, Solar Power Energy Facts.
- NEN. (2014). Top 10 energieverbruikers in het huishouden. *HR-ketel is de standaard*. Retrieved 2015-08-06, from <https://www.nen.nl/NEN-Shop/Vakgebieden/Gas-Water/Actualiteiten-Gas-Water/Top-10-energieverbruikers-in-het-huishouden.htm>
- Nguyen, T., Spendelow, J., & Margolis, R. (2014). Levelized Costs of Electricity from CHP and PV. In P. R. O. o. S. E. F. C. Technologies (Ed.): United States of America, Department of Energy.
- NLAGency. (2012). Get to know the SDE+ 2012 In M. o. E. Affairs (Ed.): NLAGency.
- OECD. (1996). The knowledge-based economy. *Organisation for Economic Co-Operation and Development*(General Distribution OCDE/GD(96)102).
- Orehounig, K., Evins, R., & Dorer, V. (2015). Integration of decentralized energy systems in neighbourhoods using the energy hub approach. *Applied Energy*, 154(0), 277-289. doi: <http://dx.doi.org/10.1016/j.apenergy.2015.04.114>
- Oxera. (2011). Discount rates for low-carbon and renewable generation technologies *Prepared for the Committee on Climate Change*. . Oxford: Oxera Consulting Ltd.
- Palazzi, Titiaan, Lovins, & Amory. (2014, July 2014). Micropower Database 2014 (July. Retrieved 2015-08-15, from http://www.rmi.org/Knowledge-Center/Library/2014-18_MicropowerDatabase
- Parra, D., Gillott, M., Norman, S. A., & Walker, G. S. (2015). Optimum community energy storage system for PV energy time-shift. *Applied Energy*, 137(0), 576-587. doi: <http://dx.doi.org/10.1016/j.apenergy.2014.08.060>
- Payne, R., Love, J., & Kah, M. (2011). CFCL's BlueGen Product. *The Electrochemical Society*.
- Pelet, X., Favrat, D., & Leyland, G. (2005). Multiobjective optimisation of integrated energy systems for remote communities considering economics and CO₂ emissions. *International Journal of Thermal Sciences*, 44(12), 1180-1189. doi: <http://dx.doi.org/10.1016/j.ijthermalsci.2005.09.006>
- RCI. (2012). Investing in sustainable growth. In R. C. Initiative (Ed.), *Rotterdam Sustainability Monitor*.

