DEGREE PROJECT IN THE FIELD OF TECHNOLOGY
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INDUSTRIAL MANAGEMENT,
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SIMON LUNDQVIST

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by

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Master of Science Thesis TRITA-ITM-EX 2020:209
KTH Industrial Engineering and Management
Industrial Management
SE-100 44 STOCKHOLM

Undersöker off-grid elproduktion i Sverige: Fördelar mot kostnader

av

Jesper Björkman

Simon Lundqvist

Examensarbete TRITA-ITM-EX 2020:209

KTH Industriell teknik och management

Industriell ekonomi och organisation

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Approved 2020-06-09	Examiner Niklas Arvidsson	Supervisor Fabian Levihn
	Commissioner Power Circle AB	Contact person Johanna Barr

Abstract

Over the past decade, technologies that facilitate household electricity production and storage have seen a rapid development along with a significant cost reduction. Research points to an increased share of household-produced electricity within the existing national grids across the globe. In some cases, self-sufficiency is possible where households are able to decouple from the grid and become independent on their electricity, in other words, go off-grid. Furthermore, this change puts additional pressure on how the electricity system is set up, which, challenges prevailing incumbents to adapt. Depending on the geographical location, circumstances for self-sufficiency varies. Sweden is a country with high seasonal variations with its Northern position, which raises the question of how off-grid households are feasible and, how they can receive traction.

To investigate possible changes within large technical systems such as the electricity system, which is a vital part of the society, theories within socio-technical systems have shown much promise. However, these theories often lack the more techno-economic aspect of concrete and future investment costs from a consumer perspective, suggesting an existing research gap. Hence, the purpose of this study is to provide further knowledge regarding off-grid applications in the Swedish Context. This is done by investigating what circumstances could trigger existing electricity consumers to go off-grid.

The research process and structure of the report can be interpreted as indiscriminate, however, the study has focused on combining theories surrounding socio-technical changes whilst applying techno-economic modelling to strengthen the work, similar to a dual paper study. Data was collected in the form of a literature review and interviews to provide a holistic representation of off-grid and its nexus to the electricity system. In addition to this, complementing modelling of grid-connected-, prosumer-, and off-grid households were performed.

Results point towards a scene where off-grid reaches grid parity within the coming two decades, which, will increase the economic rationale of investing in an off-grid. Opposingly, there is currently no economic rationale in off-grid applications considering the relatively low electricity costs in Sweden as of today. Moreover, conditions show promise if the adopters see beyond economics and, possesses a strong will towards independence. However, implications suggest that the high reliability and low costs of the Swedish electricity grid impedes the ability of new radical innovations to receive traction.

Furthermore, this study has contributed by filling the research gap between socio-technical changes and techno-economic projects in regards to electricity systems. Consequently, contributing to the academic field of socio-technical change, it has been shown that the combination of socio-technical change and techno-economic projections is applicable and beneficial. Additionally, it can be argued that the results of this study highlight that the consumer have a greater role in the development of off-grid applications than what the theories suggest. Lastly, the electricity system is a complex mechanism and, to further strengthen the perception of how a relatively new application, as in the case of off-grid, will impact the system, appurtenant suggestions for possible future research within the area are proposed.

Keywords: Battery storage; Grid defection; Grid parity; Grid tariff; HOMER Pro; Hydrogen storage; Off-grid; Off-grid applications; Partially off-grid; Prosumer; Prosumer household; Self-sufficient household; Socio-technical change; Socio-technical systems; Solar PV; Sweden; Utility death spiral.

Examensarbete TRITA-ITM-EX 2020:209

KTH Industriell teknik och management

Utforskar off-grid elproduktion i Sverige: Fördelar mot kostnader

Jesper Björkman

Simon Lundqvist

Godkänt 2020-06-09	Examinator Niklas Arvidsson	Handledare Fabian Levihn
	Uppdragsgivare Power Circle AB	Kontaktperson Johanna Barr

Sammanfattning

Under det senaste decenniet har teknik som underlättar hushållens elproduktion och lagring haft en hastig utveckling tillsammans med en betydande kostnadsminskning. Forskning pekar på en ökad andel hushållsproducerad el inom de befintliga nationella elnäten över hela världen. I vissa fall är självförsörjning möjligt där hushållen kan koppla bort sig från nätet och bli oberoende av sin elförsörjning, med andra ord gå off-grid. Vidare leder en potentiell förändring mot off-grid till ytterligare påtryckningar på hur elsystemet är uppbyggt, vilket utmanar många aktörers sätt att agera. Beroende på geografisk plats så varierar förutsättningarna för självförsörjning. Sverige är ett land med stora säsongsvariationer i och med sin nordliga position, vilket väcker frågan om off-grid hushåll är genomförbara i Sverige och hur de kan skulle kunna etableras.

För att undersöka möjliga förändringar inom stora tekniska system som elsystemet, som är en viktig del av samhället, har teorier inom socio-tekniska system visat vara till stor nytta. Däremot saknar dessa teorier emellertid den mer tekno-ekonomiska aspekten av konkreta och framtida investeringskostnader ur ett konsumentperspektiv, vilket antyder ett befintligt forskningsgap. Följaktligen är syftet med den här studien att ge ytterligare inblick om off-grid-applikationer i svenska sammanhang. Vilket har gjorts genom att undersöka vilka omständigheter som kan leda till att befintliga elkonsumenter går off-grid.

Forskningsprocessen och strukturen i rapporten kan vara svårtolkat, men studien har fokuserat på att kombinera teorier kring socio-tekniska förändringar samtidigt som man använder tekno-ekonomisk modellering för att stärka arbetet. Data samlades in i form av en litteraturstudie och intervjuer för att ge en holistisk representation av off-grid och dess koppling till elsystemet. Utöver litteraturstudie utfördes kompletterande modellering av hushållsanslutna, prosumer- och off-gridhushåll.

Resultaten pekar mot scenarion där off-grid når nätparitet under de kommande två decennierna, vilket kommer att öka den ekonomiska rationaliteten för att investera i ett off-grid. Det finns det för närvarande inga ekonomiska skäl till att investera off-grid-applikationer med tanke på de relativt låga elkostnaderna i Sverige idag. Förhållandena visar dessutom löfte om att potentiella användare ser förbi ekonomin och har istället en stark vilja mot självständighet. Implikationer tyder emellertid på att det svenska elnätets höga tillförlitlighet och låga pris hindrar nya radikala innovationers förmåga att ta få fäste.

Det är argumenterbart att den här studien har bidragit med att fylla forskningsgapet mellan socio-tekniska förändringar och tekno-ekonomiska projektioner inom elsystem. Samtidigt har studien bidragit till det vetenskapliga området kring socio-tekniska visat på möjligheten och fördelen i att kombinera teorier kring socio-teknisk förändring och tekno-ekonomiska förändringar. Dessutom kan det hävdas att resultaten av den här studie visar att konsumenten har en större roll i utvecklingen av applikationer utanför nätet än vad teorierna föreslår. Slutligen är elsystemet en komplex mekanism, och för att ytterligare stärka uppfattningen om hur en relativt ny applikation, som i fallet utanför nätet, kommer att påverka systemet föreslås lämpliga förslag för eventuell framtida forskning inom området.

Nyckelord: Batterilagring; Delvis Off-grid; Grid paritet; Off-grid; Prosument; Vätgaslagring; Självförsörjande hushåll; Socio-tekniska förändringar; Socio-tekniska system; Solpaneler; Sverige.

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Glossary

Distribution grid – *Final stage of electrical grid that distributes electricity to end users.*
Feed-in tariff – *Compensation for providing self-produced renewable electricity to the grid.*
Grid defection – *Disconnection from the electricity grid.*
Grid parity – *When power from an alternative energy source can produce electricity with levelized cost of electricity that is equal to or lower than buying electricity from the grid.*
Grid tariff – *Cost of being connected to the grid.*
Incumbents – *A company that holds a significant share of the market in an industry.*
Net metering – *Bi-directional meter that allows the individual prosumer to consume the electricity at any time, not only at the time of production.*
Off-grid – *Stand-alone power system that is not connected to the grid.*
Off-grid applications – *Technology that is used in a stand-alone power system, such as, solar photovoltaic panels, batteries, other forms of power sources, and energy storage.*
Partially off-grid – *A system that can produce electricity, however, still connected to the grid. Hence, a partially off-grid household is self-sufficient but uses electricity from the grid when necessary. Used interchangeably with the term "Prosumer".*
Prosumer – *A person that both consume and produce a product, in this case, electricity. Hence, a prosumer household is connected to the grid whilst also producing electricity from, e.g. solar panels. This term is used interchangeably with "partially off-grid".*
Transmission grid – *Network of transmission lines, power stations, and substations on the national and regional level.*
Utility death spiral – *Loss of utility demand due to grid defection, resulting in higher electricity costs for households still connected to the grid, which, could lead to further grid defection and even higher costs.*

Abbreviations

AC – *Alternating Current*
BESS – *Battery Energy Storage System*
DC – *Direct Current*
DSO – *Distribution System Operator*
EEA – *European Environment Agency*
Ei – *Swedish Energy Market Inspection Agency*
EV – *Electric Vehicle*
HEMS – *Home Energy Management System*
IEA – *International Energy Agency*
IRENA – *International Renewable Energy Agency*
KPI – *Key Performance Indicator*
LCOE – *Levelized Cost of Electricity*
MLP – *Multi-Level Perspective*
MRL – *Manufacturing Readiness Level*
NPC – *Net Present Cost*
NPV – *Net Present Value*
O&M – *Operations and Maintenance*
P2P – *Peer-to-Peer*
PEM – *Proton Exchange Membrane*
PV – *Photovoltaic*
R&D – *Research and Development*
RET – *Renewable Energy Technology*
SNM – *Strategic Niche Management*
STS – *Socio-Technical System*
TIC – *Techno-Institutional Complex*
TIS – *Technological Innovation Systems*
TM – *Transition Management*
TRL – *Technology Readiness Level*
TSO – *Transmission System Operator*
TT – *Technological Transitions*
VRE – *Variable Renewable Energy*

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Jesper Björkman & Simon Lundqvist.

Stockholm, June 2020

1 Introduction

In the following chapter, an introduction of the chosen theoretical field is given to provide the reader with a brief presentation about the study. Additionally, departing from the presented background, the problem formulation is presented together with the following purpose and research question of this study.

Sustainable transitions of electricity systems will have the potential of overcoming key challenges, such as, energy security, consumption of natural resources, and lowering emissions (Siemieniuch et al., 2015). Sustainability transitions, on the other hand, involves not only the incorporation of new innovative technologies but also the more social parts of consumption behaviours, institutional setups and knowledge that creates a more complex scene of change. Hence, a transition considering both the technological and the social aspects of a system must be referred to as a socio-technical change (Geels, 2002; Kemp et al., 1998). In a socio-technical transition, barriers and drivers for deployment may not only depart from the technological components but also in terms of actors, networks and institutions (Bergek et al., 2008).

The deployment of new technologies will often face financial barriers from the start, as well as lack of infrastructure compatibility and a low technical maturity (Geels, 2002; Kemp et al., 1998). Simultaneously, the potential user of the technology will not take any adoption decisions unless any incentives from adoption are visible (Jensen, 1982). Hence, the importance lies in the potential attributes, in relation to existing or other technologies, a user can receive from choosing to take on a specific technology (Rogers, 2010). Nevertheless, as time passes, a general situation is that the costs decreases and the maturity of the technology increases. Despite this, social barriers of deployment may still be present once the technological and economic competitiveness of the innovation has grown. At this point, the technological lock-in referred by (Unruh, 2000) plays a major role. Radical innovations are often poorly aligned with existing institutional setups that were created to support the existing technological regime and faces severe competition for incumbents with the interest of maintaining the current system structure as well as economic benefits of keeping the user costs low (ibid.).

However, there is evidence that triggers for change, such as sustainability concerns, may speed up the process of change and compete with the existing technological regime (Rip and Kemp, 1998) as well as the motives for adoption from the users not only depart from the original instrumental aspect of economic rational but also symbolic and environmental aspects (Noppers et al., 2014). Consequently, depending on the desired outcome of a socio-technical change, policy instruments and subsidy schemes can have an influential role towards the rate of adoption (Bergek et al., 2008; Geels, 2002; Kemp et al., 1998; Rip and Kemp, 1998).

This paper intends to investigate the technology of household electricity production. More specifically, self-sustaining systems consisting of Solar Photovoltaics (PV) and storage in Sweden and how the technology can come to be adopted by users whom today are connected, as well as dependent on the existing national electricity system. By taking on a future scenario perspective, the aim is to reduce the uncertainties around the potential take-off of self-sufficient households together with the subsequent effects on the electricity system. The thesis takes a socio-technical systems approach defined by the interrelationships between technology and institutional setups, actors and infrastructure that is further discussed in relation to a techno-economic modelling analysis households operating at different levels of electricity self-sufficiency.

Similar studies regarding the conditions for off-grid deployment have been performed from a specific nation or international perspective (Defeuilley, 2019; Hojčková et al., 2018) but there is a gap in studies related to the Swedish electricity market, as well as studies strengthened with modelling analyses. However, studies where Solar PV and, to some extent Solar PV plus battery storage, are investigated for the Swedish market exists (Energiforetagen, 2019; Palm, 2017; Palm and Tengvard, 2011; Swedish Energy Agency, 2016) but not any comprehensive studies of complete off-grid households.

1.1 Background Swedish electricity system

The Swedish Energy Agency (2019a) states multiple goals that align with UN's SDGs regarding energy security, the share of fossil fuels, and share of renewable energy. Currently, the Swedish power grid is highly reliable, very few outages last for more than a day across the nation. In fact, the Swedish electrical system is one of the most reliable and sustainable systems in the world (World Energy Council, 2015). Additionally, fossil fuels only make up 1,3 % of the electricity production while the transport sector is having a 75 % share of fossil fuels; however, this is steadily decreasing. Consequently, the continued decrease in the usage of fossil fuels in the transport sector puts more pressure on electricity production. Sweden also aims to have a 100 % renewable electricity production by 2040, a goal that also, implicitly, mitigates the usage of nuclear energy (Swedish Energy Agency, 2019a).

Being continuously discussed and considered as a present reality for the Swedish energy market is the topic of power capacity shortage. Meaning that the actual energy and power exists whereas the power grids are under dimensioned at a certain point of peak demand and thus cannot transport and deliver the desired level of electricity (Swedenergy, 2019). On different sites across Sweden, new connections of electricity users and organizations striving to increase their operations are forced to be put on hold because of this problem. Underlying reasons for this capacity shortage are not only the poor projections made 50 years ago which the grids are built from but also, on the consumer side, increased population, urbanization, electrification of the transport sector, and the digitalization of both individuals and businesses. Further, the upcoming transition of the Swedish power grid will have new requirements when the non-traditional wind and solar power become connected on a regional level to cover for this capacity shortage (Winnhed, 2019).

Local electricity production from the non-renewable sources is currently being downsized and a local capacity shortage in regions of Sweden is starting to become visible. Instead, the lost local capacity must be taken from the national grid. However, Svenska Kraftnät (SvK), the national grid owners, cannot respond to such events in a short period of time as the average time for permit processes and construction is almost 12 years. Nevertheless, in the shorter timeframe, SvK participates in collaborations that promote and enable technical developments and innovations to meet the challenges with a capacity shortage (Medelius-Bredhe, 2019).

Renewable energy supply creates a scene where power generation becomes variable and determined by weather conditions and further uncertain in terms of specific power output until the realization of the plant. Much depends on conditions from the geographical site and how it correlates to the demand from the load centres (Kondziella and Bruckner, 2016). The current situation on the Swedish energy market where solar and wind power becomes increasingly more implemented creates, according to the Swedish Energy Agency (2019b), a scene where system flexibility and balance regulations become vital for the future energy supply since demand and actual supply must be correlated. Moreover, a significant role is played by the consumers and how willing they are to increase their own consumption flexibility to cope with the actual supply (SvK, 2015). The Swedish population is generally engaged towards sustainable innovations and willing to cope with the surrounding situations to strive for sustainable development but it is argued that the almost non-existing economic incentives of being a flexible consumer result in a somewhat passive mindset towards energy consumption patterns (IVA, 2016; SvK, 2015).

1.2 Background Solar PV and Storage

From an electricity system perspective, Solar PV can be seen as a radical innovation that requires compatibility with existing infrastructures, institutions and practices (Kemp et al., 1998; Palm, 2017; Schleicher-Tappeser, 2012). Compared to other established means of electricity production, Solar PV can be seen as a disruptive technology because of its: (1) high reliability without any moving parts and almost zero maintenance during its operational lifetime, (2) possibilities for mass production and economies of scale, (3) scalability, meaning that efficiency does not depend on the size of installation (4) shorter innovation cycles with only weeks of installation, (5) compatibility of being connected at many different points of the grid instead of only at a few centralized power plants, and (6) advantage of having the feasibility of being connected at households behind the user side of the connection point (Palm, 2017; Schleicher-Tappeser, 2012).

Furthermore, over the past four decades, prices on renewable technologies such as Solar PV have drastically decreased. This is mainly due to an increased module efficiency and an increased demand in collaboration with government subsidies and initiatives that has fuelled market growth globally (Kavlak et al., 2018). The increasingly affordable PV panels have led to increased usage in the residential sector, allowing energy consumers to become prosumers (consumer and producers) (Nordling, 2017). PV panels with a storage system can facilitate electricity access for rural areas not connected to the grid, an off-grid system. This is a highly valuable solution for developing countries that lacks a fully operational national power grid. Whereas, in industrial countries where electricity access is a commodity, PV panels on a household can be an addition to the grid provided electricity to cut electricity costs. A household with only PV panels can, when electricity is generated but not consumed, sell it back to the grid. Alternatively, a storage system is installed to store unused electricity in, e.g. batteries or as hydrogen that can be consumed when the PV system is not generating electricity. Today, in Germany which is a far more mature market in self-sufficiency, every other PV panel is sold with a storage system, allowing more households to become self-sustainable on electricity (Philipps and Warmuth, 2019). Respectively, in Sweden, only 5 % of the consumers that applied for PV subsidies, also applied for a storage system subsidy in 2019 (Swedish Energy Agency, 2019c). Battery storage is a mature and efficient technology, however, it is not suitable as a solution for long term storage and seasonal variations that is required with the mismatch between PV produced electricity and demand in Nordic regions (Zhang et al., 2017). Instead, hydrogen storage technology is considered to be a promising technology for long-term storage in areas with high seasonal variations such as the Nordics (Kosonen et al., 2015; Zhang et al., 2017).

Off-grid systems provide a solution for consumers that either lacks grid access or, alternatively, wants to be self-sufficient. These systems often rely on renewable energy technologies such as Solar PV panels and wind turbines combined with energy storage technologies and generators (Guerello et al., 2020). off-grid systems are often low in operations and maintenance costs. However, the capital cost for investing in these systems are still relatively high but steadily decreasing (ibid.). As mentioned, off-grid systems can be a viable solution when providing electricity access to developing countries, not only providing households with electricity but also supporting public services and livelihoods (IRENA, 2019). On the other hand, off-grid systems can be seen as a vital component to support the push towards the increasing implementation of more decentralized renewable energy systems in developed countries (Quintero Pulido et al., 2019).

The scene of prosumers and solar panels installed on buildings create an optimal situation where energy, whether fed back to the grid or locally consumed, is generated directly at the load and transmission losses from large central power plants is avoided (Sommerfeldt, 2019). However, historically it has been a complex scene for prosumers to make use and sell their overproduction in the Swedish market since it is often small amounts involved, but the public interest increases along with the loss of regulations, implemented economic subsidies, and declining investment costs (Lindahl et al., 2018). Nonetheless, a potential future of increased small scale prosumers indicates a challenge in adapting and developing the national grid system since electricity will not only go in one direction but also coming back from the prosumer and fed into the grid (Swedish Energy Agency, 2019b).

Sweden is a geographically challenging country for applications within self-sustaining energy solutions concerning its elongated northern position with influential seasonal changes in the weather (RISE, 2018). Geographically considered, most of the installed solar power capacity is placed in the southern parts of Sweden (Swedish Energy Agency, 2018). Not only because of solar irradiation levels but also because of the local incentives which have played a major role in making Simrishamn and Orust two of the municipalities with the highest installed PV capacity per capita (Lindahl et al., 2018). Nevertheless, today, the investment aids households can receive for both Solar PV and storage are about to expire and there is an ambiguous question about its future existence (Swedish Energy Agency, 2020). The latest published number of actual installed PV capacity in Sweden was at the end of 2018 and estimated to 411.56 MW-peak consisting of 20.04 MWp centralized PV and 391.52 MWp distributed PV primarily set for self-consumption. Compared to 2017, this is an increase of 82 % in distributed PV and 294 % in centralized PV – displaying a rapid development (Lindahl et al., 2018).

1.3 Problem Formulation

Households within the Swedish electricity system are continuously increasing their share of renewable energy technologies, such as Solar PV and storage, to enable a decrease in their electricity consumption from the grid (Lindahl et al., 2018). Additionally, the economic rationale of investing in such technologies is much driven by the increasing module efficiency and steadily decreasing costs together with governmental support (Kavlak et al., 2018). Meanwhile, an ambitious goal of having 100 % renewable electricity production in Sweden by 2040 exists (Swedish Energy Agency, 2019a), which, implicitly, can make self-sufficient systems a vital component to support the transition (Quintero Pulido et al., 2019).

However, facing a potential large-scale deployment of household electricity production entails great challenges for a national electricity system, both, in adapting and developing a system that can support such a means of production (Swedish Energy Agency, 2019b), as well as to form subsidies that incentivise consumers who possess the ability to produce their own electricity to remain connected to the grid instead of going off-grid (Khalilpour and Vassallo, 2015).

Previous studies exist from scholars investigating the prerequisites for self-sufficient households in specific countries showing results of, for example, how local electricity production from households if integrated to the grid can increase the reliability of the grid and reduce capacity shortage through peak shaving (Hittinger and Siddiqui, 2017; Khalilpour and Vassallo, 2015). Despite this, the same studies show how countries that develop certain structures of grid-tariffs versus subsidies are facing severe a grid-defection and increasing costs of operating the main-grid as more and more households find profitability in leaving the grid. Hence, great importance lies in creating a setup that incentivizes households to support the system with net utility.

To explore the conditions for new configurations and potential transition pathways in national electricity systems from a socio-technical perspective is well-acknowledged within academia (Geels, 2002; Kemp et al., 1998). However, previous literature is displaying a low level of influence from techno-economic projections, such as costs of investing and operating a self-sufficient household, which is argued by the authors as an important aspect to reach higher reliability of the results regarding the scale of adoption and effects on the electricity system (Defeuilley, 2019; Hojčková et al., 2018). In addition, these studies are not aimed toward the Swedish market which, together with the lack of incorporating cost projections, point towards a gap in the existing research field that can be seen as relevant to explore.

That being said, it has been shown that self-sufficient households can support national electricity systems but also result in increased costs and challenges. Accordingly, for policymakers, incumbents, and other actors in the Swedish electricity system to understand the potential take-off with self-sufficient households and strive towards incorporating it in a sustainable path of development, the research field must be further explored.

1.4 Research Purpose

The purpose of this study is to increase the understanding of the rising phenomena of off-grid households and to recognise the circumstances required for a potential take-off in the Swedish context.

Additionally, by exploring both the techno-economic and socio-technical aspects with respect to off-grid households, the aim is to reduce the current research gap of studies connecting theories of socio-technical change to techno-economic projections. This, by exploring the techno-economic part based on modelling of economic and technical projections and the socio-technical part through well-accepted theories in the field and thus being able to strengthen or contradict the outcomes.

Furthermore, since this work will explore the relatively unexplored subject of complete self-sufficient households in Sweden, it is arguable that this paper will be delivering a foundation of insights for Swedish electricity actors to support the understanding of possible future developments.

1.5 Research Questions

The following main research question was established:

RQ What are the prerequisites for off-grid applications to be used in the Swedish electricity system and by its existing consumers?

Whereas sub-questions found relevant to support the research question, as well as bridge the research gap between socio-technical and techno-economic projections of off-grid applications, was established to the following:

SQ1 What are the drivers and barriers for off-grid electricity production in Sweden?

SQ2 What is the economic rationale of investing and running off-grid and partially off-grid applications today and within the future?

SQ3 Why would a potential adopter invest in off-grid applications?

SQ4 How could a transition of the Swedish electricity system form with off-grid applications?

SQ5 What is the implications of policies and regulations on off-grid applications?

1.6 Delimitations

This study will be considering the Swedish electricity system and its potential development. This means that despite Sweden´s electricity system situation of being interconnected with other countries, it is not taken into consideration. Therefore, the application of results from this study will be limited to the Swedish market as the geographical conditions, policies, subsidies, and economic instruments differ from most countries.

The purpose is not to investigate how a beneficial set of policies, subsidies and economic instruments can be formed, but only taking already made projections and use it as points of departure when investigating the economic rationality of self-sustaining electricity systems. Consequently, the results will differ to a certain degree depending on how these sets of assumptions are implemented. Available techniques for self-produced electricity systems will be limited to Solar PV. Other techniques exist and might be suitable, such as wind power and small scale hydro, but will not be considered since the study intends to investigate households that are not located in remote areas, where wind power and small scale hydro is often unavailable. When modelling each household, it will only be modelled as a single-family house, excluding multi-family houses or communities. Other appliances exist e.g. industries and companies but will not be considered. Additionally, an off-grid solution with hydrogen storage is considered and examined, even though solutions such as diesel generators could serve the same purpose. However, with sustainability as a focus area, fossil-fuel solutions are excluded from this study.

Furthermore, the modelling part intends to strengthen the results acquired from a more theoretical and socio-technical perspective. Hence, it is detailed enough to do this, however, delimitations are required in some areas due to the choice of modelling software and access to data, which, are further explained in the study.

2 Literature Review

The purpose of this chapter is to display a review of published literature on the chosen academic topic and to define a set of theoretical lenses that will help to explain, predict and understand a certain phenomenon. Firstly, a brief investigation of the academic field will show the reader findings from previous studies. Secondly, this chapter will show the reader the chosen theoretical foundation as well as an explanation for its applicability. Thirdly, a concise conceptualization of how the theories will be used together with its boundaries and, lastly, a thorough explanation of the different theories. Overall, the theories presented in this chapter will be used to guide the research, in parallel with the modelling outcomes, to further strengthen the findings with the aim of delivering a solid level of analysis.

2.1 Perspectives of household electricity production

The concept of both consuming and producing electricity is defined as prosumption where individuals, instead of being either a producer or consumer, takes to role as a *prosumer* (Ciuciu et al., 2012). Here, the historically passive consumer instead becomes an active distributor of electricity to the system (Parag and Sovacool, 2016). By including prosumers into the electricity mix, renewable energy produced by the prosumers can be used as a new source of energy and further shared to other people connected to the same grid (Ciuciu et al., 2012; Razzaq et al., 2016). Consequently, prosumers are said to potentially compete with incumbents and existing infrastructure (Parag and Sovacool, 2016). On the other hand, projections from Skopik and Wagner (2012) and Parag and Sovacool (2016) pointed towards a scene where the prosumption and an electricity sharing economy could help address the social, economic and environmental challenges related to the increasing energy demand by diversifying the electricity supply.

Nevertheless, it is of importance to understand, when exploring self-sufficient households, that such means of production, in general, follow two different paths. Either towards complete off-grid which is a rather disruptive scene where self-sufficient households manage their production and consumption autonomously without any connections to the grid. The second path is described as a future of prosumers who still engage with the grid-connection (Parag and Sovacool, 2016).

