CHALMERS
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Foresight into emerging power system architectures

A scenario of maximised self-consumption in Sweden

Master's thesis within the Master's Programme Industrial Ecology

DANIEL BÖCKIN

EMILIA INGEMARSDOTTER

Department of Energy and Environment

Division of Environmental Systems Analysis

CHALMERS UNIVERSITY OF TECHNOLOGY

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DANIEL BÖCKIN, EMILIA INGEMARSDOTTER

Supervisor: Björn Sandén

Examiner: Björn Sandén

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Department of Energy and Environment

Division of Environmental Systems Analysis

Chalmers University of Technology

SE-412 96 Göteborg Sweden

Telephone + 46 (0)31-772 1000

Cover: Photograph of solar panel at Egen El's energy test park "Kullen" in Katrineholm, Sweden.

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Abstract

The purpose of this study is to investigate a future scenario with an increasingly distributed power system in Sweden, in order to add to the discussion on possible and desirable development paths for the Swedish energy system. A household completely self-sufficient in electricity and heating is visualised and its economic and technical properties assessed. The time scope reaches to 2050, up until which trend analysis for the cost of each system component is performed. By identifying key parameters for realising a self-sufficient residential energy system, and by applying long-term target values for each parameter simultaneously, perspectives of the future state can possibly be broadened.

A further purpose is to discuss the effects of an increasingly self-sufficient residential sector on the national energy system, and possible resulting system transitions. The analysis is performed through compiling data from various sources and through interviews with experts within the many fields of relevance for the study. The discussion is based on the application of transition theory onto the Swedish energy system and its actors.

A feasible self-sufficient household level energy system in 2050 is identified as constituted by PV modules (5 kW) as the main power source, lithium-ion batteries (10 kWh) for overnight storage, hydrogen for seasonal storage (1500 kWh), an electrolyser (1 kW) and a fuel cell (1 kW) for converting back and forth between electricity and hydrogen. The system design is based on a significant reduction in household electricity demand, to 3500 kWh annually.

Installation costs for such a system in 2050 are calculated to reach approximately 15 000 – 20 000 USD (120 000 – 170 000 SEK). The corresponding levelised cost of electricity is approximately 0.3 – 0.5 USD/kWh (2.5 – 4.2 SEK/kWh). The most significant uncertainty in the economic assessment is the cost of hydrogen storage.

The effects on the national energy system are discussed, along with the dynamics of a decentralised energy system, which are fundamentally different from those of the current system. Further efforts are made into understanding how customer preferences, policy measures and utility business models could affect the development.

Keywords: Renewable energy systems, prosumer, self-consumption, self-sufficiency, grid defection, distributed generation, decentralisation, PV, fuel cells, hydrogen storage, electrolysers, batteries.

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Abbreviations

AC	Alternate Current
CF	Capacity Factor
CHP	Combined heat and power
CO_2	Carbon dioxide
COP	Coefficient of Performance
DC	Direct Current
DER	Distributed energy resources
DG	Distributed Generation
DHW	Domestic Hot Water
ENE-Farm	Subsidy system for fuel cells in Japan
ES	Energy storage
EV	Electric Vehicle
FC	Fuel Cell
H_2	Hydrogen gas
HPE	High pressure electrolysis
IEA	International Energy Agency
kWh_e	Kilo-watt-hours electrical energy
kWh_{th}	Kilo-watt-hours thermal energy
LCOE	Levelised cost of electricity
MH	Metal hydride
NCD	Net consumption day
NPD	Net production day
PEMFC	Proton Exchange Membrane Fuel Cell
PV	Photovoltaic
RES	Renewable energy sources
RIC-E	Reciprocating Internal Combustion Engine
SC	Self-consumption
SOEC	Solid Oxide Electrolyser
SOFC	Solid Oxide Fuel Cell
USDOE	US Department of Energy

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1 Introduction

1.1 Background

Present electricity systems are facing significant transformation, largely due to changes in electricity demand patterns and the spread of small-scale, distributed power generation (DG). One of the most studied scenarios is that of a "smart grid", which uses information technology among other things to achieve a reliable and efficient large-scale grid where DG can be integrated. Another scenario points to the declining importance of the grid in a future where electricity can be produced as well as stored locally thanks to lower costs of e.g. photovoltaic solar panels (PV) and batteries.

Solar PV has experienced a remarkable decline in prices during recent years and is already competitive without subsidies, in many parts of the world. Furthermore, storage technologies are developing quickly and several countries are now enacting regulations favouring energy storage. Storing energy closer to the site of consumption can increase the efficiency in energy usage as well as allowing for a greater amount of self-production and self-consumption (SC). Combining local production and storage has the potential of being a game changer for households since it allows for self-consumption, i.e. allowing the prosumer to use a larger share of the power produced within the household limits, thereby reducing grid dependence. The dynamics of DG differ from that of large scale centralised production since installations are fast and pay off relatively soon. This means that a transition can happen rapidly and largely independent from utility companies' plans and projections.

Simultaneously, the grid infrastructure faces large future investment needs because of ageing technology as well as new requirements from renewable energy integration and larger variations in production and demand. SC and local storage of electricity would mean lower reinforcement requirements on the grid network and thereby allow for higher penetration of renewable electricity, which, without energy storage, would cause increased strain on the grid. Costs savings from reduced reinforcement requirements and smaller transmission losses can drive the system towards more local production and storage. However, increased SC also means reduced income for utilities. Since electricity tariffs are based on kWh used, revenues decrease as consumers need less electricity from the grid. This is a complex issue where the question of “grid value” becomes increasingly important. The value that the customer experiences from a grid connection determines his or her tendency to stay loyal to the system or to favour maximised independency. The value that a distributed power source or a local storage package adds to the grid, from the utility perspective, largely determines to what extent utilities are willing to adapt to or promote such installations.

There is a potential conflict in interests regarding SC between personal benefit and system optimisation. Even though continued development of renewables in the energy system is favoured in principle by most parties, there is a point of disagreement as to which system architecture is optimal. If customers and utilities found a way to simultaneously benefit from increased DG integration, deployment could take off rapidly. Thus one challenge is to design pricing structures and utility business models that allow for this. If shared value cannot be created, customers will try to maximise SC by means of increased generation and storage combined with enhanced energy efficiency. In the extreme case, customers could strive for total independence from the grid system and a fully self-sufficient residential energy system.

Conditions for DG vary significantly between countries, depending on factors such as climate, current status of the grid infrastructure, electricity prices and customer energy demand. Efficiency measures and development in the area of construction and design are also likely to affect the conditions in the energy system, especially changing the amount of energy needed for heating and cooling of buildings.

Recent studies have discussed the consequences of the decreasing costs of becoming completely self-sufficient in energy. The technology used in such a system would depend on the requirements and local conditions. In the case of Sweden, where climate as well as demand varies strongly between seasons, a self-sufficient residential energy system would require larger complexity than a comparable system in a country with large amounts of sunshine and small seasonal variations. The cost of a self-sufficient household in Sweden today is likely very large. With time however, price development, technology advancements and energy efficiency measures might make the option more feasible. In addition, households and services make up roughly half of the electricity consumption in Sweden, which implies that changing demand patterns for this user group could have an important effect on the larger energy system. It is thus relevant to study the probability of the development of increased SC and its effects on the energy system.

1.2 Purpose

The purpose of this study is to investigate what an increasingly distributed power system in Sweden could look like. By hypothesising the extreme case where Swedish households are totally self-sufficient in electricity and heating, the thesis is meant to demonstrate a possible self-sufficient Swedish residential energy system and to discuss its feasibility. Using trend analysis for potential small-scale production and storage technologies, as well as for demand profiles, the technical and economic dimensions of a self-sufficient residential power and heat supply in Sweden can be assessed, from today until the year 2050.

Additionally, the purpose of this thesis is to study how the emergence of increasingly independent households would affect the larger energy system and its actors. By analysing key factors and resulting consequences in the transition towards increased self-consumption of energy, the thesis can add to the discussion of the future for the Swedish power system.

1.3 Research questions

This study will seek to answer the following research questions:

RQ1. What does a Swedish household's energy demand look like today and what potential for energy efficiency is there?

RQ2. What DG technologies are available and which are more suitable on the residential level?

RQ3. How will the cost of the residential level distributed technologies develop over time?

RQ4. How can these DG technologies be combined into a self-sufficient residential energy system and what would it cost today and in the future?

RQ5. How would a transition to more self-sufficient households affect the larger Swedish energy system and its actors?

1.4 Scope and Limitations

The general approach of the study is to investigate how many simultaneous developments in technology, price and consumption patterns can shape what we consider feasible, realistic or even profitable. One by one, the development trends cannot change the system significantly. When combined, however, the result might be further away from what we see as the current reality.

The study investigates a self-sufficient residential energy system. As defined in this study, self-sufficiency requires that dedicated energy carriers cannot be imported to the system, be it in the form of heat, fuel or electricity. Imported matter in the form of water (unheated), food or other consumption products, can pass the system boundary without violating the requirement of self-sufficiency.

Furthermore, the analysis mainly concerns the Swedish electricity system but includes outlooks to and comparisons with the European as well as global systems. Focus will lie with the consumers and small-scale producers, often termed “prosumers”. In the extreme case visualised here, there is no large-scale central production, thus economics or policies for such businesses will not be considered in depth. Moreover, the study starts from the perspective of the end customer. Economic estimations and investment calculations are made for the end customer and do not include system related costs other than in qualitative discussions. The study only deals with single family houses and has thereby excluded categories such as multifamily buildings and commercial energy consumers. A future scenario, about 30 years from now (i.e. around 2050) is considered as well as, to some extent, the development from today up until the future state.

1.5 Report structure

The outline of this report can be summarised as having two main parts: one quantitative investigation of the reasonability of a self-sufficient residential energy system in Sweden, and a following qualitative discussion on the impacts that increased self-consumption could have on the larger energy system. The quantitative part includes an analysis of demand patterns and demand reduction potential, monitoring and selection of relevant technologies, trend analysis for costs of the selected technologies, as well as a section describing the system modelling. Results for the quantitative part of the study are presented and used as a basis for the extended qualitative discussion on implications for the energy system, presented in the final part of the report.

2 Theory

This study looks at a future scenario, and consequently includes forecasts. The forecasting literature is extensive, and only a brief introduction is given here. The theory presented aims at highlighting important aspects to consider when performing future studies, as well as common pitfalls to avoid. The forecasting theory forms a basis on which the methodological structure for this study has been built. Additionally, several calculations performed within the study require knowledge of basic economic measures in the field of power generation, presented below.

2.1 Forecasting theory

A range of methods exists as attempts to formalise socio-technical future studies. Examples of such tools are trend extrapolation and curve fitting, computer modelling, cross impact analysis, Delphi methods e.tc. (Elzen et al., 2002). However, Elzen et al. (2002) state that each of these methods suffers from fundamental problems, some of which are presented below.

Coates (1989) points out an exaggerated focus on quantitative predictions in foresight, at the expense of qualitative aspects such as judgemental factors and stakeholder positions. He sees communication, delivery of information and effective investigation of complexity and assumptions as potentially more valuable than exactness in quantitative forecasts.

Further, Sapio (1995) states that forecasting is frequently carried out as extrapolations from an initial state, which often implies a focus on incremental rather than radical change. The same author stresses that it is necessary to combine quantitative and qualitative factors in scenario analysis, in order to allow for direct application in decision making while still allowing for real world complexity. Sapio (1995) suggests the inclusion of a quantitative central core in a qualitative framework in order to maintain contact with the general context of the problem as well as obtaining specific forecasts of future variables.

Elzen et al. (2002) also identify that forecasting methods often suffer from a too narrow study range. If a very specific topic is investigated, and the systems perspective is left out, the forecasts are of no use. Furthermore, trend analysis is often performed for specific technologies independently, without considering parallel trajectories that can reinforce or stabilize change. Pistorius and Utterback (1997) conclude that technologies influence each other via multi-mode interaction including pure competition, symbiosis and predator-prey interaction. One example of a predator-prey relationship can be an emerging technology, which enters the market on a platform that is enabled by the mature technology. From that platform, the new technology steals market shares and negatively influences growth rates for the old one. In this case the emerging technology affects the mature technology negatively while the mature technology reversely has a positive effect on the emerging technology. Moreover, the interaction can change over time, adding more complexity.

To cope with the above-mentioned problems, Elzen et al. (2002) suggest that more qualitative elements should be included in the analysis, even if this makes the methods "looser". Actor strategies, social networks and learning processes should all be considered. Focus should also be more on radical change. When attempting future studies, one should also use a broad systemic view where different modes of technology interaction are included. Additionally, the study should not neglect the fact that user preferences are not fixed but changing, and influenced by factors such as policy, culture and infrastructure. Finally, the method should include the interaction between actor groups and not only depend on macro-scale factors.

With this in mind, this study has been set up to have two main parts: one quantitative investigation of the reasonability of a self-sufficient household in Sweden, and one qualitative discussion about the impacts that increased self-consumption might have on the larger energy system and its actors. Many technologies are monitored in parallel, allowing for a systems perspective including interaction between development paths. Also, by identifying key parameters and pushing each of these to its reasonable limit – an attempt is done to open up the perspective to include not only incremental but radical system changes.

2.2 Economics of power generation

2.2.1 Net Present Value[1]

The net present value (NPV) of an investment is a measure of the sum of all revenues and costs that will occur during a set period of time, corrected based on the concept that one dollar or unit of utility is worth less to us in the future compared to today. If NPV>0 for an investment, the investment will generate value for the investor and should be considered a good option from an economic perspective.

Mathematically, the NPV can be defined as

$$NPV(T,r) = \sum_{0}^{T} \frac{R_t}{(1+r)^t}$$

Where T is the time over which the net present value should be calculated, representing the lifetime of the investment, R_t is the revenue from the investment (negative if it is a cost) and r is the so-called *discount rate*.

The principle of *discounting* is based on the time value of money, namely the concept that one dollar or unit of utility is worth more today than tomorrow. If a person, company or government are to calculate the NPV of future income or production, then the discount rate is the interest rate at which future costs and benefits are discounted in comparison with present costs and benefits. An alternate definition regards the interest rate at which national financial institutions can borrow from the central bank, but when used throughout the study, discounting refers to the former definition.

The higher the discount rate the lower the value of future income. The specific value of the discount rate can be set as the rate of return which one at least expects to get when making alternative investments (i.e. opportunity cost). Another approach is to use the social rate of time preference. Since people expect to be richer in the future it is better to have money now when we are not so rich. This idea, coupled with impatience and uncertainty, means that people would rather receive a certain amount of money today than next year. Furthermore the actual discount rate of a consumer is dependent on his or her personal judgment and level of risk aversion.

2.2.2 Levelised cost of electricity (LCOE)[1]

The Levelised cost of electricity (LCOE) is defined in this study as the sum of yearly costs (for all years of the system lifetime) including operation and maintenance costs, fuel costs and replacement costs as well as the discounted investment cost, divided by useful energy consumed during the same period of time. In mathematical terms it can be defined as

$$LCOE = \frac{C_{O\&M} + \frac{C_f}{\eta} + C_I \cdot T \cdot CRF}{T \cdot D_a}$$

where $C_{O\&M}$ is operation and maintenance costs [USD], C_f are the fuel costs [USD], η is the conversion efficiency, C_I is the investment cost [USD], T is the system lifetime [years], D_a is the annual useful energy consumed [kWh] and CRF is the capital recovery factor, defined as

$$CRF = \frac{r}{1-(1+r)^{-T}}$$

[1] All information in this section has been collected from Azar (2013).

where r is the discount rate.

The LCOE [$/kWh] is a useful measure in that it can be directly compared with the cost to sell or buy electricity from the grid.

2.2.3 Payback time

The payback time of a power-producing unit can have two separate meanings, one in terms of energy and the other in terms of economics. The former illustrates the time it takes before the unit has produced the same amount of useful energy that went into producing, transporting and installing it (Sandén and Arvesen, 2015). In other words it is the time before it has produced a net positive amount of useful energy. This is not the meaning that will be assigned to the payback time in this study.

Rather it is the payback time in economic terms that will be used. In the case of a grid-connected power-producing unit this is the time when the income from selling the produced electricity equals the investment cost of the unit (Investopedia, 2015). In the case of an off-grid system there is no selling of electricity (only local use) and thus no actual income. Instead, what serves as the "income" is the electricity costs avoided by meeting the local demand on-site.

3 Method

The study includes several consecutive analysis steps, described in detail below, with the aim to identify suitable technologies to use, to design and dimension the system and to estimate its future cost. After monitoring potential system components and electing the most relevant ones, trend analysis is performed for the selected technologies. With the aim of enabling the reader to imagine a radically different system that could potentially appear with parallel development on many fronts, forecasts of all key parameters have been stretched to ambitious yet substantiated levels.

Complementing the quantitative analysis is a qualitative investigation regarding the impact of increased self-sufficiency on the larger energy system and its actors. The qualitative discussion includes factors such as policy, culture and actor strategies, thus widening the technological viewpoint to include the dynamics of socio-technical change and transition dynamics. The general approach of the study has been to gather enough data to make "educated estimates" of magnitudes for all key parameters. No figure given in this study is to be read as an exact finding - but as a pointer to a reasonable size of a quantity. This approach makes the study a rough conceptual model rather than an accurate representation of any specific system, and it is therefore less sensitive to changes in specific system circumstances.

Data gathering for this study has mainly been achieved through literature studies. In addition, informal interviews with technology experts and energy systems stakeholders have been carried out in order to anchor hypotheses and key concepts. Literature studies have not been limited to a specific field, but explored many possible fields of research and industry.

Residential energy demand

As a first step, average energy patterns for Swedish customers today are investigated. The amount of energy needed, the costs that the customers face in order to obtain the energy as well as what useful services the energy would bring, is clarified.

Demand patterns for a single-family house in the future are estimated. Starting from today's demand, calculations of possible energy savings are performed. Potential efficiency measures are based on state of the art technology available today combined with a few additional future improvement estimations made together with experts. Note that focus in this section is on what efficiency measures are feasible, and that no time scale is assumed in the development towards reduced demand patterns.

Thereafter, estimates for realistic production and storage capacity in the residential setting are performed in order to identify limits for what system size and weight can be reasonable. Limits are based on available roof area for a standard house, as well as a reasonable estimate on spare volume that could be available in a cellar, garage or similar space. When assessing reasonable values for system weight and volume, numbers are compared to alternative residential energy systems widely used.

Technology Monitoring and Selection

Based on the estimated demand patterns, possible technological combinations for year-round self-sufficiency in Sweden are assessed. The technologies are divided into *local energy harnessing, energy storage systems, energy conversion to storage,* and *energy conversion from storage*. Aspects such as cost, size, weight, technology maturity level, development potential and efficiency are investigated and compared to the system limitations already identified. Many possible technologies are monitored, whereupon the most suitable technologies are selected and assessed further.

Market Status and Trends

Trend analysis is performed for the selected technologies regarding technology maturity and price development. In this section, the aim is to obtain time series for cost development for each selected technology. These data sets are interpolated to form piecewise linear price development curves over time. The cost estimates used for each technology and year consists of the averaged values of all interpolated data sets gathered for the respective technology. The trend analysis is built on historical data sets as well as forecasts, all collected from external sources. For some technologies, no time dependent cost data could be found. However, ultimate price projections and targets without specific time indication are used for estimating a range of possible future prices. It should be clarified that within the trend analysis, forecasts are based on external data. Except for the identification of reliable data sources and, in a few cases, the estimation of reasonable data ranges, the authors perform no cost forecasts.

System modelling, design and cost

Through modelling, the combination of technologies needed as well as the price optimal system dimensions are estimated for a given energy consumption pattern and a given price development level.

The total system price is determined by development in the household energy demand and cost for the respective technology. Both dimensions are important for the total outcome and can develop independently of each other. Starting from an initial state, where demand and cost levels compare to today's values, three cases of future potential development are identified.

1. Cost improvement case
2. Reduced demand case
3. Combined improvement case (improvement in price as well as reduced demand)

Cost estimations for the fully self-sufficient system are made based on demand levels and the respective price development estimates for each technology. Different cost measures are considered. Firstly the upfront *investment cost* is used, which is an important measure for private customers. Replacement costs and reinvestments are included when calculating the upfront investment costs, by adding their NPV. Secondly the *payback time* is calculated, though it is directly dependent on future avoided electricity costs and hence difficult to predict accurately. Lastly the *LCOE* is used, which enables an easy comparison to electricity prices, though it depends strongly on the discount rate, which is not commonly used by private consumers when assessing profitability.

Sensitivity analysis is performed in order to show the sensitivity of the results to different parameters. As a means of roughly assessing the impact of the technology selection process, two variations in system design are investigated. The cost savings realised by these alternative solutions are then estimated.

Implications for the energy system transformation

In an extended discussion section a qualitative analysis is performed in order to understand how the national energy system could be affected, should the scenario of self-sufficiency be fulfilled. The analysis is based on transition-theory, which enables an understanding of the probability as well as the consequences of a system transition.

4 Residential energy demand

This section details the residential energy system in Sweden, where the annual demand in the current residential energy sector is first shown, followed by descriptions of seasonal and diurnal demand variations. The aim is to estimate the electricity demand of an average Swedish household, as well as future demand reduction potential. Additionally, physical limitations of an average residential energy system are identified that will eventually be used as input data to the feasibility assessment of different technology options in terms of size and weight. Finally an attempt is made to estimate the energy related costs that customers are currently facing.

4.1 Present annual demand

A household uses energy to perform various everyday activities. Firstly, there is a need to regulate temperature in the building. In Sweden this requirement is dominated by heating the air in the building to a comfortable indoor climate. In other parts of the world, cooling can be the dominant temperature regulation capability. The part of the energy demand used for heating the air in the building is throughout this report termed *space heating*.

In addition to space heating there is also a need for heating water, for showering, dishwashing and similar activities. The hot water that is consumed in the household is here termed *domestic hot water (DHW)*.

Finally, there is a need for electricity to be used directly in electric appliances. These can be refrigerators and washing machines - but also computers, microwave ovens, cooking stoves etc. The electricity needed for running these kinds of appliances is here termed *household electricity*.

Note that the demand for space heating and DHW can be supplied by water (waterborne electric heating), by electricity through electric heating of air (direct electric heating) or by using a heat pump that efficiently uses electrical energy to transfer heat from a reservoir into a room. Heat can also be supplied by solar heating or directly as thermal energy, e.g. via a district heating system or from burning of fuel or biomass. In order to distinguish between energy in the form of heat and electricity, the energy form in question is within this report denoted by indexing, i.e. by using kWh_{th} as the unit for *thermal energy* and kWh_e as the unit for *electrical energy*.

4.1.1 Space heating

Space heating demand in single-family houses varies significantly based on consumption patterns, building standards and the heat system installed. According to the Swedish Energy Agency (Energimyndigheten, 2015a), the average yearly energy demand for space heating was 12 200 kWh_{th}/year.

The corresponding electricity demand for space heating is directly dependent on the heating system installed. A direct electric heating system would require 12 200 kWh_e to supply the 12 200 kWh_{th} whereas with a heat pump installed, the electricity demand for heating could be reduced to a fraction of the thermal demand depending on the efficiency of the heat pump. If instead district heating were used as the heat source in a single-family house, there would be no electricity need for heating at all. However, in this study, district heating will not be considered an option since it does not allow for self-sufficiency of energy.