- Reichelstein, S., & Sahoo, A. (2015). Time of day pricing and the levelized cost of intermittent power generation. *Energy Economics*, 48(0), 97-108. doi: <http://dx.doi.org/10.1016/j.eneco.2014.12.005>
- Rijksoverheid. (2015a). Bijtelling in 2016. Retrieved 2015-09-26, from <https://www.rijksoverheid.nl/onderwerpen/inkomstenbelasting/vraag-en-antwoord/wat-zijn-de-regels-voor-bijtelling-als-ik-een-auto-van-de-zaak-heb>
- Rijksoverheid. (2015b). Slimme meter en privacy (Smart meter and privacy). *Hoe zit het bij de slimme meter met mijn privacy?* Retrieved 2015-08-26, from <https://www.rijksoverheid.nl/onderwerpen/slimme-meter/vraag-en-antwoord/slimme-meter-privacy>
- Risto Linturi. (2000). The role of technology in shaping human society. *Foresight*, 2(2), 183-188. doi: doi:10.1108/14636680010802636
- Rushing, A. S., Kneifel, J. D., & Lippiatt, B. C. (2013). Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis (Vol. Annual Supplement to NIST Handbook 135 and NBS Special Publication 709): National Institute of Standards and Technology - U.S. Department of Commerce.
- RVO. (2010). Progress report: energy from renewable sources in the Netherlands 2009-2010 *EC Renewable Energy Directive (2009/28/EC)*: Government of the Netherlands.
- RVO. (2014). Saldering, zelflevering en tariefkorting. Retrieved 2015-08-17, from <http://www.rvo.nl/onderwerpen/duurzaam-ondernemen/duurzame-energie-opwekken/duurzame-energie/saldering-en-zelflevering>
- RVO. (2015). Cijfers elektrisch vervoer. *Aantal geregistreerde elektrische voertuigen in Nederland*. Retrieved 2015-07-31, from <http://www.rvo.nl/onderwerpen/duurzaam-ondernemen/energie-en-milieu-innovaties/elektrisch-rijden/stand-van-zaken/cijfers>
- Rydh, Carl, J., Sandén, & Björn, A. (2005). Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies: Elsevier Ltd.
- Scheer, H. (2007). *Energy autonomy the economic, social and technological case for renewable energy*. London: Earthscan.
- Schweizer-Ries, P. (2008). Energy sustainable communities: Environmental psychological investigations. *Energy Policy*, 36(11), 4126-4135. doi: <http://dx.doi.org/10.1016/j.enpol.2008.06.021>
- Scientific American. (2008). Storing the Breeze: New Battery Might Make Wind Power More Reliable. *Scientific American*. Retrieved 2015-07-30, from <http://www.scientificamerican.com/article/storing-the-breeze-new-battery-might-make-wind-power-reliable/>
- Sechilariu, M., Wang, B. C., & Locment, F. (2013). Building-integrated microgrid: Advanced local energy management for forthcoming smart power grid communication. *Energy and Buildings*, 59, 236-243. doi: 10.1016/j.enbuild.2012.12.039
- Slingerland, S., Rothengatter, N., Van der Veen, R., Bolscher, H., & Rademaekers, K. (2015). The Balance of Power – Flexibility Options for the Dutch Electricity Market. *TEC1070NL*.
- Smith, K. W. (2010). Saint Paul's Integrated Community Energy System.
- Smith, K. W., & Rancone, M. (2014). 2014 Annual report District Energy St. Paul 'Everyday heroes'.
- Solar Online. (2015). Solar Online Your solution to green energy. Retrieved 2015-08-06, from <http://www.solaronline.nl/>
- Soshinskaya, M., Crijns-Graus, W. H. J., Guerrero, J. M., & Vasquez, J. C. (2014). Microgrids: Experiences, barriers and success factors. *Renewable and Sustainable Energy Reviews*, 40, 659-672. doi: <http://dx.doi.org/10.1016/j.rser.2014.07.198>
- St. Denis, G., & Parker, P. (2009). Community energy planning in Canada: The role of renewable energy. *Renewable and Sustainable Energy Reviews*, 13(8), 2088-2095. doi: <http://dx.doi.org/10.1016/j.rser.2008.09.030>
- Staffell, I., & Green, R. (2013). The cost of domestic fuel cell micro-CHP systems. *International Journal of Hydrogen Energy*, 38(2), 1088-1102. doi: <http://dx.doi.org/10.1016/j.ijhydene.2012.10.090>