Renewable energy generation that adds electricity locally in distribution grids produces multiple benefits to the power system. Prosumer households could provide grid flexibility by utilizing self-produced electricity and storage in order to shave and reduce the load during peak hours (Bost et al., 2016). The locally added electricity can specifically mitigate upstream overload of distribution lines, reduce electricity transmission losses, and improve the reliability of electricity supply (Starke et al., 2019; Y. Liu et al., 2019). Consequently, in the larger transmission grid, the results of improvements on the distribution lines will result in lower pressure towards potential required transmission grid upgrades (Y. Liu et al., 2019). Additionally, a study by Marnay and Lai (2012) indicated that the option of increasing the share of small scale microgrids to support a national electricity system and leave the old paradigm of utility-scale electricity supply could be more cost-effective than improving the upstream traditional energy system.

The energy system is facing challenges of integrating the large proportion of variable renewable energy into the system. Hvelplund (2006) argued that during a rapid integration of variable renewable energy into the energy system, local energy markets were a key objective to fulfil the objective of integration. Additionally, as smart grids enable the end-users to become prosumers, the energy markets need to integrate the prosumer perspective into the decentralized business models to satisfy the intention, as well as, capture the system benefits from prosumers (Linnenberg et al., 2011). Structuring electricity market places that utilize the benefits of prosumer generation as well as minimizing the potential welfare losses from self-sufficient individuals going complete off-grid are a key objective for policymakers (Parag and Sovacool, 2016).

If prosumers with sufficient generation and storage are unable to find any benefits from being a part of the distribution networks and transmission lines, they will potentially find incentives for going off-grid (Morstyn et al., 2018). This is however only said to be arguable if the individuals can manage to install enough production and storage capacity to meet their needs. Limitations for such a scenario is dependent on the geographical location, economical driving forces and technological development of self-sustaining technologies (Parag and Sovacool, 2016).

To integrate the prosumers into the system, scholars argue for different settings of markets. Ranging from the independent "island" market where prosumers operate detached from the grid to a market where the prosumer, connected to the grid, only acts as a flexible load of the main system (Espe et al., 2018; Lavrijssen and Carrillo Parra, 2017; Muqeet et al., 2019; Parag and Sovacool, 2016; Zhang et al., 2018, 2019). Peer-to-peer (P2P) trading is a concept inspired by the sharing economy which promotes collaborative consumption of resources (Hamari et al., 2016). In their work, Zhang et al., (2018) present a result of how P2P energy trading can reduce the need for energy exchange from Transmission system operators (TSO) and Distribution system operators (DSO) and further balance local demand issues. However, depending on the energy policies, laws, and energy trading systems the outcome can look different. Additionally, results show that P2P energy trading encourages consumers and prosumers to become aware of their energy consumption and act after the availability of energy.

2.2 Motives for adoption

The adoption motives by organizations and individuals are a quite complex and much influenced by behavioural and economic factors departing from both the demand and supply side of innovation (Tidd and Bessant, 2018). According to Jensen Jensen (1982) the motives are vital because an adoption decision will not happen unless the adopter itself gain some incentives from adoption. Historically, Renewable Energy Technologies (RET) has been framed as innovations for the environment and, thus, imply that the main motive is the environmental benefits from the technology (Stern, 2000).

However, other studies show that the motive for adoption of RETs is primarily the economic rationale and profitability opportunities (Michelsen and Madlener, 2013). Together with the environmental and economic/instrumental motives, Noppers et al. (2014) identified symbolic motives, similar to the behavioural, as well. Symbolic motives, that is, how the sustainable innovation can signal positive characteristics to oneself and others. Overall, the group of non-traditional renewable energy adopters i.e. individual households and small scale communities, are a heterogeneous group with different motives. Hence, a key motive of adoption is not present but rather a combination of instrumental, environmental and symbolic motives (Bauwens, 2016).

Worth mentioning, the motives for adopting home Solar PV solutions are explored to a higher degree, whereas the motives for investing in storage as well as complete off-grid households remain kind of unexplored. Nevertheless, as storage solutions and off-grid applications are in a much lower state of maturity one can see how the adoption have similar characteristics as of home Solar PV solutions in the early stages and thus it is of interest to this study.

Instrumental

First, the *instrumental motives* include the relative advantages in terms of the technology's functional use in relation to the cost (Noppers et al., 2014). The advantage itself can be different among potential adopters e.g. some might prefer cost reduction whereas others prefer reliability, meaning that advantage cannot be seen as fixed (Michelsen and Madlener, 2013). Most potential adopters of RETs are motivated on finding long-term investments that can lower the electricity bill and eliminate other costs (Nygrén et al., 2015).

Studies on the Swedish market and its motivational factors for influencing the homeowners decision on adopting small-scale RETs pointed towards the homeowners will to utilize the natural resources available in the close environment (Palm and Tengvard, 2011). Findings from Nygrén et al. (2015) showed how one type of household owners adopted small-scale RETs because of their wish to improve the energy efficiency. Moreover, a motivation to have individual production as a means of becoming self-sufficient can generate advantages if situated in the rural parts of Sweden. People desiring to live near nature and be self-sufficient, from growing their own veggies to producing their electricity can find those advantages to be larger than the economic downturns (Palm and Tengvard, 2011).

Symbolic

Second, the *symbolic motives* derives from symbolic status of usage from sustainable innovations and can have a large effect on purchase intentions. For example, symbolic attributes could encourage adoption of sustainable innovations since it can signal that the adopter is a green or an innovative person (Noppers et al., 2014). Sustainable innovations, in general, holds drawbacks in terms of a higher price or lower user convenience, despite this, instrumental drawbacks can become less important compared to the potential symbolic motive of adoption. Creating an interesting stimulation that if the instrumental attributes are perceived as low for the sustainable innovation, the symbolic status motivation from potential adopters can become even higher (Griskevicius et al., 2010).

Households taking on home Solar PV by symbolic motives tend to be the more later adopter. Moreover, a rather disturbing aspect of the symbolic motivation could arise with the future as the adoption of home Solar PV could increase and thus the symbolic value shifts from status regarding innovativeness towards more as a social norm (Mundaca and Samahita, 2020). Consequently, if a social norm of having home electricity production realizes, the deployment could launch in numbers because of, for example, individuals fear of being the one who is not pro-environmental (ibid.).

An interesting aspect of symbolic motivation, in regards to the Swedish market, is how individuals could invest in home Solar PV to act as a role model and set example for others (Palm and Tengvard, 2011). The visibility of PV could encourage neighbouring households to invest and thus result in a peer effect. This is proven to be a substantial motivator and driver for adoption in Sweden from Mundaca and Samahita (2020) where peer effects, in particular, can reduce many of the uncertainties regarding the innovation and thus, indirectly, shorten the decision making time.

Environmental

Third, the *environmental motives* is exactly what it says and a sustainable innovation, by its nature, have less negative environmental impact than other non-sustainable alternatives. However, in regards to the adoption of sustainable innovations, the importance of environmental motives compared to other motives are relatively unexplored since most studies of environmental attributes exclude the symbolic and instrumental attributes (Noppers et al., 2014). Additionally, from Nygrén et al. (2015), an environmental motivator can be the aim to support product development within sustainable innovations.

In the recent study by Mundaca and Samahita (2020), results showed that the early adopters of home Solar PV in Sweden was motivated by the environmental concerns. Further, a concern regarding the pro-environment motivation was found meaning that once it becomes more of a social norm to have home Solar PV, early adopters and pro-environmental individuals may no longer find it motivating to adopt the technology. In Sweden, many households are already provided by green electricity and thus the environmental motivation could have a lower impact on the Solar PV uptake unless the households hold a high dissatisfaction of their electricity suppliers (ibid.).

2.3 Adoption push

The classic concept of technology innovation and its adoption following a s-shaped curve where the cost of adoption decreases as the market increases have been accepted among scholars. This is called the diffusion curve and according to (Rogers, 2010), in the early parts of the curve, the innovation technology tends to be expensive and thus the market adoption rates are reduced except for the first movers of adoption or innovative adopters who are willing to pay a little extra to be in the more risky and exiting technology frontier.

As in the case of new technology, it can be difficult for innovative firms to capture the benefits of their products before reaching the mainstream market because of high cost and risk for adoption, leading to the so-called technology “valley of death”. However, in order for innovative firms to survive the early stages, governmental institutes can from different incentives help the firms to gain market shares (Grubb, 2004).

The diffusion of RETs are much driven by the governmental policies and incentives because of their fundamental characteristics of large upfront costs. Additionally, the advantages of RETs in a larger context of energy security together with environmental and social considerations makes the adoption of RETs an interesting topic for subsidies (Rao and Kishore, 2010).

In the case of renewable energy integration and local small-scale power plants, an important milestone for the diffusion of microgrids systems is the *grid-parity* concept which is a cost-competitive model meaning that grid-parity is reached once the cost of generating electricity is lower than the price of receiving the electricity from a retailer (Breyer and Gerlach, 2013). This is generally said to be true once the Levelized Cost Of Electricity (LCOE) for a certain self-sustaining technology is lower or equal to the electricity price and implies that such technologies does not need any subsidies to be marketable anymore (Nissen and Harfst, 2019).

Grid-parity is much driven by subsidies but, even without subsidies, the self-sustaining system of Solar PV was already in 2010 the least cost option for off-grid rural electrification with bright promises for the developing countries (Breyer and Gerlach, 2013). Revenues from feeding the surplus electricity into the grid, referred to as feed-in tariffs, have caused an increasing deployment of PV in many countries and in some cases this has led to discussions on whether subsidies is still necessary (Nissen and Harfst, 2019). Hence, grid parity is an important milestone when pushing for the integration of local electricity production but on the other hand, it is important to not “over” incentivize self-sustaining technologies in order for them to make it across the valley of death since consumers might find it uninteresting to be a part of the existing electricity system (Karneyeva and Wüstenhagen, 2017).

2.4 Barriers for adoption in Sweden

Although there is a great potential in residential Solar PV and storage deployment departing from the individual motives and institutional pushes, a set of complex barriers exists which plays an important role in the shaping of a future electricity system of Sweden. According to Palm (2017), these barriers are important to reveal in order for policymakers to gain useful information. In Sweden, as mentioned before, motives are mostly studied in regards to Solar PV but can also be seen as valuable in respect to the storage part and thus strengthen this study. Barriers for deployment exist both on the consumer perspective (Palm and Tengvard, 2011), and the more socio-technical system perspective (Palm, 2017).

System barriers

From a socio-technical system perspective, Palm (2017) investigated the deployment of Solar PV and found that, particularly in Sweden, the PV deployment was small in regards to the relatively rapid pace of market growth for PV (ibid.). The solutions were mostly purchased by the actual user resulting in *poor market design* for potential business models compared to other more established markets where third-party actors have flourished the market. Additionally, market regulations in many countries have historically governed monopoly utilities, TSOs, and DSOs. Hence, regulations tend to work in favour for maintaining status quo which creates a barrier for energy efficiency and distributed small-scale generation together with utilities to form innovative market designs more broadly (IEA, 2014).

However, Oberst et al. (2019) argue that legal frameworks and prosumer markets heavily influence how prosumers behave and contribute to the grid. Inês et al. (2019) suggests that in order for prosumer markets to flourish, countries need to set more ambitious and transparent goals of decentralized energy production for the coming decades. Today, in Sweden, it is not legal to create a sharing community of electricity between households which limits the potential value from acting self-sufficient. However, there are revisions on the way from EI which might take away this barrier to some extent (Ei, 2020).

Further, a lack of commercial actors providing a full-scale installation at a specialist level showed a barrier towards the purchasing and implementation of decentralized Solar PV systems (Palm, 2017). In his study, Sandahl (2019) further investigated the reasoning behind storage implementations within residential Solar PV systems in Sweden and found a strengthening argument; there is no or only limited amount of actors providing a full scale Solar PV and storage installation. Additionally, in line with above mentioned of potential business models, a barrier is the absence of third-party ownership that could manage most areas of ownership, including first planning, legal applications, installations and maintenance (ibid.).

Additionally, as the subsidy schemes regularly change it structures and limits together with the risks of reaching its budget cap, a discontinuous scene of Solar PV deployment exists because of the subsidy schemes substantial part in an investment decision (Palm, 2017). In other countries where self-sufficiency has reached a higher maturity, subsidy and feed-in tariffs schemes are curtailed ahead of schedule and taken away which causes a disruptive scene where households find more value from not investing in Solar PV or from operating off-grid (Candas et al., 2019; Quintero Pulido et al., 2019). Similar scenarios in Sweden has caused problems for installation firms who suddenly can lose their sources of revenue. Leading to a rather passive development and recruitment scene of professional actors for off-grid applications (Palm, 2017).

Current subsidy-schemes are can be considered sub-optimally designed, which, has led to a scene where, for example, storage solutions are becoming even more non-profitable (Palm, 2017). The potential tax reduction on feed-in electricity from consumers are incentivizing households to rather sell their excess electricity than store it (Sandahl, 2019). Making the relative value of storing instead of selling inadequate. Heinisch et al. (2019) modelled a prosumer household in Sweden with a PV-battery system from two different perspectives: (1) annual cost optimization for the household, and (2) overall all system benefit. The authors concluded that with the Swedish tariff-system in 2018, a household with a PV-battery system that is set up for low-cost optimization would actually increase the usage of utility power plants in the system.

One significant barrier in Sweden is argued to be the low economic profitability of investing in a system. However, this is not only reflecting the cost of investment in Solar PV and poor geographical conditions but derives from the low cost of electricity in Sweden compared to many other countries where the self-sustaining markets have grown rapidly (Palm, 2017).

Moreover, to cope with the dilemma introduced by attempting to reach optimal prosumer value whilst also striving for overall system benefits with increased decentralized electricity production, the utilization of *aggregators* could work in favour of both parties. An aggregator can be described as an entity that, through smart systems such as Home Energy Management System (HEMS), establishes communication between prosumers, prosumer communities, or alternatively, DSOs as well in order to control electricity trading and load flows through the system (Koch, 2015). The overall cost and system benefit that aggregators could bring to the systems are acknowledged within the European Union. However, an issue that has been brought up is their potential impact on suppliers (de Heer, 2015). If aggregators facilitate electricity-trading between prosumers or within prosumer communities, that is if this is a more beneficial option for prosumers, it could affect the overall *utility demand*, potentially leading to a loss of revenue (Baker, 2016). Hence, to avoid this, the role and obligations of aggregators in the energy market should be transparent (Bray and Woodman, 2019). Furthermore, it is noticed that an aggregator could combine multiple prosumers or prosumer collectives to enhance flexibility within the system if integrated cautiously (Keay et al., 2014).

Consumer barriers

First off, in Sweden, a large share of the electricity generation is available from renewable sources. Furthermore, consumers have the option of signing a green electricity contract that guarantees 100 % renewable electricity and thus, adopters holding the motivation to become a "green" consumer might not see the need to invest in self-sufficient renewable electricity systems (Mundaca and Samahita, 2020). Instead, motivation might point towards the economic benefits, which, at the moment, are uncertain.

Further, with the low support of full-scale planning and installation actors, potential owners of Solar PV and storage systems must possess a relatively extensive level of "technical know-how", both to understand the concept of self-sustaining systems and the actual installation phase (Sandahl, 2019). The "non-adopters" are interpreted by Palm and Eriksson (2018) as individuals without any technological knowledge or already made investments within Solar PV and their studies show that this category of individuals find it too technical to even consider an investment.

Moreover, interconnection and review fees to enable a bi-directional flow of electricity with the grid can be substantial and serve as a barrier for households to be a part of the system (IEA, 2014). On the other hand, this can be seen as a driver for fully off-grid applications. Hence, a barrier to overcome is both legislative changes towards a strict subsidy scheme and lower storage investment costs (IEA, 2014; Sandahl, 2019)

The adoption of self-sufficient systems must be interpreted from a socio-cultural perspective when investigating how consumers take on this innovation. Hence, once a consumer invest in a system, they will integrate with the system in their everyday life. On this basis, Palm (2018) found several potential barriers disturbing the consumers investment decisions. Firstly, a uncertainty and mistrust exists towards if the system will perform as promised, as well as, uncertainty around regulations and subsidies. Secondly, households in Sweden are in general pleased with their existing electricity supply and do not want to change their routines.

Large invectives for adoption departs from subsidies and to lower the large upfront investment. However, in Sweden, there is lack of transparency regarding the subsidy schemes and feed-in tariffs that can be exploited, causing a difficulty for households to estimate their potential advantages from home Solar PV (Mundaca and Samahita, 2020).

2.5 Electricity system - trajectories of change

In order to find an answer to whether it will become a reality with self-sufficient households, it is important to consider both adopters and system ingredients (Palm, 2017). Therefore, the trajectories of change (orientation, magnitude, and pace) that will shape the future electricity sector are not only driven by the outcomes from physical and technical characteristics but also influenced by institutional frameworks and social functions. Altogether, with surrounding needs and dynamics, the future electricity sector will be shaped thereafter (Defeuilley, 2019). Consequently, there is a lot of influence from global megatrends departing from European Environment Agency (EEA) which affect the realization of development (Swedish Energy Agency, 2016). Furthermore, the trajectories of change within the electricity system are investigated to a great extent on a scholarly level where a country-specific market is not considered. There is, however, studies performed in regards to the Swedish market on the behalf of the Swedish Energy Agency and other incumbent actors which can be seen as a supportive base for the presented future trajectories (Energiforetagen, 2019; Swedish Energy Agency, 2016).

It is evident that sustainable energy transitions can be analysed through a scientific lens of socio-technical transformations to discuss and analyse the disruptive nature of electricity transitions (Geels et al., 2016). In his seminal work, (Defeuilley, 2019) applies a system perspective towards the changing environment of decentralized electricity systems with the aim of finding potential trajectories for future electricity systems. Additionally, Hojčková et al. (2018) investigated complete sets of socio-technical system elements e.g. off-grid and prosumers, that supports alternative futures. Departing from the historical centralized electricity regime, findings point towards multiple scenarios with different levels of influence from decentralized local electricity production. Moreover, Hojčková et al. (2018) present a system architecture where the decentralized production has almost no influence, instead, the centralized production will increase its leading role in a so-called Super-grid configuration.

Determining factors and projected futures

A general theme in the presented papers is that depending on the trajectory, the most vital difference is the structural impact of decentralized electricity production and the amount of centralized versus decentralized production. Further, the main variables that affect the trajectories are the costs of decentralized production as well as governmental support and decisions (Defeuilley, 2019; Energiforetagen, 2019; Hojčková et al., 2018; Swedish Energy

Agency, 2016). Consequently, depending on how these variables play out in the future, it is possible that certain directions of development occur.

Firstly, if governmental decisions of reducing support mechanisms such as subsidies for renewable energy installations, there will probably be less structural impacts on the system (Defeuilley, 2019). Also, if market support shifts from feed-in tariffs and investment aids for decentralized production, it is possible that support for centralized renewable production increases and centralized production re-gain its relevance (Defeuilley, 2019; Hojčková et al., 2018). Defeuilley (2019) is referring to this as a *re-arrangement* pathway where incumbents will absorb most of the new decentralized innovations and incorporates it into their business models whereof a challenge could form from a drastic decrease in costs for household production. Hojčková et al. (2018) argue that such development could lead towards, to an extreme extent, a globalized system where lots of countries are interconnected in a *Super-grid*.

Applying it to the Swedish context, findings from Energiforetagen (2019) indicates that a similar scenario of electricity production could serve as a means of achieving 100 % renewable electricity from centralized and renewable production based on hydro-, wind- and solar power. Here, the trajectory is mostly driven by slow technological development of solar panels and energy storage without cost reductions, consumers who are unwilling to adapt their consumption and produce their electricity on their own, and a national concern placed in the hands of system operators and decision-makers to handle. Furthermore, the (Swedish Energy Agency, 2016) argues that for Sweden to become even more dependent on centralized production, increased globalization of the world would be the main driving force towards such a scenario.

Secondly, in the case of a more ambitious policy objective for local power plants there is a potential pathway, conceptualized as *incremental change,* with increased decentralized small-scale renewable electricity production replacing the more centralized ones to a great extent. The share of centralized vs. decentralized production will much depend on the implemented support mechanisms and the level of subsidies incorporated with them (Defeuilley, 2019). Hojčková et al. (2018) refers to this as a *Smart-grid* scenario based on decentralized interconnected electricity production that compared with the above-mentioned scenario involves a decreased size of production units and shorter distances of electricity transportation. The system will be interconnected in which electricity and information are transported in a bi-directional flow in a network of *prosumers* (ibid.).

Drivers for this scenario are maintained price reductions in decentralized systems and that a major part of the renewable electricity is generated locally by both individual households and municipalities (Defeuilley, 2019; Energiforetagen, 2019). In the context of the Swedish electricity system, this scenario is much supported if the expansion of overlying transmission grid is time-consuming, slow and receives low acceptance from stakeholders, as well as if an increasing wish for integrity and independence arises from the consumers (Energiforetagen, 2019). Additionally, the Swedish Energy Agency (2016) emphasizes this scenario where smart and cost-effective applications for self-sufficiency develops, driven by enthusiastic individuals who gladly share experiences to their peers, which, in turn, increases the pace of innovation and development for household electricity applications.

Nevertheless, within this scenario, local energy storage near the consumers is key together with residential rooftop-mounted solar panels, as well as, strategically placed in the grid where bottlenecks of capacity shortage exist (Energiforetagen, 2019). Additionally, electric vehicles (EVs) and Vehicle-to-grid configurations will act as a dynamic storage device and a driver for flexible balancing technology by supporting the integration of variable RETs into the grid (Hojčková et al., 2018).

Decentralized policy objectives push for distinctive decentralized solutions e.g. microgrids, peer-to-peer trading platforms (Defeuilley, 2019; Hojčková et al., 2018). (Hojčková et al., 2018) expresses a vision for the Smart-grid termed *internet of electricity* where trading applications could enable quicker and even more decentralized transaction systems between prosumers. In a decentralized pathway, a challenge will be to cover the costs of the grid with the increasing share of self-consumption and thus its of importance to integrate rules, restrictions and standards towards self-generation, as well as overlook grid-tariffs, in order to finance the network costs (Defeuilley, 2019). Also, challenges will exist in managing the energy losses by enabling real-time power flow configurations where, for example, at peak hours of production when the local solar panels generate high electricity volumes, advanced metering infrastructure and storage solutions will need to implemented to guide prosumers in their production and consumption. Here, it is evident that centralized solutions will still be needed to support the system with stability and secure flow of electricity to the consumers (Defeuilley, 2019; Hojčková et al., 2018)

Lastly, imagining policy instruments that push for local systems, individual actors and new entrants, if so, a *paradigm shift* towards decentralized local systems could transpire through the electricity system leaving the centralized model marginalized together with great structural changes in the system. The existing system is disrupted and the incumbents lose their monopolistic role to be replaced by radical niche technologies. Overall, decentralized technologies have emerged from enhanced consumer engagement and the following need for societal acceptance i.e. peer effects (Defeuilley, 2019). This is the extreme opposite to the first presented Super-grid scenario meaning that this scenario could lead towards a large-scale grid defection where consumers operate off-grid (Hojčková et al., 2018). Yet, scenarios for the Swedish electricity system are not pointing in this direction where households are completely independent (Energiforetagen, 2019; Swedish Energy Agency, 2016).

Driven by the pace of price reduction of enabling technologies, such as Solar PV and storage solutions, a new renaissance for off-grid systems has evolved. Hence, a key condition for this scenario is the development of efficient and safe storage solutions able to operate at various scales of time i.e. from intraday to seasonal storage. However, for this scenario to be possible, economically rational and robust, sharp accelerations of the technical improvements would be needed, above all within the field of storage and decentralized flexibility solutions like behind-the-meter applications and demand response (Defeuilley, 2019; Hojčková et al., 2018). The storage solutions will have to handle the missed beneficial effects, such as, energy security and power balancing which is more guaranteed from having a large interconnected centralized grid (Defeuilley, 2019). Additionally, for this scenario, a great obstacle is the general structure of subsidy schemes combined with reasonable feed-in tariffs which makes it economically beneficial for self-sufficient consumers to stay connected to the grid (Hojčková et al., 2018).

2.6 Theoretical foundation

Because of the large scope of this study to both explore the potential adopter of off-grid applications and the context it will be placed in, more specifically the Swedish electricity system, it can be seen as beneficial to combine several different theories which individually focuses on a specific topic but together creates the desirable holistic point of view.

Diffusion of innovation

The first framework involves the *Diffusion of innovation* theory and more specifically the innovation attributes that determine the plausibility for adoption depending on the characteristics of the innovation (Rogers, 2010). The theory itself is not limited or constructed towards the research field of electricity system innovations but can serve as a foundation to understand the potential barriers and enablers of adoption for household electricity systems.

Hence, as this thesis aim towards delivering insights on the conditions for existing electricity consumers to adopt technologies that promote self-sufficiency, diffusion theory can be seen as a promising tool. Moreover, to explore how a transition of the electricity system could form with off-grid applications, diffusion of innovation theory can serve as a first level of analysis at the micro level. Consequently, it may be necessary to understand the micro-level, depending on the results and magnitude of adoption, to explore how this innovation can form future trajectories at a macro level of the electricity system.

Technological innovation systems (TIS)

Within diffusion of innovation theories the potential adopter is in focus, however, the potential adopter is only a part of the puzzle in the deployment of self-sustaining technologies as it is much driven by institutional setups and higher actors. Hence, a strategic move for this work could be to complement the diffusion theory with a broader lens of analysis. The *technological innovation systems* (TIS) framework could serve this purpose as it was developed to analyse the development, production, and deployment of innovative technologies from a socio-technical perspective (Bergek et al., 2008). Throughout the last decade, the TIS framework has been applied in studies to both identify and assess drivers and barriers of technology diffusion to facilitate policy recommendations, frequently with the aim of understanding how renewable energy innovations can be supported (Jacobsson and Bergek, 2011; Sandén et al., 2008).

Additionally, the broad scope of the TIS theory implies that it might not be detailed in all the parts, for example, the different actors (users) and because of the overlap with Rogers diffusion of innovation theory that mainly departs from the adopters, a combination of the two theories could be beneficial (Palm, 2017).

Technological transitions (TT) and Multi level perspective (MLP)

The second set of theories is within the field of *socio-technical transitions* where three different but related core research streams have been identified as the Multi-Level Perspective (MLP) theory, Strategic Niche Management (SNM), Transition Management (TM) (Falcone, 2014; Markard et al., 2012). Socio-technical transitions, similar but yet different to the diffusion of innovations theory, is a concept within the field of innovation that explains the nature of technological change (Smits, 2002). Socio-technical transitions, however, embraces a larger scope and refers to rearranging processes between technological change and industry structure, policy instruments, markets, governance and actors that enable new trajectories (Ulli-Beer, 2013).

Assuming that socio-technical systems are locked-in and complex to change (Unruh, 2000). The ambition with socio-technical transitions theory is to highlight the interaction of various aspects e.g. economical, technical, social and instrumental at different levels to enable systematic change towards a potentially more sustainable trajectory (Defeuilley, 2019). Moreover, Markard et al. (2012) highlight that MLP theory differs in from the TIS theory where MLP is more focused on analysing the transformative system change whereas TIS is more technology-specific but together, they can be combined to better understand socio-technical system changes. Conclusively, the socio-technical transition framework, from a planning perspective, can be used to pinpoint different barriers and drivers associated with a technological change to construct a legitimate set of policy efforts (Moradi and Vagnoni, 2018).

Thus, with the aim of this thesis is to identify potential disruptive trajectories with the deployment of self-sustaining technologies, socio-technical systems and transition theory could serve to guide the conducted research towards a reflection of the broader electricity system and its potential transformative changes. Hopefully, the framework guides the research in providing a first outlook of how the electricity system can form with the future.

Conceptual framework

Taking the stock out of these theories and apply them together can form a comprehensive analysis in which findings from the first level of analysis, regarding the drivers and barriers for deployment and potential adopters, can serve as a great insight towards the second level of analysis where understanding the potential transition pathways of the existing electricity system, as well as policy implications, is highlighted. The conceptual framework intended to guide the empirical research of this thesis is presented below in Figure 1.