There is a range of heating technologies used in Swedish single-family buildings today. According to Energimyndigheten (2013), 2 % of the single-family households used solely district heating in 2013 while 25% used direct electric heating or waterborne electric heating and 25% used heat pump systems. The remainder of the households used combinations of the technologies, sometimes also in combination with biomass burning. Thus there is a large variety in electricity use for different households. In this study, an *average* yearly electricity use for heating in Swedish households of approximately 8600 kWh_e has been assumed, based on Widén (2014). Widén (2014) in turn bases this result on data categorised into costumer groups from the Swedish Energy Agency end-use metering campaign for Swedish households in 2009 (Zimmermann, 2009).

4.1.2 Domestic hot water

The demand for DHW in a household depends strongly on the number of people in the household, as well as their lifestyles. According to the Swedish Energy Agency, the average yearly energy use for heating DHW in Swedish households in 2013 was 4500 kWh_{th} (Energimyndigheten, 2015). The electricity demand analogous to this is contingent on the installed heating system. Electric heating of water would require 4500 kWh_e, while a heat pump system could lower this to a fraction of the thermal demand depending on the efficiency of the heat pump. Similarly as for space heating, district heating of DHW will not be considered in this study.

Apart from lifestyle changes, energy efficient technologies in showers, dishwashers and other appliances can reduce the demand for DHW. Heat recovery can be used to reuse the heat in the wastewater before it leaves the house. According to Blomsterberg (2015), there are some technologies available on the Swedish market that can recover heat from showers, pipes and drains. However, these technologies are not yet widely spread, mainly because of uncertainties in efficiency and profitability. The theoretical potential for energy saved from heat recovery systems, as reported by Blomsterberg (2015), is 40 % of current thermal energy used for DHW.

4.1.3 Household electricity

According to the Swedish Energy Agency, the average energy use for household electricity in Swedish households in 2013 was 6000 kWh_e/yr (Energimyndigheten, 2015). Widén (2014) reports the average yearly household electricity demand to be 4350-6000 kWh_e (see numbers presented in Table 1). Consequently the rough average value of 5000 kWh_e will be used as the initial case of household electricity demand.

Table 1: Summary of data points for average energy use, space heating (SH), domestic hot water (DHW) and household electricity (HE), in Swedish single family households today.

	Total SH demand [kWh_{th} m^2]	DHW demand [kWh_{th}/yr]	Total SH demand [kWh_e/ m^2]	HE demand [kWh_e/yr]	Total elec. consumption [kWh_e/yr]
Widén (2014)	-	-	8600*	4350-6000	14500
Energimyndigheten (2015a)	12200	4500	-	6000	-

*Including DHW.

4.2 Seasonal variations in demand

Demand for *heating* varies significantly with climate. In a country with strong seasonal variations, like Sweden, the heating demand thus has a periodic pattern following the seasons. Heating demand will be highest in the cold winter season, and smallest in summer.

From Zimmermann (2009), the seasonal heating demand relative to the total yearly heating demand (space heating and DHW) is estimated to vary according to the values given in Table 2.

For *household electricity* demand the seasonal dependency of demand is not as clear. Many activities that require electricity, such as cooking or computer usage, do not necessarily follow any seasonal patterns. However, Zimmermann (2009) does present some seasonal variations in household electricity consumption. There seems to be an increase in demand for lighting, cooking, and TV usage during the winter months, while cold appliances like fridges and freezers consume somewhat more energy during the summer.

Table 2: Relative heat demand (space heating and DHW) per season of the year as compared to yearly heat demand. Numbers are based on Zimmerman (2009) [Figure 2.448].

Season	Relative energy demand for heating, as percentage of yearly heat demand [%]
Winter (November - February)	55
Spring (March - April)	20
Summer (May - August)	5
Autumn (September – October)	20

In Table 3, these variations are presented. Moreover an estimate is made for the energy consumption of the different appliances in 2050, to give an indication of the relative contribution to total household electricity demand from the seasonal variations. It can be seen in Table 3 that the variations are small compared to the total yearly demand for household electricity (17 kWh_e compared to thousands of kWh_e in yearly demand). Seasonal variations in demand for household electricity are therefore neglected.

Note that all numbers given in Table 3 are estimated, and only meant to give an indication of the relative impact of the seasonal variations compared to the total electricity consumption.

Table 3: The seasonal variation in electricity use for different types of appliances, together with the estimated impact on the annual energy demand of the household.

	Present annual consumption [kWh_e]	Estimated annual consumption 2050 [kWh_e]	Average seasonal consumption 2050 [kWh_e]	Seasonal variation (%)	Estimated winter consumption [kWh_e]	Compared to average [kWh_e]
Lighting	750	150*	40	± 10 %	44	+ 4
Cooking stove	300	150**	40	± 20 %	48	+ 8
TV	300	150**	40	± 20%	48	+ 8
Fridge/ Freezer	200	100**	25	± 10 %	22	- 3
Total	1550	550	145		162	+ 17

*Assuming LED lighting is approximately 5 times more efficient in 2050.

** Assuming doubled efficiency in 2050.

Assuming a sinusoidal shape in seasonal heat demand, following the relative demand contributions per season as presented in Table 2, and a seasonally independent household electricity demand, the shape of the total annual demand curve for a household can be estimated as presented in Figure 1. Note that Figure 1 only gives an indication of the shape of the demand curve and does not display specific demand values.

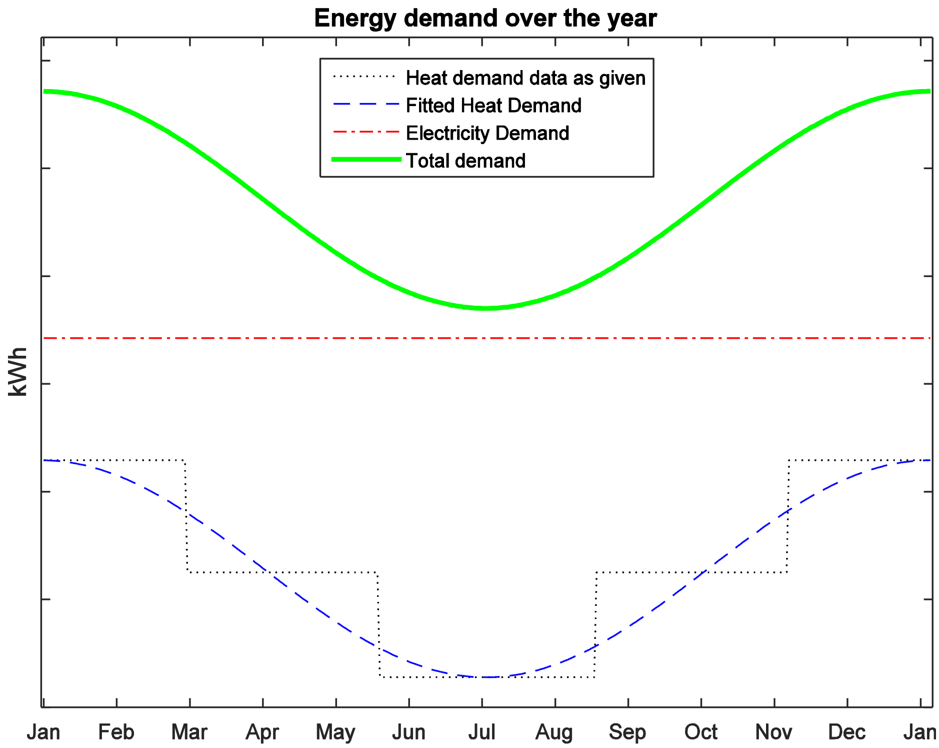

Figure 1: Seasonal variations in heating demand and household electricity demand, as modelled based on approximations of data.

4.3 Daily variations and power requirements

Peak power demand differs considerably between households. The average maximum value given by the Swedish Energy Agency is approximately 6 kW with direct electric heating and 4 kW without (Zimmermann, 2009).

Peaks in electricity at the household level can be managed by scheduling appliances to run at different times of the day. When a house is detached from the power system and all the energy is managed in isolation, it has been deemed likely that there is a natural change in behaviour towards "peak shaving", i.e. that the power demand required by the system is relatively smooth and without unnecessary peak values. The main effect of this is averting considerable over-dimensioning of the electricity system, only to handle large peaks during a few minutes every day. According to Widén (2014) there is evidence that households spontaneously increase energy awareness and decrease electricity consumption after a PV installation. This effect is likely to appear after the installation of other types of technologies that increase self-consumption as well.

With increasingly "smart" appliances that can be controlled and scheduled easily, it is estimated in this study that the peak maximum power value needed is lower than 4 kW, which is today's average maximum power value found for households without direct electric heating. Analysis will therefore be based on a required maximum power value of 3kW.

4.4 Potential for demand reduction

In order to estimate the requirements on the future self-sufficient residential energy system, it is necessary to analyse the potential for demand reduction. The cost of the system will of course depend on the dimensions of each component, and some technologies might even become impractical to use if the system must support too high a consumption level. Here follows a list of steps and assumptions based on which households could reduce demand from the present level down to an anticipated future state.

As previously stated, the largest share (12000 kWh_{th}) of the energy consumed at the household level is currently dedicated to *space heating*, where significant energy efficiency potential is noted. If all households were to use a state of the art heat pump, the average electrical energy demand for space heating would be approximately 3000 kWh_e/yr compared to 12000 kWh_e with direct electric heating (a COP value of 4 is assumed for the heat pump, see Section 5.1.5 for details). Using the heat pump for heating the DHW as well, the average electrical energy demand for DHW would be approximately 1250 kWh_e/yr compared to 5000 kWh_e with direct electric heating. The total electrical demand for heating would then sum up to roughly 5000 kWh_e. The demand for household electricity would remain unchanged at 5000 kWh_e (see Section 4.1.3), making the total annual demand 9250 kWh_e.

➔ **If all households installed well performing heat pumps, average yearly electricity demand could be reduced to 9250 kWh_e.**

Furthermore the thermal energy demand for *space heating* can be reduced substantially by using best practices for construction and design. International Passive House Standards for space heating dictate a maximum of 15 kWh_{th}/m^2yr (Feist, 2007). That would mean a thermal energy demand for space heating of approximately 2000 kWh_{th} per year in an average single family house of 150 m^2 (assuming 3 million heated square meters in 2 million single family houses in Sweden, according to Energimyndigheten, 2013), compared to the present 12 000 kWh_{th}.

The corresponding electricity consumption for space heating would be around 500 kWh_e (again, a COP value of 4 is assumed for the heat pump, see Section 5.1.5 for details). Using passive house standards combined with a heat pump, the total electricity demand for space heating and DHW could thus be reduced to 1750 kWh_e per year, whereof 500 kWh_e are for space heating and 1250 kWh_e for DHW.

➔ **Passive house standards for buildings and state of art heat pumps could reduce electricity demand to 6750 kWh_e.**

Moreover, heat from *DHW* can be recovered in so called spill water heat exchangers, thereby reducing energy demand. Blomsterberg (2015) estimates that a combination of heat exchange solutions could potentially reduce the heat demand in Swedish buildings today by 40 %. Under the slightly more ambitious assumption that the DHW heating demand is cut by 60 % in the self-sufficient system, the electricity use becomes approximately 500 kWh_e instead of 1250 kWh_e (note that this reduction could also be achieved by using a more efficient heat pump). The total electricity use for heating would then be approximately 1000 kWh_e, 500 kWh_e of which is used for space heating and 500 kWh_e for DHW.

➔ **Spill water heat exchangers, passive house standards, and state of the art heat pumps could reduce electricity demand to 6000 kWh_e.**

There are many uncertainties in how the demand for *household electricity* will develop over time, until 2050. On the one hand, technology improvements increase efficiency in many appliances (see Table 3) and the need for electricity is thereby reduced. On the other hand, the number of appliances in a household is likely to increase as our lifestyles adapt to further digitalisation and technology innovation, and the electricity demand could therefore rise. Under the assumption that the household electricity consumption can be cut in half by efficiency measures, the demand for household electricity could be reduced from 5000 kWh_e to 2500 kWh_e.

➔ **Spill water heat exchangers, passive house standards, state of the art heat pumps, and efficiency improvements for appliances could reduce electricity demand to 3500 kWh$_e$.**

Resulting estimates for demand reduction capacities can be seen in Table 4 and Figure 2 below. Seasonal variations are calculated based on the heating demand variation given above, and an average electricity use that is constant throughout the year.

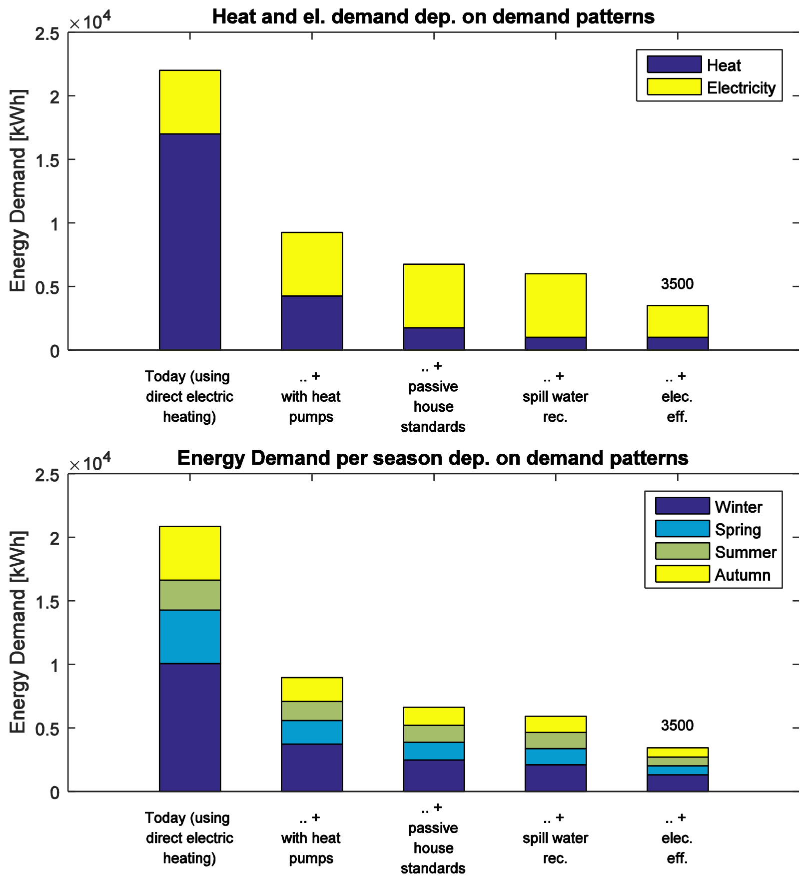

Figure 2: Estimated energy demand (per energy type above, per season below) in single-family building depending on what technology is used for building, heating etc.

Table 4: Estimated energy demand in single-family building depending on what technology is used for building, heating etc.

[kWh$_e$]	Current average	… with heat pumps	… and passive house standard	… and spill-water heat recovery	… and reduced electricity demand
Space heating	12000	3000	500	500	500
DHW	5000	1250	1250	500	500
Household electricity	5000	5000	5000	5000	2500
Total	22000	9250	6750	6000	3500

4.5 Physical limitations

Estimates for realistic production and storage capacities in a residential setting are needed in order to identify limits for what system sizes and weights could be reasonable for the residential scale self-sufficient energy system.

One limiting factor is the roof area for an average house. This area has been approximated to 120 m^2, whereof half, i.e. 60 m^2, could be assumed having a southward facing position (Dalenbäck, 2015).

Additionally, a reasonable estimate on spare volume that could be available in the residential setting needs to be set. Spare volume can be found in cellars, garages, sheds or similar spaces. A reasonable assumption is a system size comparable to the, now rarely seen, oil boilers used extensively for heating houses in Sweden before the usage started to decline in the 1980s (SCB, 2001). Such oil boilers were often of the size of a few cubic meters, thus a size of 5 m^3 has been set as the maximum volume limit for the energy system in this study. Assuming a density of oil of 840 – 950 kg/m^3 (Jernkontoret, 2015), such a system would weigh approximately 5 tons. The reasonable limit in weight for the energy storage system has, based on this, been set to 5 tons.

4.6 Impact of an electric car

The addition of an electric vehicle (EV) to a household would of course increase the annual electricity demand. To the best of the authors' knowledge, energy efficiencies of EVs on the market today range from 0.12 kWh_e/km for the *VW e-up!* (VW, 2015) to 0.2 kWh_e/km for the *TESLA S-model* (PluginCars.com, 2015) and upward for older models. The average electric car used today has an efficiency of 0.2 kWh_e/km according to Svensk Energi (2014). It has been deemed reasonable to assume an efficiency of future electric vehicles in the order of 0.1 kWh_e/km.

The annual distance that a vehicle is driven varies greatly. The average driving distance per personal car in Sweden was 12180 km in 2013 (SCB, 2013). For electric cars, this number was significantly lower, 7200 km per year (SCB, 2013). One possible explanation can be that the electric car is usually not the only car in the household. 10 000 km per year has in this study been considered a best estimate for driving distance in a scenario where EV is the dominant car technology. The corresponding annual energy requirement for a driving distance of 10 000 km would be 1200 kWh_e with the VW e-Up and 2000 kWh_e with the Tesla S-model.

In Table 5 the numbers presented in this section are summarised, and low and high estimates are given as to what extent an electric vehicle EV would impact energy demand on the household level. Note that all numbers are rough estimates and only meant to give an indication of the level of impact that an EV could have on the system.

It is clear from these numbers that the electricity consumption associated with an electric car is significant in comparison to other residential electricity demand. However, as long as the requirements on self-sufficiency are not extended to transportation, the energy system might only be slightly affected by the electric vehicle. As is the case today, charging or refuelling takes place at stations providing this service, and it is a reasonable assumption that such stations will provide electricity charging in the future. In this study, the effects of an eventual EV are therefore neglected and self-sufficiency in energy does not include transportation.

Table 5: Low and high estimates of the impact of an EV of energy demand for a household. Current Swedish averages are also given for comparison.

	Efficiency [kWh_e/km]	Amount driven [km/yr]	Resulting energy use [kWh_e/yr]
Low estimate	0.1	5000	500
Sweden today	1.2 - 0.2	10000	1200 -2000
High estimate	0.2	30000	6000

4.7 Electricity costs for costumers

In order to understand customer demand patterns it is also important to have a picture of the energy costs that customers face. According to SCB (2014), the large majority of Swedish house owners paid approximately 12 – 15 US cents (1.25 – 1.5 SEK) per kWh for their electricity in 2014, depending on their contract with their utility and electricity trading company. This number includes all costs: grid fees, spot price, energy and environmental taxes and VAT. Out of the total electricity price, the grid fee (fixed and variable fees combined) was 4-7 US cents (0.3 – 0.6 SEK) per kWh while the electricity-trading price was 4-8 US cents (0.3 – 0.7 SEK) per kWh. Energy and environmental taxes were 2-4 US cents (0.2 – 0.4 SEK) per kWh depending on where in the country the building was located. VAT added an extra 25% of the combined costs of grid tariff, electricity trading price and energy and environmental taxes.

The same report further states that costumers with low energy demand paid the highest prices. Customers with very low electricity demand, <1000 kWh, stand out in the cost statistics by paying as much as $0.35 (3 SEK) per kWh, i.e. almost three times what a regular customer pays. The statistics do not explicitly tell what kind of costumer a demand level below 1000 kWh corresponds to, but it could e.g. be vacation houses that are not permanently inhabited.

In order to discuss electricity costs for grid-connected customers, in the future state investigated in this study, some estimation of future electricity prices would be in place. Future prices are however very difficult to predict and depend on varying factors such as new installed power capacity, eventual decommissioning of plants, policy regulations and the economic situation in other parts of society. Thus no price projections for electricity prices have been performed within the scope of this study. Instead, investment costs are compared to current electricity prices when applicable.

5 Technology monitoring and selection

After specifying the energy needs as well as the physical limitations of the household, an assessment of potentially interesting micro scale energy technologies is in order. Here follows a review of a number of technologies for energy harnessing, conversion and storage. A broad range of technologies is presented together with their respective benefits and drawbacks. A selection is then performed on the basis of relevance for this specific study. The selection of which technologies to investigate further is based on practical limitations for a household in terms of size and complexity, as well as on the criterion that all technologies should be powered by renewable energy.

Additionally, the technologies should have the potential to sustain a fully self-sufficient energy system in order to be considered interesting. In this study, self-sufficiency requires that dedicated energy carriers cannot be imported to the system, be it in the form of heat, fuel or electricity. Imported matter in the form of water (unheated), food or other consumption products, can pass the system boundary without violating the requirement of self-sufficiency.

The technologies are presented below, together with argumentation regarding their suitability and feasibility, categorised into *local energy harnessing, energy storage systems, energy conversion to storage,* and *energy conversion from storage*.

5.1 Local energy harnessing

Based on the system criteria specified above, some energy harnessing technologies can be directly discarded from further investigation. Complex, large-scale energy harnessing technologies such as nuclear power and fusion cannot be considered practical on the residential scale. Moreover, hydro power, tidal power and wave power are not considered suitable universal options since the conditions for such units depend largely on geographical conditions.

Interesting options are instead technologies that can capture energy from the sun or the wind. Solar energy can be harnessed using direct conversion to electricity, in a photovoltaic (PV) cell, by heating a medium or a body by solar radiation or by making use of energy stored in plants and trees that have previously converted solar energy to chemical energy via photosynthesis. Wind energy can be harnessed in mechanical constructions that move as the wind blows. Specific technologies are presented below.

5.1.1 PV

A photovoltaic (PV) cell converts incoming solar radiation into direct current (DC)-electricity by letting photons excite electrons in a semiconductor through the so-called photovoltaic effect. Most commonly this semi-conductor is silicon (Si, either monocrystalline, polycrystalline or amorphous), chemically doped to create an external electric field. There are also several other possible material compositions, which give the cell different properties such as varying efficiency (Ginley et al., 2012).

PV cells are arranged into modules. The power output is scalable and only limited by the available installation area and the efficiency of the cells. Today commercial PV modules have an efficiency of around 15-20%, while some lab scale cells show efficiencies above 40%. The latter are significantly more expensive but are likely to become cheaper in the future (Dalenbäck, 2015).

With PV efficiencies currently available on the market a 1 kW system requires roughly 7 m^2 of south-facing roof. One such system produces on average 1000 kWh annually in Sweden (Dalenbäck, 2015). The lifetime of a PV module is believed to be in the order of 30 years (Thygesen and Karlsson, 2014), but the technology has not been used widely long enough to know the lifetime with certainty. Due to degradation there is a loss of efficiency of roughly 0.5%/year (Sommerfeldt et al., 2014), which means that e.g. a system with an initial efficiency of 15% would show a 13.5% efficiency after 20 years.

A PV system is a promising option for the generation of electricity at a household level, with a number of advantages. These include low running costs as a result of the absence of fuel requirements as well as low maintenance costs. Furthermore PV panels do not produce noise or pollution in operation and have no moving parts, hence these stationary conditions grant stability and a long lifetime. Additionally the sizes of PV systems are fully scalable and can therefore be seamlessly adapted to site-specific conditions.