- Strathclyde. (2015). Demand Profile Generators. Retrieved 2015-08-14, from http://www.esru.strath.ac.uk/EandE/Web_sites/06-07/Carbon_neutral/tools%20folder/Demand%20Profile%20Generators.htm
- Su, W., & Wang, J. (2012). Energy Management Systems in Microgrid Operations. *The Electricity Journal*, 25(8), 45-60. doi: <http://dx.doi.org/10.1016/j.tej.2012.09.010>
- Swan, L. G., & Ugursal, V. I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13(8), 1819-1835. doi: <http://dx.doi.org/10.1016/j.rser.2008.09.033>
- Tesla Motors. (2015). PowerWall - Tesla home battery. Retrieved 2015-07-30, from <http://www.teslamotors.com/powerwall>
- Teslarati. (2014). Top 5 Tips to Maintaining EV Battery Life. *Don't leave your battery sit at a 100% state of charge*. Retrieved 2015-08-06, from <http://www.teslarati.com/top-5-tips-to-maintaining-ev-battery/>
- TFUE. (2007). *The Lisbon Treaty on the Functioning of the European Union*.: European Union.
- The World Bank. (2015). World Development Indicators: Power and communications, transmission and distribution losses. Retrieved 11-06-2015, from <http://wdi.worldbank.org/table/5.11>
- Times, L. A. (2015). 4 years after Fukushima, Japan considers restarting nuclear facilities. Retrieved 10-07-2015, from <http://www.latimes.com/world/asia/la-fg-japan-nuclear-20150330-story.html>
- TNO. (2006). Vaststellingsmethodieken voor CO₂-emissiefactoren van aardgas in Nederland (S. m. v. VROM, Trans.). In D. C. Heslinga & v. H. A.K. (Eds.), (Vol. 2006-A-R0079/B): TNO Apeldoorn.
- Tolkien, J. R. R. (1954). *Lord of the Rings: The Fellowship of the Ring*. UK: George Allen & Unwin.
- van der Schoor, T., & Scholtens, B. (2015). Power to the people: Local community initiatives and the transition to sustainable energy. *Renewable and Sustainable Energy Reviews*, 43, 666-675. doi: <http://dx.doi.org/10.1016/j.rser.2014.10.089>
- Vereniging eigen huis. (2015). Ontwikkeling huizenprijzen (Development in house prices) Retrieved 2015-08-26, from <https://www.eigenhuis.nl/woningmarkt/cijfers/huizenprijzen/>
- Walker, G. (2008). What are the barriers and incentives for community-owned means of energy production and use? *Energy Policy*, 36(12), 4401-4405. doi: <http://dx.doi.org/10.1016/j.enpol.2008.09.032>
- Wang, X., Hou, Y., Zhu, Y., Wu, Y., & Holze, R. (2013). An Aqueous Rechargeable Lithium Battery Using Coated Li Metal as Anode. *Scientific Reports*, 3, 1401. doi: 10.1038/srep01401
- <http://www.nature.com/articles/srep01401#supplementary-information>
- Wholesale Solar. (2015). Solar Panels from Wholesale Solar. Retrieved 2015-08-06, from <http://www.wholesalesolar.com/>
- Wilson, L. (2013). Shades of Green. In S. T. Footprint (Ed.), *Electric Cars' Carbon Emission Around the Globe: Shrink That Footprint*.
- WINEUR. (2006). Wind Energy Integration in the Urban Environment. *Techno Economic Report*.
- World Energy Council. (2013). World Energy Resources 2013 Survey. London, U.K.
- Yougen. (2015). Introduction to Combined Heat and Power. 2015, from <http://www.yougen.co.uk/renewable-energy/Combined+Heat+'26+Power/>
- Zhang, Z., Lohr, L., Escalante, C., & Wetzstein, M. (2010). Food versus fuel: What do prices tell us? *Energy Policy*, 38(1), 445-451. doi: <http://dx.doi.org/10.1016/j.enpol.2009.09.034>
- Zonnepanelen-Weetjes. (2015). Zonnepanelen: informatie en kosten. Retrieved 2015-08-06, from <http://www.zonnepanelen-weetjes.nl/>

Appendices

Appendix A System configuration vector - stored household parameters

vector	description	units
System number	the index of the randomly generated configuration	number
Household type	type of household (one, two adults, family or pensioners)	1,2,3,4
ICAP	Installed capacity solar PV	kW
S_Thermal_size	Configuration number solar thermal system	0,1,2,3,4
Boiler_size	size of thermal boiler for heat storage	litres
PeakShave_TH	indicate thermal storage uses peak shaving (1) or direct use (0)	0, 1 or NaN
windsystem	indicate wind turbine is installed (1) or not (0)	0 or 1
EV_init	indicate electric vehicle is installed (1) or not (0)	0 or 1
Battery_init	indicate battery is installed (1) or not (0)	0 or 1
PeakShave_B	indicate battery uses peak shaving (1) or direct use (0)	0, 1 or NaN
CHPorFC	indicates CHP is installed (1) of Fuel Cell is installed (0)	0 or 1
FC_Demand_E_leading	indicates Fuel Cell electricity demand (1) of heat demand (0) is leading	0,1 or NaN
CHP_size	Size of CHP unit in kW (heat)	kW
E_produced_day_GRID	Electricity demand from grid, shortage that could not be produced locally	kWh
kWh_price_E	average price per kWh electricity from household's production	€
kWh_price_H	average price per kWh heat from household's production	€
EA_H_weighted	Energy autonomy heat	%
EA_E_weighted	Energy autonomy electricity	%