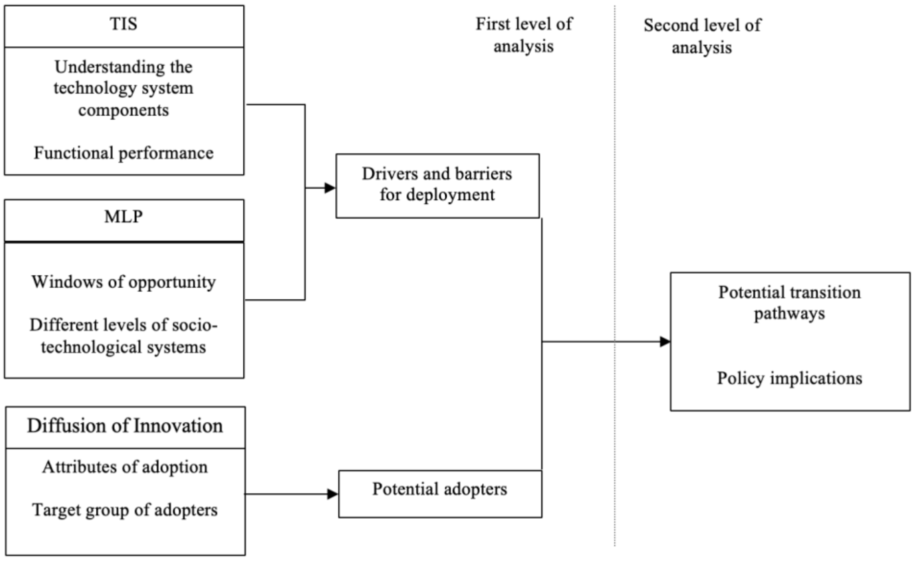


Figure 1. Conceptual framework.

2.6.1 Diffusion of innovations

Within the diffusion of innovation literature, the adopter side is in focus, however, it also covers those who try to influence the potential adopters decision of adopting or rejecting the innovation. The diffusion process according to (Rogers, 2010) is defined as “the process by which an innovation is communicated through certain channels over time among members of a social system”. The social system is defined by its different personality types and the framework focuses on the decision making processes of these individuals and how the different attributes of an innovation could influence the adoption rates.

Further, a core concepts of his work is the curve with the shape of an S explaining how individuals decision of adoption varies over time. At the beginning of the commercialization of an innovation, only a few potential adopters make the decision to accept the innovation. As time evolves and the innovation is communicated between potential adopters and actors, the curve gradually becomes steeper as the adopters increase (Rogers, 2010). However, as in the case of household electricity and storage systems in Sweden, there is no real commercialization taking off yet and, thus it is arguable that an S-curve is difficult to define in terms of its magnitude and time of diffusion.

Despite this, a key feature of this framework is the categorization of (potential) adopters and their roles in the diffusion process regarding the diffusion curve. Rogers argues that there are five ideal types of potential adopter groups even though, in reality, he admits that there is no such thing as sharp boundaries between the groups:

- *Innovators* are the first movers to adopt the innovation. The innovators motivation departs from eagerness to try on new ideas and is often perceived to be a group that brings new ideas into their social system and facilitates the diffusion rate. However, this group tend to be perceived as “too innovative” by its peers to actually have some major influence on decision-making process
- *Early adopters* are less open towards innovations than the innovators but, on the other hand, they entail a higher level of influence towards their peers. This makes early adopters perceived as role models and thus often opinion builders in their social system.
- The *early majority* takes on innovations before the average individual and serves as an important link between the early adopters and the late majority making them an interesting group in the diffusion process of innovations.
- The *late majority* is the other large group, similar to the early majority but are perceived as less risk-taking individuals. Their decisions of adoption are not reached until most of the potential risks around the innovation is removed and is clearly driven by the economic advantages of adopting the innovation. However, the late majority can be persuaded to adopt as peer pressure from their social system increases.

- *Laggards* must be certain that the innovation will not fail before they even consider adopting it. They hold limitations in resources and are suspicious against innovations creating an lengthy decision process.

For this thesis, a deeper knowledge and explanation of different adopter groups could improve the understanding of how one might choose to invest in a self-sustaining electricity system. It is arguable that as of today there are only a few innovators that have taken on the scene of running self-sustaining home operating independently from the grid. However, this type of categorization of social groups, as well as their preferences for adoption, could aid the potential transition pathways and its magnitude.

Moreover, the aim is not to focus on, nor try to understand the adopter behaviour but to understand how different *attributes* of innovations may affect the decision-making process of potential adopters. According to Rogers, five categories of innovation attributes are remarkably influential on the rate of adoption in a social system and could further explain the adoption variance between different innovations:

- *Relative advantage* in relation to existing alternatives.
- *Compatibility* with existing infrastructures or norms, beliefs and behaviours.
- *Complexity* as seen from adopter perspective.
- *Observability* is the level of an potential adopter can observe the results of an innovation in a social system.
- *Trialability* in terms of possibilities for the adopter to test the innovation before potential adoption

In the case of Solar PV and storage systems, it is arguable that existing alternatives, such as remaining connected to the grid fulfil a higher level of these attributes. Particularly since the storage solutions of today have not reached a high level of maturity in terms of costs, capacity and seasonal storage. However, as this thesis will explore different scenarios, taking technological developments into consideration, potential futures may point towards a shift where attributes with self-sustaining systems are fulfilled to a higher level.

2.6.2 Technological innovations systems

The technological innovation system is focused on a specific technology (Bergek, 2002), in this case, self-sustaining electricity, and the technology system is usually described to be made up of four components (Bergek et al., 2008; Suurs et al., 2009):

- *Actors:* Actors includes the organizations and individuals contributing to certain technology and are relevant for the development and/or deployment of the technology. Having a deployment focus, it is important to consider actors that influence directly, e.g. suppliers, installers and potential adopters, or indirectly, e.g. policymakers. Actors have interrelated relationships, for example, policymakers can have an influence on the potential adopter from incorporating different subsidy schemes.
- *Networks:* Networks include the linkages in which information is being exchanged between the actors. For example, the information exchange between different suppliers installers, and authorities, as well as potential adopters, is important during the deployment phase.
- *Institutions:* Formal, as well as, informal institutions involve the societal rules which affect the development and/or deployment of the specific technology, such as

technology standards, laws, and practices. The underlying theme of institutions is that they can either facilitate a push for innovation adoption or sometimes they can complicate the adoption process.

- *Technologies:* Technologies involve both the technology itself and the infrastructure in which the technology is integrated. Techno-economic aspects such as costs, safety and reliability are also considered.

Further, functions necessary for a TIS to perform well and have a chance for deployment have been identified. If a TIS is performing bad or having a low level of adoption, identifying the specific function can facilitate policymakers to add and remove drivers in their process of either nourishing or weakening the technology deployment. Following functions is identified within a TIS (Bergek et al., 2008; Hekkert et al., 2007; Suurs et al., 2009):

- *Entrepreneurial activities:* Hekkert et al. (2007) stated that without any the entrepreneurs there is no such thing as an innovation system. Their key role is to emphasize all the potential new knowledge, networks and markets and turn into concrete actions later establish new business opportunities. Entrepreneurial activities can either depart from new entrants holding a vision of establishing business opportunities towards a market, or from incumbents who diversify their core businesses to gain advantage from the new technical developments.
- *Knowledge development:* This function is all about learning activities connected to the emerging technology, proposed market, potential users and networks. It can involve “learning-by-doing” as learning in a practical context or “learning-by-searching”, as in R&D activities.
- *Knowledge diffusion:* Basically, it is a function of interactive learning. The activity is important for the deployment phase as potential adopters, firms and policymakers need to develop an understanding of how to implement and market the technology, as well as regulate and support the use of it.
- *Guidance of search:* Refers to the activities shaping the need, expectations and requirements of actors, more specifically, functions that influence the direction of which resources are deployed by actors. For example, governmental goals can justify a level of resource allocation for specific technology development, as well as increase the visibility and clarify the specific wants/needs from technology users
- *Market formation:* Activities which create a demand for the specific technology and is considered crucial for the deployment process. Further, emerging innovation systems cannot compete with incumbents at their start and support is often needed in terms of creating appropriate “safe” markets and temporary competitive advantages e.g. favourable tax regimes and market regulations.
- *Resource mobilization:* Allocation of financial and human capital to support the development and increase the knowledge of the TIS. Financial capital can be incorporated by specific subsidy schemes pushing for the promotion of a certain TIS.

2.6.3 Socio-technical transitions

A large technological system, such as the electricity system, can be described as a system of components created by leaders, financiers, engineers, and innovative individuals (Hughes, 1987). The situation of electricity systems, generation, and its distribution can however not only be understood as a set of discrete technological artefacts but must be interpreted as complex systems of technologies fixed in a robust social context of private and public institutions. Unruh (2000) argues that systems similar to the above-explained, further defined as *Techno-Institutional Complex* (TIC) develops from a co-evolutionary, path-dependent process including the aspects of positive feedback loops in between the technological infrastructures, the organizations, and the institutions that shape, diffuse and apply them. An agreement among scholars can be seen where the infrastructure behind systems, like the electricity, must be treated in this direction (Geels, 2004, 2002; Hughes, 1987; Unruh, 2000).

The highly appreciated work by Hughes (1987), defines the concept as a *socio-technical system* (STS), where he refers to the electricity system as well, which further serves as the basis for the socio-technical innovation theory and *technological transitions* (TT) by Geels (2004, 2002). Socio-technical systems are embedded in society's daily life and Hughes (1987) highlights the barriers to change such systems. Moreover, Unruh (2000) defines that once TIC systems are *locked-in*, they become difficult to change and can *lock-out* alternative technologies for an extended time even if they can be perceived and demonstrated as an improvement to the current TIC. For this work, it is important to understand how dependent both the society and the operating organizations is on the existing system, as well as, how potential changes to the system is affected by interrelated socio-technical relationships.

However, during the last decades, research within socio-technical systems has changed its direction, from focusing on how these systems evolve, towards exploring processes and mechanisms that enable and *trigger changes* within these systems. The underlying reasons for an academic turn in this field is because socio-technical systems often involve sustainability issues, such as carbon emissions and the fossil fuel addiction, which in turn is a critical and important challenge for the society as a whole to overcome (Rip and Kemp, 1998). The adoption of residential renewable electricity systems, as the scope of this project, can be seen as a “green” movement and could have the potential of acting as a trigger for change.

On one hand, the setting of socio-technical systems can be interpreted as a system undergoing changes incrementally within their respective *technological trajectory* (Dosi, 1982) and not in a radical fashion, as often needed towards sustainability transitions. On the other hand, transitions towards increased sustainability of socio-technical transitions have been addressed and promoted (Geels, 2004, 2002; Rip and Kemp, 1998). One potential framework for addressing the promotion and analyse the processes of sustainable socio-technical systems is the MLP in which the dynamics of change is investigated on three different levels (Geels, 2002). Hence, the MLP perspective will help to investigate the potential technological transition towards self-sustaining energy systems, as well as, the difficulties for radical innovation to reach the mainstream market.

Multi-level Perspective for technological transitions

As a tool for understanding the twisted dynamics of socio-technical transitions, MLP theory can serve as a framework to investigate technological transitions from a sustainability perspective (Geels, 2011). The framework is conceptualized to investigate three different levels of analysis for change, *niches*, *regimes*, and *landscapes* all interrelated to each other. First, the socio-technical *regime* level exists in well-established rules and practices. This level is the most difficult to change because of the high level of stability and the regime is further characterized by existing technologies and infrastructures but also lifestyles, user practices, shared beliefs, capabilities, and competences.

Second, the socio-technical *niche,* a protected space associated with research and development projects, subsidized pilot projects but also smaller niche markets with users who hold special demands and are driven to support the emerging innovations. Actors within the niche level work on radical innovations that differ from the existing regimes with the hope of putting novelties into the regime or in the best case replace the existing regime. Socio-technical niches are said to be crucial for technological transitions because of their abilities to plant important ideas for systematic change (Geels, 2011). Niches can develop from three core processes (Geels and Schot, 2007; Rip and Kemp, 1998): *first*, expectations and visions to the innovative practices that provide the innovations with attention and, *second*, the building of social networks with an increase in actors that expand the resource base and, *third*, learning and adoption in different dimensions including market demand, technical design, infrastructure requirements, business models, policies and user preferences. Niche innovation can gain momentum if these processes become broadly accepted, result in a stable configuration of dominant design or if the niche networks grow in size (Geels, 2011).

Third, the socio-technical *landscape* which is the wider context, influencing the regime and niche dynamics. The landscape involves not only the technical and material compositions of the society but also the societal values, macroeconomic patterns, political trends and ideologies, and external events. Together they form a context unable to be influenced by the regime and niche, at least in the short-term (ibid.)

On the basis of this multi-level perspective framework, socio-technical change is said to occur when a window of opportunity creates from arising from destabilized regimes and landscape pressure together with prominent niche innovations. A window allowing radical niches to break through and push for sustainable socio-technical systems (Geels and Schot, 2007). For this work, the deployment of self-sustaining systems will be focused on the early stages of socio-technical transitions, earlier described as niche innovation, and how the scene of off-grid systems can come to develop towards a larger system transition.

Technological transitions – Transition Management (TM)

In their work, Rotmans et al. (2001) a theoretical framework at the conceptual level of how these socio-technical changes evolve, both similar and in respect to the MLP framework, but more focused on the transition process rather than how the different levels. The four phases of transition include the *predevelopment phase*, *take-off phase*, *acceleration phase* and the *stabilization phase*. Firstly, the *predevelopment phase* becomes evident in technological niches but does not change the existing system, it is rather a status quo. Secondly, in the *take-off phase*, the technological niche can start to improve along a trajectory and integrate into small niches markets. The take-off phase is a vital step where lots of niches fail because of its unfit with existing practices and infrastructures (Smith and Raven, 2012). Here, it is important that the niche can continue to develop in an artificially created protected space (ibid.). Thirdly, an *acceleration phase* in which changes of institutional, economic and socio-cultural aspects react to each other and visible structural changes of the system take place (Rotmans et al., 2001). Niche innovations spread into the markets and the established technologies are challenged (Andersson and Jacobsson, 2000). Lastly, the speed of change decrease in the *stabilization phase* (Rotmans et al., 2001) and, referring to Geels (2002), the innovation enables for a regime shift and enters the mass markets.

Strategic niche management

Kemp et al. (1998) presents a perspective called SNM management that focuses on how to expedite promising technological transitions into new socio-technical regimes. The focus is pointed towards empirical examples of niche experiments including research and developments programs, pilot projects and demonstration activities (Hoogma et al., 2002), as well as, governmental policy implications (Geels and Schot, 2007). Further, niche management ,in general, presents a linear and technology push approach describing a bottom-up process in which innovative technologies through experimentation emerge in technological niches to, later on, conquer market niches and eventually transform and replace the existing regime (ibid.).

As niche innovations have a vital role in the early steps of socio-technical transitions, it is important to understand how niches can reach a higher degree of contexture. Once the niche innovation have reached a certain degree of structuration, the niche can leave its protected experimentation space to eventually compete with existing regimes in the hunt for socio-technical change (Geels and Schot, 2007; Kemp et al., 1998).

From Hoogma et al. (2002), a case study of niche management of sustainable transitions within the transport sector shows empirical results on how sustainable niche innovations acts as stepping stones in regime shifts. In order for radical niche innovations to evolve into a regime shift, four main conditions could be considered as vital to the speed and strength of socio-technical changes: (1) The niche technologies need to have sufficient room for improvement that nurses for cost efficiencies and for branching out. (2) The gap between current domains of application and new ones cannot be too big. (3) They need to have a synergetic relation with additional developments in technology and markets to gain new users and capture new areas of applications. (4) The rate of progression of the emerging technology system offering particular services should imply greater than that of present technologies with which it competes (ibid.).

Transition pathways

Having the MLP theory in mind, a transition is said to occur when existing socio-technical systems are challenged by disruptive changes at different levels (landscape, regime, niche).

Depending on the strength and magnitude of these challenges, different transition pathways is possible and overall four general pathways are distinguished (Geels, 2011, 2004, 2002; Geels et al., 2016).

- *Substitution pathway:* Within this pathway, new entrants provide radical innovations that do not align with the core businesses of the incumbents leading towards overthrowing them. Radical innovation(s) substitutes the existing technology where different actors, in terms of new entrants, e.g. citizens, incumbent from other sectors, communities and social movement actors replace the established incumbents. Regarding rules and institutions, this pathway can evolve in two separate directions. The first direction involves limited institutional change as new innovations with better price and performance characteristics disrupt the existing technologies but also fit the existing rules and institutions. In the second direction, rules and institutions are re-formed to suit the niche innovations.
- *Transformation pathway:* Gradual reorientation of the existing regime through adjustments made by incumbent actors, social influence and pressure from institutional changes. However, within this pathway, incumbent actors may as well take on radical niche innovations and step away from the original scene where incumbents are said to be "locked-in" and only do incremental innovations. Existing technologies are often incrementally improved with performance/cost enhancement and incorporated with niche-innovations and add-ons leading towards limited institutional change. On the other hand, depending on the depth of reorientation among technologies, a substantial change in rules and institutions may occur.
- *Reconfiguration pathway:* Here, niche-innovations and existing regime combine to change the system's architecture. Regarding actors, this pathway could form new alliances between new entrants and incumbents instead of overthrowing them as in the substitution pathway. Niche-innovations could initially be accessed as modular or "add-ons" to existing technology, similar to the transformation pathway but eventually form new combinations between new and existing technology that changes the system architecture.
- *De-alignment and Re-alignment pathway:* This is the most radical pathway where the existing regime is disrupted by external shocks followed by a rise in niche-innovations. The decline of existing technologies creates an opportunity for several new innovations to compete.

Nevertheless, pathways may shift over time from one pathway to another because of major challenges in institutional setups or new disruptive niches. The pathways have been studied in electricity system transitions over time with proven results of its applicability. By distinguishing the most plausible pathway with an existing institutional setup, actor involvement and technology, this framework may exploit the potential future challenges towards achieving a specific goal. Having this in mind, early regulations and drivers towards a desirable outcome can be formed (Geels et al., 2016).

3 Methodology, Data Collection, and Tools

This chapter defines the research approach and methodology used in this study. Firstly, the research design is motivated followed by an overview of the data gathering and analysis process. Furthermore, research quality and a brief overview of the technical simulation tool are covered.

3.1 Research design

This thesis originated from a market-specific case, more specifically the electricity market in Sweden, whereas the work has been to place this case into an academic context to interpret certain phenomena. Hence, the research approach has shifted between exploring the case through empirics, market-specific data, existing scholarly literature, and theories. Such an approach, referred to as an *abductive research approach*, is emphasized by scholars to provide the necessary flexibility to adjust and revise data by iterations (Eisenhardt, 1989), and to help understand a new phenomenon (Alvesson and Sköldberg, 2008). Which, in this case, is the notion of household electricity production in Sweden. Therefore, an *abductive research approach* is taken. This way, it possible to shift between ideas and theory presented in the literature and how they influence the interpretation of empirical findings and vice versa (Kemp et al., 1998).

The empirics consist of both qualitative and quantitative data, the procedure of a mixed-method design. This can be argued to strengthen the perception of the stated research problem (Cresswell, 2014). The qualitative data, presented as empirics, was used to understand the underlying driving force associated with off-grid households through the lens of theoretical frameworks in the field of industrial management. In addition to this, both qualitative and quantitative data was used to build a model that was used to conduct a scenario analysis through modelling off-grid and prosumer households, see *Chapter 3.4 & 3.5* for further details. The modelling part was applied to highlight plausible futures scenarios (Wright et al., 2009). In this case, quantitative data was gathered in the form of weather data, progress lines, and economic trends. Additionally, two forms of participatory research was included in this study due to a lack of available data on demand profiles and future electricity prices which prohibited the completion of the modelling setup. Participatory research supplied expert knowledge in this area that allowed this study to arrive at a conclusion, which, research suggests is a valid tool to utilize (Cornwall and Jewkes, 1995; Park, 2006).

Moreover, understanding sustainability transitions within the energy system involve challenges for social science theories alone and a consensus exists that integration of tools emphasizing economics and energy technologies, such as techno-economic outlooks, are necessary for a comprehensive understanding of transitions (Cherp et al., 2018). Consequently, the empirical findings and modelling section were analysed separately and, thereafter compared to see if they confirm or invalidate each other (Cresswell, 2014), see Figure 2 for an illustration of this design.

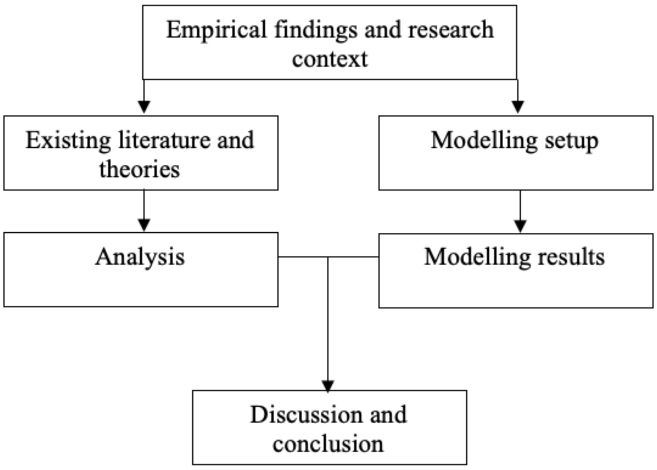


Figure 2. The mixed-methods research design of this study. Left side, the socio-technical part, right side techno-economic.

3.2 Data gathering method

This thesis consists of qualitative empirical data gathered through both unstructured and semi-structured interviews, as well as empirical data collected in terms of technology projections, costs and other topics provided by respondents and open-sources. The unstructured interviews were held at the beginning of the project to explore the subject, whereas the semi-structured interviews were conducted throughout the later parts of the project (Blomkvist and Hallin, 2015). Worth mentioning, the data gathered in this project are to no extent received from the individual household, meaning that there is no incorporation of potential adopters. It is arguable that such data could be seen as beneficial and the idea of incorporating it to the study has existed, however, it has been neglected due to the complexity of conducting such data.

Further, when configuring the model setup for the techno-economic analysis of self-sufficient households a benchmarking project was used as a point of reference to get the modelling part underway. In addition, larger sets of hourly data that were necessary for the modelling such as, historical- weather data and electricity prices, which, were all considered to be quantitative data (Blaikie, 2003).The data used in the modelling setup and scenario analysis section was gathered from recent studies, empirics, manufacturers, and thereafter, critically compared to determine up to date specifications and costs of each component. A promising tool for this is a methodological triangulation (Denzin, 1970), i.e. using more than one data gathering and analysis method, which has been applied to interpret a certain phenomenon in this study, in this case the cost and development projections regarding the modelling inputs. Consequently, triangulation was used to overcome the weaknesses and biases of only utilizing the data from a single source (Bogdan and Biklen, 2006). The three data gathering methods used for the modelling inputs is presented in Figure 3.

To provide an overview of the off-grid topic, modelling research context, and the surrounding technologies. *Chapter 4, Research Context* was necessary to both provide the reader and the authors with sufficient information of the characteristics and current situation of the area. Furthermore, the aforementioned chapter is a combination of literature, reports, technical and economic data, intended to serve as groundwork for the modelling part.

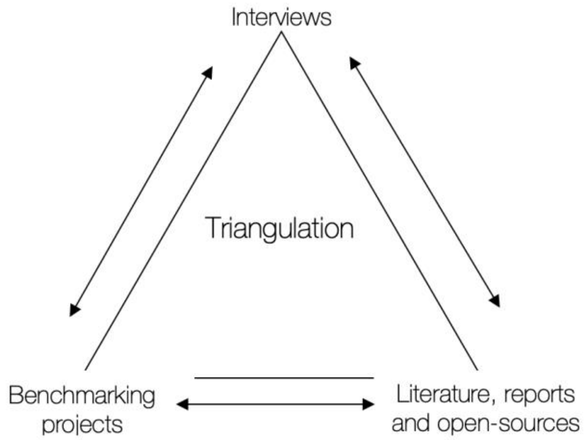


Figure 3. Illustration of triangulation method.

3.2.1 Unstructured interviews

In the early stages of a project, it can be beneficial to the study to incorporate unstructured interviews with the aim of exploring the studied subject (Blomkvist and Hallin, 2015). Therefore, in order to narrow down the scope of potential technologies for a self-sustaining household, two interviews were held with experts in different fields, namely Paradis and Nilar. Both interviews started with a brief description of our project and a presentation from the respondent about their expertise followed by randomly selected questions. The questions were aimed a delivering an understanding of the technologies and the important aspects to consider this type of study. Further, unstructured interviews were held throughout the work to support the modelling setup. An overview of the respondents for the unstructured interviews can be seen in Table X, mostly referred to in *Chapter 4, Research context* and *Chapter 7, Modelling.*

3.2.2 Semi-structured interviews

The study consisted of eleven interviews conducted in a semi-structured approach, meaning that the questions were formulated in advance whereas their specific order of presentation depended on the situation and some questions were added depending on the respondents area of expertise (Blomkvist and Hallin, 2015).

The selection of respondents is based on the idea of having a diverse group to capture a more holistic picture of the discussed area. The integration of scholars in the field of sustainability and environmental system analysis can be seen as beneficial support to the many respondents who are active in the electricity market. Overall, except for the lack of TSOs and DSOs, the group of respondents can be seen as diverse.

All respondents were given a pre-encounter delivered in an email, see Appendix I, where a brief summary of our project together with the aim of the interviews and four introductory questions to consider in beforehand were presented. The template used for all the semi-structured interviews were inspired by Research Methods for Business Students (Saunders et al., 2009). Respondents and the interview specifications can be seen in Table 1 below.

Table 1. List of respondents.

Respondent	**Area of expertise**	**Company/ organization**	**Venue**	**Date**	**Time-frame**	**Pre-encounter**
Paradis, Johan**	Solar PV	Paradis energi AB	Skype	2020/02/06	60 min	Research scope and methods
Nilar**	Energy storage	Nilar	Nilar office	2019/02/10	60 min	Research scope and methods
Nilsson, Hans-Olof	Off-grid households	Nilsson energy	Skype	2020/03/16	90 min	Appendix I
Werner, Anna	Solar PV	Svensk solenergi	Email	2020/03/11		Appendix I
Palm, Jenny	Urban transformation	Lund University IIIEE*	Skype	2020/03/18	60	Appendix I
Sanden, Björn	Professor in Innovations and sustainability	Chalmers technical university	Skype	2020/03/18	90	Appendix I
Hult, Göran	Research and Development energy	Fortum	Skype	2020/03/19	90	Appendix I
Wallnér, Erik	Solar PV applications	Solcells-kollen	Skype	2020/03/19	60	Appendix I
Lindborg, Joachim	Energysystem Utility-residential cooperation	Sustainable innovation	Skype	2020/03/18	90	Appendix I
Torstensson, Daniel	Energy and Environment	Fortifikations-verket	Skype	2020/03/26	60	Appendix I
Reuter, Cecilia	Off-grid solutions	Nykvarns energi	Skype	2020/03/23	90	Appendix I
Lindahl, Johan	PV market and policy analyst	IEA	Skype	2020/03/25	60	Appendix I
Hojčková, Kristina	Phd, Environ-mental Systems Analysis, Technology Management and Economics	Chalmers technical university	Skype	2020/03/24	90	Appendix I
Martin Jonasson**	Electricity prices	Jämtkraft	Telephone	2020/04/06	20 min	Research scope and methods

Sandels, Claes**	Demand profile	RISE	Telephone	2020/04/14	30 min	Research scope and methods
Krönert, Frank**	Swedish energy sector	Sweco	Telephone	2020/04/24	20 min	Research scope and methods
Kulin, Daniel**	Vehicle-to-grid (V2G)	Power Circle	Power Circle office	2020/04/07	20 min	Research scope and methods

*International Institute for Industrial Environmental Economics (IIIEE)
** Unstructured interview

The interviews were recorded with the approval of the respondents and conducted in Swedish. However, notes were taken during the interviews and afterward fully transcribed. To delimit the risk of misinterpretations during the analysis and translation of the transcripts to English (Flick, 2014), measures further taken into consideration are described in *Chapter 3.3, Data analysis.*

3.2.3 Benchmark projects

The concept of complete self-sufficient households has not been commercialized to a great extent and thus it was difficult to fully estimate how such a building is constructed with its power-generating components and installations. However, to fulfil the purpose of this study by not only making assumptions based on theory and knowledge from different actors, this project has taken a benchmarking project into consideration to connect with the reality as well to provide comparative an examples to this study (Blomkvist and Hallin, 2015). The project taken into consideration as a point of reference is an off-grid project received from one of the aforementioned respondents, namely Nilsson energy.