One of the main disadvantages is the variable solar irradiance, which means an intermittent power production, limited by cloud coverage and seasonal and daily variations. This gives rise to the need of energy storage or backup power if full self-sufficiency is to be achieved. Another disadvantage has historically been high investment costs, but this has changed very rapidly in recent years (see Section 6).

Said disadvantages are here deemed to be outweighed by the advantages, leading to the selection of a PV system as a valid option for energy harnessing in the self-sufficient residential energy system. Note that no specific PV technology is selected.

It should be observed that most PV systems installed today are accompanied by electronic equipment to enable efficient use and connection to the grid. One of these appliances is the power inverter, which converts the direct current produced by the PV modules into alternating current to be used on site or fed into the grid.

In a future scenario where houses are disconnected from the grid it might be possible that the domestic micro-grid actually runs completely on DC, eliminating the need for an inverter. Furthermore the cost of an inverter is low (Hoppmann et al., 2014; Photon Newsletter, 2015) and well within the margin of error for the purchase and installation cost of a PV system. Thus inverters will be excluded from the system modelled in this study.

5.1.2 Wind

Wind power is a renewable energy source where kinetic energy in the wind is transferred to mechanical energy in a rotor, and thereafter converted to electrical energy in a generator (Robinson, 2012). Such a system has a lifetime of roughly 20 years (ESMAP, 2007). In good conditions, such as high average wind speeds and a high elevation above ground, the capacity factor of a wind turbine is around 25-40%, which means that over a given time the turbine will produce 25-40% of the electricity it would have produced, should it run on maximum power the whole time (IEA WIND, 2014). For smaller turbines and worse wind conditions this capacity factor decreases significantly (Robinson, 2012).

A wind turbine in a residential application would fill the role of diminishing the need for seasonal storage as it produces electricity all year round, though the technology of micro-wind is not used on a wide scale (ESMAP, 2007). It has the advantage of producing energy all year round, however there are considerable drawbacks that prevent it from being a desirable option for a residential system. The output of a wind turbine is optimised if the positioning of the plant is in an open space with high average wind speeds (Robinson, 2012), which is generally not the situation in residential areas. Moreover, the turbines cannot be constructed tall enough, which prevents them from reaching the high wind speeds necessary. Furthermore there are problems with high costs, noises and vibrations, which are difficult to avoid (Robinson, 2012). Finally, the direction of development is towards large wind turbines with tall towers and a large rotor blade sweeping area, whereas micro-wind turbines receive significantly less attention (Robinson, 2012). These disadvantages are here judged to outweigh the advantages that a residential wind turbine could provide, and wind has therefore not been included in the self-sufficient energy system of this study.

5.1.3 Bioenergy

Bioenergy is energy stored by photosynthesising plants, or in the tissue of animals. On the residential level, one could grow energy crops and use the energy that they harness from the sun to power parts of the self-sufficient energy system. However, the efficiency by which bioenergy systems convert solar energy to electricity is typically a hundred times lower than conversion via PV (Rajeshwar et al., 2008; Kushnir and Sandén, 2011). Growing energy crops would therefore require large amounts of land in order to give any significant contribution to the energy supply. For this reason, it is here considered unrealistic that growing energy crops would be a viable option to produce energy for the residential system.

Moreover, organic household waste contains bioenergy that can be used. This energy flow is likely small on the residential scale and this is therefore not investigated further in this study. In farms or in multi-family buildings however, it could potentially be interesting to look at local energy technologies that make use of organic waste.

5.1.4 Solar heat

By letting a medium, such as water, be heated by solar radiation, thermal energy can be captured from the sun. There are different technologies available to achieve this. On the residential scale, the most common option is to heat DHW in pipes on the roof. This technology is commercial and relatively widespread. However, solar heating systems use roof area that could instead be used for PV. Coupled with a heat pump, PV cells can efficiently produce both electricity and heat. PV systems have therefore been prioritised over solar thermal systems, and solar thermal has thus not been considered part of the self-sufficient energy system. This does not mean, however, that there might not be cases where solar heating could be an interesting addition - especially if rooftop area is not a limiting factor.

5.1.5 Heat pumps

Heat pumps use electricity to pump heat from an external source, e.g. the ground or the air, to a room. Heat pumps can therefore be said to harness solar energy that has been stored in the surrounding environment (air, ground or water). The output thermal energy is thereby larger than electric energy consumed. The quota between the electricity input and the heat output is called the Coefficient of Performance (COP). Common COP values today are 3-5 (Thygesen and Karlsson, 2014) but they are expected to improve in the future, potentially reaching values as high as 7 or 8 (Dalenbäck, 2015). Heat pumps for space heating only have a slightly higher COP value than heat pumps heating both air- and water in combination. Throughout this study a COP-value of 4 will be used. The high conversion factor of a heat pump makes it a very effective efficiency measure for the residential system.

In this study, it will be assumed that by 2050 every Swedish household has a heat pump. Today Sweden is a world leader in heat pump installations. In 2009, Sweden had half of the world market for heat pumps and 20% of all single-family buildings in Sweden had a heat pump installed (Energimyndigheten, 2009). Sales spurred in the late 1990s and peaked around 2008-2009 but were still around 40 000 units per year in Sweden in 2013 (Energimyndigheten, 2009). The result is that there are presently more than 1 million heat pumps installed in Sweden (Green Match, 2015). It is thus realistic to assume that heat pumps will be used to a large extent also in the future, and need not be considered in the economic calculations for the self-sufficient system.

5.2 Energy storage systems

Based on the system criteria specified above, some energy storage technologies can be directly discarded from further investigation. Utility scale energy storage technologies such as pumped hydro and compressed air energy storage (CAES) cannot be considered practical on the residential scale. Also, there is no real need for short-term energy storage (seconds to minutes) on the residential level, and consequently technologies like flywheels, super capacitors and superconducting magnetic energy storage (SMES) can all be excluded from further analysis in this study. On the residential level, energy storage is instead interesting on the diurnal and seasonal time scales. Specific technologies that can achieve this are presented below.

5.2.1 Batteries

Batteries are devices that store chemical energy and convert it into electric energy. This can be done in various ways, with a large number of possible combinations of chemistries. All batteries have an anode and a cathode, upholding the chemical potential, and an electrolyte between them to conduct charge and from this process energy can be harnessed. If the process can be reversed repeatedly the battery can be used as energy storage in a variety of applications.

The battery has an important role to fill in a self-sufficient system. It provides possibilities for overnight storage (IEA, 2014b), allowing for the use of solar PV electricity at night as well. Battery technology is suitable for relatively short-term energy storage, i.e. hours up to a few days, but not optimal for long-term (seasonal) storage applications, since it is likely too heavy, bulky and expensive per stored unit of energy (Johansson, 2015).

Presently the most common secondary battery technology (with reversible chemistry) is the lead-acid (PbA) battery (Johansson, 2015). PbA batteries are easy and cheap to manufacture and have a long lifetime. However, they will probably not be used on a large scale, in future electric vehicles (EVs) or in stationary applications, due to their poor energy- and power performance (Johansson, 2015). Additionally, lead is toxic and the sulphuric acid used as electrolyte is also potentially dangerous, which limits the future utilisation of the technology.

Lithium (Li-) based batteries are another example, which shows a high energy density of 0.15 kWh/kg, or 0.25 kWh/l (Bresser et al., 2015). Furthermore it can withstand large charge-discharge windows without affecting the lifetime (meaning it can stray closer to 0 or 100 % total charge, respectively, compared to other chemistries) (Johansson, 2015). For stationary applications this window could possibly be extended even further compared to today's automotive applications. The lifetime of a Li-battery is roughly 12-13 years (Andrews and Shabani, 2012; Itron, 2012).

Another common technology is Nickel Metal Hydrides (NiMH) that are utilised in some EVs and can withstand many cycles (Johansson, 2015). However, NiMHs have low energy density compared to Li-ion batteries (Whittingham, 2012), and would thus require larger volumes to offer sufficient overnight storage. NiMHs are therefore here considered less suitable for use on the residential scale, compared to Li-ion batteries.

The technologies mentioned above are widely available, but there are several emerging types of batteries with interesting properties that can play a part in the future battery market. Some show improved properties in terms of energy density or economics, while other use more easily accessible or abundant materials. Most are in the research phase and need considerable development to compete with Li-ion batteries. Some examples are water based batteries, sodium-ion, Li-S, Li-air and redox-flow batteries (Johansson, 2015).

On a diurnal time scale a battery was deemed the best and most reliable storage option. It is of appropriate size to place in a household and requires low maintenance efforts. The Li-ion chemistry was chosen, in part due to its high energy density and future promise but also because of the large amount of easily available data and its commercial success.

5.2.2 Heat

Storage of energy in hot water is, according to Pinel et al. (2011), a mature and relatively cheap technology for which applications are well demonstrated, clearly understood, reliable and widely used. Furthermore it is stated that water is a suitable storage medium in the 20-80 ˚C range since it has a high thermal capacity and a low cost.

DHW can be stored in an accumulator tank. Common sizes for single-family homes today are 100-300 litres. This amount approximately covers the diurnal consumption and since there are significant long-term energy losses in water tanks, they are mainly suitable for short-term storage.

Instead of in tanks, water can also be stored underground. In this case, reversible heat pumps can cool the building by pumping heat back to the ground for storage. This technology it not suitable everywhere however, since it puts some requirement on the type of ground beneath the house (Paynes Energy Solutions, 2015).

The main use for thermal storage in water tanks is as a potential complement to other energy storage. The major drawback of using warm water for seasonal storage is its low volumetric energy density, making tanks impractically large if all warm water used during winter should be stored. In addition to this large heat losses would make the system impractical. However, warm water tanks can be very practical for smaller amounts of energy storage, on a daily scale, and is likely required for any standalone house. Consequently a warm water tank will be utilised in the self-sufficient energy system, but not included in the additional investment costs, since all buildings already have them.

5.2.3 Fuels

Fuel storage could be an option for seasonal storage of energy on a residential scale. The fuel (gaseous or liquid) could be produced when electricity production is abundant and retransformed into electric energy when needed. See Section 5.3 for details on fuel processing alternatives. Specific possible storage technologies are presented below.

5.2.3.1 Pressurised Tanks

The most common way of storing gaseous fuels is in pressurised tanks. This type of storage is used extensively in industrial settings. Depending on the pressure used, the volumetric energy density varies as well as the requirements on tank materials and the possible need for a compressor. Low-pressure tanks usually have pressures in the order of tens of bars and can be constructed by materials such as steel. The volumetric energy density is very low, which makes low pressure gas storage bulky. In the residential setting, such tanks are likely to be impractical because of their size.

High-pressure 700 bar tanks, which are standardised in automotive applications today, show higher volumetric energy densities, around 1 kWh/l (Stetson, 2012). These systems require compressors as well as materials that can withstand the large pressure, such as carbon fibres, which increases their cost. High-pressure tanks also require a compressor that adds additional costs. In addition, compressors are often noisy during operation, which is a significant drawback in the residential setting.

Depending on the process used to produce the fuel, storage in medium-pressure tanks (150-300 bar) could be a possible solution even without a compressor. Moreover, using medium-pressure tanks lowers requirements on expensive materials compared to high-pressure tanks while still retaining a high volumetric density compared to low-pressure tanks.

Tanks at different pressures have different benefits and drawbacks on the residential scale. In this study, pressurized tanks are considered a valid option for residential storage of energy. No evaluation is made as to what pressure level will be the most favourable at the household level. Instead, low- medium- and high-pressure tanks are all considered viable options in the analysis.

5.2.3.2 Liquid Storage

Liquid fuels can easily be stored in tanks. If the fuel used for storing energy is in liquid state at room temperature, this is a suitable storage option at the residential level.

Fuels that are in gaseous form at room temperature, e.g. hydrogen and methane, can be cooled and *cryogenically* stored as liquids. However, to achieve liquid hydrogen, cooling to just a few Kelvin is required. Cryogenically stored hydrogen is therefore considered an impractical option for residential applications, and will not be investigated further. Methane can be stored in liquid form, often termed LNG (liquid natural gas). This kind of storage system is commercially used. However, pressure builds up in the tanks and has to be released regularly. In the residential setting, this kind of regulation maintenance work is considered impractical.

Also, when releasing pressure, methane is released causing climate gas emissions. Storage of LNG is therefore not considered a viable option in this study.

5.2.3.3 Metal hydrides

Metal hydrides are solid, metal-based structures in which hydrogen atoms can be absorbed. The absorption and desorption processes, though relatively slow, can be done at low pressures and they can store large amounts of energy per unit weight and volume. Theoretical future energy densities can reach 5 kWh/l and 6 kWh/kg (Züttel et al., 2003). Metal hydride storage is an inherently safe alternative for hydrogen storage since it needs only moderate temperature and pressure (Sakintuna et al., 2007). The energy densities of presently available storage systems are still too low, though they have a huge future potential. The hydrogen is stored at close to atmospheric pressure, so no compressor is needed, keeping the system complexity down. Since the kinetics are relatively slow, the power output from a MH storage is limited which might be a problem in e.g. automotive applications, but should not be a problem on the residential side. On the other hand the technology is in the research phase and not yet commercially available.

Hydrogen storage in metal hydrides has here been considered a viable seasonal storage option since it offers a quiet and safe option that does not require maintenance work. Note that no evaluation about what specific metal hydride chemistry is more favourable has been performed within the scope of this study.

5.3 Energy conversion to storage

5.3.1 Electrolysis

An electrolyser converts water to hydrogen and oxygen by splitting it, using an input of electricity (Jooss and Tributsch, 2012). The physical dimensions of a residential size electrolyser today are comparable to that of a fuel cell, i.e. around 0.2 m^3 (see Section 5.4.2) (Wiberg and Karlström, 2015). The efficiency of electrolyser technology only varies a few percentage points between the MW and the kW scale (the variation is generally more dependent on the different manufacturers involved) (Wiberg and Karlström, 2015). Electrolysers thus show beneficial properties for a residential level system (a few kW).

The two most common electrolyser technologies today are PEM cells and alkaline electrolysers. Alkaline electrolysis is the most mature technology at present but is lacking in performance since they only offer non-reversible chemistry and low efficiencies (Benjaminsson et al., 2013). PEM systems are available in smaller capacities, but offer long-term performance and cost benefits (Penev, 2013), with a more complex electrolyte offering a reversible process as well as high efficiency (Benjaminsson et al., 2013).

A third technology currently under development based on high temperature electrolysis is so called Solid Oxide Electrolyser Cells (SOECs). A SOEC is effectively a Solid Oxide Fuel Cell (SOFC) run in reverse (see Section 5.4.2) and one appliance could in the future work as both a SOEC and a SOFC simultaneously (Wiberg and Karlström, 2015). SOECs are not yet commercially available (Penev, 2013) but the high temperature has the potential to provide efficiencies in the 80 % range at a low cost (Penev, 2013; Andrews and Shabani, 2012). The lifetime of these types of electrolysers is in the order of 50 000-100 000 h (corresponding to approximately 10-20 years) (Benjaminsson et al., 2013; Andrews and Shabani, 2012).

A possibly interesting development in electrolysis technology is the so-called High Pressure Electrolysis (HPE), which gives a pressurised output stream of hydrogen gas. The high pressure is achieved directly through the electrolytic process (so-called electrochemical compression) from which the output can be fed straight into a pressurised storage tank. The pressures achieved in HPEs today are around 50 bar but with lab tests of 150 - 300 bar (Fateev, 2013; Millet et al., 2009). HPE has the potential to make hydrogen storage more practical since it allows for higher storage pressures, and thereby smaller storage volumes, without adding the requirement of a compressor.

Due to their high efficiency, micro scale compatibility and commercial availability, electrolysers are here selected as a suitable electricity-to-chemical energy conversion technology for the residential energy system. Thus, hydrogen is selected as a viable storage medium to be used for seasonal storage of energy in the residential energy system.

5.3.2 The Sabatier process

Another option for chemical storage of intermittent electricity is to first produce hydrogen through electrolysis and subsequently reform it into other fuels, such as methane (CH_4) or methanol (CH_4O). This can be done in a so-called Sabatier reactor, after adding CO_2 to the process. The CO_2 could be retrieved from another process or even captured from the air (Mohseni, 2012). Thus it would be possible to produce a liquid fuel for seasonal storage, to be used during winter months.

Today, electrofuels are produced in relatively large facilities (MW rather than kW) and the main application is thought to be fuel for vehicle transport, though residential applications could be a future possibility. Such plants have the advantage of producing an energy-dense product such as gaseous methane or liquid methanol. Unfortunately the drawbacks are significant; the process is normally performed on the MW scale, and very little research has been done on producing electrofuels on a micro-scale. Finally the CO_2 requirement is probably the biggest barrier to adoption on this scale. Without a large carbon source in the vicinity there is only the option of carbon capture and storage (CCS) from air, which is still an immature and very expensive technology with an uncertain future, at least on a micro-scale (Grahn et al., 2015). For these reasons electrofuels are not considered a possible solution for this study. Instead, hydrogen produced by water electrolysis is considered the most viable option for seasonal storage of energy.

5.4 Energy conversion from storage

A selection of fuel-driven power producing units are available that are used as back-up power all over the world. Such units could run on conventional fossil fuels, but also on various kinds of biofuels. In the residential energy system, this subsystem should convert energy stored in fuels back into electricity. Since hydrogen has been chosen as the seasonal energy storage medium, the fuel-to-electricity conversion technology needs to be compatible with hydrogen fuel.

Apart from power, these technologies also produce heat. In residential applications, a way to increase efficiency and environmental performance is to make use of that excess thermal energy to heat the building, making the system a micro scale so called “Combined Heat and Power”-plant (micro-CHP). There are several types of micro-CHP technologies available, listed below.

5.4.1 Engines and turbines

Reciprocating internal combustion engines (RIC-Es) are in effect internal combustion engines (ICEs) where the excess heat is used. In an ICE a fuel is injected into a combustion chamber and ignited, its expansion then drives a piston, thus converting the chemical energy of the fuel into mechanical energy that can drive a generator. This conversion is subject to losses in efficiency through e.g. heat. But the reuse of this heat can increase the efficiency from the electric efficiency of ~40% (Angrisani et al., 2011) to a combined heat and power efficiency upwards of 80-90% (Pepermans et al, 2005). The fuel is normally fossil-based, such as diesel, but the engine may be adapted to run on bio-fuels (bio-diesel, biogas or even hydrogen) to improve environmental performance, but at a higher cost.

The electric power for residential applications ranges from 1-13 kW, while the thermal power is 1-29 kW (Angrisani et al., 2011; Barbieri et al., 2012). The technology is mature and, but not yet widespread in the residential sector (De Paepe et al., 2006).

A *gas turbine* is an internal combustion engine where air is compressed, ignited with a gaseous fuel and driven through a turbine, the rotation of which can drive an electric motor, generating electricity from the mechanical energy (ESMAP, 2007). Large-scale gas turbines are widely used, but they are not commercially available on a micro- scale (ESMAP, 2007). Gas turbine capacities on the micro-scale ranges from 1-80 kW_e (Pilavachi, 2002). Electrical efficiency is 10-35% while thermal efficiency is 45-80% (Pilavachi, 2002; Simader et al., 2006). Most types are internal combustion, in which case it runs on liquid or gaseous fuel, e.g. biogas, can also be run with external combustion where it can run on lower quality fuel, e.g. biomass, that heats up air going through, and running, the turbine (ESMAP, 2007).

Stirling engines utilise the heat difference between two sources to generate electricity via a generator and can run on almost any heat source. They are commercially available and micro scale capacity ranges are 1-9 kW_e and 6-26 kW_{th} (Angrisani et al., 2011; Barbieri et al., 2012). Electric efficiencies for Stirling engines are rather low, reaching approximately 12-24% (De Paepe et al., 2006).

Stirling engines require heat sources to produce electricity, and thus entail a heat energy storage system. In order to be suitable for use in the residential energy system, there needs to be a large availability of excess heat. If not, fuel needs to be used to create a heat source, something that would be disadvantageous in terms of efficiency. It is here deemed unpractical to achieve sufficiently large thermal energy storage to make Stirling engines a valid option in the residential energy system. Stirling Engines are therefore excluded as an option for power production in this study.

One common drawback of RIC-E and the Gas Turbine is that they produce large amounts of noise and pollution. Moreover, electric efficiencies are below 40 %, implying large energy losses in the energy conversion. Considering the disadvantages it is here deemed reasonable to exclude RIC-E and Gas Turbines as options for the self-sufficient residential energy system.

5.4.2 Fuel Cells

A fuel cell (FC) produces electricity by combining hydrogen and oxygen into water, its fuel being hydrogen gas and oxygen that can be pulled from the surrounding air (Kocha et al., 2012). The process is essentially the one taking place in an electrolyser, only reversed, and technological development could potentially enable the two processes to be performed by the same machine (Wiberg and Karlström, 2015). In a FC, protons are channelled through an electrolyte while electrons are led through an external load where electricity can be extracted. The only residue of this process is water vapour. FCs have high efficiencies and no moving parts (Kocha et al., 2012).

According to Wiberg and Karlström (2015) fuel cells can be combined with a fuel reformer so that the system is able to run on other fuels than hydrogen, such as natural gas or methanol. Fuel-flexibility would make the fuel cell system beneficial to use as a back-up power system (in the absence of hydrogen it could be possible to purchase fuel to run the FC). However, fuel reforming reduces the system efficiency.

The technological development for FCs is mainly driven by the automotive industry but there is a large potential in the residential sector as well. The power of a FC ranges from roughly 1 W to 100 kW of electrical power output. The heat output of a given FC is of the same magnitude as the electric power output, i.e. for each kWh_e that the system produces approximately 1 kWh_{th} is produced as well (Panasonic newsroom, 2011). For residential applications, as compared to automotive, one of the key aspects is the lifetime. For presently available FCs it is confirmed to be at least 10 000 h (Wiberg and Karlström, 2015). The industry claims achieved lifetimes of 50 000-60 000 h, but there is yet little evidence of this in the academic literature (Elmer et al., 2015).

A number of different technologies are available but one of the most common is the Proton Exchange Membrane Fuel Cell (PEMFC). PEMFCs are advantageous since they run at low temperatures (<100 °C) and have a relatively short start up time. Drawbacks include that PEMFCs require expensive catalysts and very pure hydrogen fuel. Another interesting option is the Solid Oxide Fuel Cell (SOFC). Major benefits of the SOFC cell are that it does not use precious metal catalysts, and that the efficiency has the potential to be as high as 70 %. A drawback is that the current technology needs an operation temperature of about 600 – 1000 °C, which might be impractical in the residential setting. (Elmer et al., 2015)

Physical dimensions for FCs vary widely, depending on various parameters, but an example is a 700W SOFC system currently available in the Japanese subsidy scheme ENE-FARM's which is approximately 0.2 m^3 and weighs 100 kg (Osaka Gas, 2013). This is well within a reasonable range for practical dimensions of a residential system.

Considering advantages and disadvantages presented here, the FC is selected as the storage-to-electricity conversion system in the self-sufficient residential energy system. No specific fuel cell technology is selected, but the FC efficiency is assumed to reach 60% by 2050. The fuel cell will use hydrogen to provide electricity in the winter months (when the PV system is not producing enough energy to cover demand).