Appendix B Individual household optimal system configurations

Household	One adults household	Two adults household	Family	Pensioner(s) or unemployed
Autonomy maximisation:	System 1A (56)	System 2A (124)	System 3A (219)	System 4A (371)
Carbon reduction:	System 1C (45)	System 2C (162)	System 3C (248)	System 4C (384)
Financial optimisation	System 1F (63)	System 2F (119)	System 3F (255)	System 4F (310)

One adult household	Base case	Energy autonomy optimisation	CO ₂ reduction	Financial optimisation
Household number	1	56	45	63
System code	1B	1A	1C	1F
Capital investment costs (€)	€ 8.000	€ 20.600	€ 51.400	€ 17.100
Annual energy revenues (€)	€ 0	€ 937	€ 1.366	€ 998
Net annual energy costs (€)	€ 1.019	€ 1.038	€ 2.609	€ 859
CO ₂ emission (kg per kWh)	0.289	0.239	0.094	0.244
Energy self-sufficiency rate	0%	100%	89%	90%

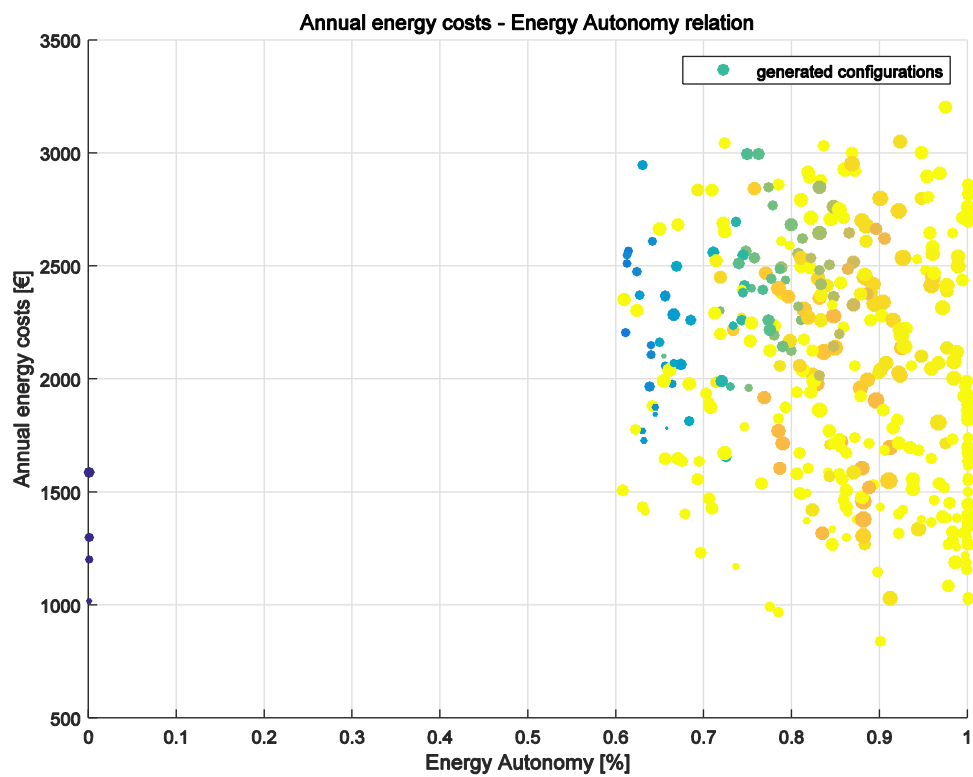
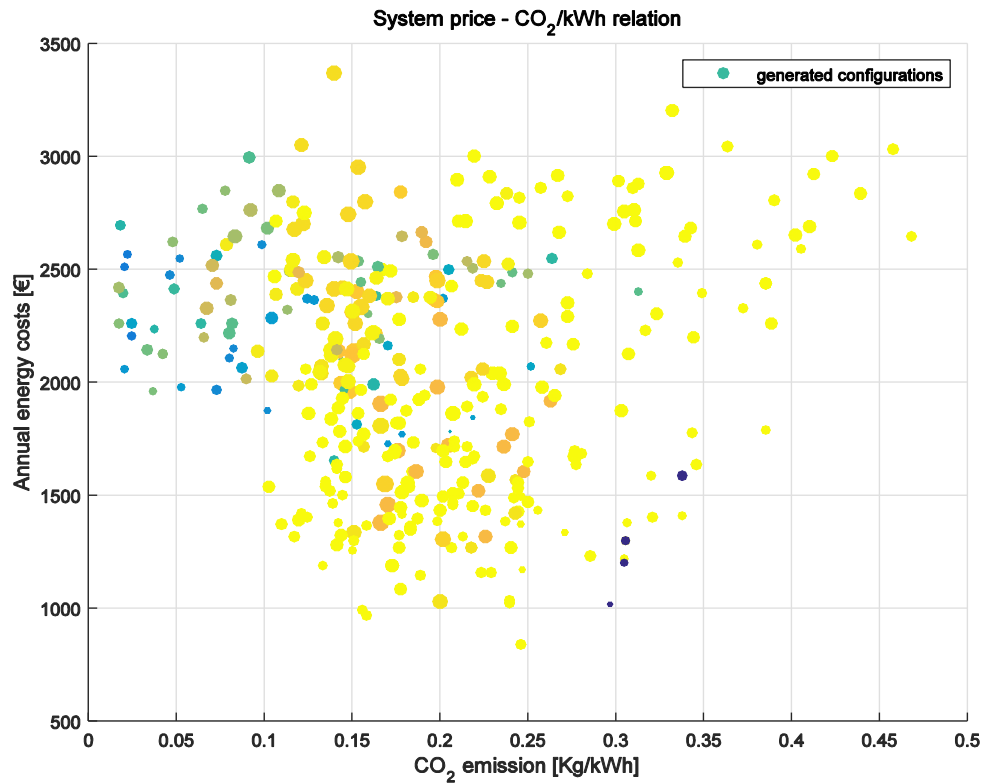
Two adult household	Base case	Energy autonomy optimisation	CO ₂ reduction	Financial optimisation
Household number	101	124	162	119
System code	2B	2A	2C	2F
Capital investment costs (€)	€ 8.000	€ 50.600	€ 52.400	€ 31.100
Annual energy revenues (€)	€ 0	€ 1618.7	€ 1.440	€ 1.714
Net annual energy costs (€)	€ 1.297	€ 2.699	€ 2.711	€ 1.315
CO ₂ emission (kg per kWh)	0.297	0.295	0.224	0.226
Energy self-sufficiency rate	0%	100%	100%	84 %