3.3 Data analysis

The conducted empirical data have been analysed to leave its raw state of presentation and enable a more legible set of findings (Blomkvist and Hallin, 2015). Data analysis have been performed through coding of the interviews and regarding the input data - comparisons between the benchmarking project and other sources have been performed.

3.3.1 Coding of the interviews

After the semi-structured interviews were transcribed the first step was to read through all the interviews once more to gain an overview of the conducted material while simultaneously listening to the recordings to avoid the misinterpretations. Also, each transcript was handled by two people separately which further decrease the risk for misinterpretations (Baxter and Jack, 2008). Later when analysing the completed transcripts, by looking for similarities and patterns from the different interviews, a thematic analysis of all interviews with common themes was conducted (Blomkvist and Hallin, 2015). The themes were categorized together from the different transcripts and later on identified into separate codes, as presented in Figure 4. Given the limited time-frame for this thesis together with a well-established set of theory, a *deductive thematic analysis* approach was taken meaning that the analysis of qualitative empirical data is theory-driven by applying the existing theoretical concepts as a lens from which the data is organized, coded and interpreted (Crabtree and Miller, 1999).

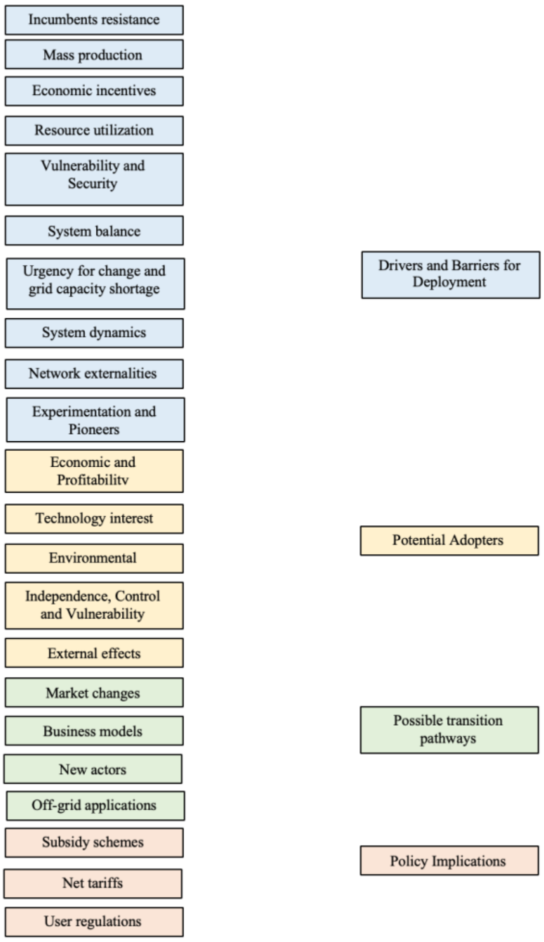


Figure 4. Coding tree.

3.3.2 Analysis of input data

The analysed benchmarking project is a real-life implementation of a self-sufficient small scale local electricity production household. Hence, the objective of this project was to analyse that the data used for this thesis and, to a great extent, how it correlated with the benchmarking project. Secondly, the technology, demand profiles, weather and cost data which is mostly gathered through discussions with experts in certain fields and annual reports have been analysed through further discussions and comparisons. However, this has been an iterative process of trying to match this works modelling setup and input data and have therefore been adjusted throughout the work. Finally, the topic of off-grid solutions is at an early stage of maturity and lots of data differ depending on whether the source holds a positive or negative attitude against the technology and, thus, overall theme of analysing the data has been to find patterns and remain objective.

3.4 Quality of research

This section presents the aspects considered with regards to the quality of research that was necessary to increase the credibility and quality of the conducted study. Reliability, validity, ethical considerations, and sustainability considerations are presented below.

3.4.1 Reliability

Reliability can be defined as to what degree the results of a study would differ if the study was repeated (Saunders et al., 2009). When research is transparent and conducted in a way that allows other scholars to replicate the study by following its detailed methodology (Bell et al., 2018). This study has intended to describe each process in detail along with an unbiased view the collected data and, successfully done so. When conducting interviews, several respondents were given the same set of question in order to present multiple views of the chosen subject that are presented in *Chapter 5, Empirical findings.* However, qualitative data received through interviews can vary depending on the selection of respondents, their mood, and knowledge in the area. Hence, the interview part of the study can be considered difficult to replicate to a full extent, but similar observations are considered to be reached by other observers. Furthermore, as for the modelling part of this study, this is considered to be presented with utmost reliability and all assumptions have been detailed with full transparency, which is considered to strengthen the reliability of this study.

3.4.2 Validity

High validity is reached by selecting an appropriate research design and drawing conclusions that are based on what is examined during the research (Bell et al., 2018; Collins and Hussey, 2014). This study chose to investigate both the socio-technical and techno-economic aspects of the research area, which can be considered to strengthen the validity of the study. Additionally, a triangulation approach was followed to ensure a research process that allowed adjustments and continuous improvements during the study. Furthermore, a large group of respondents from different areas of the Swedish electricity sector were interviewed in order to generalize the findings; each interview was also recorded and transcribed in detail. Technical and economic data regarding the modelling was selected only if, information was up to date and coherent with similar studies and manufacturers, this due to the fact that the technologies surrounding self-sufficient households are moving rapidly forward. This study has fulfilled its purpose with by investigating the appropriate literature, theory, and data in relation to the selected research area, which is defined by scholars as high validity of a study (Blomkvist and Hallin, 2015; Cresswell, 2014).

3.4.3 Ethical reflections

Throughout the parts of gathering empirical data for this thesis, ethical aspects, such as personal, professional and social (Herkert, 2005), have been taken into consideration. This is in line with the presented *ten principles in code of honour* from The Swedish Association of Graduate Engineers (2019) which have been used as a guideline. Meaning that the methods used for this thesis are all applied to benefit the personal, professional and social aspects. Moreover, despite the low level of confidential data received, there is, however, a guaranteed agreement among giving and receiving parties that such data only will be applied towards this thesis. Lastly, the Swedish Research Council (2017) states four requirements in regards to ethical consideration which have all been followed carefully to make sure that this thesis only solves the intended problem and nothing else. These requirements mean that the participants have all participated in this study in consent and with assured confidentiality, as well as, been informed with the precise aim of having them as a part of the study and guaranteed to only apply their given data towards the study in good use.

3.4.4 Sustainability considerations

Departing from the goal of achieving 100 % renewable electricity production in Sweden by 2040, as well as, how Colglazier (2015) defines that academic work can contribute to reaching certain sustainable development goals by highlighting challenges and actions together with monitoring progress and presenting innovative answers. This thesis has considered the sustainability viewpoints throughout the project period and strived towards delivering these aforementioned aspects from Colglazier.

3.5 Scenario planning tools

With the aim of constructing plausible scenarios of self-sufficient households and its role in the Swedish electricity system, this thesis applied a scenario planning tool to create a transparent presentation of future scenarios. The tool is further applied in *Chapter 7, Modelling.* Scenario planning stands out because of its promises to capture a whole spectrum of possibilities in rich detail. In general, scenario planning set departure from drivers of change and the plausible outcomes derives from the surrounding of the subject including *basic trends* and *key uncertainties*, presented in Figure 5. Finally, it is crucial to separate the two groups of trends and uncertainties and, simultaneously, distinguish the trends that surely will affect the outcome of scenarios as well as obtaining a holistic approach towards the uncertainties (Schoemaker, 1995).

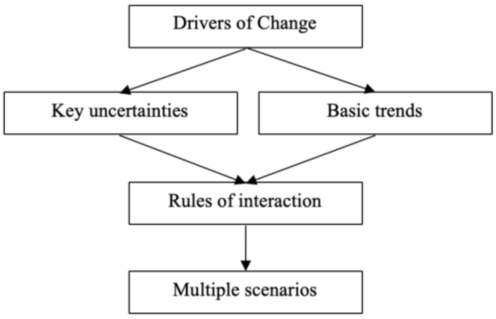


Figure 5. Scenario construction. Source: Schoemaker (1995).

This concept of separating the two groups allowed this project to investigate the effects of uncertain trends, such as subsidy schemes and regulations independently from the basic trends, for example, future cost decreases in new technology.

However, to gain insights into a specific case and its possible development, Formative Scenario Analysis (FSA) serves as a technique to construct and form well-defined sets of assumptions. The transformation from current to potential future states of a case narrows down and the process can be visualized from a systematic approach (Scholz and Tietje, 2002). Scenarios can serve as a tool for answering the questions "How might any hypothetical situation come around (step by step)?" and "What dilemmas exist at each step to prevent, disturb, or promote the process (of case development)?" (Kahn and Wiener, 1967). However, the focus is on *the possibility* and not on *accuracy* since it is difficult to achieve (ibid.). A sufficient set of *impact variables* linked in one way or another form the art of the scenario. The modelled scenarios describe a hypothetical future state of a selected system and the underlying development from the existing state (Scholz and Tietje, 2002).

The FSA is a nine-step procedure where a sequential order of activities leads towards a set of possible future scenarios (ibid.). However, for this study, the FSA was only focused on the six steps of scenario construction and interpretation, presented in Figure 6, as the scenario analysis was be performed separately in a specific modelling tool (*presented in the following section, 3.5 Technical simulations in HOMER Pro*).

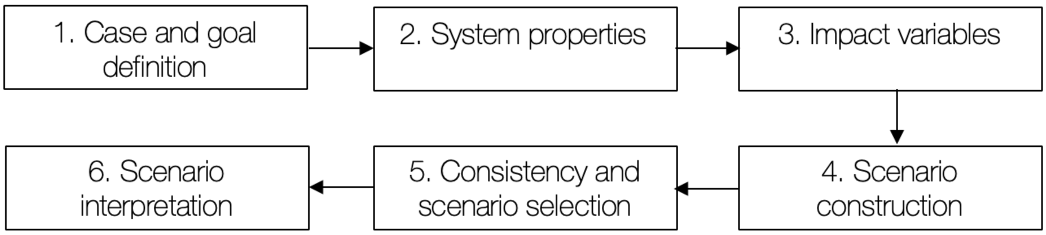


Figure 6. Formative Scenario Analysis. Source: Scholz and Tietje (2002).

3.6 Technical simulations in HOMER Pro

In order perform a techno-economic analysis on the current cost of off-grid systems and comparisons with prosumer and grid-connected systems, the HOMER (Hybrid Optimization Model for Multiple Energy Resources) Pro microgrid software by HOMER Energy was used. HOMER Pro is a simulation model that allows the user to simulate both on- and off-grid systems with many possible combinations of energy components. Furthermore, HOMER optimizes the size of the chosen system with a least-cost optimization model in order to obtain the lowest Net Present Cost (*NPC*) over the given project lifetime. In addition to this, a value for the Levelized Cost of Electricity (*LCOE*) over the project lifetime is calculated to project the cost of electricity in SEK/kWh.

There is a wide range of energy optimization models available and, a large group of scholars has utilized the HOMER Pro software in their research. Tudu et al. (2014) investigated the performance of wind-solar-hydro fuel stacks with grid connection, whereas Abdin et al. (2015)

performed a techno-economic analysis on hybrid off-grid systems with hydrogen production. In addition, Siyal (2019) performed a techno-economic assessment of wind-energy for hydrogen production in Sweden. Furthermore, with the intention of investigating off-grid systems, prosumer, and grid-connected systems, HOMER Pro was considered to be a valid tool for this study, given the substantial amount of previous studies available.

HOMER Pro calculates *NPC* by including all the system costs that incur over the project lifetime, these costs include initial capital cost, replacement costs, Operations and Maintenance (O&M) costs, and the cost of purchasing electricity from the grid. Thereafter, revenues in the system, salvage value and electricity sold back to the grid, are subtracted. In addition to this, HOMER uses a discount factor in order to consider the time value of money and then finally the *NPC* is calculated by summing the total discounted cash flows for each year during the project lifetime.

The *LCOE* is calculated by dividing the annualized cost of electricity production by the total electrical load that is served in the system each year, as seen in Equation 1.

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \tag{1}$$

$C_{ann,tot}$ represent an annualized cost of electricity that takes into account the total *NPC* of the system, annual real discount rate (*i*), project lifetime, and a capital recovery factor (*CRF*) in order to provide an annualized price in SEK / kWh during the project lifetime (R_{proj}), see Equation 2.

$$C_{ann,tot} = CRF(i, R_{proj}) \cdot NPC \tag{2}$$

The real discount rate is used to account for both one-time costs and annualized costs, which, is calculated from the nominal discount rate (*DR*) and the expected inflation rate (*f*) as seen in Equation 4.

$$i = \frac{DR - f}{1 + f} \tag{3}$$

The *CRF* is a ratio to calculate the series of equal annual cash flows by using Equation 4.

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{4}$$

When modelling an off-grid solution in HOMER Pro, input data is given in the form of load data (referred to as demand profile in this study), weather data, economic data, and constraints. Thereafter, the system is simulated, and several system profiles are given that is ranked based on the *NPC*. If the modelled setup cannot meet the given load demand, the system components are resized in order to meet the load demand. Moreover, methods for data gathering and inputs are further explained in *Chapter 7, Modelling.* The optimisation flowchart that HOMER Pro uses can be seen in Figure 7. Note that this flowchart is only used in systems where there is no grid connection available.

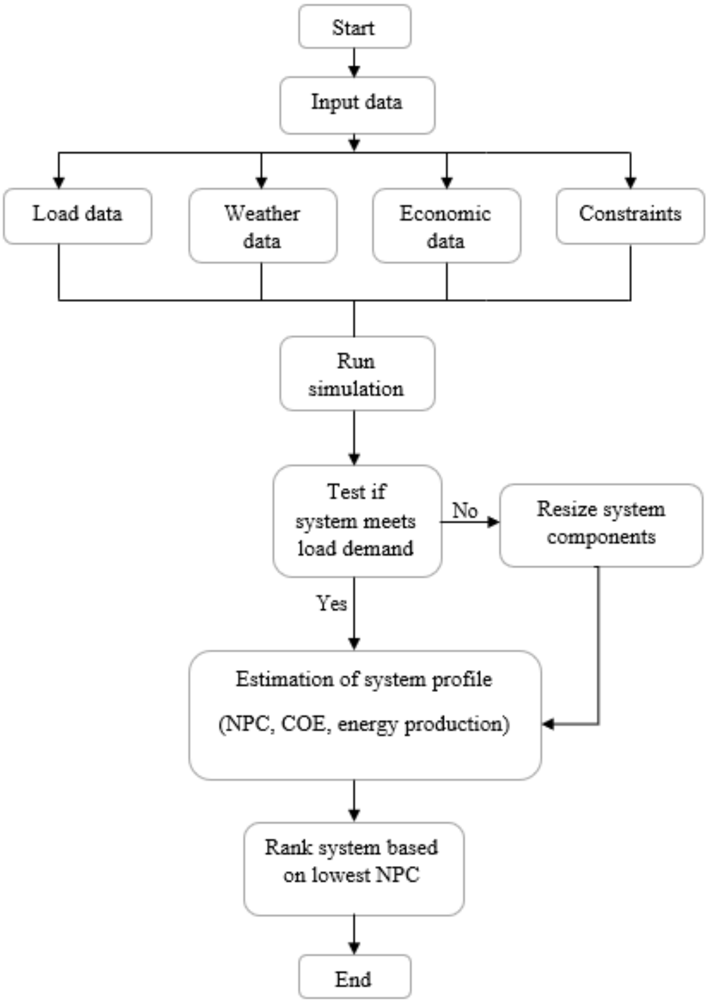


Figure 7. Optimization flow chart in HOMER Pro for an off-grid household.

4 Research Context

This chapter intends to provide a basis of perspectives, technological- and economical aspects to self-sufficient electricity systems. Furthermore, the purpose of this part was to gather up to date information of basic trends and key uncertainties surrounding off-grid solutions and investigate previous studies on the topic, with a focus on small-scale applications. Additionally, important impact variables were identified together with technical and economic data regarding the modelling of an off-grid system. Moreover, basic trends and key uncertainties collected from literature are applied in combination with input from experts in the field, in order to model the current and future scenarios, which are presented in Chapter 7, Modelling.

4.1 Off-grid

Recent studies have been performed on the feasibility of leaving the grid together with the important variables to consider (DiOrio et al., 2020; Gorman et al., 2020; Hittinger and Siddiqui, 2017; Kantamneni et al., 2016; Khalilpour and Vassallo, 2015; H. Liu et al., 2019). These studies have mostly been conducted with regard to the Australian, South-Central European and US market, taking their geographical conditions on the capacity of Solar PV, as well as their electricity market regulations and prices into consideration. Despite this, previous studies can be found valuable in the Swedish context since they tend to discuss the important variables and assumptions to consider when modelling residential electricity production which can be seen as relevant for this work upcoming *Chapter 7, Modelling*. Additionally, an interesting discussion included in most literature regarding off-grid feasibility is the disturbing scene of how the potential increase in household power plants can come to disrupt the dynamics of the power system and its incumbent actors, mostly referred to as *grid defection* or *utility death spiral*. The disruption is caused from the consumers having a vital role in the system and once consumers start to leave, the balance of the grid is affected and remaining consumers can become incentivized to follow their fellow off-grid pioneers.

4.1.1 Off-grid assumptions

Hittinger and Siddiqui (2017) performed a study about the feasibility of going off-grid in the US market and assumed that the decision to off-grid can be divided into two sections: first, consumers can find a decision to go partially off-grid by investing in a residential Solar PV system and, second, the consumer can take another step by additionally investing in a sufficient amount of Solar PV together with a storage solution. Consequently, taking this approach once studying the phenomena of off-grid, researchers can focus on the second section where the household already invested in a PV system. The sectioning is beneficial to, first, isolate the study to only investigate complete off-grid systems, second, grid-connected residential PV systems are increasing in popularity and further assumed as the potential off-grid candidates, third, precise estimations of Solar PV system installation costs can be devalued, last, an interesting comparison can, therefore, be to examine a prosumer grid-connected Solar PV system with a decoupled off-grid system.

Further, as off-grid systems not only require a Solar PV system and storage capabilities, different studies include different technological capabilities. H. Liu et al. (2019) assume that every household needs a Home Energy Management System (HEMS) to schedule their appliances and use of electricity, in order to maximize the potential benefits from a Solar PV and storage system.

An important assumption to consider is whether the system can reap payments from electricity sent back to the grid because of momentary overproduction, through feed-in tariffs (Gorman et al., 2020). If only considering an off-grid scenario, it is important to assume that the consumer has no connection to the distribution grid meaning that the excess energy cannot be sold and if no option of further storage exists, the electricity from overproduction must be excluded (ibid.). Also, the trend of decreasing cost of investing in Solar PV and storage systems may have a large impact on the results and to capture this scenario, without taking it for a certainty, it is important to both include a possible projection of cost decline (ibid.)

4.1.2 Off-grid impact variables

In order to handle the feasibility problem of leaving the grid, scholars have stated a vast amount of impact variables to consider, both to handle the issue of how much Solar PV and storage that needs to be invested but also how the cost of being connected evolves. First, it is necessary to determine *consumption patterns* over a certain time period (weeks, days, hours or minutes) and its following *demand profile* (Hittinger and Siddiqui, 2017; Kantamneni et al., 2016; Khalilpour and Vassallo, 2015). Together with consumption patterns and demand, a first intuition can be developed on how much installed *energy production capacity* that is needed. Moreover, the demand profile significantly influences the possibility of going off-grid, especially in the case of Nordic regions where consumption during winter months are high and the electricity produced by PV systems during the same period is limited (Haapaniemi et al., 2018).

Location-based household *electricity rates, network charges,* and *grid tariffs* are required to estimate the cost of being connected to the grid, as well as, the potential of gaining revenues from selling the generated excess electricity through *feed-in tariffs* (Hittinger and Siddiqui, 2017). Adding to this, if *network charges* include a minimum charge for staying connected to the grid regardless of usage, customers are more likely to profit from going off-grid (Haapaniemi et al., 2018).

Depending on what types of off-grid systems one tends to investigate, *system costs* are important variables to consider since a case of grid defection often requires high capital investments but rather low operational and maintenance costs (H. Liu et al., 2019). With the rapidly decreasing cost for both Solar PV and storage systems, these variables highly influence the economic aspects of when the case for going off-grid becomes profitable. Moreover, scholars often make assumptions based on recent trends in *system costs* along with future cost projections when studying cases of grid defection (Khalilpour and Vassallo, 2015).

Further, to estimate the amount of Solar PV capacity in regards to the actual production capacity, it is necessary to investigate *solar irradiation levels* throughout a year with the same time slices as the demand profile and the same geographical location as of the demand profile

(Hittinger and Siddiqui, 2017). As mentioned, regions with lower *solar irradiation levels* during winter months, e.g. Nordic regions, requires a storage system that can supplement the loss of electricity production from PV systems (Haapaniemi et al., 2018).

Moreover, it is important to have an impact variable regarding the *level of reliability* of the system (Hittinger and Siddiqui, 2017). In this case, the *level of reliability* refers to what share of unmet capacity is allowed for the system, meaning that consumers allow their peak load to be reduced as a trade-off for going off-grid. Khalilpour and Vassallo (2015) presents different feasible off-grid solutions based on a PV + BESS system but highlights that in the most economically beneficial cases, a high amount of unserved load is also present, in other words, *the level of reliability* is rather low. In the same study, a large storage system is required in order to achieve reliability that is equivalent to a grid-connection.

4.1.3 Off-grid KPIs of evaluation

The key performance indicators (KPIs) to a feasibility study of off-grid systems and whether consumers choose to decouple from the grid are various. In the study by Hittinger and Siddiqui (2017), economic benefits were the key indicator but with premises of how much reliability the consumer demanded from the system. Results showed that when comparing the operation and economics of Off-Grid home to a grid-tied Solar PV home, the desired reliability of the system had significant effects on the scale and costs of the system. Therefore, a determining factor of the feasibility was regarding the consumers' willingness to forego the reliability. The above-mentioned assumption of a trade-off between reduced reliability and lower costs is emphasized by H. Liu et al. (2019) as well. The idea is that, by prioritizing loads, consumers can become more aware of their actual need of electricity and thus in a scenario where off-grid solutions result in a limited capacity, increased consumer awareness is desired.

Moreover, in their work, Gorman et al. (2020) take another perspective on the determining factors of grid defection by including different KPIs and not limit the decision towards only the economic benefits. Here, a household could decide to take the step towards off-grid if, first, the off-grid systems become a cheaper alternative than the grid-connected utility service (*grid parity)* and, second, grid-tied customers become dissatisfied with the service provided by the utility service compared to the potential offer from an off-grid system. The latter includes not only services, such as reliability, but also the customers desire to go with fully "green" electricity and/or desire for self-reliance. However, as a concise measurement of KPI, off-grid scenarios is argued to viable options once *grid parity* is reached (Gorman et al., 2020; Hittinger and Siddiqui, 2017; Kantamneni et al., 2016; Khalilpour and Vassallo, 2015).

An interesting study by Chesser et al. (2018) investigated the positive feedback cycle in electricity markets, more specifically residential Solar PV adoption together with electricity demand and prices. Similar studies have been performed by other scholars but mainly focused on the US market (Eryilmaz and Sergici, 2016; Laws et al., 2017). However, this study not only focused on one national electricity market but three, the Irish, UK and Australian market where they interpret the data using a least-square approach. The hypothesis is that once households start adopting the residential Solar PV, a cycle of changes to the electricity demand as well as prices will occur. Hence, a set of three different KPIs is used in the work by Chesser et al. (2018), residential Solar PV uptake, residential electricity demand, and residential electricity price, all affected by each other.

A recent investigation is done on how to leverage the most from having a Solar PV and storage system where an option is, if needed, to capture energy from the grid. Their KPI is like other studies to find if it is economically viable to invest in such a system. However, their study takes more of an investment viewpoint where the metrics to evaluate the overall economic performance of the system is focused on the Net Present Value (NPV) over a number of years (DiOrio et al., 2020).

4.1.4 Off-grid results and implications

First off, results from existing studies indicate that the scope of consumers leaving the grid is very limited with the current technology costs. Further, results show that multi-family households and apartments have less potential of leaving the grid because of the low or non-existing rooftop area to mount a sufficient amount of Solar PV capacity (DiOrio et al., 2020; Gorman et al., 2020; Hittinger and Siddiqui, 2017; Kantamneni et al., 2016; Khalilpour and Vassallo, 2015; H. Liu et al., 2019).

The overall scene of off-grid systems is undergoing a lot of rapid changes and thus results from studies may differ depending on the year of publication. However, trends can be seen, and results show a homogenous route of answers. From the study by Khalilpour and Vassallo (2015) a conclusion is drawn that a small-scale Solar PV system is unable to meet a residential demand in Australia and thus not enough for a household to reach grid independence. Additionally, if not well equipped with storage, a lot of produced electricity is unserved. Having a larger PV system with added storage can increase the independence level whereof the best grid independence potential, which adds significant costs of storage, lies in having a smaller PV system but with a larger storage system.

Results from Hittinger and Siddiqui (2017) indicates that if consumers are willing to forego the most challenging 25 % of their demand, the LCOE from an off-grid residential system will be lowered by approximately 50 %. A more recent study by H. Liu et al. (2019) argues that this is still valid. If consumers expect higher reliability, it is far from favourable to not stay on the grid. Further, Hittinger and Siddiqui (2017) indicated difficulties of understanding the economics of off-grid once net metering and feed-in tariffs are available. Results point towards a scene where grid defection is highly undesirable for the household if net metering or feed-in tariffs are available, motivated by the assumption that a homeowner can use the PV and storage system as a backup or storage device and receive revenues from selling excess electricity back to the grid (ibid.). Further, indications from Gorman et al. (2020) point in the same direction where an increased load reduction on the grid from Solar PV installations exists whereas the actual grid defection is far from reality.

Implications

Having economics as the main driver of consumer behaviour, leaving the grid in a larger scale is not a realistic projection of the future but rather a scenario where consumers adapt to Solar PV and batteries to decrease their demand from connections (Khalilpour and Vassallo, 2015). Additionally, future grids could focus on having a bi-directional flow of energy instead of having one-directional energy flow to enable the consumer and producer option (ibid.).

In many locations, subsidized PV offers favourably economics on the premises that excess electricity can be stored. However, discussion regarding the profitability of being able to store often disregards the large battery storage costs it comes with. In reality, to break even, the LCOE of a PV and storage system must be significantly lower than the grid-connected service (Hittinger and Siddiqui, 2017).

The results from Gorman et al. (2020) implicates that a scenario of increasing off-grid households is more viable if consumers have a low demand of electricity and further accept a more variable or flexible rate of reliability together with a geographical location that enables a lower Solar PV and storage investment. Significant variability in required system sizing for off-grid households exist driven by the locational attributes in terms of solar irradiation and, if covering the heating of a household, the building assumptions made of household isolation and other affecting aspects (ibid.).