5.5 Final selection

The technology combination identified as the most suitable to comprise a self-sufficient household level energy system is presented in Table 6:

Table 6: Summary of system parts and their function

Power production	Photovoltaic solar cells
Overnight storage	Batteries (Li-ion)
Seasonal storage	H_2 storage
Energy conversion to seasonal storage	Electrolyser
Energy conversion from seasonal storage	Fuel cell

Note that no single hydrogen storage alternative was selected as the most favourable. Instead, pressurised tanks (low, medium and high pressure) and metal hydrides were both considered valid options to be investigated further.

Table 7 presents technologies that were also selected as potentially important subsystem. These system parts are however neglected when analysing the system costs, either because it was considered reasonable to assume that the technology will be a standard installation in all households in 2050 regardless of self-consumption level, or else because the cost of the system part was deemed negligible compared to other expenses.

Table 7: Technologies assessed and selected but not included in modelled system costs

Technology	*Reason*
Heat pump	Considered standard (not an added investment cost)
Inverter	Cost considered negligible
Overnight thermal storage	Considered standard (not an added investment cost)
Compressor	Assumed to be included in tank price, if needed

6 Market status and trends

The following section presents the current status and maturity for each technology selected, as well as discernible data trends pointing towards a future investment cost. The technologies selected for the self-sufficient residential energy system, as described in Section 5, are: PV, batteries, hydrogen storage, electrolysers and fuel cells.

All costs have been converted to 2015 US dollars using an estimated conversion rate of 1 USD = 9 SEK, 1 USD = 1.1 EUR and 1 USD = 125 JPY. For data in original currencies, see Appendix A.

6.1 Solar PV

Photovoltaic solar cells are based on a technology that has been present for many decades. The first silicon based PV cell was invented in 1954 and since then PVs have been used in different niche markets such as the aerospace industry and off-grid cottages (Energimyndigheten, 2014). Due mainly to large efforts in subsidy schemes for grid connected rooftop solar cells in Japan and Germany a global industry has been formed. Prices have fallen dramatically and the PV market can now be considered mature (Energimyndigheten, 2014).

The price development data collected for PV systems is presented in Figure 3. Note that the data points do not distinguish between different PV technologies and materials but rather gives an overview of PV technology in general.

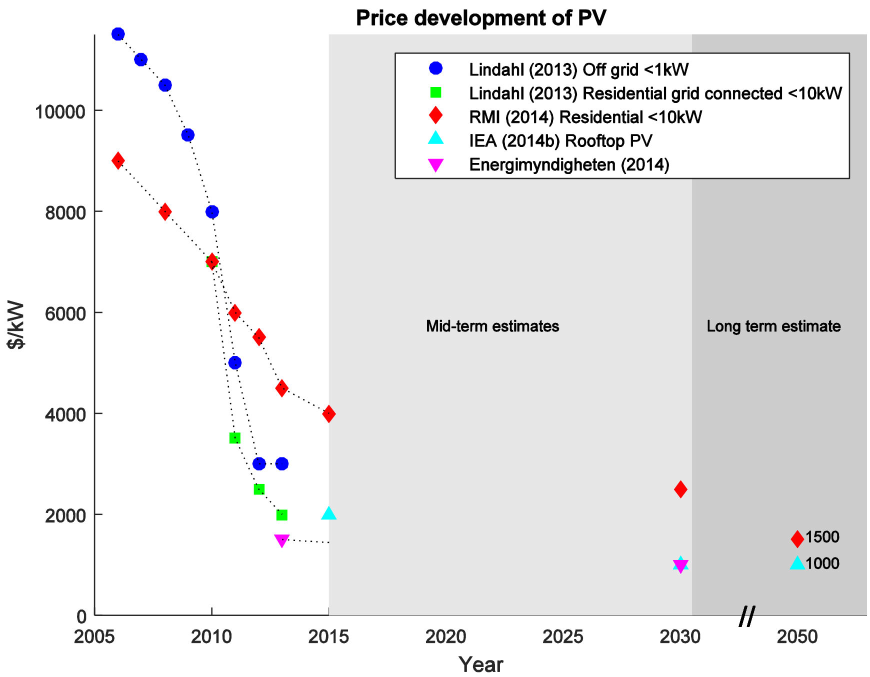

Figure 3: Price development of solar PV systems from 2005 to 2050. Note that the prices given by RMI (2014) correspond to the situation on the American market. These numbers are therefore higher than the prices reported from the other, European, sources. Reported prices before 2015 and estimates and targets after 2015.

As seen in Figure 3 the cost of solar PV systems has declined dramatically during the last decade, reaching the present costs of between $2000 and $4000 per kW. As the global market grows and production practices continue to develop, the price is expected to drop further in the future. Note that the installed prices of PVs differ significantly between countries. For example, current US prices are twice as large as the Swedish prices, one reason being differences in installation costs (Energimyndigheten, 2014).

The price development of PV is documented within the IEA National Survey reports of the Photovoltaic Power Systems Programme (PVPS). The numbers regarding Sweden are based on Lindahl (2013). Data points for US conditions have been collected from RMI (2014) presenting historical price development of residential PV systems below 10kW in the US as well as future price projections. RMI (2014) have based their historical numbers on Barbose et al. (2012) in which it is reported that the presented prices are likely to be slightly overestimated since the dataset is dominated by numbers from the state of California, which has the largest market share for PV in the US, but also high PV prices compared to other states.

The multiple future price projections presented in RMI (2014) are based on different scenarios, among them a base-case scenario and an “accelerated technological development” scenario. Here, the combined average of projections were used as a data point for the year 2030. For the final 2050 projection the data point given in the RMI’s ”accelerated technology improvement scenario” was used, namely $1500/kW.

From the final source, namely the IEA Technology Roadmap for PV Solar Power (IEA, 2014c), were taken global price projections for rooftop PV. The projections represent installed prices, thus including hardware as well as installation costs. They are based on the “2DS hi-Ren” scenario (two degree global average temperature increase, high renewable integration), defined in IEA's Energy Technology Perspectives report (IEA, 2014b) in which solar PV becomes the dominant electricity source by 2040, providing 26% of global generation by 2050. The final projection reached for 2050 is $1000/kW.

Thus the projected costs of solar PV in 2050 lie in the range $1000 to $1500/kW.

6.2 Batteries

Batteries are by far the most common form of storing electrical energy at present and the technology has been around since the early 19th century. There is a wide range of technological options and sizes for batteries. Some technologies are very mature while others are in the R&D phase. (Whittingham, 2012).

In terms of rechargeable batteries, Lead-Acid (PbA) are still the most commonly used. Nickel-metal-hydride (NiMH) batteries have played an important part in the development of electric vehicles but are now being replaced by the more energy dense, and lower cost, Li-ion batteries (Whittingham, 2012).

The development of batteries is currently going through an intense R&D phase and it is anticipated that technological advancements in battery storage will become a key enabler for renewable energy integration. Therefore research is progressing rapidly in the area and it is highly uncertain what chemistry or design will eventually be optimal for different applications.

The collected price development data for batteries is presented in Figure 4 (note that the data represents Li-ion batteries). The largest set in the data series is derived from RMI (2014), which presents price curves, from several sources, for Li-ion batteries on a US market. The most complete set, a combination of reported historical data together with further extrapolations up to 2050, was the one used in this study.

Another data set was acquired from a report by UBS (2014), where they investigate the disruptive potential of PV, batteries and electric cars on the future energy system. The report provides a price development curve between 2009 and 2025, depicting the decline in costs for Li battery packs. Further data points were found in an article by Cho et al. (2015), which reviews, summarises and compares the situation for different electrochemical storage technologies. A range of 500-2500 $/kWh is given for the system prices of stationary and automotive Li-ion batteries. From this the best available value of 500 $/kWh is presented here.

A final data series was taken from IEA Global EV Outlook (IEA, 2013), who reports that automotive Li-ion batteries cost approximately 1000 $/kWh in 2010 and then assumes a learning rate of 9.5% resulting in a 2020 price of $300/kWh.

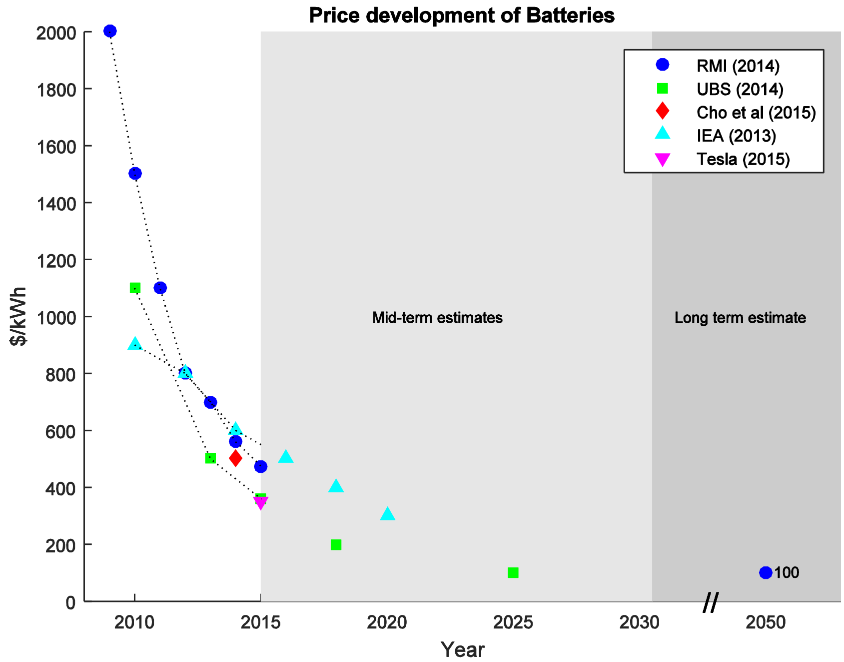

Figure 4: Price development of Li-ion batteries from 2009 to 2050, as reported by different sources. With reported prices before 2015 and estimates and targets after 2015.

In general the sources agree on the downward trend of the battery prices. This development is to a large degree driven by the automotive industry and its applications in electric vehicles (EVs). Consequently, the numbers presented largely concern automotive applications, though stationary applications should follow closely behind. One example is the "Tesla Powerwall" which, according to Tesla Motors (2015), will begin to be shipped to customers during the summer of 2015 at a price of $350/kWh.

In conclusion, the projections point to a 2050 price of around $100/kWh for Li-batteries.

6.3 Hydrogen storage

As mentioned, a system based on hydrogen could allow for purely clean energy year round. One important question then is how to store the energy in a practical and cost efficient manner. There are numerous technologies for storing hydrogen but the market for residential scale applications is basically non-existent. Instead most research and development lies in the automotive industry, specifically in developing high-pressure tanks for on board storage in fuel cell cars. Stationary hydrogen storage on the industrial scale is common but requires large volumes and has not been adopted at the residential setting. Metal hydride hydrogen storage is not yet commercial but still in the R&D phase.

No time dependent price development data has been found for hydrogen storage. Instead, the data presented in Figure 5 shows the distribution of prices reported from a set of data sources. The different storage types considered are metal hydrides and pressurised gas tanks, the latter being divided into low, medium and high-pressure tanks, of 20-45 bar, 200-350 bar and 700 bar respectively. The data sources from which the numbers in the figure have been collected are described in some detail below.

In the 2009 USDOE annual merit review, Satyapal (2009) presents data for high and medium-pressure tank system costs as well as metal hydride costs. In the subsequent 2012 annual merit review from the US DOE, Stetson (2012) provides an updated status of hydrogen storage prices for tanks of 700 and 350 bar as well as metal hydrides. Stetson (2012) also reports a projected price of 700 bar tanks assuming a high production rate of 500 000 units/year. By including this price projection, a rather large price range of 12 – 18.9 $/kWh is obtained for high-pressure tanks. Following up on these numbers, in the 2013 USDOE annual merit review, James et al. (2013) also provide projections assuming a high production rate of 500 000 units/year resulting in data points for high and medium-pressure storage tanks.

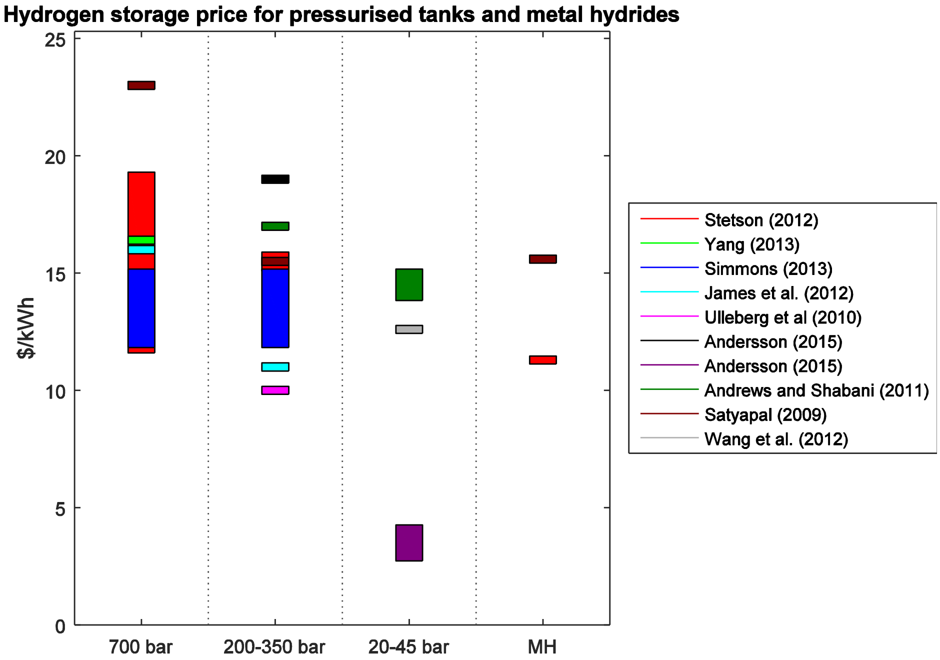

Figure 5: Storage costs for different hydrogen storage technologies, per source.

Similar numbers are given for 700 bar tanks at mass production in a presentation by Yang (2013), for Austin Power Engineering, about PEM fuel cell system costs for automotive applications. Kevin and Simmons (2013) of the Pacific Northwest National Laboratory report a baseline hydrogen storage cost of 15 $/kWh, for both 350 and 700 bar tanks as well as an additional 20% cost reduction on the short term due to presently identified savings and efficiency measures, giving a range of 12 – 15 $/kWh.

Ulleberg et al. (2010) gives a single data point for the price of a 200 bar tank used at the wind/hydrogen demonstration system currently in place at Utsira in Norway. Wang et al. (2012) from Aachen University also described a demonstration system, but for a low-pressure tank at 45 bar. Further data ranges are found in Andrews and Shabani (2011) who give current prices for low and medium-pressure tanks as well as projections in 2030 for medium-pressure tanks. Lastly, Swedish industrial gas company AGA was contacted for information about the hydrogen refuelling station being built close to Arlanda airport in Stockholm, which will use carbon fibre tanks at medium pressure for storing hydrogen (Andersson, 2015). Furthermore they provided current price figures for stationary steel tanks at low pressure.

As for possible future price developments, high-pressure tanks have a large cost reduction potential since the majority of the cost, approximately 70 %, is due to the carbon fibre composite layer (James, 2013; Stetson, 2012). If the cost of carbon fibre can be reduced, or through dematerialisation, there is a large price reduction potential for the high-pressure storage tanks. It should be noted that the reason for using carbon fibre material is to optimise weight and robustness for transport applications, since weight is a limiting factor in the automotive industry and the tanks need to withstand large amounts of stress in operation. For a residential application, on the other hand, the weight is not an important factor and the need for carbon fibre could possibly be reduced in such systems. In addition, a stationary tank would not be exposed to any significant wear and tear. Thus stationary tanks could potentially be made from steel even at high pressures, which is likely to be a cheaper option.

In Figure 6 is presented a summary of the reported costs for the different technologies, along with data on volumetric energy density and the USDOE long-term target cost of 2 $/kWh, as reported by Satyapal (2009). Low-pressure hydrogen gas tanks are cheap but require an impractical amount of storage volume, due to their low volumetric energy densities. High-pressure tanks, currently developed for fuel cell vehicles, are on the other hand efficient in terms of volume, but costly. Metal hydrides are difficult to fit in the graph since there is a large difference between currently available (first generation) technology (1G MH) and the theoretical potential. According to Sakintuna et al. (2007), metal hydrides can theoretically store hydrogen at a volumetric density of at least 5 kWh/l. Moreover, price data for MH is very difficult to come across since it has not yet been commercialised.

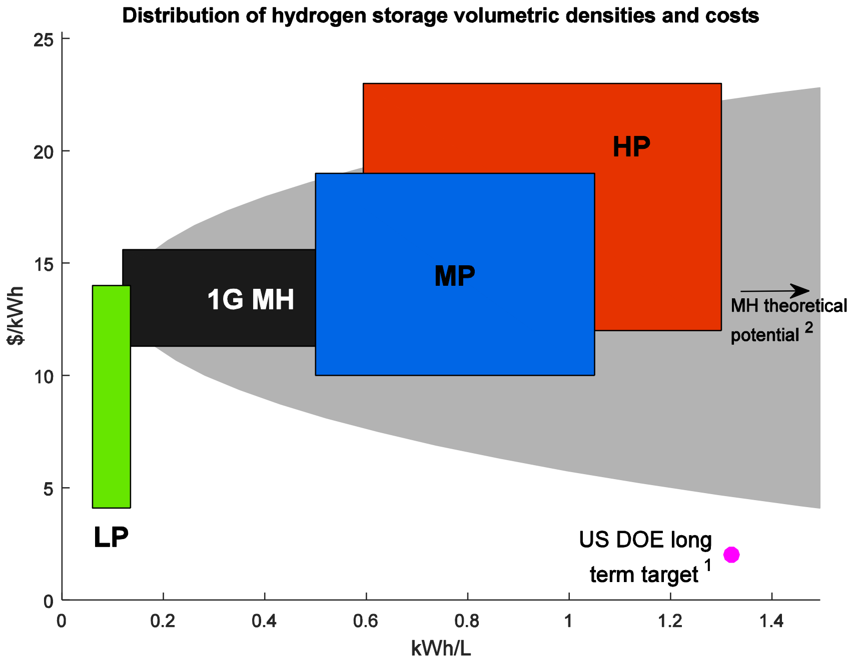

Figure 6: Distribution of volumetric densities and costs of hydrogen storage for four different technologies, as well as targets for some. LP is low-pressure tanks (20-45 bar), MP is medium-pressure tanks (200-350 bar), HP is high-pressure tanks (700 bar) and 1G MH is the first generation of metal hydride storage available. In addition a rough estimate of the future potential of MH is shown. Data sources: [1]Satyapal (2009), [2]Züttel et al. (2003).

It is clear from Figure 5 and Figure 6 that there is some disagreement between sources. Thus it is concluded that one single price estimate would be too uncertain to use as a basis for this study. Instead, a reasonable range of costs was identified that could represent a possible future storage price. This range was set to \$3/kWh - \$10/kWh, the lower bound chosen as slightly higher than the USDOE long-term target and the upper bound set to be \$10/kWh, since all technologies, with the exception of high-pressure tanks, are already available at that price.

6.4 Electrolysers

The production of H_2 from water was first demonstrated in the year 1800 and the first combustion engine vehicle was actually powered by hydrogen fuel (Jooss and Tibutsch, 2012). The notion of a clean, hydrogen based, economy where H_2 fuel can be produced from water and electricity has been a dream for many. However large-scale production of hydrogen technologies have not taken off. Even so, water based electrolysis is a mature technology (Ursúa et al., 2012), one main drawback being the PEM electrolysers' dependence on precious metal catalysts making it difficult to reduce prices. The introduction of SOECs could change this picture, potentially lowering the price (Richter et al., 2011).

The price development data collected for electrolysers is presented in Figure 7. Note that no specific electrolyser technology has been assumed but that the data should rather represent a general view on electrolyser development.

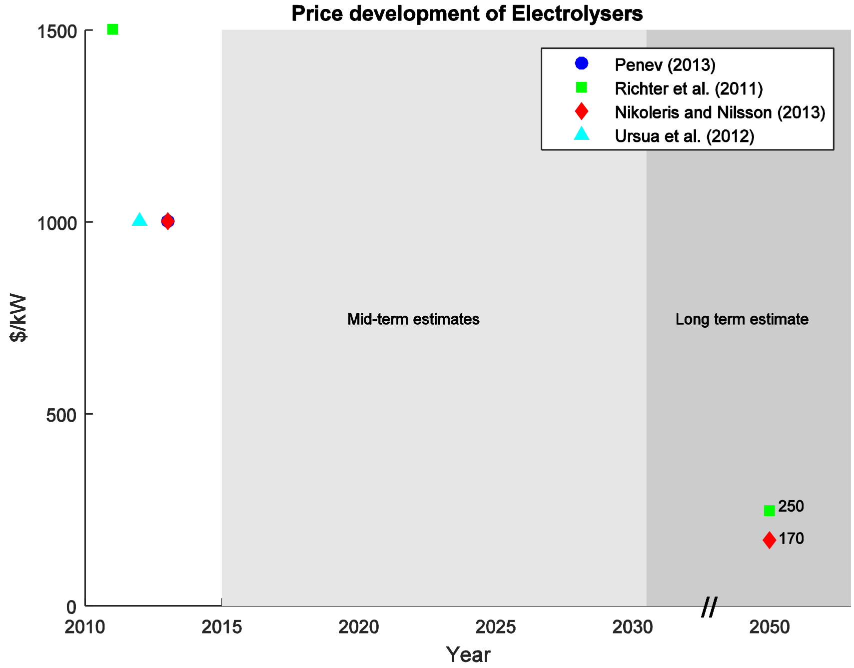

Figure 7: Price development of electrolysers from 2010 to 2050, as reported by different sources. With reported prices before 2015 and estimates and targets after 2015.

The price development data (mainly stack prices) presented in the figure shows a downward trend of electrolyser costs, as reported by different sources. Penev (2013) reports the current electrolyser costs as a part of research at the US National Renewable Energy Laboratory (NREL). The average cost of the different electrolysers presented is $1000/kW (assuming increased production volumes). However, the numbers concern MW-scale applications, and are thus uncertain in terms of small-scale systems on the kW-scale.

The Danish project “ForskEL2010 Energinet.dk” (Richter et al., 2011) reviews current state-of-the-art SOECs and report a price of approximately $1300/kW. Furthermore they estimate a theoretical potential price, assuming large-scale production, of SOECs of $250/kW, which is based on the assumption that a SOFC cell is projected to cost $200/kW on a stack level and that SOEC stacks would be slightly more expensive.

Nikoleris and Nilsson (2013) provide a report on electrofuels, in which a systematic review of the state of different technologies for storing electricity is performed, based on current literature. The reported price of SOECSs is 1000 $/kW on the short term, but their estimate is that the cost will fall to 170 $/kW in the long term, here taken to be 2050. Finally, Ursúa et al. (2012) reviews electrolysis technologies for hydrogen production and claims that values up to $1000/kW are considered in economic models for SOECs today, assuming increased production volumes, since no large-scale production is yet in place.

To summarise, long-term price projection for electrolysers was found to be in the range $170-$250/kW.

6.5 Fuel Cells

Fuel cell technology has been known since the 19th century but was left out of focus in favour of the internal combustion engine (ICE) and the following technology lock-in to fossil-fuel-based energy sources. Since the 1960s fuel cells have been an important technology in the niche market of manned space flights. Technological breakthroughs in the 1980s and early 1990s led to the development of the first marketable fuel-cell vehicle in 1993. (Kocha et al., 2012).