Family household	Base case	Energy autonomy optimisation	CO ₂ reduction	Financial optimisation
Household number	201	219	248	255
System code	3B	3A	3C	3F
Capital investment costs (€)	€ 8.000	€ 34.700	€ 38.000	€ 17.100
Annual energy revenues (€)	€ 0	€ 1.043	€ 924	€ 811
Net annual energy costs (€)	€ 1.590	€ 1.822	€ 1.863	€ 1.269
CO ₂ emission (kg per kWh)	0.333	0.176	0.132	0.239
Energy self-sufficiency rate	0 %	100 %	100 %	85 %

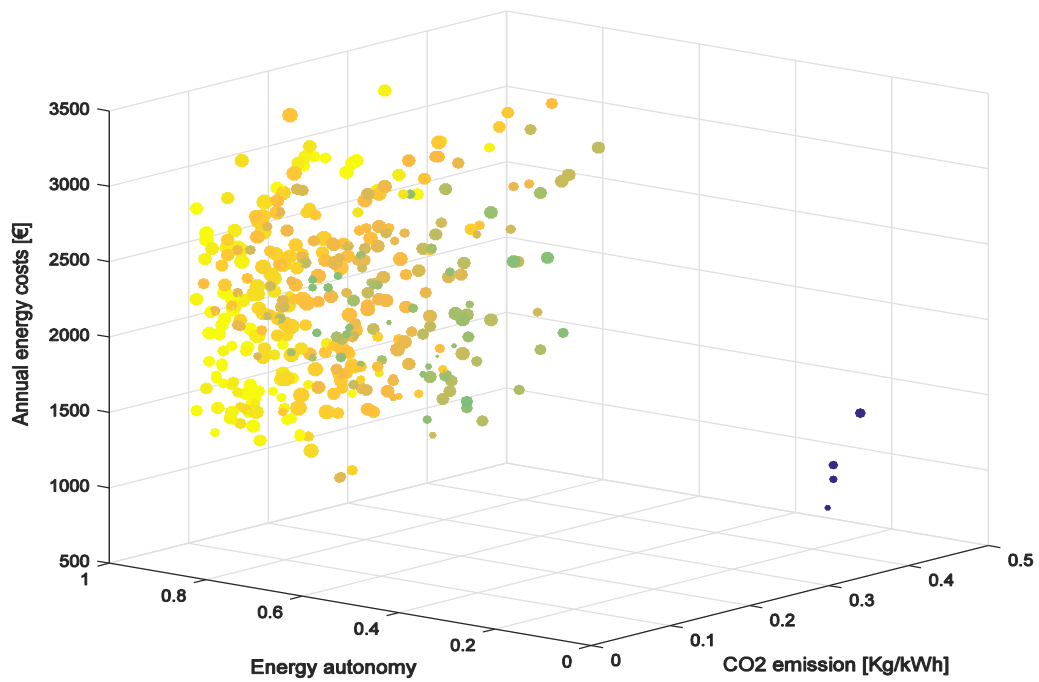
Pensioner household	Base case	Energy autonomy optimisation	CO ₂ reduction	Financial optimisation
Household number	301	371	384	310
System code	4B	4E	4C	4F
Capital investment costs (€)	€ 8.000	€ 20.300	€ 32.800	€ 19.200
Annual energy revenues (€)	€ 0	€ 838	€ 841	€ 610
Net annual energy costs (€)	€ 1.198	€ 1.160	€ 1.418	€ 1.148
CO ₂ emission (kg per kWh)	0.297	0.229	0.107	0.191