4.1.5 Grid defection and utility death spiral

On the assumption of an increasing amount of bi-directional flow in the grid, Khalilpour and Vassallo (2015) argue that in order for DSOs and utility operators to keep their position in the market, policies could be developed to help the network operators find sources of revenues from the future small scale prosumers rather than increasing the energy prices which further is assumed to be the main driver of grid defection and utility death spiral. By incorporating prosumer contracts, utilizing dynamic grid tariffs, and demand-side management mechanisms, PV and storage systems can become the main driver in load reduction and peak shaving during the critical peak hours (ibid.). Hittinger and Siddiqui (2017) strengthen this argument by suggesting that utilities and regulators are interested in using excess electricity from customers to increase grid reliability through peak demands. Meaning that grid defection is insufficient use of resources available and utilities should modify their business models in regard to the adoption of Solar PV and storage, especially if significant price drops of self-sustaining technologies occur (ibid.).

Situations in some US locations with high electricity prices from the utility services serves as an important and well-overlooked point of grid defection. Hawaiian state regulators found that the Solar PV adoption was growing too rapidly and concerns regarding the grid stability increased (Hittinger and Siddiqui, 2017). The increased adoption rate took action from the high feed-in tariffs for a households excess produced electricity and the state rewrote the feed-in tariffs to slow down the Solar PV adoption in favour for the system stability (ibid.). Moreover, once Hittinger and Siddiqui (2017) studied the economics of grid defection in Hawaii, it made economic sense for a household to defect from the grid because of the low compensation of feeding electricity back from the grid together with the high utility rate. A concise suggestion of grid defection economics could, therefore, be suggested as; net metering policy, residential solar adoption, network charge design and electricity prices are all interrelated. In order for grid defection to make economic sense, a household must face both unfavourable feed-in tariffs or net metering policies and high electricity bills – the high electricity bill make self-generation lucrative and the lack of a feed-in tariff regime can justify additional investment in storage for grid defection.

H. Liu et al. (2019) emphasizes the importance of electricity price as well, meaning that certain tariff designs could incentivize grid defection to a great extent where customers, permanently, disconnect from the grid, particularly in a possible future with decreased cost of Solar PV and storage costs. Moreover, to mitigate the rate grid defection it is suggested that implementation of demand charges where tariffs are designed to recover utility costs by charging customers for their peak demand as an approximation of a customer's actual cost on the system.

4.2 Off-grid related technologies and projections

Welcome to the jungle. The following section presents the technologies required behind off-grid households together with its operational and cost characteristics of today and within the future. Consequently, the presented data will support the work of constructing scenarios in *Chapter 7, Modelling.*

In countries with low seasonal variations and a steady supply of solar radiation, off-grid systems can consist of an electricity-generating technology such as Solar PV in combination with battery storage (Abdin et al., 2015). Moreover, excess electricity is stored in batteries and utilized when the PV panels are not generating electricity, which, can last for a couple of days or, in some cases, weeks. However, in Nordic regions, solar radiation during wintertime is very limited. Furthermore, an alternative storage process is needed in order to provide electricity during the dark winter months. Hydrogen storage is one way to tackle this long-term storage issue, in this case, excess electricity during summer months is converted to hydrogen gas through electrolysis and stored in a tank, usually in the form of compressed gas (Kosonen et al., 2015). During winter, the compressed hydrogen gas is used as fuel in a fuel cell that generates electricity and heat.

4.2.1 Solar PV

In order to utilize energy captured by renewable energy sources such as individual wind plants or solar panels, the energy source must be connected to the electricity grid or, alternatively, use some form of energy storage (Scamman et al., 2014). One of the most common residential solutions for electricity production is PV panels, which can generate electricity directly from sunlight. Over the past decades, PV panels have been used with a varying purpose, traditionally, PV panels were used to facilitate the use of electrical appliances in remote areas such as off-grid houses, cell phone towers, and water pumps. However, with the increasing global shift towards more major renewable energy, grid-connected PV now make up 99 % of the market share (IEA, 2019a).

With the increasing usage of solar energy, prices on both large- and small-scale Solar PV have plummeted due to the larger scale of production and continued progress in research, resulting in higher efficiency (Philipps and Warmuth, 2019). In Germany, prices on a basic PV rooftop-system has seen a net-price regression of 92 % (ibid.). Consequently, large-scale Solar PV projects are also becoming more cost-effective and prices are expected to drop even further in the coming decade (IRENA, 2018). Projections suggest that module costs are expected to drop an additional 30 % globally, by the end of the decade (BloombergNEF, 2019).

4.2.2 Energy storage

In the case of Renewable Energy Technologies (RET), mainly referring to wind and solar, storage systems play a vital role. One key challenge to overcome with RET is the variability of electricity production due to its fluctuating state of production. This intermittency in production is dependent on external factors, e.g. wind-conditions, sunlight, and seasonal conditions (Abdin et al., 2015). Whereas, on the contrary, a controllable RET such as hydropower or coal can be utilized independently of external factors and supply the demand when most needed. To deal with this, energy storage can provide relief by storing the produced electricity in various forms, to be utilized when the demand is high. As of today, there is a range of different energy storage solutions available. Pumped hydro is the most common form of energy storage, accounting for over 95 % of the total energy storage share (IRENA, 2017). This technology pumps water from lower to higher elevation and is thereafter stored in the form of gravitational energy during an off-peak and low-cost period in the system (ibid.). However, Battery Energy Storage Systems (BESS) have seen rapid development over the past decade both on utility- and small-scale (IEA, 2019b). Additionally, hydrogen technologies are an effective way to transform excess produced electricity that can be stored long-term (IEA, 2019c).

4.2.3 Energy storage - Batteries

Batteries have been around since the 19th century and there is a wide range of technologies available on the market (Mohanty et al., 2016). Lead-acid batteries used to be the most common solution in the case of simple Solar PV solutions (ibid.). However, over the past decade, along with the growing EV market, Lithium-based batteries are now the most widely utilized, making up for almost 85 % of the capacity installed (IEA, 2019b). In addition to this, there is a range of other types of batteries being used in the BESS industry, e.g. flow-batteries, Zinc-hybrid batteries, and Nickel-metal-hydride (NiMH) batteries to name a few (IEA, 2019b; Jiang et al., 2019). Furthermore, a BESS is built upon a rechargeable electrochemical cell (EC) that stores or provides electricity depending on if its charging or discharging (Safari and Hardy, 2019). As mentioned, there is a variety of EC technologies on the market and they all vary in its chemistry and level of maturity, but are available for the same purpose, to store energy.

In the case of BESS, there are a couple of more components that are vital in order to provide a functional storage system. Firstly, a Battery Management System (BMS) is often used to monitor battery parameters and ensure it is functioning properly (Yang et al., 2015). Furthermore, a BMS main task is to keep track of the cell voltages, temperature, and state of charge (SOC) to ensure these values remain within an acceptable value that prolongs the lifetime and safety of the battery (Starke et al., 2019; Yang et al., 2015). In addition to this, a Power Conversion System (PCS) (i.e. inverter) is needed to convert the DC in the battery to AC used the energy system (Starke et al., 2019). The PCS controls the flow in and out of the storage system depending on the state of charge (ibid.).

Adoption of technology such as BESS is driven by complex factors (Xylia et al., 2019), important aspects to consider is the Technology Readiness Level (TRL) and the Manufacturing Readiness Level (MRL) (Mongird et al., 2019). Additionally, it is important to look at the cost and cycle-life of each battery technology. Cost is measured in a price that is normalized to the storage size ($/kWh), whereas cycle-life represents how many cycles the battery can withstand before it is considered inefficient and should be replaced (Safari and Hardy, 2019). Cycle-life is usually assumed to be one cycle per day for a BESS, charge-discharge-charge is defined as one cycle (Battery University, 2019). As mentioned, the development of Lithium-based batteries are highly driven by the booming EV market, making it the best option in terms of TRL, MRL, cost and cycle-life (Mongird et al., 2019). Zinc-hybrid technology looks very promising in terms of cycle-life and cost, however, TRL and MRL are still low (ibid.). Lead-acid batteries are low in cost and have a high TRL and MRL, however, cycle-life is very limited which would require frequent replacement compared to other technologies (ibid.). Furthermore, complexity and maturity are still affecting the BESS market and it is still highly uncertain what the dominant technology will be in the future, on things seems to be certain, BESS market is expected continue to grow and cost will drop over the coming decade (Cone, 2018; IRENA, 2017). Each technology could be described and investigated further, however; it goes beyond the range of this study.

4.2.4 Energy storage – Hydrogen technology

Electrolysers can be used to store excess electricity in the form of hydrogen. The process of electrolysis requires electrical work in order to separate water into hydrogen and oxygen (Millet and Grigoriev, 2013). Furthermore, when intermittent energy sources such as wind and Solar PV are producing more electricity than demanded, the electricity can be used to power an electrolyser that produces green hydrogen gas. Green meaning that the hydrogen is produced from a renewable energy source. The hydrogen gas is stored in a compressed tank and is thereafter used as fuel in a fuel cell when electricity is required.

As with batteries, there is a variety of electrolysis technologies available on the market. Moreover, three of the most common types are: (1) alkaline water, (2) proton exchange membrane (PEM), and (3) anion exchange membrane (AEM). The alkaline type is a mature technology with low manufacturing costs, however, many disadvantages such as complicated maintenance, corrosion and slow start-up are present (Guo et al., 2019). PEM electrolysers are advantageous due to simple maintenance, fewer components, and a fast start-up, however, manufacturing costs are still high. AEM is a relatively new technology with a promising future, one of the leading manufacturers of AEM, Enapter (2020), is projecting a price reduction of 75 % by 2025.

Hydrogen storage is a key enabler for the continuous improvement of electrolyser and fuel cell technologies. Hydrogen is for the most part stored in gaseous form but can also be stored in liquid or hydride form and, for longer periods of time than BESS. Electrolysers can produce hydrogen at pressures between 10 and 30 bar. However, hydrogen as a gas is typically stored in high-pressure tanks with the tank pressure ranging from 200-700 bar (Zohuri, 2019). In order to reach higher pressures, additional compressors are used after the process of electrolysis. Furthermore, storage tanks and compressor are both mature technologies which suggest that manufacturing costs will not likely decrease significantly. However, near-term goals aim towards compressed hydrogen gas at 700 bar in fibre-reinforced composite tanks, which will result in more stored hydrogen per kg and therefore reducing costs (ibid.).

A fuel cell generates electricity and heat through a chemical reaction by supplying fuel and an oxidizing agent to the fuel cell. Energy efficiency is in the range of 50 %, however, waste heat is also produced in this process which, can be utilized as a thermal energy source and, therefore, provide higher efficiency (New Energy World, 2014). The chemical reaction generates electricity by separating electrons from the H_2 atoms by adding air and, with the help of an anode, electrolyte, and a cathode, electrons flow via an electric connection where the electricity can be used (O'hayre et al., 2016). There are a variety of fuel cell technologies available on the market with different key characteristics, however, for stationary power supply, the proton exchange membrane (PEM) type is the most common (Lindorfer et al., 2020).

There is still a low level of market penetration for fuel cells and scholars still believe that there is a low TRL (Wang et al., 2018). Currently, high investment costs are still a major challenge to overcome. However, costs are expected to decrease significantly as the market continues to grow. In fact, with an increased focus on low-carbon technologies energy systems, cost and TRL for both fuel cells and electrolysers are expected to follow the same trajectory as PV and BESS have in the past over the coming decades (Lindorfer et al., 2020; Liu et al., 2018).

4.3 Electricity costs, subsidies, and sources of revenue in Sweden

To support the scenarios in *Chapter 7, Modelling* that relies on receiving electricity from the grid, as well as feeding electricity back to the grid, it is necessary to explore the costs and revenues of electricity in Sweden. Additionally, the different subsidies and investment aids one can receive from household electricity production are explored in this section.

After reviewing the total cost of electricity and feed-in tariffs in Sweden, it turns out to be a rather complex market. Mainly, the total cost of electricity for a Swedish household consists of the following three components and its related costs (Elskling, 2020; Energimarknadsbyrån, 2020a; Skatteverket, 2020a):

1. Electricity price
    a. Market spot price
    b. Electricity certificate
    c. Handling fees
    d. Fixed costs
2. Network charges
    a. Fuse charge
    b. Grid tariff
3. Taxes and government fees
    a. Energy tax
    b. Government fees
    c. VAT (25%)

The market spot price is provided by Nord Pool, a power market that offers intraday and day-ahead power trading and data. Price calculations are made based on an aggregated demand curve and an aggregated supply curve that is calculated each hour (Nord Pool, 2019). There are several bidding areas within the market to make sure congestions in the transmission grid are limited. Each bidding area can have a balance, surplus, or deficit of available electricity. If the transmission capacity is limited at a point in time, it will result in different area prices. Sweden is divided up into four regions (SE1, SE2, SE3, and SE4) and many of the power plants are located in the north, whereas demand located towards the southern parts, resulting in a lower average price in the north compared to the south (ibid.).

Furthermore, price projections for the coming decades regarding all components in the total cost of electricity has been impossible to gather. Noteworthy is the fact that most respondents believe in a rather unchanged market spot price as more wind power is implemented into the system. An analysis performed by Energiforetagen (2019) that investigated several scenarios of the future Swedish electricity system suggest the same outcome regarding the spot price when measured in SEK / kWh. Additionally, a publication by the Swedish Energy Agency (2016) modelled four potential electricity systems scenarios up until 2050, and all scenarios show an increase in the spot price. Network charges have been following basic trends for the past decades with a steady increase (Energimarknadsbyrån, 2020b). However, after a decade of continuously rising network charges, in 2018 the Swedish energy inspection agency enforced a limit on how much the DSOs can charge their customers in the 2020-2023 time period. Over a ten year period, some of the major DSOs were increasing their network charges by up to 5 % per year, whereas the new enforcement limits this increase to about 2 % per year for 2020-2023, what will happen after this period remains uncertain. Between the years 1996-2019, network charges have increased by 2.9 % per year on average (SCB, 2019).

Grid tariff design is a hot topic and the Swedish Energy Market Inspection Agency (Ei) is, at the time of this study, working on how these tariffs should be designed in the future to promote flexibility and efficient use of the electricity grid (Ei, 2018). Additionally, energy tax is paid on every kWh purchased. Between the years 1998-2019, the energy tax increased, on average, by 4.8 % per year (Holmström, 2018). To conclude, projections for the total cost of electricity in the future consist of both basic trends and key uncertainties.

4.4 Subsidies and potential revenues

According to the Swedish Energy Agency (2019), producers of self-sufficient electricity that produce an excess amount of electricity (micro-producers) have the right to sell the surplus to an electricity retailer. In general, electricity retailers purchase their needed amount of electricity from the Nordic power exchange Nord Pool to further sell it to their customers. The price of purchasing from Nord Pool is variable and depends on a lot of factors and the buy-in price from self-sufficient producer's excess electricity production is often correlated to the spot price from Nord Pool. However, the offered feed-in tariff often depends on the many available different electricity retailers. Beyond the offered electricity price, producers can receive a *tax deduction*, *electricity certificate,* and *compensation* from the electricity retailers for feeding the grid.

The regulations and subsidies for micro-producers have a history of changing a lot. However, today according to the Swedish Tax Authority (2020b) a micro-producer of renewable energy has the following rights and obligations regarding *tax deduction*, presented in Table 2.

Table 2. Regulations and subsidies for micro-producers in Sweden.

Tax	Only the income tax is affected by the micro-production system. As long the installed peak capacity is below 255 kW, energy tax is not required.
VAT	Registration of Value Added Tax is not required as long as the micro producer is not exceeding an income of over 30 000 SEK from the excess electricity sold.
Tax deduction	Micro-production facilities shall have the same connection point and main fuse as the private home's connection to the electricity grid. Meaning that the electricity being fed-in and fed-out must go through the same connection. The main fuse at the connection point cannot exceed 100 amperes. The tax deduction is valid for maximum 30 000 kWh and only for same amount of kWh as the micro-producer has taken out from the electricity grid. The tax deduction is 0.60 SEK/kWh giving a maximum of 18 000 SEK a year.
ROT-discount (Renovation, Reconstruction and Extension)	Micro-production facilities on private homes have the right to obtain a renovation, reconstruction and extension discount when installing the facility. This is only valid for the construction work and not the specific components. ROT-discount is eligible for 30 % of the total installation cost but at a maximum of 50 000 SEK a year.

Further, compensation for supplying electricity to the grid can be given because of the many benefits with having local distribution. If transporting electricity long distances, the electricity providers will suffer from energy losses. Thus, it is beneficial to the losses if the transmission is supported by local energy plants. Therefore, electricity grid companies are obliged to pay compensation for the surplus that a solar cell owner provides to the grid, which is sometimes called *grid utility* or *energy compensation*. The amount is only a small part in relation to the electricity price, depending on where the producer is located and the utilized electricity grid company (Swedish Energy Agency, 2019d). Moreover, after going through real electricity bills from prosumers and inquiring electricity providers, the actual feed-in tariff that a customer can obtain from excess electricity sold, is similar to the market spot-price on Nord Pool, excluding the tax deduction of 0.60 SEK / kWh.

The electricity certificate system is a market-based support system that aims to increase the production of renewable energy in a cost-effective alternative which is applied via the Swedish Energy Agency. For every MWh of renewable electricity produced, a certificate can be received from the state. Thereafter, producers can sell the certificates on an open market to a buyer where the price is decided between the two parts. An incentive to give the producer an extra income besides the price the electricity is sold at (Swedish Energy Agency, 2019d, 2019a). The price of electricity certificates has varied since the arrangement was introduced and past prices do not guarantee the value in the future, in fact, the price has dropped significantly over the past decade and is close to 0.01 SEK / kWh (SKM, 2020; Swedish Energy Agency, 2019d).

Moreover, in addition to the value added by running a micro-production of renewable electricity, private persons can receive an investment aid to the total cost of investment and installation. The investment aid covers 20 % of the total investment and can only be applied for once. However, this is regulated by the state and the level of available money for aid shifts with every budget statement. This means that the investment aid of 20 % is only valid until 31st December 2020. Another aspect to consider is the restraints of only being able to choose either the ROT-discount or the investment aid. Overall, the ROT-discount is approximately summing up to a 9 % support and thus it is beneficial to go with the investment aid. However, the time for approval is long with the investment aid whereas ROT-discounts are paid directly (Swedish Energy Agency, 2019e).

To increase the area of applications with Solar PV systems, an investment aid on storage solutions is present as well. The Swedish Energy Agency provides private persons with an investment aid on storage solutions for up to 60 % of the total investment with a limit of 50 000 SEK. In order to receive the support, the energy storage system must be connected to a plant for self-production of renewable electricity connected to the electricity grid. However, the same issue of future uncertainty regarding the support exists and the promised support of 60 % is only valid if provided that you install your storage system by December 31, 2020, as well as the option of either choosing the ROT-discount or investment aid (Swedish Energy Agency, 2020).

5 Empirical Findings

The following chapter presents the results from the empirical research and aims to inform the reader with opinions from experts within different fields of the studied subject. This chapter set departure from the representative's themes identified when coding the interviews.

5.1 Drivers and barriers for deployment

The respondents present an unshared set of drivers and barriers for the deployment of household-level electricity production. Interestingly, there is a common belief that off-grid households are today technically feasible whereas a great barrier are the existing structures and different interests in the market. Actors want to support and motivate their own source of energy production (Torstensson, 2020), the grid owners are not interested in losing their connected customers (Lindahl, 2020), no matter the course of development some actors will be on the losing side (Hojčková, 2020). Additionally, within a developed system, such as the electricity system, incumbents have had and still holds a large role in the shaping of regulations on the market which, implicitly, could prohibit new innovations to reach the market (Reuter, 2020).

With self-sufficient households, what happens is that the common consumption society breaks into the electricity system, which historically, has been top-down driven and designed for large-scale optimization and guaranteed supply (Hojčková, 2020; Sandén, 2020). Hence, based on a completely different dynamic than self-sufficiency and, therefore, a clash occurs between these systems of individual consumption, societal supply, and optimization of energy (Sandén, 2020).

When looking at the actual electricity system and how it is affected by a conversion towards off-grid, it can be beneficial and negative depending on the context. If the system of today is already overloaded with demand during certain times of the day, the system is benefited from households that can act as self-sufficient as possible (Hojčková, 2020). Moreover, having individual systems within the larger system that can operate independently if disruption occurs, or even serve as a power resource if needed, could be improving the system utility (Lindborg, 2020). On the other hand, if households become too self-sufficient, then suddenly the infrastructure is not being used enough to pay off investments (Hojčková, 2020).

From a grid perspective, if assuming a full decoupling from the grid, one disconnection does not change anything. However, if considering all the actions required for a household to support a grid disconnection, in terms of production, storage, and flexibility solutions. These required actions and components could serve a powerful value to the larger system, much greater than to the small individual system (Hult, 2020).

Resistance

The respondents argue that the incumbents are very much dependent on the consumers and, based on their interest in keeping their customers and market shares, it is not extraordinary that there is a resistance and slow speed of change among incumbent actors (Hojčková, 2020; Torstensson, 2020; Reuter, 2020; Wallner, 2020; Sandén, 2020). It is difficult to understand

and manage change in the market, incumbents are, because of their history on the market, more politically engaged and holds a lot of influence compared to new entrants. Therefore, it can be seen as sometimes difficult for the innovators to submit a proposal for change if it is not in line with the interest of the incumbents (Hojčková, 2020, Reuter, 2020). From a grid-owner perspective, a future towards decentralized electricity production or particularly off-grid would bring almost no benefits.

Thus, it can be arguable that because of existing structures and slow speed of change among influential actors, the transition is slowed down and kept away from being radical (Sandén, 2020; Hojčková, 2020). Consequently, it is difficult to make everyone satisfied, both grid actors and consumers have their interest with specializations towards their different things (Hojčková, 2020) and it is a fine line in which the utilities find that fairness is served (Wallnér, 2020). Even though some utilities may find interest in developing decentralized solutions, it is obviously complex to "turn a heavy ship around" and go "from being a slow camel to a running cheetah" (Reuter, 2020). Unfortunately, the incumbents are so intertwined with policymakers and dependent on each other (Hojčková, 2020). Recognizing the fact that old investments must be protected (Reuter, 2020), government cannot just take business from incumbents and let them face bankruptcy because of these necessary interconnections (Hojčková, 2020).

Mass production

Departing from the mass production paradigm, a general theme among the respondents highlights the importance of economies of scale and how the price drop for Solar PV have appeared as a trigger of interest in self-sufficiency (Lindahl, 2020; Lindborg, 2020; Torstensson, 2020; Wallner, 2020). Today, Solar PV is a cheap source of electricity and the market demand is much driven by the cost development – as with the case of electric vehicles that have really started to take off (Torstensson, 2020). However, it is starting to become a self-sufficiency mass market from a technological point of view with Solar PV and batteries. Sooner or later, electrolysers and fuel cells that supports a year around self-sufficiency household will undergo the same transition (Wallnér, 2020).

Sandén (2020) explains that the logic behind self-sufficiency is related to the mass production paradigm by stating:

"Once the mass production is available, it enables a rapid decrease in costs and further creates a dynamic unlike the one possible in a large interconnected system" – Sandén (2020)

Research on the deployment of Solar PV highlights the actual reality of how the technology followed an exponential growth curve during the last 50 years have, according to Sandén (2020), resulted in a case where research done in 2005 regarding the deployment of PV is relatively accurate today. Whether conceptions about what's reasonable for making an impact, other energy technologies that are scalable and possible to mass-produce, such as BESS, will likely follow the same pattern of exponential development. Discussions are circulating about a cost parity between local energy production and centralized large scale production in 2030-2035 (Torstensson, 2020).

Further, Hojčková (2020) explains the take-off for renewables. Because they are becoming more efficient and cheaper, it has resulted in a scene where renewables are being discussed to be a source of household production in developed countries. Also, the fact that renewables are modular, households can suddenly install solar panels on their roof which was impossible before (Wallnér, 2020; Hojckova, 2020). Nilsson (2020) argues that one of the main drivers for deployment of off-grid solutions is that the idea of becoming self-sufficient, that was only at the R&D level 5 years ago, can become fulfilled from only using standard components and according to Wallnér (2020) it is only a matter of time before the solutions start to become cost-effective.

Economic incentives

The rising fixed costs of staying connected to the grid drive the interest of self-sufficiency and, even if a household doesn't consume excessive amounts of electricity, large costs of staying connected will show up on the electricity bill (Hult, 2020; Lindborg, 2020; Torstensson, 2020). Households are, historically, not really seen as a customer to the electricity companies but more of an outlet point where the electricity companies can raise fees to the limits set by EI without ones approval (Lindborg, 2020). The situation with monopolistic grid owners leave the consumers with no alternatives (Nilsson, 2020).

off-grid solutions could, over time, generate lower costs for household energy (Nilsson, 2020). However, it is certainly not only depending on the cost development of self-sufficient solutions but also from pricing mechanisms in the grid-connected electricity system. On one hand, with regard to the household perspective, one of the greatest drivers to take the step and actually disconnect from the grid is that in many countries the subsidies provided for producing solar power to the system is expiring. If a household possesses a technical ability to become self-sufficient and there is no way of generating income from it, the household will probably disconnect from the grid (Hojčková, 2020). However, the uncertainty around investment aids, tax deductions, and feed-in tariffs can also be seen as a great barrier for the deployment (Wallnér, 2020).

On the other hand, something that can steer the course of action is whether grid owners will apply new tariff schemes which has been on discussions for a while (Torstensson, 2020). Suddenly, as soon as prices increase on the grid-connected electricity from these new tariff schemes, a driving force towards investing in batteries with or without Solar PV will occur (Torstensson, 2020; Wallnér, 2020). Because today, there are no economic incentives for running batteries or optimizing energy consumption since electricity is too cheap (Wallnér, 2020; Torstensson, 2020; Sandén, 2020; Hult, 2020; Lindborg, 2020). One respondent reflects on that power tariffs might speed up profitability of investing in local energy systems and that that might be a reason why these tariffs have not been introduced on a wider scale yet (Torstensson, 2020)

As soon as prices increase, the driving force for investment – it will happen very soon I think – Wallnér (2020)

Resource utilization

In line with the consumption trends during the last 110 years, emerging from the assembly line introduced by Henry Ford in the 1920s, an individualistic trend set sail. Once the technology becomes cheap enough, the economic argument tends to lose its power. This creates a scene where resource utilization can become ineffective and Sandén (2020) stated the following example:

"There is a large number of households keeping a lawnmower in the garage to only use it seven times a year, at the same time the neighbour has one as well to only use for seven times a year" – Sandén (2020)

According to (Hult, 2020; Wallnér, 2020), this can be seen as a barrier for deployment. To build lots of small systems creates an unnecessarily ineffective use of resources that otherwise could provide great system utility – the larger the system, the greater cost-effectiveness, and utility in terms of balancing the system. To continue building large-scale and transferring the electricity to households will probably create the cheapest electricity in the system of Sweden. Doing things off-grid just creates too much inefficiency in the system (Hojčková, 2020).

Vulnerability and security

During the last 30-40 years, Sweden has focused a lot on efficiency and rather less on security and redundancy in the system. External pressure, such as the Corona crisis can accelerate the idea of increasing security within systems and make actors more aware of whom they can trust in times of uncertainty (Sandén, 2020). In addition, discussions regarding climate change and how scientists are in agreement about an increased risk of extreme weather conditions makes the society question whether one can trust the system at all times (Lindahl, 2020).

"Elsewhere in the world we see, for example, the bushfires in Australia and then the Coronavirus, which has caused the demand for solar cells with batteries to increase significantly in Australia right now. With an increasingly uncertain world and more extreme weather, people may think about this to a greater extent" – Lindahl (2020)

If investigating the electricity grid today, from a system technical perspective, Sweden is very vulnerable to external threats and it is possible to mitigate that issue if exploiting local installations (Lindborg, 2020). Such preparations for disturbances in the public system can serve as drivers for off-grid solutions that further creates a robust system in which energy is guaranteed whenever it is needed (Nilsson, 2020). On the other hand, only one respondent pointed out the importance of how the technology behind self-sufficient households exists in an immature state regarding its safety aspects. The society is used to the current configurations and by adding, for example, solar panels, batteries, and hydrogen storage, a lot of new potential hazards arise. Hence, a barrier exists which must be considered and addressed since both individuals and actors will demand that these safety aspects are under control before investing can be possible (Reuter, 2020).