The fuel cell market is still immature with low production rates, but fuel cell technology is developing in multiple sectors simultaneously. Apart from automotive applications, three main early markets have been identified for small scale FCs (< 15kW): back-up systems (BuP), material handling equipment (MHE) and combined heat and power systems (CHP). BuP are mainly used for powering remote telecommunication towers and the like, while MHE includes equipment for construction and warehouse operations, such as fork lifts (Upreti et al., 2012).

On the residential scale development seems to be taking off. In Japan, an ambitious subsidy scheme, Enefarm, makes it possible to install FC micro-CHP systems at an affordable cost (Andersson and Sundén, 2013). Regarding residential FC applications most available data comes from the EneFarm scheme. Note that these systems currently run on natural gas supplied through the gas grid and converted to hydrogen in a fuel reformer connected to the FC system. Outside Japan, both the Californian SGIP scheme (Itron, 2014) and the European ene.field programme (ene.field, 2015) promote fuel cells for use in residential scale micro-CHP systems.

The price development data collected for small-scale fuel cell applications is presented in Figure 8. Note that no specific fuel cell technology has been selected but that the datasets are meant to give an overview of the development in the field of small-scale FC micro-CHP systems.

The figure shows the historical prices as well as future projections for stationary FCs. Note that there is a large disparity between reported costs before 2015. This can be due to discrepancies in assumptions in different sources, such as the inclusion of taxes or subsidies in the price. Also, some studies consider systems of 5 kW, which are not necessarily linearly scalable to the 1 kW level. Finally some of the numbers are not empirical numbers, but rather expected prices based on cumulative production capacity and industrial growth (see more details below). Despite this initial disparity, most long-term projections point to a price below a few thousand USD/kW.

Going into more detail for each source, Andersson and Sundén (2013) report the costs of the stationary high temperature FC systems sold within the EneFarm scheme in Japan, as well as the target cost for the systems. Elmer et al. (2015) present a review of state-of-the-art residential FC systems, including the historical development within Japanese subsidy scheme EneFarm, and predict $3000-$5000/kW to be a feasible cost target for 2020, from which the average value of $4000/kW is used here as a data point.

The IEA Advanced Fuel Cell Annual Report (IEA AFC, 2014) presents the status of different fuel cell technologies of the IEA member countries. The series included in Figure 8 represent the Japanese market, including projections for 2020-2030 made by the Japanese government organisation NEDO (New Energy and Industrial Technology Development Organization) of approximately $4500/kW. Staffell and Green (2013) present a systematic review of cost data for FC manufacturers as well as near term projections from the industry, where they conclude that a realistic price target is $3000-$5000/kW by 2020. Here, the average value of $4000/kW is used.

Within the Self Generation Incentive Program (SGIP) in California, US, Itron, 2014 presents a model for how the SGIP will affect the future costs of DG technologies, based on historical learning rates (the decrease in cost associated with a doubling in cumulative production volume). They conclude that the system price for a 5 kW CHP FC system will drop from $14 000/kW in 2009 to $3000/kW in 2020. Upreti et al. (2012) present another model for the price development of "non-automotive" FCs, in order to predict the effects of government policies and market growth. They present a 2010 FC price of $10 000/kW (for a 5kW system) and also estimate that the EneFarm scheme cost target of roughly $5000/kW will be met by 2018, through an average annual cost reduction of 15% after 2010. Finally

Satyapal (2009) presents, as a part of the US Department of Energy (DOE) Hydrogen Program and Vehicle Technologies Program, the USDOE long-term cost target for stationary fuel cells of $750/kW. This is expected to be achieved through economies of scale by increasing production volumes, e.g. by government acquisition, and is used here as a 2050 target.

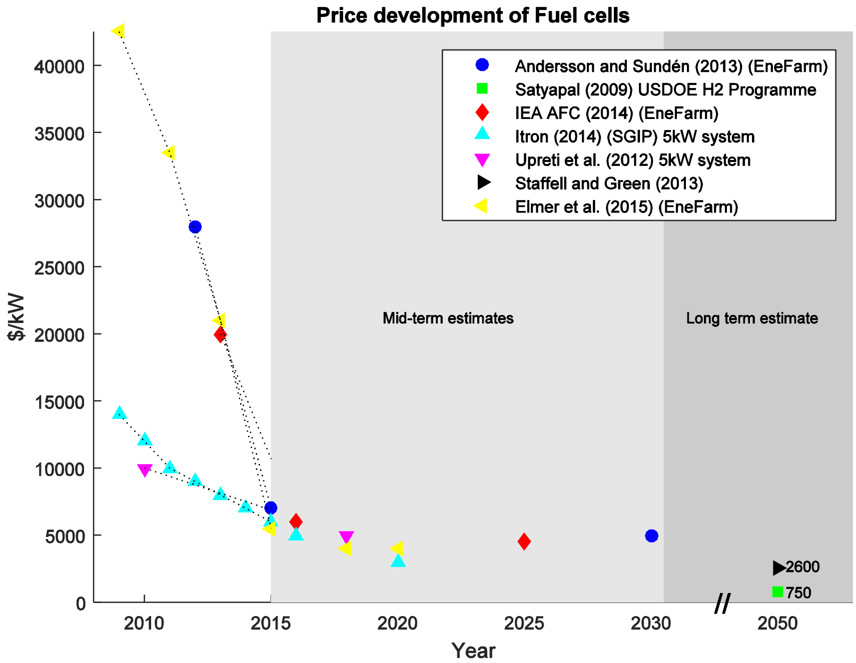

Figure 8: Price development of fuel cells from 2009 to 2050, as reported by different sources. Reported prices before 2015 and estimates and targets after 2015.

Most sources seem to agree on the fact that small scale FC system will come down in price in the future. There is ongoing work on identifying possible cost reduction potentials in the technology. The costs of a fuel cell are normally divided into stack costs (the actual FC) and balance of plant (BOP) costs (all secondary components). According to Yang (2013) the BOP costs constitute more than 50% of the total price and thus represent a significant price reduction potential. Stack prices on the other hand have already experienced a substantial price reduction (almost 75% decrease between 2002 and 2008), largely due to the decreased need for a Pt-catalyst in PEMFC systems (Satyapal, 2009). Also, SOFC technology is not as mature as PEMFC technology, and an increase in production rates of SOFC could allow for future cost reductions. It thus seems that it is not unreasonable to expect further price drops in FC prices. However, the development is at present largely driven by the automotive industry, so there might be some delay before the effects are transferred to stationary FCs.

To summarise, the projected long-term costs of stationary FCs lie in the range $750 to $2600/kW. The average value of this range, i.e. $1675/kW, has been used in the calculations.

6.6 Summary

The final investment costs projected for 2050 is presented in Table 8.

Table 8: Summary of estimated installation costs in 2050 by technology

PV	Battery	Fuel cell	Electrolyser	H2 storage
$1250/kW	$100/kWh	$1675/kW	$210/kW	$3-10/kWh

7 System modelling

Based on the selected technologies and their performance and cost, the self-sufficient residential energy system can be designed. This section lays out the design specifications, and how the system components were dimensioned and combined to fulfil all requirements. PV production and seasonal storage are first dimensioned based their relative prices, and the demand profile. Thereafter, overnight storage and the energy conversion components (to and from seasonal storage) are dimensioned accordingly.

7.1 Important design specifications

7.1.1 Energy requirements

The self-sufficient system needs to be able to supply enough energy to meet demand every day of the year, while accounting for system losses. Since demand varies, there has to be a means of matching supply in a satisfying way that does not reduce the comfort level of the user.

7.1.2 Power requirements

Except for covering the total energy demand over the course of the year, the self-sufficient system also needs to be able to meet requirements in power demand. As stated in Section 4.3, the system should be able to meet the peak demand of 3 kW of electricity at all times.

7.1.3 The role of storage

Storage technologies allow for a decoupling of electricity production and demand, which means that they can bridge temporal gaps in supply (IEA, 2014). Many storage options, especially those that allow for long term storage, include conversion between energy forms. Thus storage technology can also be a bridge between currently disconnected energy systems, e.g. the power, transportation and heat systems. At the household level, energy storage provides flexibility by making energy available in different forms, to be used for various things at different times, which allows improved matching of production and demand.

7.2 System model overview

The system was modelled as a combination of the selected DG technologies presented earlier to be able to meet the demand. The system configuration chosen is presented here.

The core energy production unit was set to be a solar PV rooftop system. The PV system would produce energy during daytime the year round; delivering more energy than consumed during approximately half of the year and producing less energy than consumed during the remaining 6 months.

A battery storage system was included in order to bridge the gap in energy supply on the diurnal time scale. In order to do the same on the seasonal time scale, a hydrogen storage system was added. The conversion from electrical energy into chemical energy in hydrogen would be realised via an electrolyser. The energy stored in hydrogen would then be converted back to electricity in a residential scale micro-CHP fuel cell system producing both electricity and useful heat for the building.

7.3 PV production and seasonal storage

PV production has been modelled as a sinusoidal curve with a period of one year (see Figure 9). According to Andrews and Shabani (2012) this is a reasonable assumption when modelling PV production, with the possible exception of locations very close to the equator. Peak values for the production are based on Widén (2008).

Comparing the modelled production curve to the energy demand curve (modelled according to Section 4.2) a net production curve is created, see Figure 11. Positive net production implies that energy can be added to the storage because more energy is produced than is currently consumed while negative net production means that energy needs to be taken from storage in order to meet demand. Using integration, the total energy production surplus during Net Production Days (NPDs) and the total energy deficit during Net Consumption Days (NCDs) can be calculated. In order to achieve year round self-sufficiency, the surplus during all integrated NPDs must be at least as large as the deficit during all integrated NCDs, accounting for system losses.

In summary, the combined system of PV production and seasonal storage has been modelled based on the following basic assumptions:

1. The surplus production from the PV system during NPDs must be at least as large as the energy deficit during the NCDs, accounting for system losses (approximately 50 %).
2. The PV system size should be optimised in terms of total system price in correlation with the seasonal storage size since a larger PV system decreases the need for storage by granting additional NPDs.
3. The area required for the PV system should not exceed practical dimensions.
4. The volume required for the storage system should not exceed practical dimensions.

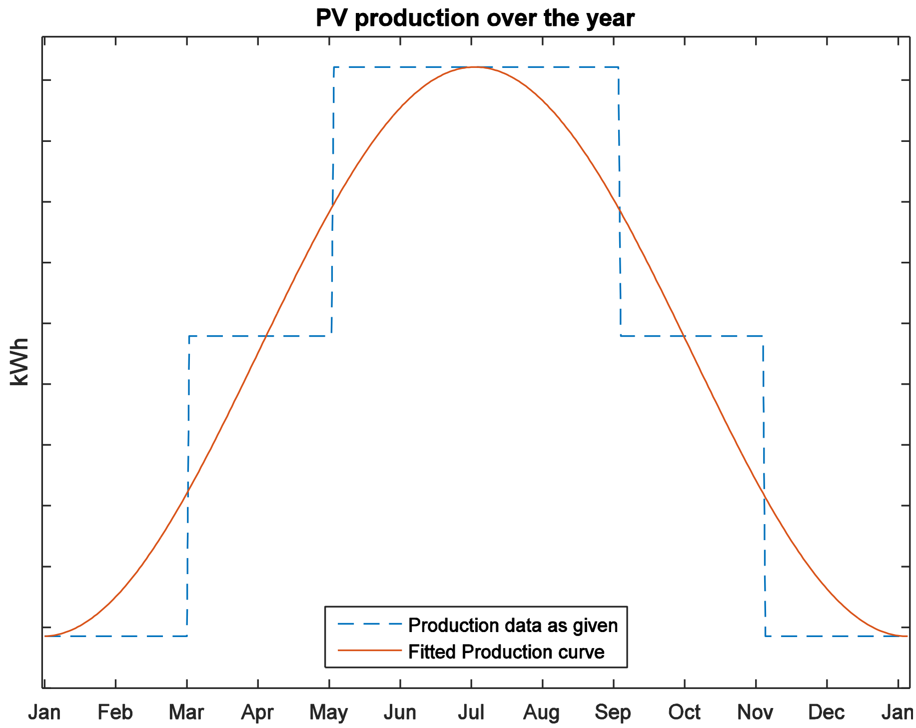

Figure 9: The energy production from the PV modules is estimated as a sinusoidal curve with the period of one year. The dashed step-wise constant curve describes the production data averaged per season as given in Widén (2014).

For a specific energy demand, there is a continuous range of possible value pairs for PV size and seasonal storage size. For a PV system where production exactly matches the energy deficit during NCDs, the storage system needs to be larger compared to if a larger PV system is installed. In addition, the price-optimal value pair for the two dimensions depends on the prices for seasonal storage and PV respectively. Figure 10 shows the optima for H_2 storage price of \$3/kWh and \$10/kWh, given a set PV price (\$1250/kW), and a set energy demand profile (3500 kWh/yr in total), corresponding to the combined improvement case in 2050.

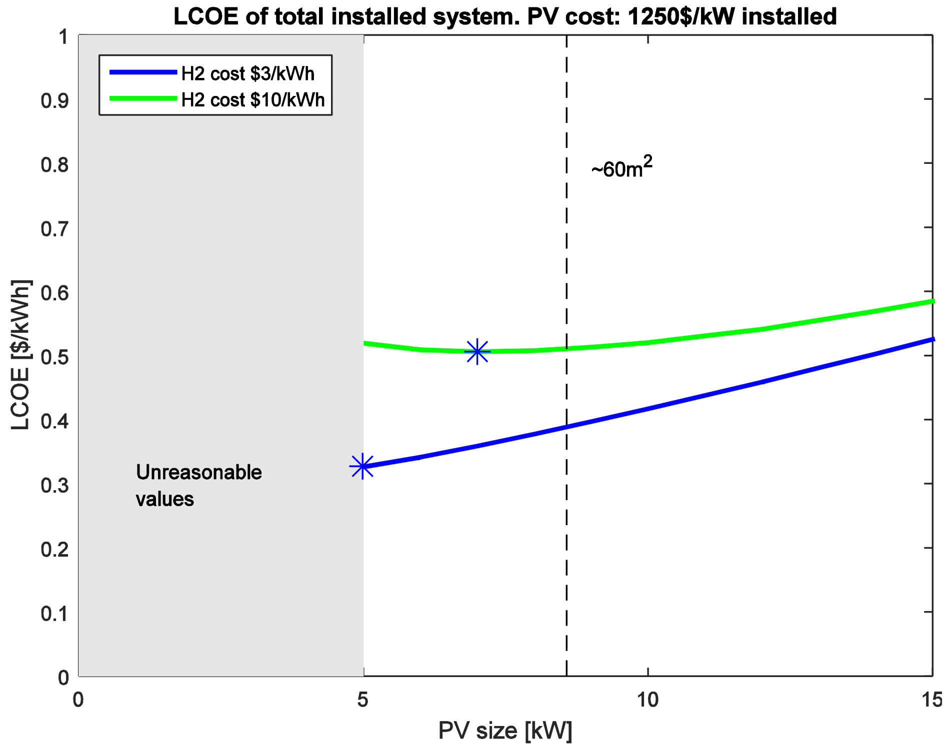

Figure 10: The price-optimal PV system size depends on the relative cost of generating surplus PV energy in summer compared to having a larger seasonal storage, and thereby on the price of H_2 storage. Dimensions that minimise the LCOE for the combined system are marked with an asterisk. Here, a demand of 3500 kWh_e has been assumed (corresponding to the demand reduction case). The calculation is done for a PV price of \$1250/kW and for H_2 storage costs of \$3/kWh and \$10/kWh respectively. The dashed line at 60 m^2 corresponds to the previously defined practical limit for available rooftop area.

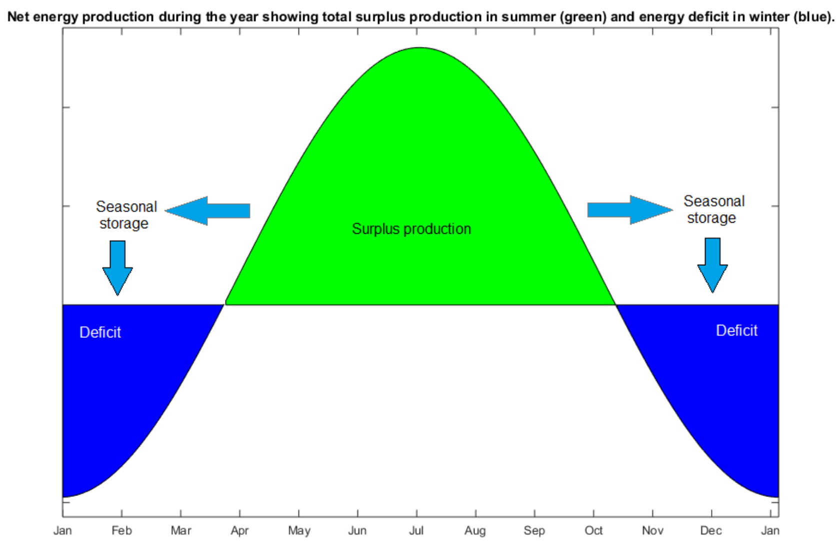

Figure 11: Net production of energy from system. Overproduction during the NPDs is converted to hydrogen in an electrolyser and stored. In winter when there is an energy deficit because of larger consumption and smaller production, the stored energy is converted back to electricity in a fuel cell. The green area needs to be at least as large as the total blue area in order for the system to be year-round self-sufficient.

7.4 Overnight storage

Overnight storage is dimensioned as the amount of production or consumption on a "net zero day", i.e. a day when production exactly matches consumption. This means that the battery should be able to hold the amount of energy produced during the last day before the deficit period starts and the seasonal storage becomes available.

The overnight storage also has to be dimensioned according to power requirements. All energy that is not consumed directly from the PV production will be temporarily stored in the battery. When energy is needed, it is withdrawn from the battery, which then has to be able to discharge fast enough to meet the peak power requirements for the system (see Section 4.3). Note that the Depth of Discharge (DoD) for the Lithium battery has been ignored. This is because, even though it would entail a slight over dimensioning of the battery, such effects are on the order of 10 % and thus within the margin of error for the system costs.

7.5 Conversion to and from seasonal storage

The *fuel cell* is modelled based on *average* power demand during the NCD period (i.e. winter months) and can thus only deliver that amount of power at any time. Note that the fuel cell is only used during NCDs since that is the only time that energy is drawn from the seasonal storage. The choice to use the average power demand value includes an assumption that some level of peak shaving has been achieved. This means that peaks in demand above the average value can be managed, as long as there is enough energy stored in the battery. This assumption is considered reasonable since all energy produced by the fuel cell passes through the battery system, which therefore works as an interim storage. The *electrolyser* is assumed to have the same power specifications as the fuel cell since it has to be able to convert electric energy to chemical energy (to be stored in the seasonal storage) at approximately the same rate as the fuel cell performs the opposite conversion.

Except for electricity, the fuel cell also produces *heat*. The amount of kWh_{th} produced is approximately the same as the kWh_e. Assuming that the electric energy produced is x, the amount of thermal energy produced is also x. Assuming a COP in the heat pump of N, the electricity saved from using that heat instead of producing heat via the heat pump is approximately $\frac{1}{N}x$. Assuming that the electric energy demand during the NCDs is Y, the relation between the electric energy produced by the fuel cell and the actual demand is $x = Y - \frac{x}{N}$ which means that the electric energy that the fuel cell needs to produce is $x = \frac{N}{N+1}Y$ if all heat can be used. Consequently the fuel cell is dimensioned based on the smaller x instead of Y. This calculation includes the assumption that the heat demand during the NCDs is at least as large as $\frac{x}{N}$, which is considered reasonable since the heat demand is largest during this period.

8 Results: System design and cost

Earlier sections have presented energy demand requirements for the households, as well as cost and technological performance of technologies suitable to make up the self-sufficient residential energy system. This section will describe the finalised design of the system and what it would cost, today and in the future.

It has been concluded that the technology combination most likely to make up a self-sufficient household level energy system includes PV, battery storage, hydrogen storage, an electrolyser and a fuel cell, as is presented in Table 9.

Table 9: Summary of system parts and their function

Power production	PV modules
Overnight storage	Batteries
Seasonal storage	H_2 storage
Energy conversion to seasonal storage	Electrolyser
Energy conversion from seasonal storage	Fuel cell

The flow of energy in the system is described in Figure 12.

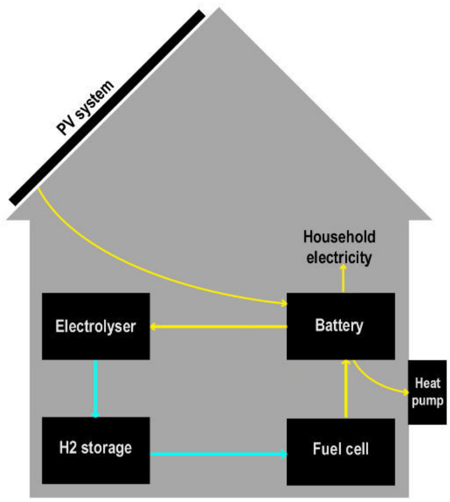

Figure 12: Schematic view of residential energy system as modelled.

The dimensions for the different systems depend on the total demand and the relative cost of each system component. Table 10 below shows the respective system part dimensions for each energy demand scenario. Observe that the low estimate value for H_2 storage cost ($3/kWh) has been assumed when optimising the dimensions in Table 10.

Table 10: System dimensions depending on total energy demand for the house.

Total energy demand [kWh]	H2 storage [kWh]	PV capacity [kW]	Battery storage [kWh]	EC capacity [kW]	FC capacity [kW]
22 000	13 000	32	60	3	3
9250	4500	14	25	1	1
6750	3000	10	20	1	1
6000	2500	9	15	1	1
3500	1500	5	10	1	1

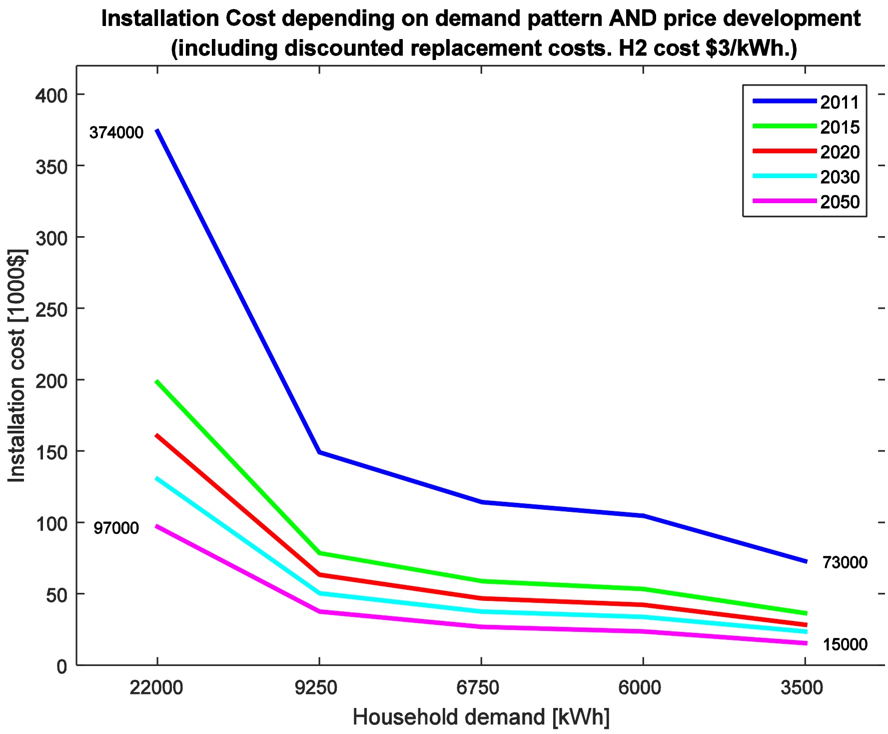

Figure 13: The installation cost depends both on the price development of technologies and the development in energy efficiency measures for the households. Replacement costs for technologies with lifetime less than 30 years are included (discounted to NPV). Note that the low estimate value for H_2 storage cost ($3/kWh) has been assumed when calculating the costs.