Energy self-sufficiency rate	0 %	100	97 %	90 %

Optimal technology mix per household type													
House hold type	Optimisation	System number	PV size [kW]	Thermal size [kW]	Boiler size [litres]	Thermal storage mode	Wind turbine	EV	Battery	CHP	FC	FC leading demand	CHP size
One	Autonomy	56	3.6						yes		yes	Heat	
One	CO ₂	45	1.8	5	300	Peakshave	yes			yes			2
One	Costs	63	3.6							yes			2
Two	Autonomy	124	3.6				yes		yes	yes			5
Two	CO ₂	162	2.4	2.5	100	Direct use	yes		yes	yes			5
Two	Costs	119	1.5								yes	Heat	
Fam	Autonomy	219	2.7				yes		yes	yes			2
Fam	CO ₂	248	3.0	2.5	100	Direct use	yes		yes	yes			2
Fam	Costs	255	3.6							yes			2
Pens	Autonomy	371	3.3						yes	yes			2
Pens	CO ₂	384	1.2	5	300	Direct use	yes			yes			2
Pens	Costs	310	2.7	2.5	100	Peakshave				yes			2

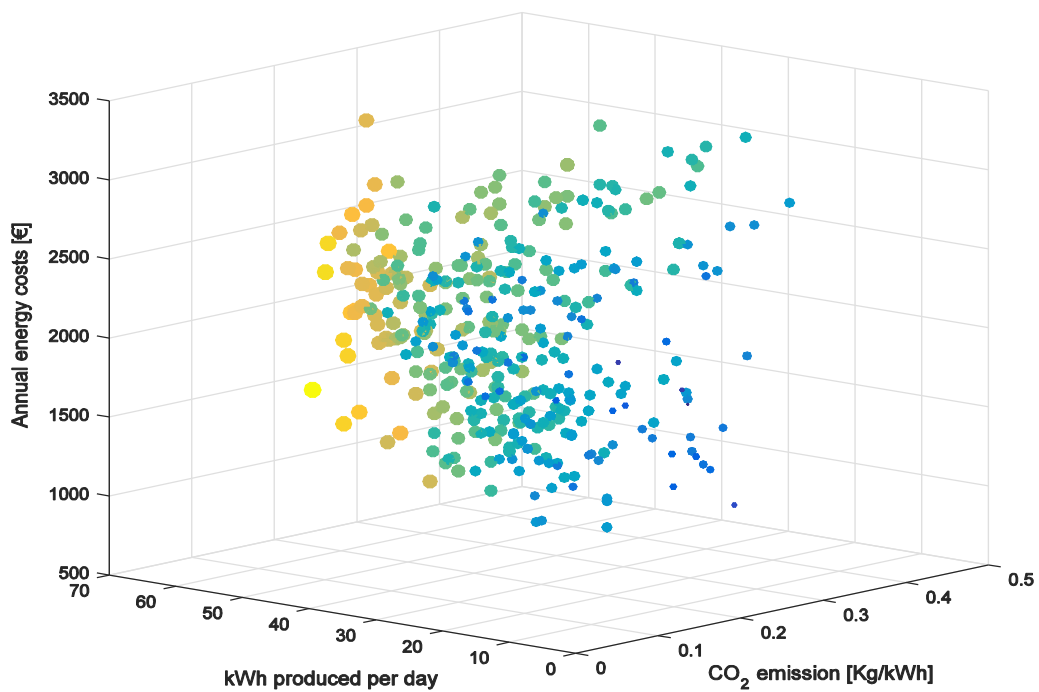
Appendix C Model details: all generated system characteristics