Balance in the system

Solar PV is a production form that contributes to shaping an imbalance in the system meaning that it only increases the large problem in Sweden with heavy seasonal variations between the summer and winter. On one hand, installing a battery might be a step towards the possibility of leaving the grid by symbolizing the flexibility that is needed. On the other hand, if the household decides to stay with the grid, the battery can be operated towards the market and its pricing mechanisms and support the system balance when needed. A great net utility could be served from the households if one manages to steer the course of actions towards the frequency control market where this source of actual capacity is needed (Hult, 2020; Lindborg, 2020). Once the grid is strained, the household can operate on its own but also assist with great power (Lindborg, 2020).

However, (Hojčková, 2020; Hult, 2020) states that if an increasing amount of self-sufficient households with Solar PV do stay on the grid, terrible duck curves (the timing imbalance between production and daily peak demand) could form in the system together with negative wholesale prices. Therefore, to create a balance between how much is kept behind the meter and how much household electricity that serves the system can be seen as one of the biggest issues within and transformation towards self-sufficiency (Hojčková, 2020). Moreover, in order to mitigate the peaks and valleys of demand, it is important to support local production with storage options (Sandén, 2020).

The urgency for change and Grid capacity shortage

Another important driver is argued to be the capacity shortage, above all in Stockholm, Uppsala and Malmö where the overhead grid has not been expanded at the same rate as the population increase and elevated electricity usage from different applications (Lindborg, 2020; Sandén, 2020; Wallnér, 2020; Hojckova, 2020; Torstensson, 2020). To expand the overhead grid is a time-consuming process and, thus, local power production is key (Hojčková, 2020; Sandén, 2020; Torstensson, 2020). The capacity shortage creates a barrier for new expansions of businesses and other applications which in other geographical locations probably could be mitigated from the realization of local wind power projects. However, urban cities hold a lot of restrictions because of flight routes and other existing specific regulations for wind power. Hence, as local power plants are required and Solar PV applications could serve that purpose to limited regulations, a driving force for local PV applications exists (Sandén, 2020). The fact that some utilities, for example, Vattenfall, invest in local electricity solutions can be seen as a real game-changer (Torstensson, 2020).

Historically, Sweden has been very great in developing centralized systems and extending transmission lines, but today it seems to get into issues and discussions have recently turned towards doing something that is less time consuming (Hojčková, 2020):

"Instead of waiting for time-consuming permissions and processes that happen when building large scale – What if we tried building small-scale?" – Hojčková (2020)

Hult (2020); Hojckova (2020) and Wallnér (2020) argues that grid capacity shortage will not, to a great extent, be solved from households leaving the grid. Instead, an idea exists of mitigating the capacity shortage in, for example, Stockholm, Uppsala and Malmö, by using the local households as a power bank.

Regulations

In order to support the existing system and make sure it can operate correctly, regulations have been structured to the advantage of the system which always makes it difficult for radical change. Regulations can stimulate a certain change of a system to a high degree, which, is not always for the better (Sandén, 2020). However, the structure of regulations could serve as the biggest barrier for any new type of business model and electricity configuration to really move forward (Hojčková, 2020).

Today, it is probably not so easy to make an off-grid house as old laws and regulations say that a household must have a connection (Reuter, 2020). On one hand, existing regulations about sharing of electricity between households creates a barrier to many applications within self-sufficient households and limits the household system to reach its full potential (Palm, 2020; Sandén, 2020; Reuter, 2020; Lindahl, 2020; Lindborg, 2020). On the other hand, regulations of sharing electricity could be seen as a driver towards increased self-sufficiency only within the household (Sandén, 2020).

Lindborg (2020) argues that the potential changes of regulations regarding sharing electricity directly between households, in an energy community manner, could make the market of self-sufficiency take off to a great extent. Consequently, a real game-changer could be if these communities or multifamily houses were able to go into an island-mode and share electricity within the community or houses when needed (Lindahl, 2020).

System dynamics

Hojčková (2020) argues that Sweden is quite late, in relation to many other developed countries when it comes to the interest of off-grid households. This is because the electricity system is very well developed and it also provides cheap electricity and reliable electricity with a 50 % share of renewables. Another important factor to reflect upon is the competition between dynamics, for instance, if expanding the large scale wind and solar plants it will become cheaper to buy electricity on the main market and thus promoting for such a dynamic (Sandén, 2020). The fact that the Swedish electricity prices are very cheap is one of the biggest barriers for people to do something else than staying on the grid. In other parts of the world, like in Australia, electricity prices are very high because of the large overbuilt electricity system, which, has resulted in an increased off-grid market (Hojčková, 2020).

Network externalities

Energy is starting to become a broad subject and everything is coming together as interconnected e.g. households connected to the grid are also connected to vehicles (Reuter, 2020). There is an aspect that external events, such as vehicle-to-grid and other car configurations can facilitate and act as a trigger point for transitions towards a certain type of household electricity production (Lindborg, 2020; Sandén, 2020). However, whether electric vehicles and their role in the electricity system will serve as a barrier or driver of self-sufficient households, it will certainly affect the outcome. Much depends on the possibility of Vehicle-to-grid or Vehicle-to-house configurations. Partly configurations of how one can store energy in batteries and interact with the grid but also in interplay with the household (Sandén, 2020). Firstly, if the household holds the technological ability it can use the electricity from the car battery and, secondly, which probably holds more barriers than with a regular household battery, is that the battery from the car can be used against the electricity market (Hult, 2020).

Nevertheless, electric vehicles are flourishing and pushing the technological frontier of batteries together with utilities finding increased usage of batteries in the system (Wallner, 2020; Lindborg, 2020; Sandén, 2020). Today, Lindborg (2020) argues that one can buy a battery and receive a car for free, meaning that the actual battery provided in the car has a much lower cost-to-capacity than a separate household battery. Conclusively, this could become a cultural driver where the interplay between electric vehicles, Solar PV, and batteries form some kind of techno-culture (Sandén, 2020). It is not only the development of electric vehicles that can serve as a driver for self-sufficient households but also the fuel cell cars. (Lindborg, 2020), explains that in Toyota City one can use the Toyota fuel-cell car to bring hydrogen to the household and utilize the fuel cell that powers the car to generate electricity to the residence without the need of investing in a separate fuel cell.

Moreover, respondents argue that development around hydrogen solutions, which, today are one of the biggest investments a household must take to become self-sufficient will continue. Firstly, the goal of reaching 100 % renewable electricity is difficult to manage without the support of storage capacity. Secondly, industries such as the steel (Hult, 2020) and transport industry (Torstensson, 2020; Lindborg, 2020; Wallnér, 2020) will increase the usage of hydrogen. Hence, because of its applicability of large scale storage, utilities may find great interest in developments around hydrogen storage which will push down prices of the technology and, hopefully as a spill over effect, the cost of running hydrogen storage in households will drop to a great extent (Torstensson, 2020; Wallnér, 2020).

Reverse network externalities

The biggest disadvantage of going completely off-grid is the decreasing amount of users who share all the costs of running the transmission and distribution system. It creates an imbalance in the society because obviously, the first ones that will go off-grid are those that have the money. Those that cannot afford their own system will be left and forced to pay the rest of the grid (Hojčková, 2020). Hult (2020) reasons that the following effect cannot cause that much of a problem:

"After all, it is a volume that is disappearing and I find it incredibly difficult to believe that it is more than 10 % which is still extremely high and If we say 10 % of households, that's kind of 5 % of the market. So I don't think it is going to play such a big role" – Hult (2020)

Hojčková (2020) argues from her research, that in Sweden, most development around self-sufficiency is regarding partially off-grid solutions hence the fear of infrastructure becoming useless is not too big. The idea behind "utility death spiral" and how utilities suddenly go out of business because they cannot recover their costs is at the moment, not a concern (Hojčková, 2020; Lindahl, 2020; Sandén, 2020). However, they do argue, assuming that more individuals will find profitability in off-grid solutions, less trade will happen on the grid and that the costs of maintaining it will become higher per user. Hence, the disadvantage with societal imbalances together with the risk of "utility death spiral" creates a situation where off-grid, from a systems perspective, is not a beneficial idea for everyone but only the ones that cannot connect or wants to be excluded from the system (Hojčková, 2020; Lindahl, 2020; Sandén, 2020).

There is one more dimension to consider once a large system becomes divided into many subsystems and respondents argue that to include the consumer as a producer is highly complex – the more systems the more data to process (Lindborg, 2020; Torstensson, 2020; Hojčková, 2020) and this pushes for an important question:

How complex do we really want the system to become? – Torstensson (2020)

Utilities must learn to understand the off-grid consumers and realize when households require energy from the grid or not (Lindborg, 2020). Hojčková (2020) argues that in the future, data to understand consumption and production patterns of households will be the dominant factor that decides who will become the market leader.

Experimentation and pioneers

With off-grid solutions, the user can do a lot of experimentation and learn on the way – the initial capital investments are not that high (Hojčková, 2020). Households can step by step increase their level of self-sufficiency and still have maintain a high level of reliability. For instance, by investing in Solar PV, individuals have reached a certain degree of off-grid and further, if investing in storage, the household becomes even more off-grid (Reuter, 2020). People who start investing in self-sufficient technologies realize that it is possible to produce a great deal of electricity and becomes eager to expand one's level of self-sufficiency (Lindborg, 2020). However, Reuter (2020) argues that the most significant driver for a deployment is that a transition towards self-sufficiency is market-driven with a lot of mad enthusiasts out there experimenting with the technologies and wants to prove its applicability for producing household electricity.

5.2 Potential adopters

The reasons why some individuals tend to be open or not for off-grid solutions are much determined by their area of interest, lifestyle and ideological beliefs (Hult, 2020; Sandén, 2020; Nilsson, 2020; Palm, 2020; Lindborg, 2020; Hojčková, 2020; Torstensson, 2020; Wallnér, 2020; Werner, 2020; Lindahl, 2020). However, interestingly, synergies exist in terms of how Solar PV, storage and increased self-sufficiency support very different and non-related groups of individuals who all benefit from the technology. For example, Lindahl (2020) and Wallnér (2020) stated that in the US, the republican driven Tea Party movement, as well as the environment movement, both emphasized Solar PV because of their ideological aspects.

Republicans because of their belief of self-sufficiency and to become more independent from the system, and, the environmental movement because of their environmental concern.

There is a heterogeneous view on the economic rationality from the adopter's perspective and whether it is the determining factor for investment. Hult (2020) argues that the motivation behind the investment is not economic but rather potential adopters holding a large interest for the technology or even a frustration against the large grid companies:

"I believe that a lot of individuals would like to cut the wire and cancel the contract with grid companies because of their grid tariff monopolism" – Hult (2020)

Whereas other respondents argue that potential adopters are seeing economic value with the investment, not value as in profitability of investment but more from the control of expenses and other relative advantages compared to being dependent on electricity from the grid.

Economic/Profitability

Despite the poor profitability of operating off-grid today, it is arguable according to Nilsson (2020) that potential adopters might be the ones holding a lot of capital to invest. Additionally, households or villages located in very remote areas or islands without grid access where a new connection is expensive might find economic motives of investing in off-grid solutions (Torstensson, 2020; Hojčková, 2020). Individuals might realize that investing in a 100 % off-grid solution is too expensive and instead find economic motivation take a "golden shortcut" where they systematically invest in Solar PV and other appliances (Reuter, 2020).

"Decentralized energy supply is a bit expensive at present, but those who can finance a Tesla could also finance their off-grid system" – Nilsson (2020)

Technology interest

Beyond any interest in achieving economic incentives lies the motivation of individuals to take on technological developments (Wallner, 2020; Hult, 2020; Reuter, 2020). At the very immature levels of Solar PV, individual households might adopt the technology because Solar PV can be seen as an interesting thing. Further, it improves the visibility of the technology that later on, when subsidy schemes are introduced, can act as the first step of neighbourhood dissemination (Sandén, 2020). Lindborg (2020) explains that technology interested individuals might start to see how their first Solar PV installation brings value and how a motivation to continue the investments by increasing the level of self-sufficiency develops.

Environmental

From his own experience in meeting a lot of potential adopters of self-sufficient solutions, Nilsson (2020) argues that there is an interest in off-grid electricity production from individuals who feel like they want to contribute towards the transformation of a zero-carbon electricity production. Additionally, Wallnér (2020) mentions that people who are interested in environmentally friendly technology find a lot of curiosity with off-grid applications. Further, Hojčková (2020) argues that when it comes to households that want to go off-grid in Sweden, more than anywhere in the world, it is about the environment, this because they want to be environmental friendly and thinks that the government is not doing enough and does not want to wait for others to do something about it.

Independence, control, and vulnerability

In Sweden, when it comes to completely off-grid, it has to be a person that just wants to be self-sufficient because it will be so much more expensive than staying connected to the grid (Hojčková, 2020). There is a satisfying feeling of being self-sufficient and less dependent on the system (Lindahl, 2020; Reuter, 2020) and some people might have a dream of doing things on their own (Lindborg, 2020; Reuter, 2020).

However, the idea of being independent is kind of limited to the individual houses which only is a small part of the market but a group of individuals holding a rather high purchasing power (Lindborg, 2020). Further, compared to other countries, where off-grid solutions exist on a larger scale, Hojčková (2020) argues that there is a higher level of trust between Utilities and consumers in Sweden.

A private person or commercial actor that would like to have control over their future expenses could find great value in being self-sufficient because of low exposure to external pricing mechanisms and possibilities to make accurate forecasts of their costs in the future (Lindahl, 2020; Wallnér, 2020). It is like comparing subscription based district heating and heat pumps as a source of heating where the heat pump can be more expensive but, instead, you have a more predictable cost calculation (Wallnér, 2020). Moreover, from the perspective of organizations, it can be a motive to make sure that their operations will run even if the electricity system is down (Sandén, 2020). Consequently, consumers who are very dependent on the electricity system and sees a lot of value in being able to go into island mode if needed may find it attractive with self-sufficiency (Lindahl, 2020; Torstensson, 2020).

External effects

In order for new applications to become interesting for a potential user, the application must reach a certain degree of legitimacy and security. There is a large number of individuals where the information diffusion and knowledge regarding Solar PV are lacking and such items make it difficult for new applications to spread (Sandén, 2020). Today, there is a problem that individuals must possess technical knowledge on how to assemble an off-grid solution and the technologies needed (Reuter, 2020) and all forms of insecurities are barriers to investment decisions, especially in the case of Solar PV where a lot of individuals have zero knowledge of the technology (Wallnér, 2020).

5.3 Possible transition pathways

The role of household electricity production in Sweden and how it will play out within the larger electricity system is impossible to state. A consensus among the respondents is not visible of how the decentralized will form with the centralized production and depending on the respondent's interest it is feasible that their opinions are narrowed down towards it. Nevertheless, Sandén (2020) argues that it is, as of today, very difficult to state what will become obvious and how lots of non-predictable subjects can come to affect the course of development. However, no matter the course of development, it will take time and a transition period will occur. Whether the system continues in the direction of large-scale or not, it surely will not work as before because renewables are different in many ways (Hojčková, 2020).

Additionally, it will not only be determined by the internal dynamics within the electricity system but also from landscape effects, such as the Corona crisis, which can push the development towards certain ideals (Sandén, 2020) or displaying the importance of having a well-functioning system regardless of external effects (Reuter, 2020). Nevertheless, Lindahl (2020) argues that external crisis will matter but the one thing that can be seen as a determining factor is the upcoming price trends of the two alternatives centralized vs. decentralized production. Torstensson (2020) argues that Sweden is in front of an energy paradigm where the historical priorities in the electricity systems are changing – energy might be present in abundance creating a path where, for example, low conversion losses will lose its importance and new applications can become more relevant. Finally, Sandén (2020) and Hojčková (2020) reasons that because of Sweden's situation of having one of the most developed energy systems, drastic changes will likely not happen unless heavily influenced by the rest of the world.

Market changes

During the past decades, a globalized world has been developed in which systems are more and more interconnected to each other (Sandén, 2020; Reuter, 2020). Either development continues in probably the most logical way of still connecting systems to the larger system or towards a development where partially decoupling systems is a priority (Sandén, 2020). However, there are some changes in the market right now, if overlooking the expansion of powerplants it is not the classic energy companies on top but rather other financial investors (Torstensson, 2020):

"It feels like the market is being transformed where energy companies may be looking at some other business" – Torstensson (2020)

Utilities are looking into distributed electricity systems, especially the partially off-grid solutions that bring the possibilities of running a new business and ownership models (Hojčková, 2020; Torstensson, 2020). Further, utilities seem to be quite out there because they understand that they need to work closely and collaborate rather than going against new actors. Previously, it was easy for the system to control everything in a top-down model but this is changing as the demand side is becoming more and more active meaning that a system that understands both sides must be formed (Hojčková, 2020; Lindahl, 2020). Increased self-sufficiency could mean a higher level of equilibrium in the power relationship between consumers, utilities and the electricity grid actors – creating new prerequisites for negotiation between the parts (Torstensson, 2020). Consequently, assuming that self-sufficient technologies reach a higher level of maturity could engender a situation where a lot of pressure is placed on the incumbent's work of designing a system in favour of the society to remain its position (Wallnér, 2020). Finally, off-grid is argued to be a great thing because of its role in questioning and challenging the existing system (Hojčková, 2020).

Business models

Business models will be a key determinant as to which type of system that will be driving the future. For the common man as well as for industries, energy will mostly be regarded as something that should be smooth and easily handled and thus the formation business models will be an important driver or barrier for deployment (Sandén, 2020). How one can trade electricity and what return it will yield will have a vital role in deciding the level of complete off-grid vs. prosumer households (Sandén, 2020; Lindahl, 2020). With a transition towards potentially very low electricity prices, it is unclear where in the value chain businesses will lie in the future (Torstensson, 2020).

New actors

The Swedish electricity system will not only consist of the traditional actors of today but an increasingly diverse mix of actors from different markets (Hojčková, 2020; Lindahl, 2020; Sandén, 2020; Torstensson, 2020). A reality where an increasing share of electricity production is no longer owned by the classic energy companies – because that is what happened in other parts of Europe where self-sufficiency increased (Lindahl, 2020; Sandén, 2020; Torstensson, 2020). The reasons might be that the utilities are too conservative on adapting their business models towards change (Lindahl, 2020; Hojčková, 2020) or that detached households are much more complex to manage in terms of regulations since they are found behind the meter/connection point (Sandén, 2020). Further, arguments are highlighting that new actors can be beneficial for development:

"It is always exciting with actors that come from another line of business since they tend to think another way than the incumbents of the energy sector" – Torstensson (2020)

"I think you should facilitate the involvement of a lot of players in the electricity system, I think that is a bit fundamental no matter what path you will go" – Sandén (2020)

"It is great that new players are admitted who in some cases run faster than the old ones" – Reuter (2020)

"You shouldn't shut any actors down or any ideas down. If you give dominant utilities the power to decide "who receives the money and who receives the experiment" it might lead to quite incremental changes and a slow transition" – Hojčková (2020)

The majority of the respondents argue that self-sufficiency opens up for a third party of actors on the market, namely aggregators, next to the two classical two-party markets of consumer and producer (Torstensson, 2020; Hult, 2020; Hojčková, 2020; Lindahl, 2020). Aggregators can come to be formed by new actors who seek business opportunities in the decentralized electricity market or by the existing actors if they act fast enough (Lindahl, 2020; Hojčková, 2020). New actors will provide devices to control and regulate the household which is far away from the incumbent's businesses whereas the incumbents will still have an advantage when it comes to providing pure electricity because of their ability to have large trust and security from the households (Sandén, 2020). Consequently, aggregators or other new actors can come to affect the role of incumbent energy companies (Torstensson, 2020). Lindahl (2020) reasons that, as a general rule, incumbents will have a weaker role but a role specialized into managing the systems instead of delivering the energy – they will still own the grid and their position will very important in managing the course of development in the right direction.

Moreover, aggregators could take the role as a function of managing the interplay between the households and the grid to supporting the system utility (Wallnér, 2020), or even manage the whole process of installing and running the systems where the actual household only pay for the system in a rental basis (Torstensson, 2020) – much like the situation today with centralized solutions. Sandén (2020) argues that having distributed grid-connected systems that are managed and controlled from a central authority is not an unplayable future where groups of prosumers sell the right to an aggregator of controlling their system to a certain degree.

Off-grid applications

The one common vision among the respondents is that a complete off-grid household will probably not bring any economic incentives to either the individual household or to the actors of the electricity system and therefore not serve as a feasible option in the larger context.

"I'm spontaneously allergic to the idea of off-grid" – Lindborg (2020)

"off-grid is a very poor solution, it is only a beneficial idea where there is no possibility of connecting to the grid" – Hult (2020)

"If Sweden were to transform towards a non-integrated system it will probably happen because of influence from the rest of the world" – Sandén (2020)

"It is only if the existing grid is very unreliable or super expensive it makes sense for you to go off-grid" – Hojčková (2020)

"I find it difficult to see that it is becoming a mega trend in Sweden to go off-grid using hydrogen and fuel cells or electrolysers and such" – Wallnér (2020)

"Complete off-grid, I do not think it will be so in the future, I do not think it wise if we create a lot of own small islands where lots of actors make their electricity and keep it to themselves" – Reuter (2020)

However, the respondent's speculations of how off-grid households will be utilized are many but some common views can be seen. Firstly, the historical centralized system will most certainly not remain its dominant market role and a mix between centralized and household-level production will exist. Further, respondents argue that the system will most likely become complex with several layers of local and central production and not to any extreme extent in any direction. Respondents push for a situation where electricity is kept within households but in certain times of shortfall, electricity can be sent back to the grid or surrounding buildings (Hult, 2020; Sandén, 2020; Reuter, 2020; Palm, 2020; Lindborg, 2020; Hojčková, 2020; Torstensson, 2020; Wallnér, 2020; Werner, 2020; Lindahl, 2020).

To support a complete transition towards decentralized production is very costly for both private individuals and the society. Instead, it is more relevant to push for a transition where the existing infrastructure is guaranteed to maintain its relevance and reliability but with help from the local production (Sandén, 2020) – a dynamic system that benefits from the cooperation between different layers of production depending on the time and situation (Reuter, 2020).

5.4 Policy implications

Sweden is not that far into a transition towards household electricity production, many other countries have come further in their journey. Hence, to avoid unnecessary issues it can be valuable to learn from other countries – how they have managed the transition, what problems they met and to what extent a transition should go (Reuter, 2020; Hojčková, 2020).

Grid tariffs

Referring to the idea of running the self-sufficient household towards the market, Hult (2020); Lindborg (2020); Sandén (2020) and Lindahl (2020) further argues that the structure of grid tariffs and energy taxes is a problem for reaching the actual net utility a household could serve. Lindahl (2020) argues that the tariffs of today where a large proportion is fixed should be prohibited since it incentivizes the consumer to make no adjustments to their consumer behaviour. Considering a household still connected to the grid but with the capacity to store energy. If the taxes and grid tariffs in an easy way could be excluded from battery charging, which it should since batteries operating towards the system always serves for net utility in the long-term, consumers would be able to make money by charging at low-load occasions and further discharging at high-load occasions when the grid needs it (Lindborg, 2020; Hult, 2020).

However, Lindborg (2020) ads a dimension to this issue and further conceptualizes it into a rather concise situation. For example, a project is running in Uppland intending to use a collaboration of 300 household heat pumps to create 2 MW of demand flexibility that could be further scaled up which is a rather big deal in a municipality concerned with a capacity shortage. Despite, applying the pricing mechanisms of today, a manoeuvre to release 2 MW of demand would only imply revenue of about 2500 SEK to be distributed between the 300 households. Nevertheless, the actual value of 2 MW momentary is approximately 0.5 MSEK which could make it kind of interesting for the household owners and, thus, a reconceptualization of incentives to make it worth steering one's consumption towards a certain direction could be beneficial. This example could be of batteries as well but, instead, the households will deliver their glorious electricity at the hours of peak demand.

Subsidy schemes

Whether the subsidy schemes are aimed towards the goal of achieving a 100 % renewable electricity system, to support the well-being of the system, or accelerate the market of residential electricity production, a mixture of thoughts from the respondents is visible. Today, the current subsidies (investment aids) on Solar PV and storage are about to expire. The technologies can stand on their own and the yield from the investment aids has been great – Solar PV has gone from being the most expensive to one of the cheapest sources of electricity (Lindahl, 2020).

However, Hult (2020) argues that the subsidies are not optimal structured to assist the situation of reaching a 100 % renewable system. The investment aid for installing private Solar PV could be seen as a barrier towards reaching the renewable goal because of the twisted situation that Solar PV, if not managed properly, increases the difficulties of manoeuvre the gap between the seasonal production capacity. Instead, he argues that the structure today of Solar PV and battery investment aid only serves to optimize the homeowner's small system which further could be seen as a way of avoiding the necessity of paying energy taxes. Lindborg (2020) expresses frustration as well, that one can receive great amounts of investment aids without any requirements except the need for reporting that the solar panels have been used to produce electricity throughout a certain period.

"If overlooking the incentives for off-grid, the subsidy schemes are very obvious – a carrot! The more people that leave the system to go off-grid, the more expensive it becomes for the ones who are left – and this is supported by governmental money. – Lindborg (2020)

Moreover, Hult (2020) and Wallnér (2020) argues that one should be incentivized for running a household system against the market, with or without having a household electricity production system. Further, Lindborg (2020) argues that some sort of requirement for receiving the investment aids should be formed in terms of being a part of the Swedish back-up system in the case of crisis.

As mentioned, the situation where subsidies for running a self-sufficient household against the grid are expiring creates a scene where the economic incentives for staying on the grid decreases. Hojčková (2020) have performed a lot of studies on the US and Australian off-grid/ prosumer market and she argues that households are starting to look for alternatives when policymakers state that they are getting rid of the subsidies. Such alternatives could lead towards households going complete off-grid since the consumer is not interested to give their electricity to the grid without them paying for it:

"So you have two alternatives for people who suddenly don´t have any subsidies. Either to invest in storage or try to trade with other households by creating some kind of virtual powerplant way where they can monetize on the electricity they produce but don´t consume" – Hojčková (2020)

Nevertheless, Lindahl (2020) reasons that the grid owners hold a key role in creating business models that provide lowered grid tariffs in exchange for the option of running the household against the grid to exploit possible net utility.

Regulations

The transition towards increased household electricity production would need a lot of support and regulations that work in favour of that kind of system (Reuter, 2020; Sandén, 2020; Hojčková, 2020; Hult, 2020; Lindahl, 2020). A lot of different actors need to be involved to not steer in one specific direction (Sandén, 2020), households need to be incentivized in a way that benefits both the system and the individual. Further, policy makers should focus on being equally accessible for both large established actors, as well as smaller and new ones. Otherwise, it will slow down the transition, as well as making the transition incremental (Hojčková, 2020). However, from her experience in analysing other markets than the Swedish, Hojčková (2020) argues that the policymaking actors in Sweden, such as the Swedish Energy Agency, are doing a great job in being quite objective and courageous to engage with new actors.

"Policymaking should be designed in a way where new actors can collaborate with the old ones and you find the way of how to create the value of the old system in the value of the new. But for that, you need to have an objective decision-maker on the top who can evaluate what's the value of the old and what's the value of the new" – Hojčková (2020)

Moreover, it is not only regulations of the dominant actors in the system that is important to consider but also the individuals (Lindahl, 2020; Sandén, 2020; Hult, 2020). One can work with a carrot or a stick by either setting up requirements on households and their electricity production/consumption or making sure that there is a value in making a certain change (Lindahl. 2020). Hult (2020) argues that there is no need to set requirements on households to create a desirable outcome but instead it is important to manage all the obstacles. Finally, Sandén (2020) associates the idea of setting up regulations on the household level with the ongoing Coronavirus crisis:

"The Chinese dictatorship probably works a lot with requirements and rules, while here in Sweden we appeal to people's rationality and common sense in contributing to the best of society" – Sandén (2020)

6 Analysis of empirical findings

This chapter aims to analyse the gathered empirical findings towards the presented literature and theoretical foundation. The overall theme of presentation in this chapter follows the conceptual framework presented in Chapter 2.6, Theoretical foundation, Figure 1.