Previous sections have concluded that the total installation cost for such a system depends on two key factors, namely the *price development* of the technologies included and the buildings *yearly energy demand*. The system costs corresponding to each demand case are presented in Figure 13, depending on the price level development assumed to be achieved for different years. Each extreme value in the figure represents one development case as described in Section 3. The maximum value of the blue curve, in the upper left part of the graph, represents the *initial state*, without development in neither price nor demand reduction. The maximum value of the green curve, in the lower left part of the graph, represents the *price development case* whereas the minimum value of the blue curve, in the far right of the graph, represents the *reduced demand case*. The minimum value of the green curve, in the lower right corner of the graph, represents the *combined improvement case*. Results for each case are presented in more detail below.

Figure 14 presents the 2050 costs for different demand levels, divided into the cost for each system component. In this graph, costs are assumed to take 2050 values, and are thus fixed, while demand levels vary. Figure 15 presents LCOE values corresponding to the electricity produced during 30 years in the self-sufficient residential energy system with a demand of 3500 kWh/yr. Note that in Figure 15, demand is assumed to have been reduced to 3500 kWh/yr, and is thus fixed, while costs vary over time. A discount rate of 4% has been assumed here. This value is likely too high, since individuals seldom include discount rates when calculating private investments. A sensitivity analysis related to discount rate is presented in Section 9.1.2.

8.1 Initial state

As seen in Figure 13, the initial state, without improvement in technology prices or efficiency, would result in an installation price of 300 000 – 400 000 USD (~2 – 4 million SEK).

8.2 Price improvement case

The installation cost for a house with today's average energy demand (22 000 kWh/year) and the lowest estimated future prices, i.e. for the *price improvement case*, would be approximately 100 000 USD (~850 000 SEK). The price improvement case corresponds to the leftmost bar in Figure 14.

8.3 Reduced demand case

With today's prices but the lowest estimated yearly energy demand, i.e. the *reduced demand case*, the total system cost would be approximately 70 000 USD (~600 000 SEK).

The reduced demand case corresponds to the far left values in Figure 15, with a LCOE of approximately $2/kWh.

8.4 Combined improvement case

In the *combined improvement case* where price development as well as demand reduction has been realised, the total system installation cost would be approximately 15 000 – 20 000 USD (~120 000 – 170 000 SEK). The combined improvement case corresponds to the far right values in Figure 14 as well as in Figure 15, with a LCOE of approximately $0.3-0.5/kWh. These numbers should be compared to electricity costs paid today by Swedish end consumers of about 12 -15 US cents per kWh (as discussed in Section 4.7).

Assuming constant electricity cost for Swedish customers of 12 – 15 US cents per kWh_e, an installation cost of 15 000 USD would have a payback time from avoided costs of roughly 30 years assuming an annual consumption of 3500 kWh_e.

Table 11 presents the system dimensions that would be needed to fulfil demand in the combined improvement case. Observe that the combined improvement case, the system has an excess power production in summer of approximately 100 – 2000 kWh (depending on relative prices of PV and H_2 storage) that cannot be stored and used later and is basically lost, unless used for additional functionality such as cooling during warm summer days.

Table 11: System dimensions in the combined improvement case.

System dimensions	H_2 storage	PV capacity	Battery storage	EC capacity	FC capacity
Energy/Capacity	1500 kWh	5 kW	10 kWh	1 kW	1 kW
Physical dimension	4 m^3 (1000kg)	35 m^2	40 dm^3 (70kg)	0.2 m^3	0.2 m^3

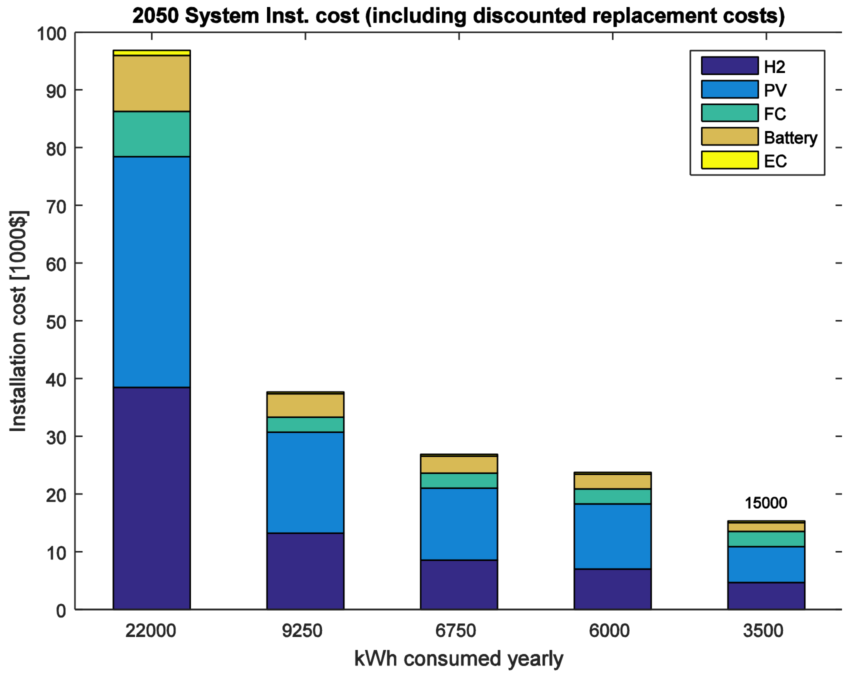

Figure 14: The total upfront installation cost divided into the cost for each system component. With demand reduction (following the x axis to the right in the graph), the total installation cost reaches a level of approximately 15 000 USD in 2050. In the final case, H_2 and PV costs make up similar shares of the cost, FC makes up approximately a sixth of the cost while the battery and the electrolyser make up small shares. Note that a H_2 storage cost of \$3/kWh has been used here.

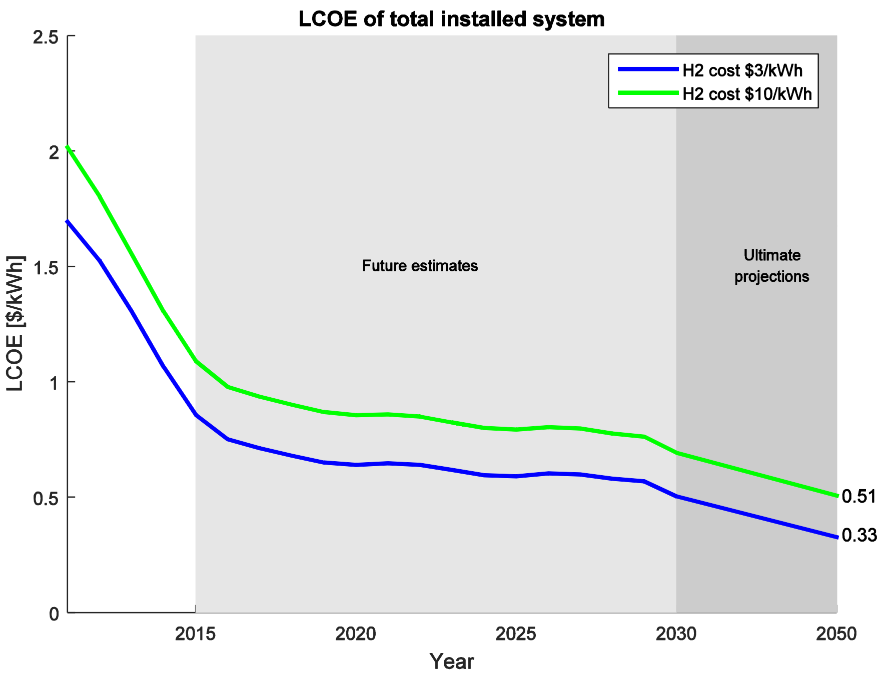

Figure 15: Resulting LCOE values for the reduced demand case depending on the price development of technologies, using a discount rate of 4%. At 2011 prices, the LCOE ranges from approximately \$ 1.7-2 /kWh while at 2050 prices the LCOE ranges from \$0.33-0.51/kWh.

9 Discussion

The following section discusses the relevance of the results presented in Section 8. Sensitivity analysis based on technology choices and economic assumptions is carried out. Thereafter follows a discussion on methodological choices and assumptions in system design and calculations. Some general thought on technology acceptance and global parallels rounds off the discussion.

9.1 Sensitivity analysis

9.1.1 Alternative technology choices

As a means of roughly assessing the impact of the technology selection process, two variations in system design have been investigated. Firstly, by installing a micro wind turbine, both PV production demand and seasonal storage requirements would be reduced. Secondly, a means of reducing the need for seasonal storage would be to buy fuel externally (slightly alternating the requirement of full self-sufficiency) to run the system during the days of highest demand.

The cost savings realised by these two alternative solutions have been estimated below.

9.1.1.1 Adding Wind power

Adding a wind power plant costs approximately $3500/kW (average from numbers in Table 22 in Appendix A). A 1kW plant would produce approximately 300 kWh during winter (assuming 120 days in winter and a capacity factor of 10%) and approximately 500 kWh during the rest of the year (240 days, slightly lower capacity factor). A rough estimate of the costs saving that this would bring is:

- 300 kWh less hydrogen storage, a cost saving of 900-3000 USD.
- 800 kWh less PV production is summer -> 0.8 kW smaller PV installation, a cost saving of 800 USD

In total, the saving would be approximately 1500-4000 USD, which is less, or at maximum similar in size, to the added installation cost for the wind turbine - which is approximately $3500 (see Table 22 in Appendix A). Moreover, maintenance costs for wind turbines are quite high, at least compared to PV and hydrogen storage. It is therefore considered unbeneficial to add a wind turbine to the system.

9.1.1.2 External fuel for running fuel cell

During times of high demand and low supply there could be a reason to buy fuel externally, since this has the potential to reduce the need for seasonal storage as well as over-production in summer. This situation arises in the darkest parts of the winter months; consequently it is there that the most benefit can be achieved by an external fuel infusion. Due to the nature of fuel cells, which is the power-producing unit in question, their lifetime is maximised by minimising the intermittency of operation. Thus the mode of operation considered is to run the FC on external fuel for a set number of consecutive days, ranging from 1 to 30 days. By doing so, the effective demand curve for the self-sustaining system alters into something similar to what can be seen in Figure 16 where demand (from storage) is zero during the peak consumption days in winter. This affects the total requirements on the system and reduces the price for both seasonal storage and PV production.

Regarding the type of fuel that could be bought and used to run the fuel cell there are several options. Buying hydrogen on tank is problematic, since, in order for it to be conveniently transported, it needs to be pressurised. Thus expensive carbon fiber tanks might be needed, potentially making the solution less beneficial. An alternative is to purchase some liquid fuel, such as methanol, which is easily transported, though this entails a fuel reformer, which adds an additional one-time cost for the system and results in a reduction of FC efficiency.

To estimate the fuel costs the price of methanol is needed, which is approximately 0.05 $/kWh (assuming a price of $0.28/kg (Ahlvik, 2002) and an energy density of 19.9 MJ/kg (Thomas, 2000)). Over the course of the system lifetime of 30 years, this amounts to a total additional cost of roughly $500. Considering the reduced storage and production demand, together with the methanol fuel costs, using methanol for 30 days per year would take the total system installation cost down from $15000 to approximately $12000. Note that the reduced efficiency in the fuel cell that comes with the reformation process is not included in this cost estimation, though it would diminish the potential cost reduction.

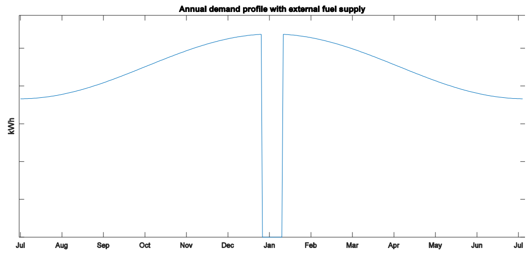

Figure 16: Demand requirements on the self-sufficient system change when external fuel is used during the days of highest consumption.

Considering the extra work and discomfort required to buy and transport the fuel, it is not judged beneficial to use this option for the sake of cost savings. However, it is a clear benefit that the system can potentially run on externally bought fuel since this allows for a reliable back up option if some part of the system is experiencing a fault. This reliability is probably important to have in order for the costumer to feel comfortable in investing in an off-grid system.

9.1.2 Parameter Tuning

The LCOE values presented in Section 8 are based on the assumption that the discount rate is set to 4%. In order to investigate how the results depend on this assumption, sensitivity analysis was performed. The LCOE was calculated for discount rates ranging from 1% to 8%. It can be seen in Figure 17 that for a very low discount rate, the LCOE could be as low as 0.2 $/kWh. On the other hand, for a very high discount rate (8 %), the LCOE value is around 1 $/kWh when using the high estimate for H_2 storage cost and 0.6 $/kWh if the low estimate is used. It is clear that the results depend on the discount rate selected and that this implies a large source of uncertainty for the calculation of a LCOE value, and consequently for the comparison with present electricity prices.

Moreover, sensitivity analysis has been performed regarding the 2050 cost estimates for each specific technology. By varying the price from 50% up to 150% of what was projected as the 2050 cost for each technology, a range of LCOE values from 0.3 – 0.65 $/kWh were obtained. This range is not significantly different from the range obtained without parameter tuning, which was 0.3 – 0.5 $/kWh. It should be mentioned however, that there is likely larger uncertainties in the future technology price estimates than ±50 %. The reason that a larger parameter sweep was not performed is that higher technology costs are represented in the time dependent results, see e.g. Figure 15 and the topmost graph in Figure 17.

It is clear that the technologies that have the largest impact on total system price are the H_2 storage cost and the PV installation cost (see Figure 14). Throughout the analysis the costs of the two systems are balanced against each other, where a high cost in PV can be offset by a large hydrogen storage system or a unnecessarily expensive hydrogen storage can be avoided by over-dimensioning of a cheaper PV system. The relative impact of each cost on the result depends to some extent on demand patterns. In a scenario where heat demand is high most of this will be required during the winter months, thus increasing the need for seasonal storage and the importance of the H_2 storage cost. In a low heat demand scenario the PV costs instead become more important relative to the storage cost. However, in all scenarios there are large uncertainties in the cost of H_2 storage, which is not to the same extent the case for PV cost projections (see Figure 3 and Figure 5). Consequently the hydrogen storage costs can be considered the most important key parameter to investigate when it comes to predicting the future costs of the self-sufficient residential energy system.

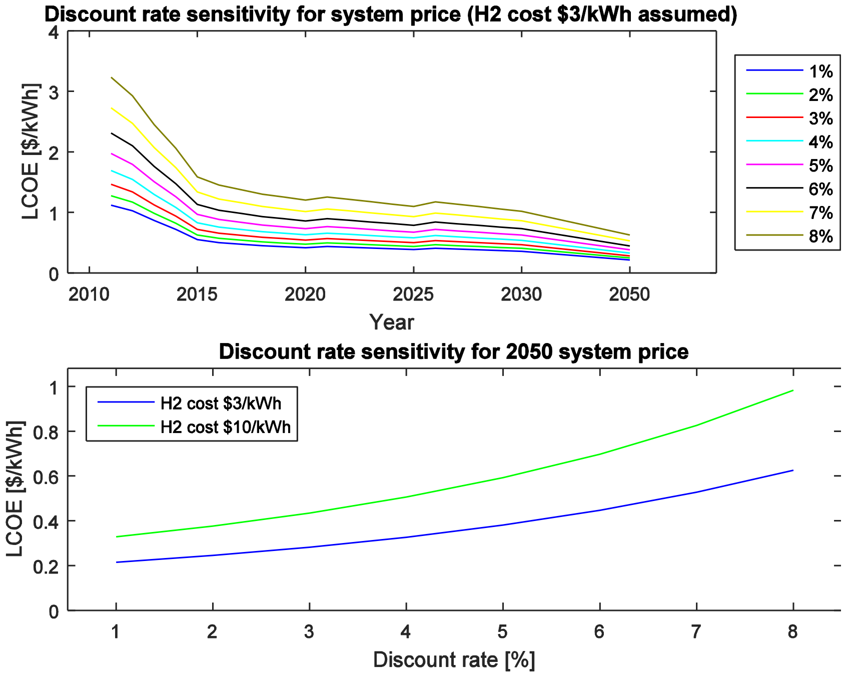

Figure 17: LCOE as a function price development for different discount rates and a H2 storage price of $3/kWh (top most) and the LCOE as a function of discount rate for the three H2 storage price estimations (lower most).

9.2 Method and assumptions

9.2.1 Technology availability and neglected costs

Throughout the data gathering, modelling and subsequent analysis, a number of assumptions were made with regards to the different technologies involved, concerning efficiencies and performance on the one hand and neglected costs on the other hand. A discussion about the reasonability of these assumptions is in place.

One central assumption is that the average household has a heat pump installed so that the cost related to the heat pump can be excluded from the cost for the self-sufficient system. This is not unreasonable since there is, already at present, a high penetration of heat pumps among Swedish households. When investigating the low demand case, it is therefore deemed reasonable to exclude the cost of the heat pump in the system cost. In the cases where houses do not have heat pumps the most likely alternative is *district heating*. For this study, such a connection would however violate the self-sufficiency criterion and is thus not considered. A further assumption is that heat pumps have a technological performance of COP = 4. This is a conservative estimate, since state-of-the art heat pumps have already show COP values of 4-5. A more optimistic assumption would be a COP of 7 or 8, assuming reasonable technological development. However, when heat demand has already been reduced substantially, higher heat pump efficiencies would not have a significant effect on the total demand.

A related consideration has to do with passive houses and energy consumption. One of the "boldest" assumptions made is that of the low energy consumption in the self-sufficient building of 15 kWh/m^2, and that the cost of achieving this is not included in the system costs. This assumption is based on the guess that most new buildings in the future will be passive houses and that older buildings have been renovated to have low energy consumption. For this to happen, a continued interest for increased energy efficiency is required, which is deemed reasonable here. The cost of achieving the low energy consumption then does not need to be allocated to the cost of the self-sufficient system, but will rather be a natural part of the cost of any building.

Moreover, the assumption that electric household appliances use 50% of today's average is deemed reasonable since many electric appliances are showing reduced energy usage already today, driven by costumer demand as well as certification schemes. One could even imagine larger reduction in household electricity demand, but it is difficult to estimate an exact percentage value.

Other neglected costs in the calculations performed in this study are those of a PV-coupled inverter and of a compressor needed to achieve high gas pressures. In many cases the cost of an inverter is included in the PV system price, since AC/DC inverters are installed with most present PV systems, and then should not be added separately. Furthermore, as argued in Section 5, an inverter is potentially not needed if the micro-grid is run solely on direct current. Coupled with the low cost of inverters it is reasonable to neglect inverters in the economic calculations for the self-sufficient system, which are not performed to enough accuracy for the effect of an inverter to be noticeable. Compressor costs could potentially add to the system costs but have here been assumed part of the storage system cost, when needed.

9.2.2 Technology selection

The technologies making up the system (presented in Section 5.5) were selected as the most cost-effective and versatile combination. However, details can be questioned and alternative combinations discussed. One possible alteration is to add a small-scale wind turbine in order to decrease the need for seasonal storage. This can be a good idea in theory, because a wind turbine produces the most energy in the winter months, when the storage system is strained the most, allowing for down-sizing both the storage system as well as the amount of PV modules. In practice though, a small-scale wind turbine is expensive (almost in the same price level as the total hydrogen storage system at $3/kWh) and the wind conditions close to residential areas are much too unfavourable for this to be a viable solution (see Section 9.1.1.1).

Another possible amendment is to reduce the winter storage need by allowing for some of the demand to be met by buying external fuel, such as methanol. During the few winter days with the longest nights, and thus the least amount of sunlight, the system demand can be met by feeding the FC a fuel other than the stored H_2 (to which extent this is done is completely scalable and optional). On the one hand this reduces the installation costs by reducing the need for storage. On the other hand it entails the addition of a fuel-reformer, under the assumption that the fuel bought is methanol (or some other liquid), for easy transport. Along with the need for transportation to buy the fuel the system configuration consequently becomes less practical. Furthermore the self-sufficiency criterion is no longer fulfilled, which might affect the perception of and value of the system solution significantly, though it might work as a back-up solution to ensure energy safety in all eventualities.

Besides the alterations mentioned it is likely that the optimal system configuration depends on many different factors and might look significantly different in another context or climate. For instance a multi-family building (or apartment complex) has a considerably higher electricity demand than a single-family home, but they might produce enough compostable waste to enable the on-site production of biogas. The same can be true for a commercial building, like a farm or a supermarket, where the demand curve would also likely be better suited for a PV system, with high cooling demand in summer and during daytime. Furthermore there are smaller restrictions on space, e.g. allowing for larger storage tanks. The increased scale might also make the system eligible for electro-fuel synthesis, assuming access to CO_2. As mentioned in Section 5 the process is presently only available on the MW scale, which is not a definitive limitation for the mentioned systems, where it might also be possible to find the necessary CO_2 source as input to the process.

Micro CHP based on fossil fuel or bio fuel could perhaps work as bridging technologies in the transition towards a more self-sufficient residential energy system. Such units are commercially available and have the potential of being environmentally sound. The latter is debatable, but if bio fuel is used it can (in a best case scenario) at least be carbon neutral, though there will still be emissions and pollution at the site of combustion. Since this study aims to look far ahead and consider the ultimately most interesting technologies for the residential setting, micro CHP systems based on fossil fuel or bio fuel have not been studied in detail here, though they might be mature and cost efficient, at least in the form of diesel generators.

Further complexity is introduced if transportation is integrated into the service required from the residential energy system, specifically using an electric car. As stated in Section 4.6 the additional demand corresponding to including an electric vehicle is between 500 and 6000 kWh_e/yr, which is in the same order of magnitude as the annual electricity demand for the entire household. Hence this entails further over-dimensioning of the system, though the vehicle battery can also serve as an extended storage option, potentially reducing the need for overnight storage. In conclusion, the inclusion of an EV has a negative impact on the economics of the system and it might be necessary to accept occasional charging of the vehicle in external locations, such as the workplace or a charging station.

9.2.3 Cost projections

All cost projections presented within this study are retrieved from published reports and thereby reviewed externally. It should be noted however that some projections are very optimistic and assume future system conditions such as increased production volumes and learning rates.