A larger marker indicates a larger installed capacity and more kWh being produced. The colour is an indication of heat autonomy. A yellow marker represents a configuration with a high energy autonomy and a blue marker represents a system with a low energy autonomy.



A larger marker indicates a larger installed capacity and more kWh being produced. The colour is an indication of heat autonomy. A yellow marker represents a configuration with a high energy autonomy and a blue marker represents a system with a low energy autonomy.



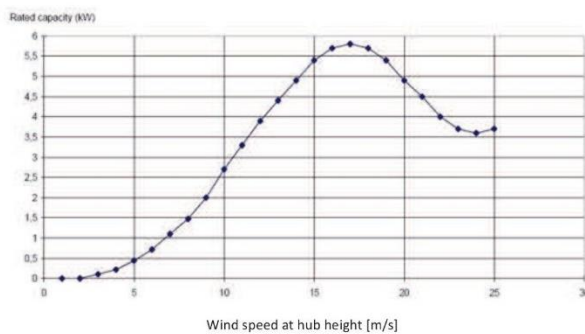
Both size and colour are a function of the kWh production per day. Large and yellow markers indicate a system that produces more kWh while small and blue markers indicate a system with less energy production.

Appendix D Fortis Montana Datasheet

Technical Specifications

Max. output	5800W
Output @ 11m/sec	3.4kW
Wind speed:	
cut in	2.5 m/sec.
rated	17m/sec.
survival	60 m/sec.
Rotor blades:	
number	3
diameter	5.0 m
area	19.63m ²
airfoil	E 387
tip speed ratio	7
material	glass-fibre reinforced epoxy
Generator:	
type	brushless permanent magnet 9-pole
RPM operation range	120 - 450
voltage	from 48 to 500VDC standard other voltages on request
frequency	0-70 Hz
Other:	
gearbox	none
braking mechanism	Automatic breaking switch
rotor speed control	Inclined hinged vane
output control	voltage control with dump load
rectifiers	built inside controller
hub type	rigid
yaw system	tail vane
rotor position	upwind
tower	guyed steel tubular (height: 12- 24m) free standing tube mast (height: 12 -24m)
Head weight	200 kg

Power Curve Montana & AEP*



*AEP
Annual Energy
Production

Appendix E LG Mono X Neon G3 300W Mono PV Module Datasheet



LG305N1C-B3 / LG300N1C-B3 / LG295N1C-B3

Mechanical Properties

Cells	6 x 10
Cell vendor	LG
Cell type	Monocrystalline
Cell dimensions	156.5 x 156.5 mm / 6 x 6 in
# of busbar	3
Dimensions (L x W x H)	1640 x 1000 x 35 mm 64.57 x 39.37 x 1.38 in
Static snow load	5400 Pa / 113 psf
Static wind load	2400 Pa / 50 psf
Weight	16.8 ± 0.5 kg / 36.96 ± 1.1 lb
Connector type	MC4 connector IP 67
Junction box	IP 67 with 3 bypass diodes
Length of cables	2 x 1000 mm / 2 x 39.37 in
Glass	High transmission tempered glass
Frame	Anodized aluminum