6.1 Drivers and barriers for deployment

From the presented theoretical foundation, it was found that the TIS framework has been applied to successfully assess drivers and barriers of technology diffusion. Additionally, MLP was found to be valuable for exploring different barriers and drivers associated with technological change.

6.1.1 Understanding the functional performance and technology system components

The different components of *actors, networks, institutions,* and *technologies* within a technological innovation system (TIS), like the self-sustaining electricity system, are important to consider when analysing the potential barriers and drivers for deployment (Bergek et al., 2008; Suurs et al., 2009). Firstly, the findings show that *actors* affecting the deployment are not only the ones with interest in off-grid solutions but also the incumbent actors within the existing system. Here, it is evident that a situation with actors holding a diverse set of motives and business models designed for a traditional electricity market creates a barrier for the deployment of off-grid applications. Some actors want to support decentralized production and invest in local initiatives, for example, storage solutions, whereas another actor wishes to continue in another path. Also, historically, the incumbents have established business models that are not aligned with the idea of having households as a part of or outside of the system. Incumbents are dependent on their existing customers and their costs do not decrease if consumers leave the grid because of the already made investments. On the other hand, if more actors find value in household electricity production, which some today are, great drivers for deployment could form.

Secondly, because of the Swedish electricity system having a long history of operation with lots of incumbent actors, stable *networks* have been established between policymakers and the incumbents making it rather difficult for innovators to establish practices that challenge existing market structures. Thirdly, *institutions* within a technological innovation system are said to either facilitate or complicate the deployment phase (Bergek et al., 2008; Suurs et al., 2009). Further, from the respondents arguments, it is evident that the institutional setup for household electricity production is not shaped in a way that creates the best circumstances for large scale deployment. Individual households are not incentivized enough to find value in operating the off-grid household against the grid to bring net utility and until there is a way of actually supporting the system, a barrier exists that grid owners and utilities only see off-grid as a poor solution rather than a potential asset. In addition, the uncertainties regarding the subsidies make up a barrier for the deployment. Lastly, regarding the component of *technologies* including the technology itself and the infrastructure it is integrated into together with the techno-economic aspects of cost, safety, and reliability (Bergek et al., 2008; Suurs et al., 2009). Here, respondents reasons that off-grid applications will become increasingly more cost-efficient and reliable for the individual household. Also, off-grid applications could increase the reliability of the whole electricity infrastructure.

According to Bergek et al. (2008); Hekkert et al. (2007) and Suurs et al. (2009), different functions within a TIS influence the pace and magnitude of deployment. Here, functions such as *entrepreneurial activities* are said to be of importance and respondents claim that the development of off-grid applications is much driven by the actual market with a lot of support from pioneers pushing the technological frontier. Entrepreneurial activities open up for new business opportunities, not only from new entrants but also from incumbents who seek to diversify their core business (Bergek et al., 2008; Hekkert et al., 2007; Suurs et al., 2009). Which, respondents argue that if utilities start to explore local production and storage applications to support the centralized system, it to be a real game-changer. Further, the function of *knowledge development* and *diffusion* involves the necessary learning activities needed to deploy the technology in a market with actors and networks (Bergek et al., 2008; Hekkert et al., 2007; Suurs et al., 2009). The interviews show how a lack of understanding about the technology from the user side may exist and, that a problem today is the need for possessing technical knowledge if households want to invest in the technology. On the other hand, respondents argue that incumbent or new actors in terms of aggregators need to take a facilitating role of delivering and running off-grid applications to support the deployment. Additionally, off-grid solutions work based on splitting the larger system into many more subsystems in which the original consumer also becomes a producer and from the interviews, a concern regarding the increased complexity exists. Which, generates a scene where incumbents will have to learn a completely new pattern of consumption and production. Moreover, despite the situation in Sweden with stable and reliable electricity system, respondents argue that there are some flaws with it, since the overhead/transmission grid has not been expanded at the same rate as the demand. Hence, a demand exists for new applications and according to (Bergek et al., 2008; Hekkert et al., 2007; Suurs et al., 2009), it is essential for the deployment of a TIS that surrounding activities, much like the capacity shortage, create a demand that enables a *market formation* for the innovation. Theoretically, off-grid applications possess a value for this demand but emerging innovations, on the other hand, cannot compete directly with the incumbents and respondents highlight how the incumbents are into solving this problem by exploiting alternative solutions. The TIS theory proposes that in a competing situation between emerging innovations and incumbents, a need for safe markets and temporary competitive advantages exists. However, as respondents state that financial support is about to expire for self-sufficient applications, it can be seen as difficult for individual off-grid applications to capture this demand.

6.1.2 Different levels of socio-technical systems

Departing from the idea that the electricity system is a complex system of technologies fixed in a social context of public and private institutions (Unruh, 2000). In addition to, how a large socio-technical system like the electricity system is a shielded space with lots of barriers for change (Geels, 2002; Hughes, 1987). Respondents argue that a transformation will occur but it will take time and the direction of either centralized vs. decentralized electricity production is not obvious. Further, findings from Rip and Kemp (1998) showed that socio-technical systems are more likely triggered to undergo change if current configuration involves issues, such as sustainability and environmental. However, on one hand, to apply this belief of trigger for change within the Swedish electricity market is not viable since respondents argue that the Swedish system is one of the most developed ones in the world with low emissions of carbon from production. On the other hand, Sweden holds very ambitious goals when it comes to the share of renewable electricity (Swedish Energy Agency, 2019a), which might serve as a trigger for change. Nevertheless, respondents are highlighting that the system is undergoing changes at different levels because of surrounding factors and, hence, the different levels of the MLP theory can make a comprehensive analysis of the system and its potential transformation pathway.

Regime level

From the MLP theory, the regime level includes the rules and practices along with the existing technologies and infrastructures which therefore makes it difficult to manage change within this level (Geels, 2002). However, findings show that there is a handful of situations that could manage to intensify the pressure on the existing regime and thereby manage change. Firstly, the situation in Sweden with grid capacity shortage, clarified from both the literature review (Swedenergy, 2019) and the interviews, indicates an issue in the infrastructure of the existing regime. Also, respondents argue that off-grid applications can serve the purpose of mitigating the issue if managed properly, meaning that disconnected off-grid households alone might not make any difference but instead, if the off-grid households remain connected to the grid, the extra local production and storage capacity added to the grid can bring lots of net utility. Consequently, off-grid households might not be the only answer to the issues but respondents argue that storage solutions will play a key role in the development of the system to meet the local electricity demand. Here, respondents argue that the fact that incumbent actors are showing interest in alternative businesses speaks for a change within the existing regime.

Socio-technical change is said to occur when windows of opportunity are presented from destabilized regimes allowing for niches to break through (Geels and Schot, 2007). The above-mentioned findings show that innovations can break into the existing regime since the regime possesses limitations that open for windows of opportunity. On the other hand, respondents express that there is a situation where old investments in the Swedish electricity system must be protected since so many actors are dependent on them, as well as intertwined with institutional setups where some of the incumbents almost act as policymakers. Here, a parallel can be drawn to the theory of *Techno-Institutional Complex* (TIC), by Unruh (2000), defined by the co-evolutionary process between infrastructures, organizations, and institutions that create a *lock-in* of a certain configuration. Consequently, Socio-technical systems are, according to Hughes (1987), embedded in society´s daily life and a system characterized by an increased share of off-grid households without any means of connection to the grid is argued from the respondents to increase the societal imbalance. Also, from a system perspective, off-grid is not beneficial for everyone if the grid defection will force utilities to charge a higher fee per connected user to cover their sunk costs since the number of connections will decrease and the infrastructure becomes less useful. Additionally, the respondents argue that the system today is too cost-effective resulting in low costs of electricity compared to many other countries where off-grid applications have a substantially larger market share. Until this point, referring to Geels (2002), a dynamically stable regime exists making it difficult for innovations to become dominant designs in the system. Despite this, regulation adjustments are about to be implemented regarding energy communities which according to the respondents would open up a for new valuable applications with off-grid solutions allowing for third-party actors to step into the electricity market with innovative services and thereby increase the pressure on the existing regime and incumbents.

Niche level

The socio-technical niche level involves the research and development around radical innovations that support the emergence of socio-technical change. Further, technological niches can evolve into a dominant design and compete with the existing regime (Geels, 2002). Respondents reason that off-grid households are technically possible to install and run but as of today it is too expensive and it is mostly a vision for users to invest in the technologies. Connecting the theory how niches develop (Geels and Schot, 2007; Rip and Kemp, 1998), it is arguable that today, off-grid household in Sweden only exists as the first order of niche where it is mostly expectations and visions to the innovative practices that support the innovation with attention. Besides, this can be seen as a *predevelopment phase* according to Rotmans et al. (2001) transition management theory where the niche becomes evident, much like actors are aware of off-grid applications but it doesn't change anything of the existing system.

On the other hand, grid-connection costs are increasing with a large share of fixed costs at the same time as off-grid applications are decreasing in investment cost, which, according to the respondents, creates a scene where off-grid challenges the system of today. This favours the niche since the rate of progression for the emerging technology, in this case, off-grid, implies to be greater than the positive rate of progression for the existing regime, in this case, the grid-connected electricity, which it competes with (Hoogma et al., 2002). Also, considering the number of arguments from the respondents that potential adopters are seeing the grid-connection fees as problematic, off-grid applications can plant ideas into the consumers mindset that there is a way of avoiding the grid costs. Linking this to the conceptualization by Geels (2011), regarding how technological transitions occur because of socio-technical niches ability to plant ideas for change, can signal that there is a foundation for off-grid households to take off.

However, respondents argue that the Swedish electricity system is undergoing change with utilities looking into distributed generation, in terms of partially off-grid solutions, where the potential of new business and ownership models take place. Concerning findings from Rip and Kemp (1998); Schot and Geels (2008), this point towards a potential start of the second process where an increasing amount of actors find interest in the distributed generation. Additionally, since the respondents believe that utilities can create value from cooperation with households, off-grid applications could gain momentum as they become more accepted by the utilities (Geels, 2011). When discussing future changes of the electricity system, respondents find it reasonable with a change towards increased decentralized production/distribution and in order for a niche to *take off,* Smith and Raven (2012) states that the niche must fit with existing practices and infrastructures. Therefore, if finding a future trajectory with increased decentralized production, off-grid applications could certainly gain popularity among actors and users since it follows the same pattern of a more decentralized system.

Moreover, today, the respondents argue that the system is highly top-down driven and designed for large scale optimization which is a total opposite of dynamic to self-sufficiency and therefore, a clash between the two different system configurations exist. Hence, if applying the *strategic niche management* and how niches evolve into regimes, the existing gap between the current setup and off-grid can be seen as too big for any radical regime shifts (Hoogma et al., 2002). Despite this, Solar PV is part of the off-grid system and respondents state that Solar PV is continuously being more and more implemented in the Swedish electricity system and thus, an important synergistic relationship with other developments in technology and markets exist. Additionally, respondents argue that the cost development which Solar PV has gone through over the recent years will most likely happen to many of the other off-grid components and it will happen because the technologies are increasingly developed for other markets e.g. electric vehicles and hydrogen solutions. This further strengthens the criteria from (Hoogma et al., 2002), that socio-technical change gains its speed and strength if relations in development from other markets exist.

The aforementioned increased usage of Solar PV electricity production displays how Solar PV, as a niche application, has evolved into changing the technological regime of electricity production and by drawing a parallel from Geels (2011). It is arguable that with a system adoption including market demand, technical design, infrastructure, and business models, the original niche has resulted in a configuration of dominant design for small scale production. Consequently, from the respondents arguments, it is only a matter of time before the same thing will happen to off-grid applications. Today, the business models and policies for off-grid are in its early phase of development which according to (Geels and Schot, 2007; Rip and Kemp, 1998) are crucial for a niche to succeed with for the niche to gain momentum. Respondents explain that business models that facilitates electricity trade will play a vital role in the level of off-grid adoption and that policies and regulations today prevent the development.

Landscape

The socio-technical landscape is said to influence the dynamics of the existing regime as well as the niches undergoing development (Geels, 2011). Referring to the Swedish energy system, it is arguable that the ambitious goals of transforming the system towards 100 % renewable serve as a pressure on the existing regime which opens up for multiple dimensions of change and windows of importunities for novelties (Geels, 2011). Respondents argue that times of uncertainties, which we find ourselves in at the time of this study, referring to the Coronavirus crisis, can act as a trigger for change and push the development towards certain ideals. Accordingly, in the event of a crisis, society can come to shape a mindset towards acting with the rationality of what is best for society. Likewise, external effects and pressure, such as the Coronavirus crisis or increased risk of extreme weather, display the vulnerability of having large interconnected systems dependent on so many different operators and suppliers. Hence, it will most certainly accelerate the development of increased security within the system. Therefore, with the idea that pressure on existing regimes opens up for novelties (Geels, 2011), decentralized solutions might be seen as an interesting application and thus work in favour of off-grid households. Moreover, the electrification of society viewed as an external event, is argued by the respondents to potentially form a techno-cultural ideology of the society where individuals see a possible interplay between their electricity production and electrical devices. Such societal values and ideologies are said to influence the regime and niche dynamics as well (Geels, 2011).

6.2 Potential adopters

The decision-making process of individuals is dependent on the different attributes the innovation serves and the rate of adoption is highly influenced by the attributes as well (Rogers, 2010). From the literature review, it was found that there are three different groups or motives for the adoption of RETs, more specifically, instrumental, symbolic, and environmental. Stern (2000) argued that RETs innovations are adopted because of its benefits for the environment, Noppers et al. (2014) reasoned that the symbolic motives are great as well, and Michelsen and Madlener (2013) expressed that the motivation for adoption is primarily the economic rationale. However, the respondents visualize a much more complex and intertwined set of motivational factors for adoption which further is aligned with findings from (Bauwens, 2016).

To argue that the main interest behind household electricity production is economic profitability can be seen as unrealistic. Instead, according to the majority of the respondents, the *area of interest, lifestyle and ideological beliefs* is claimed to be the most significant motive or attribute behind the individuals decision-making process. This is very much aligned with the original theory from Rogers (2010), where the c*ompatibility* serves as an important influential category for adoption. However, from interview findings, the interest of taking on technological developments could be seen as one of the most influential motives of adoption and also the biggest adopter group of today. Consequently, reasons for this might be aligned with the findings from Noppers et al. (2014) where symbolic attributes of adoption derive from adopters desire to signal one's innovative image. Moreover, respondents argue that there is a motivation among individuals to contribute with the transformation towards zero-emission electricity production and how individuals who are into sustainable solutions find off-grid applications to fit their lifestyle. This correlates with the findings from a Finnish study where environmental motives often boost the diffusion of sustainable solutions (Nygrén et al., 2015).

According to Rogers (2010), the rate of adoption is aligned with the *relative advantage* the innovation brings to the adopter compared with existing alternatives. From observing the findings from the respondents, it is arguable that *independence, control, and vulnerability* can be seen as the relative advantage with household electricity production compared to existing alternatives. Additionally, results from the research of Palm and Tengvard (2011) when studying the Solar PV deployment in Sweden showed that this source of motivation of becoming self-sufficient can be larger and more influential than the economic downturns from investment. Nevertheless, respondents do argue that potential adopters, despite the large investments, are the ones holding a frustration against the monopolistic exposure from being dependent on the grid and find a satisfying feeling from being independent of the system. As well as, the ones finding it valuable to create a more certain projection of future electricity costs which is not affected by the pricing mechanisms.

Furthermore, as mentioned regarding knowledge development and how individuals today must possess a technological knowledge for off-grid applications, it is arguable from Rogers (2010) that *complexity* for off-grid application exists which affects the decision-making process for potential adopters. There are, however, several respondents that point out the potential of increased visibility around off-grid technology from the current adopters which are an important attribute according to Rogers (2010) – that potential adopters can observe the results of an application in a social system. Further, findings show how RETs are scalable and potential adopters can systematically invest in off-grid applications, from only installing solar panels and try it is potential, to continue the investments for an increased level of self-sufficiency. Because of the scalability, it is arguable that there is some *trialability* existing with off-grid applications which is one of the important innovation attributes according to Rogers (2010).

Connecting the above-mentioned motives for investing in off-grid applications to the different types of adopters, in terms of social groups, from Rogers's innovation theory shows a pattern of how the small group of *innovators* are the ones who are doing the investments and development today. Respondents argue that this is necessary, to show the surrounding environment that off-grid electricity is a feasible option to grid-connected electricity. Moreover, the findings illustrate the situation where today, Solar PV has been adopted by a group of *early adopters* that have an important role in the diffusion process by acting for neighbourhood dissemination, as well as being the potential group of adopters that takes a further step towards self-sufficiency. Respondents did argue that people who have found interest and profitability in Solar PV could become interested in increasing their level of self-sufficiency and get, one step closer to an off-grid household. Such individuals could become the *early adopters* of off-grid applications because of their already made investments. Finally, in order for off-grid applications to reach the broader social group of *early* and *late majority* findings point towards a need for cost reductions or increased push from policymakers.

6.3 Possible transition pathways

The respondents argue that the electricity system stands in front of a transition period but the direction of it is difficult to predict. There is, however, a general agreement between the presented theory and gathered empirical data that a potential transition will be either towards large-scale, centralized renewable electricity production or the opposite. That is, a decentralized transition pathway where different levels of households electricity production will or will not be a part of the system (Defeuilley, 2019; Energiforetagen, 2019; Hojčková et al., 2018).

With Sweden aiming towards having a 100 % renewable electricity production (Swedish Energy Agency, 2019a), it is arguable that no matter the course of development, changes will occur to meet the goal. This is strengthened by respondents, that renewables will make changes to the existing system as well as challenge its current configuration. Further, having the MLP theory in mind, Geels (2011, 2004, 2002); Geels et al. (2016) states that these challenges, such as reaching 100 % renewable production, will form transition pathways that all are different from the existing configuration.

From the literature review, three distinct scenarios were found to be eligible. *First*, a pathway with a large share of centralized renewable production referred to as a *re-arrangement* pathway and *Super-grid* (Defeuilley, 2019; Energiforetagen, 2019; Hojčková et al., 2018). Within this pathway, there is a low level of household electricity production, and the most common means of supplying electricity is through the grid. From the respondents perspective, this can be seen as a logical path of development where new systems will be connected to the larger system. However, according to Geels (2011), within a pathway where incumbent actors still maintain their position, it is not certain that novel technologies will not come to be a part of the system. The *Transformation pathway* from Geels (2011) point towards a reorientation of the existing regime where incumbent actors might take on radical niche innovations, which in this case might possibly be electricity-producing households.

Second, respondents argue that the most value-creating utilization of household electricity production is through incorporating them into the main system. This is emphasized by Defeuilley (2019) as a potential pathway where renewable electricity is generated locally by, for example, individual households. Here, the respondents, in general, explain the concept as having a system configuration where household produced electricity is kept within the household for most but in times of limitations in the overlying grid, it is possible to send electricity from the household back to the grid. From the literature review, the concept of households able to both producing and consuming electricity is acknowledged as *prosumers* (Ciuciu et al., 2012; Razzaq et al., 2016). Additionally, Hojčková et al. (2018) conceptualize it as a *Smart-grid* where electricity, as well as information, is bi-directional flow from a network of *prosumers*. Consequently, the benefits from including the prosumers are well-recognized and several scholars push for its possibility of supporting the grid (Espe et al., 2018; Lavrijssen and Carrillo Parra, 2017; Marnay and Lai, 2012; Muqeet et al., 2019; Parag and Sovacool, 2016; Skopik and Wagner, 2012; Zhang et al., 2018, 2019). Further, this path of development could be seen as feasible in the Swedish context if the expansion of the overlying transmission grid is slow.

Drawing a parallel to the transition pathways presented by Geels (2011), it is evident that a scenario like the above mentioned would entail great changes for the incumbent actors in the system. Respondents argue that incumbents would need to adapt their businesses to monitoring and providing support for decentralized electricity production. Geels (2011) explains it as in a *Substitution pathway*, that is, the pathway where new entrants provide radical niche innovations that do not align with core businesses of incumbents, radical niche innovations could substitute the existing technology. Nevertheless, as mentioned from both the literature review, empirical findings, and the substitution pathway theory from Geels (2011), the technological niches, in this case, household electricity production and presumption, need to have a better price and performance characteristic than the existing configuration for this pathway to be qualified.

Third, the complete opposite of the first presented pathway is the *off-grid pathway*, where consumers operate independently from the grid and a *paradigm shift* towards decentralized local electricity production comes about system (Defeuilley, 2019; Energiforetagen, 2019; Hojčková et al., 2018). From the respondents, it is arguable that this is the pathway that has the least value-creating utilization of household electricity production, both for the individual household and for the actors of the electricity system. Nor does any of the presented literature accounted for the Swedish system find this as a feasible option to a larger extent (Energiforetagen 2019; Swedish Energy Agency, 2016). Additionally, it would require great accelerations in technological development to make it economically rational for households to choose this source of electricity supply (Defeuilley, 2019; Energiforetagen, 2019; Hojčková et al., 2018). However, the pathway theory by Geels (2011) highlight that great external shocks could be an eye-opener for such a radical pathway to happen which also is supported by the respondents, that those external events will come to play a major role in the creation of a future electricity trajectory.

7 Modelling

In the following chapter, system properties, assumptions, and impact variables used in the scenarios are described in detail. Furthermore, the technical and economic data that was used in the reference scenario is presented, followed by results from the reference scenario. Furthermore, cost projections are displayed and modelled for the years of 2030 and 2040, which, are presented in the final section of this chapter.

This chapter is based on the Formative Scenario Analysis (FSA) described in *Chapter 3, Methodology, Data Collection and Tools,* by Scholz and Tietje (2002). The goal of this is chapter is to present a visual representation of the current and future projected costs of an off-grid household, prosumer household, and grid-connected household. The system properties and impact variables are described in detail below, with the purpose of providing complete transparency of each assumption and enhance replicability of the modelling part.

Moreover, the multiple scenarios were modelled with the intention of not solely providing an off-grid scenario, but scenarios that are partially or completely on-grid as well. This, to receive the possibility of comparing the cost of investment, as well as LCOE, and thereafter investigate the economic rationale of the different scenarios. Consequently, these sets of modelled scenarios are, to a large extent, common with the three aforementioned transition pathways in *Chapter 6, Analysis* i.e. the Super-grid, the Smart-grid/prosumer-grid and the off-grid pathway. Additionally, it was considered valuable to look at future projections of when a potential grid-parity could be reached for an off-grid system located in Sweden. In order to do so, comparisons of prosumer and on-grid systems were performed. Furthermore, the years 2030 and 2040 were selected because many other studies and projections have chosen a similar time frame (Cone, 2018; IEA, 2019b; Lindorfer et al., 2020; Liu et al., 2018).

7.1 Demand profile, weather data, system, and house setup

Four different systems are modelled in HOMER Pro: (A) off-grid household, (B1) partially off-grid prosumer household with PV, (B2) partially off-grid prosumer household with PV and BESS, and (C) grid-connected household. Each system is modelled at two different locations in Sweden: Visby and Östersund. Two locations were chosen to show the impact of solar and temperature conditions on the off-grid and prosumer houses. Regarding the house, each system is assumed to be installed in a modern Swedish family house which will be the same for all systems. The household is assumed to be located with optimal sunlight conditions at the given location i.e. no shadowing from surrounding buildings etc. Details regarding the house are described in the next section. Each system was set up at the two locations with corresponding hourly weather data, including solar and temperature. Weather data was gathered using the Photovoltaic Geographical Information System (PVGIS) (Huld et al., 2012). Furthermore, an hourly average was used between the years of 2011-2016 in each location. Each system is visualized and presented below, in Figures 2-4.

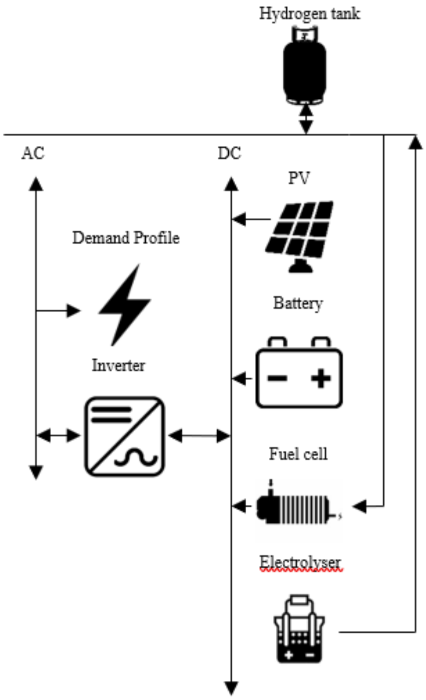


Figure 8. System A. off-grid Hydrogen + PV + BESS.

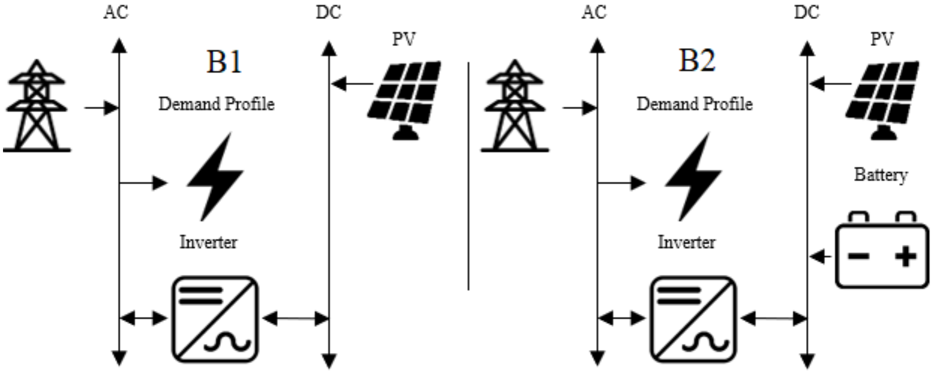


Figure 9. System B1. Grid + PV & System B2. Grid + PV + BESS.

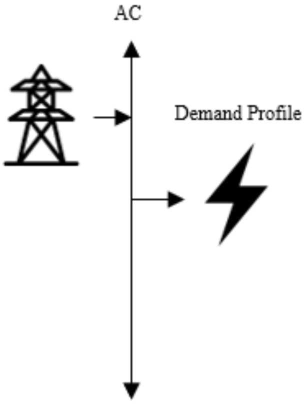


Figure 10. System C. Grid.

The demand profile was simulated using a simulation model, received through participatory research, that forecasts electricity load profiles for Swedish households in the numerical computing program Matlab based on three modules, domestic hot water consumption, space heating, and appliance usage (Sandels et al., 2014; Widén et al., 2009; Widén and Wäckelgård, 2010). Additionally, weather data is included in the simulated demand profile since it affects the required space heating. The weather data used is the hourly average as referenced in the previous section. The modelled house was assumed to be a modern house with high energy efficiency, geothermal heating, and a living area of 130 m^2. Additionally, it was assumed that two people were living in the house with one EV. Corresponding U-values and the space heating Coefficient of Performance (COP) factor for an energy-efficient house was used in the model (Adalberth et al., 2016). Ten simulations were made in each location and an average of the simulated loads was used in the model. A HEMS could optimize the demand profile even further, especially in the grid connected systems, however, it was simplified due to the scope of this study Instead, an average was considered to be a simplified way of replicating a HEMS after inquiring Sandels (2020), since it reduced the peak loads by an average of 30 %, but not the total yearly demand, and therefore chosen.. The simulated demand profile for the same house in Visby and Östersund is presented in Table 3 below.