One technology for which price projections show especially dramatic decline is the stationary fuel cells. It is also noted that different data sources disagree somewhat on the future price of stationary fuel cell systems. The long-term target cost for stationary fuel cells matches rather well between different sources. This could partly be due to the tendency of the learning rates to be lower at later development stages (Stafell and Green, 2013), but the time needed to reach the target is still very uncertain. Here follows a discussion of the current state of the market for stationary fuel cells to further understand the possible scenario of significant price reductions.

Currently early adopters in different parts of the world deploy the technology at increasing rates, and a learning curve can be expected, taking prices downwards. Shipments of stationary FC systems (in number of units) grew by approximately 50 per cent in 2011, and then doubled again in 2012 reaching about 40 000-50 000 units installed in 2013 and 2014 alike (Fuel Cell Today, 2013). Within the SGIP program in California, one has noted that applications for financial support have been made up of a significant amount of fuel cell and storage technologies since 2012 (Iron, 2014). All in all, the cost of stationary fuel cell systems is expected to come down thanks to technological improvements as well as economies of scale.

Present niche markets, outside of the automotive industry, include Japan and Korea, who invest in residential micro-CHP FCs run on natural gas delivered through extensive gas networks. Other niche markets include materials handling (fork lifts etc.) and back-up power (BuP) (e.g. servers, telecom towers and other remote applications). These markets provide an early platform for the technology to grow and diffuse. Also it helps the applications with larger markets, such as micro-CHP, to expand and eventually diffuse. In 2008, micro-CHP had smaller market shares than e.g. BuP systems and was not even considered in the Greene and Duleep (2008) study. But just a few years later, as reported in Utrepi et al. (2012), the CHP application has far surpassed the market shares of the niche applications and is estimated to have sales double to that of the "conventional" markets by the year 2017 (in the US).

Development within niche markets for stationary fuel cells shows the possibility for large-scale diffusion. It should be noted however that stationary applications are still significantly more expensive than automotive fuel cells. Although many difficulties are avoided in the stationary setting compared to a mobile one, the key property making stationary applications more expensive is lifetime, which has to be considerably longer for stationary conditions.

When it comes to small-scale electrolysers, few data points have been found, and the numbers used are consequently uncertain. However, today's prices are only about four times that of the ultimate projection, and even at today's prices, the electrolyser would make up a small part of the total system installation cost. The price estimate for electrolysers is therefore not considered a large source of uncertainty in this study.

Regarding projections for future prices of batteries and PV modules, estimates have been found to be relatively consistent between different data sources. Battery and PV prices have already seen dramatic price reductions and these seem to continue. Furthermore the American motor company Tesla recently launched a residential size battery pack for a third of the reported IEA price as of 2010 and only around thrice the 2050 projection used in this study. Estimates for future PV price reductions presented in this report are not very drastic, giving a low amount of price reduction between today and 2050 (compare $1800/kW in Sweden in 2013, and $1250/kW in 2050).

It is instead with the hydrogen storage that the largest uncertainties lay, mainly related to the potential future price reductions that are very difficult to predict, due to the low current penetration of hydrogen storage systems on the residential scale. There are, however, factors indicating that hydrogen storage technologies can come down in price. Presently the carbon fibre composite costs constitute a large share of the costs for high-pressure tanks. Decreasing carbon fibre reliance thus has a large potential for system cost reduction. Also, cost development for the carbon fibre material itself will largely affect costs for hydrogen storage. It is consequently reasonable to assume a reduction of costs in the future. In order to account/compensate for the price uncertainty for hydrogen storage, two different price options were considered; $3 and $10 per kWh. This covers a range where the lower boundary of $3/kWh is an optimistic estimate of the storage costs, though it is higher than the USDOE long-term target of $2/kWh. The upper bound of $10/kWh lies in the range of prices for present storage options (see Figure 6) and is thus a conservative estimate for the price in 2050.

The prices for the PV system and the hydrogen storage constitute the largest share of the final system price and the results are therefore most sensitive to these two price estimations.

9.2.4 Cost measures used

Various cost measures have been explored in this study. Each cost estimate communicates different aspects of the costs associated with the installation and operation of the self-sufficient energy system. For instance, the LCOE gives a cost measure per consumed unit of energy. This can be directly compared to a future electricity price and avoided electricity bills. On the other hand it entails the selection of a fixed discount rate, which is wrought with uncertainty. Furthermore, the LCOE is not what the consumer actually experiences and is a rather abstract economic calculation that does not directly reflect the willingness of a consumer to invest.

A more relatable measure is the total investment cost, which is what the consumer actually has to pay to set up the system. While the high numbers of tens of thousands of dollars (~$15000) might seem intimidating to many house owners, this gives a direct number to compare to other investments. The cost of the self-sufficient energy system is e.g. comparable to renovating your kitchen (around $29000, according to Byggahus.se (2015)). When renovating a kitchen, customers seldom ask for a direct return on investment. Rather what motivates the investment is an improved comfort- or status level and the eventual market price increase for the house. Another way to present the investment cost is to make it part of a package option when selling a house. The options could be to purchase a regular house for $300000, or to purchase the same house for $315000 and get a self-sufficient home which will never need to rely on external energy or pay electricity bills, as well as being environmentally "friendly". The price of the self-sufficient energy system, when put in relation to the cost of the building itself, could then seem quite small and only a marginal additional cost.

Furthermore, when building a new house, the self-sufficient energy system allows for avoided costs from the initial connection to the grid. This cost can be between $3000 and $12000 (Vattenfall.se, 2015) depending on the distance to the connection point (below 200 m and around 500 m respectively). Thus it can in some cases be directly profitable to be independent of the grid, if the house being built has a large distance to the nearest connection point.

Also the direct economic factors are not the only thing that acts as a base for the decision to invest in self-sufficiency or not. Many other aspects come into play, such as the strive for individuality, the pursuit of status and to be a part of the prevalent trends. The decision could also be seen as part of a lifestyle or identity connected to the prospect of total energy security, no electric bills and a fully renewable energy supply. These factors add significant value to the system, which is not easily quantifiable, but might well drive homeowners and businesses in this direction, despite the economics not being entirely profitable in the short term.

9.2.5 System sizes

The dimensions of the system components arrived at and presented in section 8, and their corresponding physical sizes can be discussed in terms of their compatibility with an average Swedish house. Firstly not all houses have ~40 m^2 of unshaded, south-facing rooftop for a PV system. This is not necessarily a substantial restriction, since there is, in most cases, additional space available, e.g. on facades, garages or fences that can be used to reach the necessary PV size. In addition it is likely that more efficient PV modules will be available at a lower cost in the future, enabling the supply of more energy per unit area. Though in the few cases where it is not possible to cover the demand with PV, an alternative power generating technology can be used, either a more expensive PV technology or a micro-CHP system run on some type of fuel.

Most other components are of small sizes, e.g. the electrolyser and fuel cell systems are small enough to be easily integrated to the residential system. An exception is the hydrogen storage tank, of roughly 4 m^3. This in not unsubstantial, and its placement needs some consideration, be it in the cellar or separated from the building, above or below ground. A construction separate from the house should give more flexibility when it comes to the shape and size of the tank. To put things in perspective, one could compare the size of the hydrogen storage with the size of a woodpile having an energy density of between 1400 and 2000 kWh_{th}/m^3 (Biomass Energy Centre, 2015). To meet the present average annual heating demand in Sweden of 12200 kWh_{th} somewhere around 5.5 to 9 m^3 of wood would be required, which is substantially larger than 4 m^3.

9.3 Technology Acceptance

In order for the self-sufficient energy system to be more than just a theoretical concept, the customers must embrace the idea and want to install it. Concerns may arise in regards to having a hydrogen fuel tank in or near a residence, due to risks associated with gas leaks, flammability and explosions. Regardless of if the risks are real or not, apprehension from the customers could potentially slow down the diffusion process. This notion might speak in favour of metal hydride storage, even if such systems are currently experiencing other disadvantages.

Other components of the system presented here could also be subject to public acceptance issues. One example is that having a high-temperature fuel cell (or electrolyser), with temperatures between 600 and 1000 degrees in the basement might be intimidating. It poses an obvious safety risk and either needs to be properly insulated or cooled, or carefully placed to avoid accidents. Though it should be noted that this is not the only technology where accidents are a risk (compare pellet boilers or oil pans) and that it is only a concern for SOFC/SOEC systems and not for PEM technology. Low temperature fuel cells, such as a

PEMFC instead carry drawbacks related to lower efficiency and higher cost.

An important additional acceptance issue concerns the complexity of the self-sufficient system. There is great value in simplicity for a private consumer, who will likely often opt for the simplest solution, even though it might not be the most economical. Hence if the electricity grid were to provide a much simpler way to provide the same service, it might prove an obstacle to the DG technology diffusion. However, even though the self-sufficient system presented in this study contains many different appliances, it only requires low maintenance, mainly thanks to the absence of moving mechanical parts. Thus the issue of complexity is largely avoided. Moreover, a self-sufficient system can provide increased flexibility, allowing the user to adapt everything to his or her own preferences. This benefit could possibly be larger than the drawbacks of increased complexity.

9.4 Global outlook

One of the largest challenges for a self-sufficient household based on PV in Sweden is the lack of sunlight in the winter months. In a more beneficial climate there is more sunlight, which means a higher PV production capacity, and less seasonal variations. In such a climate (e.g. close to the equator) the need for long-term energy storage is eliminated, while the amount of PV needed is reduced. On the other hand, the complete absence of long-term storage requires more short-term storage (i.e. a larger battery). In total, such a placement should bring down the system cost significantly. A rough estimate (assuming equal energy demand) indicates that a PV system of 3 kW together with a battery of 20-70 kWh would be enough for annual self-sufficiency in a place such as Sahara, California or northern Chile, with arid climate, large amounts of sunlight and small seasonal variations. Such a system would cost roughly $5000-$10000, i.e. potentially as little as a third of the costs for the self-sufficient system in Sweden.

It is thus clear that self-sufficient houses might spread faster and earlier in warm climates. An interesting aspect is how things could develop in countries where few houses are currently connected to the power grid. Many developing countries tend to have lower quality grids as well as a large share of off-grid households, potentially giving further acceleration to the spread of DG and SC (see e.g. the Solar Home Systems project in Bangladesh, providing residential PV systems reaching 13 million off-grid beneficiaries as of April 2014 (IDCOL, 2015)). This type of system can help the penetration of renewables in such developing countries, perhaps enabling them to ”skip” the centralised, large transmission phase of the power system development and leapfrog straight to the DG system configuration.

10 Implications for the energy system transformation

Why is it interesting to study such an extreme scenario as a self-sufficient household-level energy system in Sweden? Is there even a slight chance that new innovations can challenge the established system with all its built-in infrastructure, optimised control systems and efficient supply chains? What could be the dynamics of a transition towards self-sufficiency for Swedish households, and what would be the consequences of such a scenario for the actors that currently dominate the system?

10.1 Sociotechnical Transitions

Much work has been carried out in the attempt of understanding how new sociotechnical innovations emerge and spread, and why it is so difficult for established actors to adapt to change. Christensen (1997) discussed the "Innovator's dilemma" as the conflicting interests in *sustaining innovation* and *disruptive innovation*. He explains the former as the, for a successful company, vital task of "keeping your customers happy" and the latter as something distinctly different since it changes the *value proposition*. This means disruptive innovation does not really, at least not initially, represent what the mainstream customer wants. However, a smaller group of customers are interested in the value proposition that the new technologies offer. Furthermore, the new innovations are often cheaper, smaller, simpler and more convenient to use which opens up new markets. When, eventually, the new technologies manage to deliver sufficient performance on the attributes that the initial customers valued, they have the advantage of also adding new value to the system. Christensen (1997) stresses that, from a managerial point of view, disruptive technologies rarely make sense during the years when investing in them is the most important. Instead, successful companies are very good at efficiently "killing ideas that their customers don't like" until the customers do want them, at which point it is too late.

One way of understanding technological change on a large scale is through the framework of Socio-technical systems (STS). Grübler (1998) describes STS as systems of interconnected clusters of technology and societal structures that have extensive impact on the economy and many aspects of daily life. The system operates under the conditions upheld by the STS and these conditions are highly resilient and resistant to change. Nonetheless, after a time, another cluster of technologies will emerge, set new rules and force the old STS to change and adapt to the new circumstances.

Turning our gaze back on history, society has seen many instances of great sociotechnical transitions where the prevalent system has been overturned and replaced by another, be it in political or technological matters. The changes were often triggered by new ideas or new technologies that altered the system in minor ways at first, but ultimately changed the behavioural patterns of society, in ways that were not possible to predict at the outset. An example presented by Grübler (1998) is the early automotive industry that completely transformed transportation and large-scale infrastructure, as well as mental models shaping how people lived their lives and built their cities. Many things combined and triggered the transformation in the automotive industry, the most important being the invention of the internal combustion engine along with the Ford mode of mass production.

10.1.1 Transition Dynamics

In order to understand the dynamics of large-scale technological and societal change, theoretical frameworks for transitions and systems innovation have been developed. Geels (2005) gives a comprehensive overview of the mechanism behind system transitions and its dynamics by asking the basic questions: "How do system innovations come about?" and "Are there any particular patterns in system innovation?".

Geels (2005) provides a concept called the *multi-level perspective* (MLP), describing the socio-technical system as having three analytical levels: the niche level, the regime level and the landscape level. The macro-level is formed by the *sociotechnical landscape*, which refers to the wider environment affecting sociotechnical development. Landscapes are beyond the direct influence of actors and cannot be changed at will. The meso-level is made up of s*ociotechnical regimes*, which account for the stability in the sociotechnical system. This stability is however dynamic since regime actors constantly perform incremental (sustaining) innovation in order to make their customer services better and more efficient. The micro-level of the MLP is formed by *technological niches*, where radical innovation takes place. Geels (2005) talks about niche markets as "protected spaces" that act as "incubation rooms" for radical novelties. He further stresses that the key point of the MLP is that system innovations come about through the interplay between dynamics at multiple levels. Adoption and spread of a technology does not occur instantaneously but rather follows a pattern of diffusion through space as well as time. The innovations play out in different phases, starting in niches in the existing regime where improvisation, experimentation and learning processes take place. Eventually, niche markets are starting to form and the technology can develop further. The third phase is that of breakthrough and competition with the existing regime.

Grübler (1998) describes the *diffusion pattern* of a technological innovation as an S-curve, starting with slow initial growth followed by accelerated growth and commercialisation and levelling off before reaching saturation. This pattern is shared among most technologies, though their final saturation levels as well as the time scale of the S-curve vary widely. The *diffusion rate* is given as the number of years it takes for a technology to grow from 10 to 90 % of saturation. This pace is determined, among other things, by factors such as the perceived relative advantage of the new technology, its compatibility with the current regime, its complexity and its testability (Grübler, 1998). When a STS has established its place in society it sets the standard of a new *paradigm*, shaping the behaviour, problem agendas and ways to do businesses of society (Bergek et al., 2008).

However, owing to vested interests and the power of the large amount of people involved in the old paradigm, this change is likely to meet resistance before being widely adopted (Grübler, 1998). When the crisis in the old STS eventually makes place for a new one to set the standards, the process of *paradigm shift* has taken place. One example of a paradigm shift (related to the example of the automotive industry mentioned above) is the transformation of the transportation sector, which by the end of the 19th century was dominated by horses and trains, but where the new paradigm of automobiles not only replaced the old system within a few decades but also expanded upon its functions and had a large impact on societal habits and patterns of growth (Grübler, 1998). This new system was the foundation of the paradigm currently in place today, almost a century later.

10.2 Application on the energy system

What parallels can be drawn to the Swedish power sector and the discussion of technological transformation and its dynamics? To put things in perspective, distributed power generation is certainly nothing new. Self-sufficiency in terms of energy was the dominating paradigm until the emergence of small-scale local power sources like windmills and water wheels (Ponting, 2007). Local generation was naturally the only possible option at the time, but we also know that later - with the industrial revolution - came new phenomena such as large-scale production, industrialised agriculture and the construction of a common infrastructure (Ponting, 2007). The centralisation of efforts in factories was in line with the centralisation of energy production in large heat and power plants. There was a huge increase in energy demand, and the energy was used for new things, which created a need for a common infrastructure through which energy could be efficiently transported (Ponting, 2007). The way energy was extracted, stored and transported changed society in a fundamental and completely unforeseen way. If such a transition could happen within the energy sector once, it is not implausible that something similar can happen again.

The Swedish transmission network is one of the world's oldest and will shortly require important upgrades (SVK, 2015). Many of the organisations and institutions involved as grid actors, as well as their processes and standards, are well established. This fact creates inertia in change and adaption processes. Nevertheless, new conditions are arising in the energy sector.

An increase in the prevalence of DG is ongoing, while energy storage technologies are on the rise and predicted to spread rapidly in the coming decades. The household and service sector today make up roughly half of the electricity consumption in Sweden, corresponding to approximately 70 TWh (Ekonomifakta, 2015). If this demand was significantly reduced, that could have important implications to the larger energy system. Counting a demand of 5000 kWh per household, and 2 million households (excluding multi-family buildings and apartment complexes), the demand reduction would correspond to approximately 10 TWh. One important factor in the transformation dynamics is the speed at which change occurs at different levels. The dynamics of a decentralised energy system is fundamentally different from the current centralised system, since investments are done from the bottom up rather than from the top down. DG and storage technologies that are not yet commercialised will stay in the innovation phase for varying amounts of time, but when the ball starts rolling and customers start to invest, diffusion rates can be high.

The Swedish government has set a target for the integration of renewables to 30 TWh of new renewable energy installed by 2020 as compared to 2002 (Regeringen, 2015). Simultaneously, a protracted national debate about nuclear energy decommissioning is ongoing. The need for energy production from renewable sources is thereby significant, and DG has the potential to make up an important share of this increase. These changes on the societal levels are examples of what Geels (2005) would call *landscape development* that puts pressure on the regime, and that can open windows of opportunity for novelties in technology and innovation. Increased integration of renewable energy creates new technical challenges for the grid actors and requires additional investments in upgrading grid infrastructure (Steen et al., 2015). It is likely that production and storage technology, as well as demand profiles, will have changed significantly within 30 years. This is approximately the planned economic life of central power plants and transmission infrastructure (RMI, 2014) and it is consequently important that the changes these innovations bring to the energy system are accounted for in new plans and investments.

One important sociotechnical change in the energy system is the introduction of a new network actor: the energy-producing consumer, also known as a “prosumer”. Prosumers are customers whose role has changed from being passive recipients of a service that they fully rely on, into market players with power to determine the household’s level of grid dependence (Wickström, 2014). Prosumers can choose to maximise their electricity sales to the grid, or to maximise self-consumption, thereby minimising their dependence on the grid. Factors affecting what is favourable are the price at which the prosumer can sell electricity, the cost of buying electricity from the grid, and the relation to other grid actors.

What is then the extra value that DG and storage offers that the old system does not? Most likely, the most important aspect is the notion of having the power to control your own production and consumption. Additionally, self-sufficient systems can likely offer more flexibility than current technologies – making it easier to adapt to customer specific requirements. Environmental concerns can also be a driver, where installing your own fully renewable DG system could be a concrete and graspable way of taking control of your personal climate impact. That motivation in itself should be seen as a powerful force in changing customer behaviour.

Swedish policies for how prosumers can sell electricity to the grid have been debated back and forth, which has delayed large scale integration of residential level DG. Swedish consumers (households or companies) interested in installing grid connected PV systems can apply for installation support from the government (Energimyndigheten, 2015b). The waiting list for this subsidy is very long however and there is uncertainty in when compensation will be received (Karlberg, 2015). Furthermore, Swedish utility companies are required to provide hour-based two-way meters for customers who choose to become micro producers of electricity. Since the start of 2015, a tax reduction is given to micro producers who consume more electricity than they produce (Energimyndigheten, 2015b). High levels of complexity and, to some extent, distrust in long term policy conditions might make customers finding it more beneficial to maximise self-consumption rather than maximising sales to the grid.

10.2.1 Dynamics of grid defection

How would utilities be affected if their costumers chose to maximise self-consumption at increasing rates, and eventually became independent of the grid?

For households, the most common tariff structure is the energy-based tariff ($/kWh). Hence, the grid operators' revenue depends directly on the energy used by their customers. Increased DG and storage will decrease revenue for grid operators since the utility company transmits less electricity. The utility companies' expenditures will not decrease at the same rate, and might even increase, which will probably force the utility companies to compensate by raising fees for the customers. An increase in fees will in turn create more incentives for the customers to increase their self-consumption or decrease their energy demand, see Figure 18 (Damsgaard, 2014).

In some particularly sunny parts of the world, e.g. Australia and Hawaii, utilities are already noticing a decline in grid-connected households (RMI, 2014). The development of increased independency means less income for utilities and, in the longer term, less potential for investments in grid infrastructure and services. If customers are to stay connected, it is of great importance that grid actors understand the dynamics of increased self-consumption and production of electricity and try to find ways to offer on-grid services that provide customer value worth paying for. Utilities might have to reshape the idea of customers being on-grid in order to get the service it provides, and instead see grid-connection as a service that must compete, and coexist, with other means of energy supply (RMI, 2014).

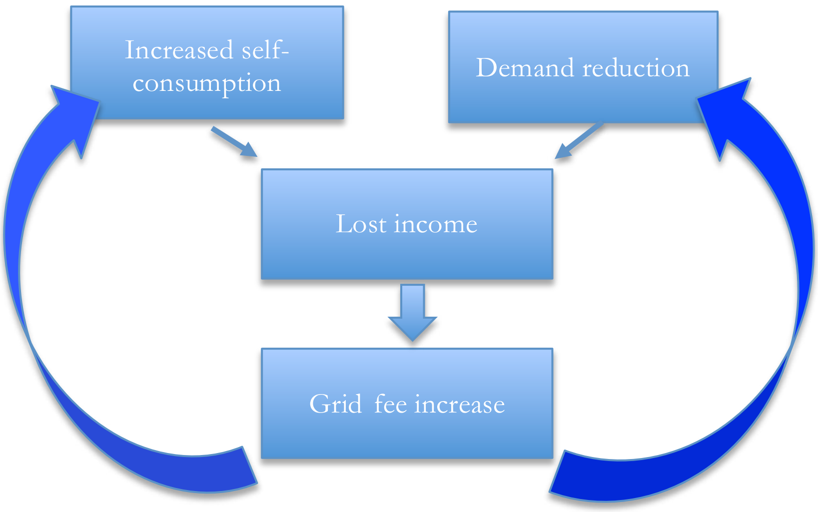

Figure 18: Increased grid fee due to lower amounts of energy distributed could act as an enhancing feedback mechanism, giving the customers even more incentive to increase self-consumption and energy efficiency. Figure based on Kind (2013).

Another issue that utilities will face as a consequence of the impacts from increased DG and energy efficiency is that with increased grid fees there is a risk for so-called *cross-subsidies*. These arise when utilities cannot discriminate between customer groups and all costumers will face increased costs. Consequently, in practice non-DG customers (who use more energy from the grid) pay for the lost income created by the entry of DG-customers (Kind, 2013; Damsgaard, 2014), provided that current tariff structures are maintained.