Certifications and Warranty

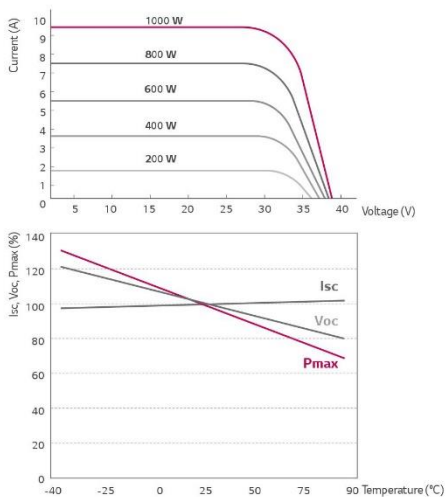
Certifications	IEC 61215, IEC 61730-1/-2, UL 1703, ISO 9001, IEC 61701, IEC 62716
Product warranty	10 years
Output warranty of Pmax (measurement Tolerance ± 3%)	Linear warranty*

* 1) 1st year: 98%, 2) After 2nd year: 0.7%p annual degradation, 3) 81.2% for 25 years

Temperature Coefficients

NOCT	45 ± 2 °C
Pmpp	-0.41 %/°C
Voc	-0.29 %/°C
Isc	0.04 %/°C

Characteristic Curves



Electrical Properties (STC*)

	305 W	300 W	295 W
MPP voltage (Vmpp)	32.1	32.0	31.8
MPP current (Impp)	9.52	9.40	9.28
Open circuit voltage (Voc)	40.0	39.8	39.7
Short circuit current (Isc)	10.1	9.98	9.85
Module efficiency (%)	18.6	18.3	18.0
Operating temperature (°C)	-40 ~ +90		
Maximum system voltage (V)	1000 (IEC), 600 (UL)		
Maximum series fuse rating (A)	20		
Power tolerance (%)	0 ~ +3		

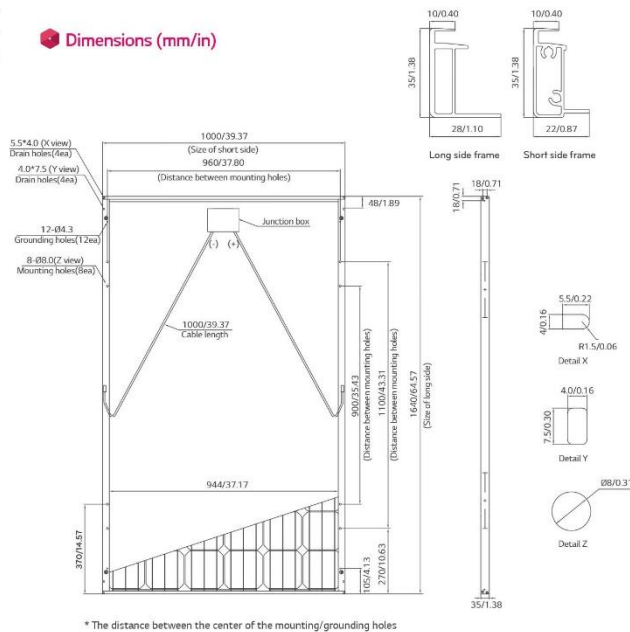
* STC (Standard Test Condition): Irradiance 1000 W/m²; module temperature 25 °C, AM 1.5
* The nameplate power output is measured and determined by LG Electronics at its sole and absolute discretion.

Electrical Properties (NOCT*)

	305 W	300 W	295 W
Maximum power (Pmpp)	223	220	215
MPP voltage (Vmpp)	29.4	29.3	29.1
MPP current (Impp)	7.59	7.50	7.40
Open circuit voltage (Voc)	37.0	36.9	36.8
Short circuit current (Isc)	8.14	8.05	7.94
Efficiency reduction (from 1000 W/m ² to 200 W/m ²)	< 2.0%		

* NOCT (Nominal Operating Cell Temperature): Irradiance 800 W/m²; ambient temperature 20 °C, wind speed 1 m/s

Dimensions (mm/in)



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Product specifications are subject to change without notice.
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