10.3 Consequences for the energy system

The development seen in DG and storage will cause vast changes for utilities and grid operators. System disruption will likely force them to adapt their business models to contend with the coming potential paradigm shift. Present tariff structures, based on the amount of electricity consumed, means that utilities will see a significant decrease in profit as DG and storage technologies continue to diffuse on the market, thereby enabling consumers to buy less and less energy. This means that under the present structure the utilities will be opposed to any development favouring DG, storage or energy efficiency. In order for them to be a part of the solution, and to survive the paradigm shift, the tariff structures need to change. Additionally, a change of tariff structures could be beneficial also for large-scale commercial energy producers. Since electricity prices are set based on marginal costs of production, an increased amount of renewable energy sources with basically no running costs pushes the electricity prices down. The current price structure worked well when investments were paid off earlier and fuel costs were the main costs for energy, but it does not necessarily fit the new "free energy" technologies. Low electricity prices make investments difficult for producers, something that affects renewable and fossil fuel producers alike (Kemp, 2015).

This study mainly deals with self-sufficiency, and complete independence from the electricity grid. However, actual grid defection is likely to be a big step for a customer since the grid could always serve as a backup “energy-pool” if needed. Conversely, if full grid defection is even remotely possible, then there are many hybrid scenarios on the way there that are likely to happen. In the report “The economics of load defection” from 2015, the Rocky Mountain Institute follows up on their report about grid defection (RMI, 2014) with introducing “load defection”. RMI (2015) explains it as a state where customers continuously reduce their grid purchases as an effect of higher electricity prices from the grid in combination with lower DG and storage prices - until the grid takes a backup-only role.

Since Sweden has a relatively well functioning grid, combined with low electricity prices, the conditions for on-grid customers are beneficial compared to other countries, and the likelihood for grid defection can be expected to be rather low. However, the grid is getting older and future quality of grid services depends on investments to come as well as the future mix of production units. If utilities experience problems financing new investments, it can have a negative influence on grid quality.

The action of actually taking the step from increased self-consumption to grid defection could be triggered by an unsatisfactory relationship with the grid owner or by a discontent with the quality of the services that the grid can provide. Moreover, the electricity price that a customer has to pay to buy electricity from the grid, as well as the price that a customer could expect when selling self-generated electricity to grid, influences the likelihood of staying on-grid or not. There are also potential *niche markets* in which self-sufficient systems can develop and ameliorate. Vacation houses with low energy use, especially in winter, are likely to be early adopters of the technology. Likewise, new houses built on the countryside, for which the expenses of connecting to the local grid would be substantial, could also constitute a potential niche market.

Assuming costumers are slowly becoming more and more independent of the grid and its market players, is there anything that grid actors can do to adapt and transform into strong players on the new market? Firstly, many grid owners are today restrictive in their promotion of DG, storage and energy efficiency measures, simply because they generate less income as a consequence and find it harder to cover their fixed expenses if less electricity is consumed RMI (2013). Instead of fighting the disruptive technologies now emerging in the power sectors, established actors should try to adapt in a way that enables them to benefit from the transition. By reshaping their business models, the utilities can not only align their profit-making incentives with their customers’ priorities, but also with social priorities, leading to reduced environmental impact and accelerated innovation (RMI, 2013).

It is not easy to predict a well-functioning tariff structure that can allow for synergies between utilities and prosumers. One possibility could be a shift to tariffs based on time of use or peak demand rather than by the kWh (Hall, 2015). Furthermore the shift will require utilities to refocus what they offer, from a product (kilo-watt-hours of electricity) to a service (e.g. installation and maintenance of PV systems, micro-grids and back-up generation) (Hall, 2015). This shift to a service-based energy sector, according to Hall (2015), means that the power bill would read "heat" and "light", rather than the amount consumed. Here, in contrast to the present situation, the energy provider would try to deliver the services as cheaply as possible, which will potentially result in great benefits in terms of energy efficiency.

Finally, the increased use of energy conversion and storage technologies (and things like electric vehicles) can increase the interconnection between energy systems, such as the power, transport and heat systems. Sectors that were previously independent of each other might interconnect, opening windows of opportunity for new business possibilities and further market transformation. System actors that manage to adapt and efficiently benefit from these emerging structures will find success in the new power sector.

Note that even if the self-sufficient system does not turn out to be cost-efficient or desirable in a Swedish setting, it is possible that there is an accelerated development in certain parts of the world with more favourable conditions. Once these initial markets act as a springboard for the spread of DG it is quite possible that grid defection and self-sufficiency will become the norm, on a global level. And even if Sweden misses the first phases of the development, the cultural influence from countries in the global community (especially on the European continent) will be felt. Once a new global norm has been established, the Swedish energy system will be affected as well, despite sub-optimal conditions, and it is not unrealistic to expect that the pattern of self-sufficiency will enter the Swedish system as well.

11 Concluding discussion

The study has found that a self-sufficient residential energy system could be affordable to Swedish customers within 30 years. In 2050, such a system could cost in the order of 15 000 USD which is less than many households are currently investing in home renovation projects. Investing in a self-sufficient energy system would likely take many years to pay off from a purely economic perspective. However, there are other benefits associated with a self-sufficient home, which offers additional value such as independence from local grid systems and fees. Additionally, in areas sensitive to power blackouts, self-sufficiency would be a means of increasing a households' control over its energy supply.

But what is the likelihood for the spread of self-sufficient households in Sweden? Since Sweden has a relatively well functioning grid combined with low electricity prices, the conditions for on-grid customers are beneficial compared to other countries, and the likelihood for grid defection could be expected to be rather low. However, the grid is aging and the future quality of grid services depends on future investments as well as the future mix of production units. If utilities experience problems financing new investments, quality can be influenced negatively. The configuration of production units that will be used in Sweden, or elsewhere, and the success of their integration into the existing system, depends heavily on political decisions and public opinion.

Electricity price development will be important for the direction of development of the energy system and can act as both a negative and a positive feedback mechanism. A high price will increase the incentives for households to install PV systems and vice versa. On the other hand a large amount of PV within the energy system can lower the electricity prices (at least during daytime). This means less incentive for grid-defection. Hence the electricity price both affects and is affected by this development, which is one of the reasons why the future price of electricity is very difficult to predict. Furthermore, the grid fees are likely to increase. They provide a larger incentive to grid defection than high spot prices, since the grid fee is solely a cost for the end consumer and does not affect the income from eventual kWh sales to the grid.

It is important to see that there is a range in the amount that different customers pay for their electricity. There will be a certain share of customers that have very high electricity prices who will have an increased incentive to maximise self-consumption. Today, some customers pay almost three times as much as others. Such customer groups generally have a small energy demand and can for example be owners of holiday cottages that are used only during certain times of the year. High price incentives and low demand (often with the majority of demand located in the summer months) makes such customers probable early adopters of technologies that allow for increased self-consumption. Likewise, when building a new house, there are significant costs for adding an initial grid connection. On the countryside where load points are further apart, this investment can be large and should be compared to the investment cost for a fully self-sufficient system, with no utility bills in 30 years.

Assume that self-consumption increases dramatically in Sweden, would this development be beneficial at the system level? It is clear that increased incentives for self-consumption would result in a system that is designed more on the level of the individual household, rather than on a system level. The end customer has more power to decide upon system properties, probably increasing the individual value of the energy system. On the other hand, more energy stays at the customer level without being shared with others in the system – something that can be inefficient from a system's perspective. When less energy is shared, there is a risk that one household has excess production that it cannot put to good use, while another household experiences an energy deficit and needs to import energy externally. The match between the system value and the individual value is not always perfect, and depends on the characteristics of the customer's energy needs.

Benefits on the individual level can be that the energy supply gets less sensitive to grid faults or blackouts. In addition, customers might find intrinsic value in being independent and not having to rely on others. Similarly, knowing that your energy is purely renewable and that you are personally taking concrete action to control your climate impact can have a value in itself.

One disadvantage on the system level is the risk for inefficiency when each separate unit over-dimensions its capacity, as mentioned above. In the combined improvement case, approximately 100 – 2000 kWh_e of excess power is produced during days of surplus production, which is not stored but lost. Note that the range in these numbers depends on the range of H_2 storages prices, affecting the optimal size of the PV and seasonal storage systems. Another possible disadvantage at the system level is the potential risk that self-sufficient customers use non-renewable energy sources as backup power, something that would reduce the environmental benefit of increased DG, storage and SC.

Nevertheless, increased SC can be beneficial for the grid in terms of less transmission (and thus transmission losses) and lower need for reinvestments. If the prosumers are still connected to the grid, it might also be possible to find ways to use the customers' energy storage to create balancing value for the grid system.

Finally, the scenario of a self-sufficient residential energy sector entails several advantages as well as significant disadvantages, at the individual level and the system level. With this in mind a potential hybrid scenario can be identified, in which DG assets and self-consumption increases, while not reaching 100% penetration, and where the national grid remains in use, but to a smaller degree. The underlying assumption is that grid actors are able to adapt fast enough to the changing conditions and that the grid value is clear enough to prevent large-scale grid defection. This would offer the individual benefits associated with increased self-sufficiency, environmental "status" and self-consumption, while still retaining the system benefits granted by the existing grid infrastructure. Grid investments can be diminished, while maintaining the high grid quality, as its function shifts to operating as a backup and balancing service and a large-scale energy storage.

12 Conclusions

A viable option, in terms of power, energy, space and weight requirements, for a self-sufficient household under Swedish conditions is a system including PV modules for electric power generation, a fuel cell and electrolyser system allowing for conversion between electricity and chemical energy in the form of hydrogen, a battery for overnight storage of electricity, and a hydrogen storage system. While such a system at present would be very expensive, entailing an investment cost of 300 000 – 400 000 USD (2-4 million SEK) for a typical single-family house, the cost could drop to about 15 000 – 20 000 USD (120 000 - 150 000 SEK) in 2050.

The drastic price drop assumes a confluent development towards more energy efficient buildings and devices and reduced cost and increased performance of all technologies that make up the self-sufficient energy system. Household energy demand has a large reduction potential, especially related to heating. It can be reduced from the present annual Swedish average of 22 000 kWh_e (with direct electric heating) to approximately 3500 kWh_e, using presently available technologies and building practices. The largest uncertainty relates to the cost development of hydrogen storage. Cost predictions used for stationary fuel cells are ambitious, and an additional source of uncertainty.

In countries with less seasonal variations in demand and production, the system could be reduced to including only the PV system for electric power generation and a (somewhat larger) battery system for storage of electric energy. This system configuration improves the economic conditions and poses fewer practical challenges than the system required in Sweden.

Finally, the dynamics of a decentralised energy system is fundamentally different from the current centralised system. The former has the potential to develop rapidly, with consumer-driven investments and relatively short planning times. Furthermore, positive feedback loops can arise and accelerate development. With this in mind, a future scenario in which self-sufficiency in energy is widespread among Swedish households is not unreasonable. Whether this scenario holds a place for a coexisting grid infrastructure depends largely on the adaptability of utilities as well as national policy measures undertaken.

13 Future work

Not covered in this study were, among other things, the investigation of the environmental aspects related to the envisioned development. There is a potential for environmental improvements due to increased supply of solar PV electricity, while there are possible negative effects of large amounts of chemical energy storage and an over-dimensioned system. The interplay between these, and other, features can be studied in-depth in order to further understand the impact of a development towards increased DG and self-sufficiency.

Another aspect that necessitates thorough investigation is the policy measures needed to allow for a large penetration of DG technologies and attempting to reach a system optimum. Furthermore a study is required on improved tariff structures that can enable the spread of DG technologies without causing grid-defection.

In addition, many technologies that might fit in this setting were not considered in this study, for reasons such as technological immaturity and site-specific requirements. This study has focused on available technologies and has not assumed substantial development in technological performance. Moreover, the approach has been to find a system that could be implemented in the average household, not putting specific requirements on the local geography or other conditions. Future studies could investigate a larger set of technologies in order to evaluate alternative system designs. It would also be interesting to study in more detail how the system conditions would change if transportation were included in the system boundaries, i.e. how the addition of an electric- or fuel cell vehicle could be integrated into the household system and what effects this would have on system properties and user experience.

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Johansson, Patrik (Professor, Condensed Matter Physics, Chalmers University of Technology), interviewed by the authors on 2015-02-16.

Wiberg, Erik (Analyst, Vätgas Sverige) and Karlström, Magnus (Editor-in-chief, OMEV Newsletter, Linköping University), interviewed by the authors on 2015-02-11.

Appendix A: Data Tables

Data tables gathered within this study are presented here, both as collected from each data source and after conversion to the unit used in calculations for this study.

Currency rates used all represent approximate 2015 rates. No difference has been made for numbers from different years, thereby neglecting inflation impacts as well as relation development over time between currencies.

Currency rates used are:

1 USD = 8.6 SEK = 125 JPY = 0.9 EUR

Table 12: Price development data for solar PV systems (installed costs) as collected per data source.

	2006	2007	2008	2009	2010	2011	2012	2013	2030	2050
Lindahl (2013) off grid SEK/W	100	95	90	80	70	45	26	27		
Lindahl (2013) grid connected SEK/W					60	32	22	16		
RMI (2014) $/W	9		8.5		7		5.5	4.5	2.3	1.5
IEA (2014) $/kW								2000	1000	1000
Energimyndigheten (2014) SEK/W								13-16		8

Table 13: Price development data for solar PV systems (installed costs) converted to USD/kW and rounded to nearest half thousand dollar value. Currency rate used: 1USD = 8.6 SEK.

$/kW	2006	2007	2008	2009	2010	2011	2012	2013	2015	2030
Lindahl (2013) Off grid <1kW	11500	11000	10500	9500	8000	5000	3000	3000		
Lindahl (2013) Residential grid connected <10kW					7000	3500	2500	2000		
RMI (2014) Residential <10kW	9000		8000		7000	6000	5500	4500	4000	2500
IEA (2014b) Rooftop PV									2000	1000
Energimyndigheten (2014)								1500		1000

Table 14: Price development data for electrolysers (installed costs) as collected per data source.

	2011	2012	2013	2050
Penev (2013)			1000 $/kW	
Richter et al. (2011)	4000 €/nm³			250 $/kW
Nikoleris and Nilsson (2013)			1000 $/kW	170 $/kW
Ursua et al. (2012)		1000 $/kW		

Table 15: Price development data for electrolysers (installed costs) converted to USD/kW nearest half thousand dollar value. Currency rate used: 1USD = 0.9 EUR.

$/kW	2011	2012	2013	2050
Penev (2013)			1000	
Richter et al. (2011)	1500			250
Nikoleris and Nilsson (2013)			1000	170
Ursua et al. (2012)		1000		

Table 16: Price development data for Li-ion batteries (installed costs) as collected per data source.

$/kWh	2009	2010	2011	2012	2013	2014	2015	2018	2020	2025	2050
RMI (2014)	2000	1500	1100	800	700	560	475				100
UBS (2014)		1100			500		360	200		100	
Cho et al (2015)						500					
IEA (2013)		900		800		600		400	300		
Tesla (2015)							350				

Table 17: Price development data for fuel cells as collected per data source.

	2009	2010	2011	2012	2013	2014	2015	2018	2020	2025	2030	2050
Andersson and Sundén (2013) (Enefarm)				2400 00 SEK /kW			5800 0- 6600 0 SEK /kW			4100 0- 4900 0 SEK /kW		
Satyapal (2009) USDOE												750 $/k W
IEA AFC (2014) (EneFarm)					2000 0 $/k W			700 00 – 800 00 JPY/ kW	500 000 – 600 000 JPY/ kW			
Itron (2014) (SGIP) 5kW system [$/kW]	1400 0	1200 0	1000 0	9000	8000	7000	6000		3000			
Upreti et al. (2012) 5kW system [$/kW]		1000 0						5000				
Staffell and Green (2013)												2600 $/k W*
Elmer et al. (2015) (EneFarm) [$/kW]	4246 4		3365 0		2100 0		5608				3000- 5000	

*$3800 whereof $1200 reformer cost

Table 18: Price development data for fuel cells (installed costs) converted to USD/kW and rounded to nearest half thousand dollar value (except for values below 1000 USD). Currency rate used: 1USD = 8.6 SEK, 1 USD = 125 JPY.

$/kW	2009	2010	2011	2012	2013	2014	2015	2018	2020	2025	2030	2050
Andersson and Sundén (2013) (EneFarm)				28000			7000				5000	
Satyapal (2009) USDOE H2 Programme												750
IEA AFC (2014) (EneFarm)					20000					4500		
Itron (2014) (SGIP) 5kW system	14000	12000	10000	9000	8000	7000	6000		3000			
Upreti et al. (2012) 5kW system		10000						5000				
Staffell and Green (2013)												2600
Elmer et al. (2015) (EneFarm)	42500		33500		21000		5500				4000	

Table 19: Price ranges for hydrogen storage as collected per data source

	Tank 700 bar		Tank 200-350 bar		Tank 20-45 bar		MH		Projec-tions
	Min	Max	Min	Max	Min	Max	Min	Max	
Stetson (2012) $/kWh	12	18.9	15.5	15.5			11.3	11.3	
Yang (2013) $/kWh	16.4	16.4							
Kevin and Simmons (2013) $/kWh	12	15	12	15					9.5
James et al. (2013) $/kWh	16	16	11	11					
Ulleberg et al. (2010)			4500 €/m³*	-					
Andersson, (2015)			500 SEK/nm³	-					
Andersson, (2015)					25 SEK/kWh	35 SEK/kWh			
Andrews and Shabani (2012) $/kWh			17	17	14	15			9
Satyapal (2009) $/kWh	23	23	15.5	15.5			15.6	15.6	2
Wang et al. (2012)					34 €/nm³	-			

* Volume at 200 bar. Recalculated to 9 €/kWh with 15kgH_2/m^3 at 200 bar and 33 kWh/kg.

Table 20: Price ranges for hydrogen storage converted to USD/kWh.

$/kWh	Tank 700 bar		Tank 200-350 bar		Tank 20-45 bar		MH		Projections
	Min	Max	Min	Max	Min	Max	Min	Max	
Stetson (2012)	12	18.9	15.5	15.5			11.3	11.3	
Yang (2013)	16.4	16.4							
Kevin and Simmons (2013)	12	15	12	15					9.5
James et al. (2013)	16	16	11	11					
Ulleberg et al. (2010)			10	10					
Andersson, (2015)			19	19					
Andersson, (2015)					2.9	4.1			
Andrews and Shabani (2012)			17	17	14	15			9
Satyapal (2009)	23	23	15.5	15.5			15.6	15.6	2
Wang et al. (2012)					12.6	12.6			

Table 21: Volumetric density for hydrogen storage technologies as collected per data source.

kWh/L	Tank 700 bar		Tank 200-350 bar		Tank 20-45 bar		MH		Future	Comment
	Min	Max	Min	Max	Min	Max	Min	Max		
Stetson (2012)	0.9	0.9	0.6	0.6			0.4	0.4	23-165	Achievable for MH
Satyapal (2009)	0.594	0.825	0.561	0.594			0.462	0.627	1.32	Target value
Theroretical*	1.3	1.3	0.6	1.05	0.06	0.135				

*Assumes a linear decrease in gas volume with increasing pressure, i.e. V~1/P.

Table 22: Price development data for micro wind systems (installed costs) as collected per data source.

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Diaf et al (2007) [$/kW]			2500								
Esmap (2007) [$/kW]	5370					4850					4450
IEA (2013) [$/kW]									2363		
Ruin (2014)										34000 SEK/kW	
Egen El (2015)											35000 SEK/1.5 kW

*Average of costs for presented <5kW turbine systems.

**Estimation of performance of demo 1.5 kW turbine from test park

Table 23: Price development data for micro wind systems (installed costs) converted to USD/kW.

$/kW	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Diaf et al (2007)			2500								
Esmap (2007)	5370					4850					4450
IEA (2013)									2363		
Ruin (2014)										4000	
Egen El (2015)											2700

Table 24: Summary of assumed O&M costs, lifetime and degradation rate by technology

Tech	O&M costs/yr	Lifetime	Degradation rate/yr
PV	$10/kW[1]	30 years[2]	0.5%[1]
Battery	$5[3]	12 years[4], 13 years[5] (5000 cycles)	0.25 %[5,6]
FC	3% of investment cost[7]	50000 - 60000 h[8] ~15 - 17 years*	<0.2% per 1000[9]
Electrolyser	3% of investment cost***	50000 - 100000 h[10] ~10 - 20 years** 20 years[4]	<0.2% per 1000 hours***
H2 Storage	-	25 years[4]	-

[1] Klintberg and Sommerstedt (2014)

[2] Thygesen Karlsson (2014)

[3] Hill et al. (2010)

[4] Andrews and Shabani (2011)

[5] Itron (2014)

[6] Braun et al. (2009)

[7] Richter et al. (2011)

[8] Elmer et al. (2015)

[9] Callux (2013)

[10] Benjaminsson et al. (2013)

* Assuming that the FC runs 24/7 during 150 days of the year (winter)

**Assuming that the electrolyser runs 24/7 during 200 days of each year. (It will not produce H2 24/7, but will likely have to be kept going to avoid frequent starting and stopping)

***Assuming same as SOFC

Appendix B: Summary of key assumptions

Self-sufficiency definition

"Self-sufficiency requires that dedicated energy carriers cannot be imported to the system, be it in the form of heat, fuel or electricity. Imported matter in the form of water (unheated), food or other consumption products, can pass the system boundary without violating the requirement of self-sufficiency."

Demand reduction

The houses in which the DG system is to be installed are assumed to be built following energy efficient technology and design, having the following characteristics:

- All heat is produced by heat pumps having a CHP value of at least 4 kWh_{th}/kWh_e.
- Passive house design is assumed to cut energy need for space heating to 15 kWh/m^2 in a standards single family building.
- Spill water exchangers are assumed to cut the need for energy to heat water by 60%.
- It is assumed that household electricity demand for a standard single family building could be cut in half by efficiency measures.
- A grid-independent house is assumed to have a natural tendency to "peak-shave", reducing power requirements to 3 kW peak.

Technology Costs

The price development of all technologies follow cost projections based on external sources and sometimes includes assumptions on learning rates followed by production scale up.

The following future costs are assumed in the system cost calculations for 2050:

PV: $1250/kW, FC: $1675/kW, Electrolyser: $210/kW

Battery: $100/kWh, H_2 storage: $3-10/kWh

A realistic cost of hydrogen storage is assumed to be $3/kWh, based on the USDOE long term target of $2/kWh. For sensitivity analysis, a cost for hydrogen of $10/kWh has also been investigated.

Inverter costs (for DC-AC conversion from PV) and eventual compressor costs (for compressing hydrogen gas into a tank) are not treated separately, and assumed part of the cost for PV or H_2 storage respectively.

System dimensions and technology performance:

- PV systems are assumed to be sized as integer kW-values, giving the minimum system size to be 1 kW.
- 1 kW PV is assumed to produce 1000 kWh of electricity during one year (Swedish conditions).
- A standard single-family house is assumed to have rooftop area suitable for PV installation of 60 square meters, giving a maximum PV system of approximately 9 kW.
- A standard single-family house is assumed to have at least 5 m^3 of available space, either in the cellar, garage or elsewhere on the buildings premises.
- Residential fuel cell and electrolyser systems are assumed to be sized as integer kW-values, giving the minimum system size to be 1 kW.
- Residential fuel cells are assumed to have an electric efficiency of 60%.
- Residential electrolysers are assumed to have an electric efficiency of 80%.
- Li-ion batteries are assumed to have a round-trip efficiency of 90%