Table 3. Demand profiles.

[kWh]	**Visby**	**Östersund**
Yearly load	9462	12 590
Yearly hourly peak load	4.48	5.67
Winter load (Oct-Mar)	5327	8042
Summer load (Apr-Sep)	4135	4548

7.2 Technical and economic data – reference scenario inputs and assumptions

With the continuous drop in costs of the technologies used in off-grid houses, cost gathered from other studies varies a lot depending on the date of the study and, additionally, the scale of the project. Firstly, a vast amount of impact variables are important to consider, these impact variables have been identified through previous studies and requirements of input variables in HOMER Pro (Hittinger and Siddiqui, 2017; Kantamneni et al., 2016; Khalilpour and Vassallo, 2015). In order to build a model with realistic dimensions and costs, respondents from interviews, manufacturers and suppliers were contacted and queried to gather input data that is as up to date as possible at the time of this study. Furthermore, HOMER Pro lets the user enter a lower and upper limit for each component to search for the optimal solution, this also referred to as search range. Which, can be used to set a limit to system sizes or prevent the program to run an excessive amount of simulations. In order to compare costs of going off-grid with the cost of staying connected to the grid or, alternatively, being a prosumer, cost data of the Swedish electricity rates, grid tariffs, and feed-in tariffs was gathered and is presented below.

For each modelled scenario in HOMER Pro, the project lifetime is set to 25 years, the discount rate is 4 %, and the inflation rate is set to 2 % (García-Gusano et al., 2016; Tradingeconomics, 2020). Furthermore, installation costs and additional technology costs that are related such as the cost of EMS, BMS, cabling and mounting are accounted for in the price of each technology. A constraint of the maximum allowed annual capacity shortage can be used to consider the reliability factor of the system, this constraint is set to 5 %, resulting in a reliability factor of 95 % for the off-grid system (Khalilpour and Vassallo, 2015). In the grid-connected cases, the fuse size is set to 16A which corresponds to a house with a yearly consumption of 0-20 000 kWh and a peak load of 11 kW (Vattenfall, 2020).

7.2.1 PV

There are a variety of PV panels available in Sweden from several different manufacturers with similar technological and economic data. For this study, the Trina Solar 340W Mono panel was used as the PV system for all models. This PV panel has an efficiency of 19.9 % and a lifetime of 25 years. In HOMER Pro, a derating factor is used to account for real-world conditions such as snow cover and soiling, this is set to 85 %. The price of PV includes all system and installation costs, according to the Swedish Energy Agency (2019) and Solcellskollen (2020) a price of 16000-18000 SEK/kW is assumed for a large house without subsidies. However, experts in the field suggest that PV prices in 2020 can be assumed to be 10 000 – 14 000 SEK / kW (Paradis, 2020;Wallnér, 2020). Hence, the PV cost in HOMER Pro is set to 13 000 SEK / kW. According to the same sources, 1 kW requires an average rooftop area of 7 m^2. Furthermore, a capacity limit of the PV panels was initially set to 20 kW. However, due to this constraint, off-grid simulations in Östersund resulted in no feasible solution. Therefore, this upper limit was raised to 35 kW in the off-grid cases. It is worth mentioning that 35 kW requires a rooftop area of 245 m^2 which is rarely available, especially in the house that is assumed for this study with a living area of 130 m^2.

7.2.2 Battery

Data was gathered from two different battery suppliers, Tesla and Nilar, in order to compare the cost and technical parameters of the BESS. The price for battery storage consists of the battery pack, BMS, EMS, inverter, and installation costs which are all included in the total cost of the BESS as SEK/kWh. Additionally, each battery has a different set of technical characteristics: (1) chemistry, (2) round-trip-efficiency, (3) and lifetime. The economic and technical data are shown in Table 4.

Table 4. Tesla and Nilar battery specifications.

	Tesla	**Nilar**
Chemistry	Li-Ion NMC	NiMH
Cost [SEK / kWh]	10 970	10 000
Round-trip-efficiency [%]	89	90
Lifetime [yrs]	10	20

Seeing as the cost per kWh is similar when comparing the two suppliers, the Nilar battery is chosen for the systems that include a battery. Round-trip-efficiency is set to 90 %, depth of discharge to 80 %, and the lifetime to 20 years. After inquiring Nilar, the cost of a small home BESS (1-10 kWh) is assumed to be 10 000 SEK / kWh. However, for larger BESS (10-100 kWh), the cost per kWh can be assumed to drop to 7 500 SEK/kWh. Moreover, these costs include the inverter cost, which, in HOMER Pro can be accounted for. Therefore, the cost for BESS is set to 5000 SEK / kWh for system A, and 7 500 SEK / kWh for system B2. Replacement costs are assumed to be 25 % of today's costs, which, will occur after 20 years. The search range in system A was set to 23-111.5kWh.

7.2.3 Hydrogen storage

In HOMER, storing hydrogen requires three components: (1) hydrogen tank, (2) electrolyser, and (3) a fuel cell. Economic and technical data on these components have been gathered from, interviews, various manufacturers and suppliers in Sweden and neighbouring countries.

The cost of a hydrogen storage tank was estimated after inquiring Nilsson Energy. A tank that holds 400 kg of hydrogen costs about 1 950 000 SEK. In addition to that, a compressor is required in order to store the hydrogen at 300 bars, which, according to the same source costs 214 000 SEK. Another study suggested a price variation between 3750-4900 SEK / kg. Furthermore, the cost of hydrogen storage includes both the hydrogen tank and the compressor and is set to 5000 SEK / kg of stored hydrogen. It is possible to set a constraint of what the initial tank level is set to, the project begins on the first of January and the initial tank level is set to 50%. Additionally, a constraint that requires the year-end tank level to equal or exceed the initial tank level to ensure that the system is dimensioned to operate equally each project year. The hydrogen tank and compressor are assumed to last 25 years; hence, no replacement is required.

Regarding the electrolyser, a PEM electrolyser from GreenHydrogen was used in the model, the HyProvide P1, with a rated capacity of 5 kW and a Hydrogen production rate of 1 Nm^3 / hour. This electrolyser can utilize multiple units in order to reach capacity between 5-25 kW. After inquiring an additional manufacturer (Enapter, 2020), the price of an electrolyser is estimated to be 100 000 SEK / kW. Replacement costs are assumed to be 25 % of today's costs, which, will occur after 15 years, this is due to the fact that according to the manufacturers, only the fuel membrane needs replacing.

The fuel cell that was used in the system was based on the Powercell PS-5 that provides an electric power capacity of 5kW, a 0-7.5kW of useful heat energy depending on load, fuel consumption of 70 standard litres per minute (slpm), 50 % efficiency, and an expected lifetime of 10 years. One PS-5 costs 390 000 SEK. Furthermore, the cost of a fuel cell is estimated to be 78 000 SEK / kW. Replacement costs are assumed to be 25 % of today's costs, which, will occur after 10 000 operating hours, this is due to the fact that according to the manufacturers, only the fuel membrane needs replacing. See Table 5 for the summarized cost estimations of the hydrogen storage-related technologies, search range, and expected lifetime that is used in the off-grid house.

Table 5. Hydrogen technology specifications and assumptions.

	Hydrogen tank	**Electrolyser**	**Fuel Cell**
Cost	5000 SEK / kg	100 000 SEK / kW	78000 SEK / kW
Search range	180-400 kg	5-15 kW	5-15 kW
Efficiency (%)	-	85	50
Lifetime	25 years	15 years	10 000 hours

7.2.4 Inverter

In systems A, B1, and B2, an inverter is required to convert DC to AC and AC to DC. The inverter used in the simulations is a bidirectional inverter, Leonics-S219Cp 5kW, that is available in HOMER Pro with an efficiency of 96 %, which, can be connected parallel with up to 10 additional units. The inverter capacity search range is set to 5-15kW, the cost is assumed to be 3000 SEK / kW, replacement cost is assumed to be 2 000 SEK / kW, and the lifetime is set to 15 years (Solcellskollen, 2018).

7.2.5 Price of electricity

In the systems that are connected to the grid, HOMER Pro allows the user to input hourly data of two components regarding the grid costs: the price of electricity and feed-in tariff. The spot price has been gathered from the European power market Nord Pool, hourly spot prices was used between the years of 2015-2019 to form an average hourly spot price. In order to form an understanding and updated price of each component in the total price of electricity, DSOs in the respective region was contacted, prices from Jämtkraft (SE2) and Vattenfall (SE3) was used for network charges. Regarding the electricity certificate, handling fees, and fixed costs for the electricity price, comparisons were made on elskling.se and major DSOs websites, together with a short un-scripted interview with Jonasson (2020). Furthermore, the summed cost of the electricity certificate, handling fees, and fixed costs range between 0.03-0.08 SEK / kWh, these are accounted for and referred to as handling fee, which is set to 0.05 SEK / kWh. Further, the total cost of electricity is calculated and referred to as the LCOE, as seen in Table 6.

The feed-in tariff for unused electricity produced in systems B1 and B2 varies depending on your DSO and what type of contract the house is bound to. After inquiring Jonasson (2020) and Kulin (2020), together with examining provided electricity bills, the feed-in tariff is simply assumed to be the spot price plus VAT at the corresponding hour. This can seem a bit too simple, but after reviewing the available deals at the time of the study and according to both Jonasson (2020) and Kulin (2020), handling fees, electricity certificates, and net utility in most cases cancels out and what a household receives at the end of the day is, the spot price plus VAT. The average LCOE with its components is presented in Table 6.

Table 6. Average LCOE for grid-connected households.

	Östersund	**Visby**
Region	SE2	SE3
Spot price AVG [SEK / kWh]	0.32	0.33
Handling fee [SEK / kWh]	0.05	0.05
Tariff [SEK/ kWh]	0.18	0.28
Fuse charge 16A [SEK / yr]	4035	4165
Government fees [SEK / yr]	58	58
Fuse + gov fee [SEK / hr]	0.47	0.48
Energy tax [SEK / kWh]	0.35	0.44
VAT	25 %	25 %
LCOE AVG [SEK / kWh]	1.71	1.98

7.2.6 Investment aids

Regarding the available governmental investment aids and tax deductions, which, in these cases, are available for the PV system, BESS, and energy sold back to the grid for system B. The maximal investment aid for a PV system is 20 % of the capital cost, or alternatively, the ROT-deduction can be utilized (capped at 50 000 SEK). In addition to this, 60 % of the BESS can be covered by investment aid (also capped at 50 000 SEK). Lastly, tax deduction can be received for the energy sold back to the grid at 0.6 SEK / kWh (capped at 30 000 kWh / year). Noteworthy is that the NPC and LCOE are presented without the investment aid and tax deduction that are available as of 2020. The available investment aid for each modelled system are taken into consideration when discussing and analysing these systems in the following chapters.

7.3 Reference scenario

These systems have been modelled in order to lay the foundation of several possible future scenarios that are presented, analysed, and discussed together with the empirics gathered from the interviews in the following chapters. Furthermore, this chapter presents the techno-economic aspects of the systems presented above.

The technology costs for the reference scenario are based on the conducted material in *Chapter 4, Research Context* and presented in Table 7.

Table 7. Technology costs for reference scenario.

Technology	Reference scenario
Solar PV panels [SEK / kW]	13 000
BESS (Off-grid) [SEK / kWh]	5 000
BESS (On-grid) [SEK / kWh]	7 500
Fuel Cell [SEK / kW]	78 000
Electrolyser [SEK / kW]	100 000
Hydrogen Tank [SEK/Kg]	5 000
Inverter [SEK/kW]	3 000

7.3.1 System A. Off-Grid Hydrogen + PV + BESS

System A can serve the given load for each location as presented in Table 8. The NPC of such a system ranges from 2.29-4.05M SEK. Additionally, the LCOE ranges from 12.33-16.42 SEK / kWh for the 25 year lifetime of the project. This includes replacement costs for the Fuel Cell, Electrolyser, and Battery.

Table 8. System A reference scenario.

	Visby	Östersund
Yearly load [kWh]	9 462	12 590
PV [kW]	17	30
BESS [kWh]	34.5	46

	Visby	Östersund
Hydrogen Tank [kg]	180	320
Electrolyser [kW]	5	10
Fuel cell [kW]	5	5
PV production [kWh / yr]	20 922	29 495
FC production [kWh / yr]	2 568	4647
Hydrogen production [kg / yr]	154	279
LCOE [SEK / kWh]	12.33	16.42
Total NPC [SEK]	2.29M	4.05M

7.3.2 System B1. Grid + PV

System B1 is a system that is still connected to the grid but with the setup of a prosumer household with roof attached PV panels. The cost of electricity and the appurtenant feed-in tariff for each location is as presented in Table 6. Furthermore, this system has an installed PV capacity of 15 kW, and an inverter with 10 kW capacity, see Table 9. These costs include replacement costs for the inverter.

Table 9. System B1 reference scenario.

	Visby	Östersund
Yearly load [kWh]	9 462	12 590
PV [kW]	15	15
Inverter [kW]	10	10
PV production [kWh]	18 311	15 109
Energy purchased [kWh / yr]	6 508	9 748
Energy sold [kWh / yr]	13 143	10 021
LCOE [SEK / kWh]	0.86	1.11
Total NPC [sek]	379 862	494 477

7.3.3 System B2. Grid + PV + Bess

System B2 is a system that is still connected to the grid but with the setup of a prosumer household with PV and a BESS. The cost of electricity and the appurtenant feed-in tariff for each location is as presented in Table 6. Furthermore, each system has an installed PV capacity of 15 kW, BESS of 6 kWh, and an inverter with 10 kW capacity, see Table 10. These costs include replacement costs for the BESS and the inverter.

Table 10. System B2 reference scenario.

	Visby	**Östersund**
Yearly load [kWh]	9 462	12 590
PV [kW]	15	15
BESS [kWh]	6	6
Inverter [kW]	10	10
PV production [kWh]	18 311	15 109
Energy purchased [kWh / yr]	6 092	9 164
Energy sold [kWh / yr]	13 121	10 117
LCOE [SEK / kWh]	0.93	1.17
Total NPC [SEK]	411 286	521 409

7.3.4 System C. Grid

This system is connected to the grid without any self-production of electricity. The load is completely covered by electricity purchased from the grid. Furthermore, this system is modelled to serve as a point of references to systems A, B1, and B2, see Table 11.

Table 11. System C reference scenario.

	Visby	**Östersund**
Yearly load [kWh]	9 462	12 590
LCOE [SEK / kWh]	1.94	1.68
Total NPC [SEK]	360 247	415 685

7.4 Future scenarios

This section intends to present future scenarios that occur when future projections regarding the impact variables are used in the model. The impact variables in this case is mainly the economic data associated with each system. Based on the research context, basic trends and key uncertainties are defined for two future scenarios. Firstly, a simulation with the assumed costs in year 2030 was modelled, thereafter, a more uncertain case with the respective costs assumed in year 2040 is modelled with the intention to serve as a case for discussion. Both future scenarios are assumed to take place in mentioned year.

Furthermore, to provide a proper comparison between the system costs between the reference and future scenarios, part of the input data remains fixed. Firstly, each system is modelled at the same location with weather data and demand profile unchanged for all scenarios. Secondly, the discount rate, inflation rate, and reliability factor also remain unchanged. When describing the price change for each component, costs for year 2020 are used as the reference and price variations for 2030 and 2040 are calculated as a percentage increase or decrease of the 2020 costs.

7.4.1 Cost projections and assumptions for 2030 and 2040

In the following future scenarios, technology development is assumed to have reached a higher state of maturity and costs have dropped significantly. Through analysis of recent trends, cost development, and future cost projections for the modelled technologies, assumptions and projections made regarding future technology costs were based on the data gathered and presented in *Chapter 4, Research Context*. These projections were necessary to investigate how the economic rationale of investing in self-sustaining technologies will develop in the future and are presented in Table 12.

Moreover, by 2030, cost of PV is assumed to have dropped by 20 % and the efficiency of the panel is now 25 %, BESS costs by 50 %, and inverter costs by 20 %. Furthermore, technology costs regarding the hydrogen system have dropped significantly, the cost of both the electrolyser and fuel cell is assumed to have dropped by 80 %, and the hydrogen storage tank cost by 35 % assuming higher pressure in the tank resulting in more storage capacity.

By 2040 most costs are assumed to have continued to drop a bit further than in the 2030 case. In these scenarios, cost of PV have dropped by 30 % and the efficiency of the panel is assumed to be 30 %, BESS costs have decreased by 65 %, and inverter costs by 30 %. Moreover, the cost of the electrolyser and the fuel cell have dropped by 90 %, and the storage tank by 50 %. A summarized table of technology cost projections used for the 2030 and 2040 scenario is presented below, in Table 12.

Table 12. Cost projections for scenarios 2030 & 2040.

Technology	% reduction from reference scenario (2030, 2040)	2030	2040
Solar PV panels [SEK / kW]	20, 30	10 400	9 100
BESS (Off-grid) [SEK / kWh]	50,65	2 500	1 750
BESS (On-grid) [SEK / kWh]	50,65	3 750	2 625
Fuel Cell [SEK / kW]	80,90	15 600	7 800
Electrolyser [SEK / kW]	80,90	20 000	10 000
Hydrogen Tank [SEK / kg]	35,50	3 250	2 500
Inverter [SEK / kW]	20,30	2 400	2 100

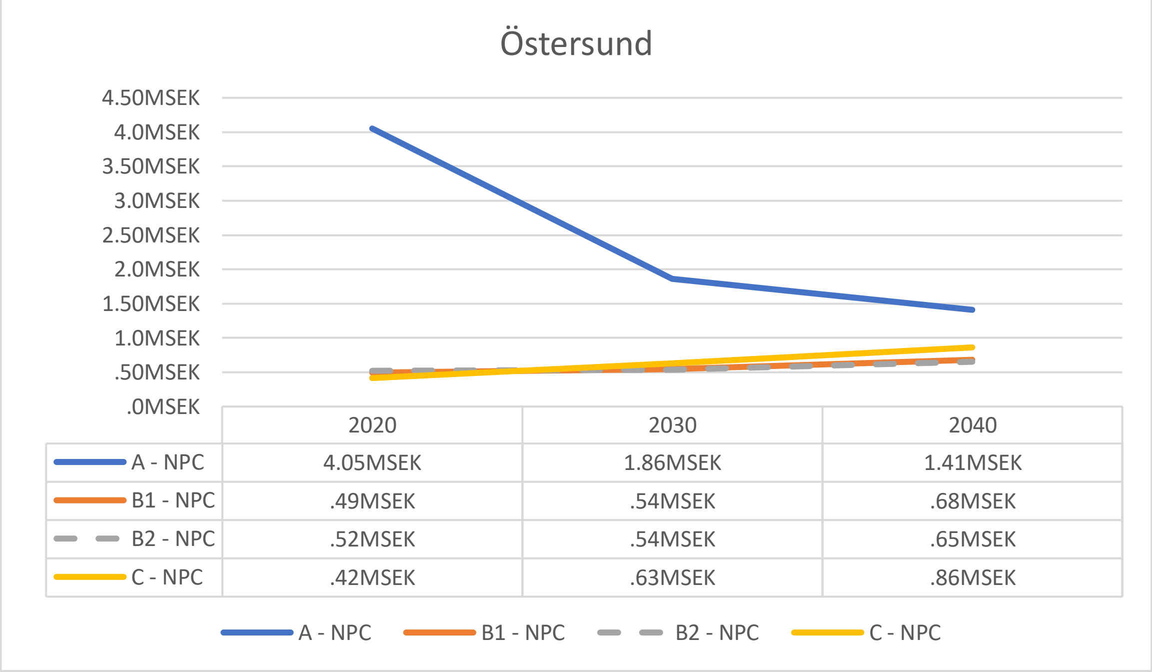
As for the grid-connected systems, B1, B2, and C, network charges and energy taxes are assumed to continue to rise with the basic trends as presented in the research context chapter. Network charges is set to rise by 3 % per year and the energy tax by 5 % per year. Additionally, hourly spot prices were used from the future scenario in the Energiforetagen (2019) report, a form of participatory research, where the average hourly spot prices had increased by 74 % in SE2 by 2030 and, 98% by 2040. Consequently, any region specific assumptions are neglected and thus, the same percentage change for both Visby and Östersund is set. The projected total costs of grid-connected electricity and its components is presented in Table 13.

Table 13. Average LCOE projections for 2030 & 2040 scenarios.

	Östersund		**Visby**	
	2030	***2040***	***2030***	***2040***
Region	SE2	SE2	SE3	SE3
Spot price AVG [SEK /kwh]	0.56	0.64	0.58	0.65
Handling fee [SEK/kWh]	0.07	0.09	0.07	0.09
Tariff [SEK / kWh]	0.24	0.32	0.38	0.51
Fuse charge 16A [SEK / yr]	5420	7300	5600	7520
Government fees [SEK / yr]	94	154	94	154
Fuse + gov fee [SEK / hr]	0.63	0.85	0.65	0.88
Energy tax [SEK / kWh]	0.57	0.93	0.72	1.17
VAT 25%	-	-	-	-
TCOE AVG [SEK / kWh]	2.59	3.55	2.99	4.12

7.5 Future scenario results and analysis

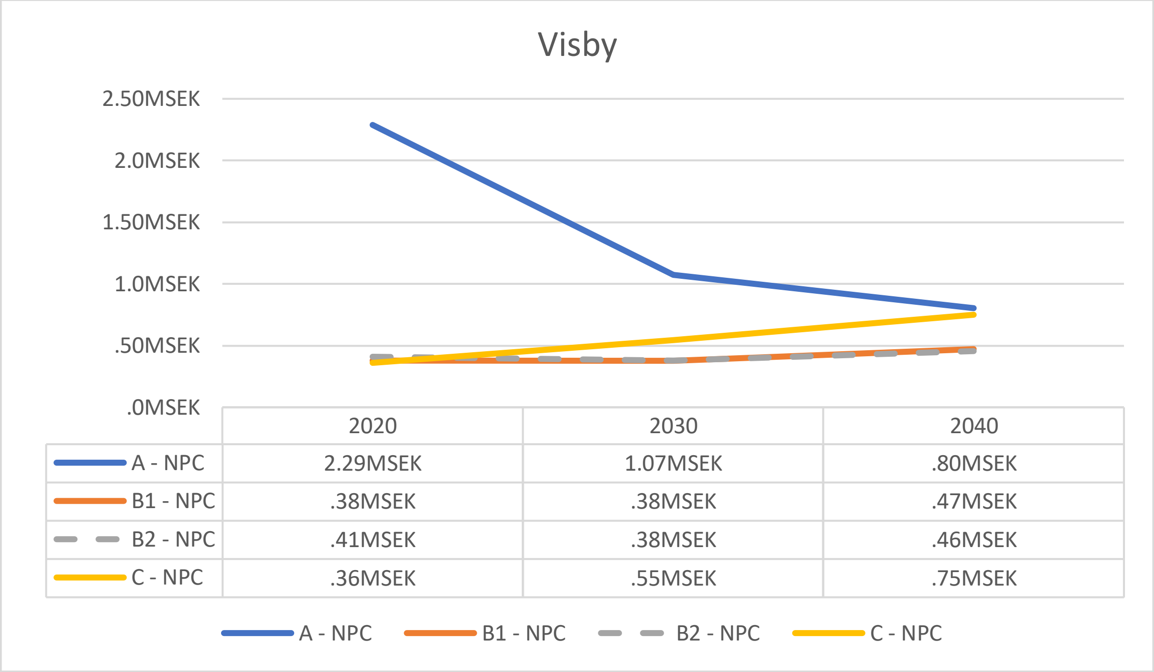
In this section, results from the 2030 and 2040 scenarios are compared with the reference scenario. Firstly, the NPC for all system setups in Östersund are shown in Figure 11. In Figures 11-12, the NPC is presented for each modelled system in the respective years and shown the table below the graph, and in the graph with its respective colour code. Hence, the lines show in the graph are drawn linearly between three points for each system in Figures 11-14. For system A, the NPC decreases significantly for years 2030 and 2040 compared to the 2020 case with the reduction in hydrogen technology. NPC for systems B1 and B2 increases slightly with the increasing grid costs but not as much as system C due to the lower technology costs in 2030 and 2040. Noteworthy is that systems B1 and B2 have a lower NPC in 2030 and 2040 compared to system C.



	2020	2030	2040
A - NPC	4.05MSEK	1.86MSEK	1.41MSEK
B1 - NPC	.49MSEK	.54MSEK	.68MSEK
B2 - NPC	.52MSEK	.54MSEK	.65MSEK
C - NPC	.42MSEK	.63MSEK	.86MSEK

Figure 11. NPC for all systems in Östersund in the years 2020, 2030, and 2040.

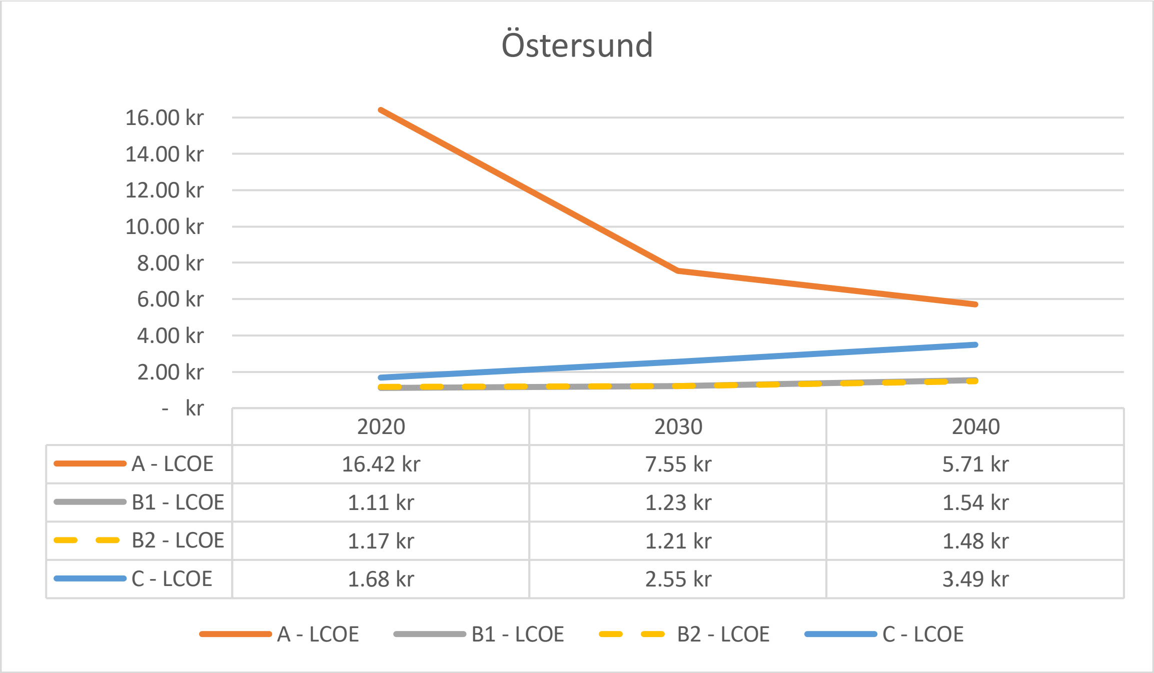
Furthermore, in Figure 12, the NPC for all systems located in Visby in the modelled years is shown. In this case, NPC for system A is near grid parity in the 2040 case with the continuous cost reduction in technology costs, mainly hydrogen technology. However, systems B1 and B2 are still the cheaper alternative.



	2020	2030	2040
A - NPC	2.29MSEK	1.07MSEK	.80MSEK
B1 - NPC	.38MSEK	.38MSEK	.47MSEK
B2 - NPC	.41MSEK	.38MSEK	.46MSEK
C - NPC	.36MSEK	.55MSEK	.75MSEK

Figure 12. NPC for all systems in Visby in the years 2020, 2030, and 2040.

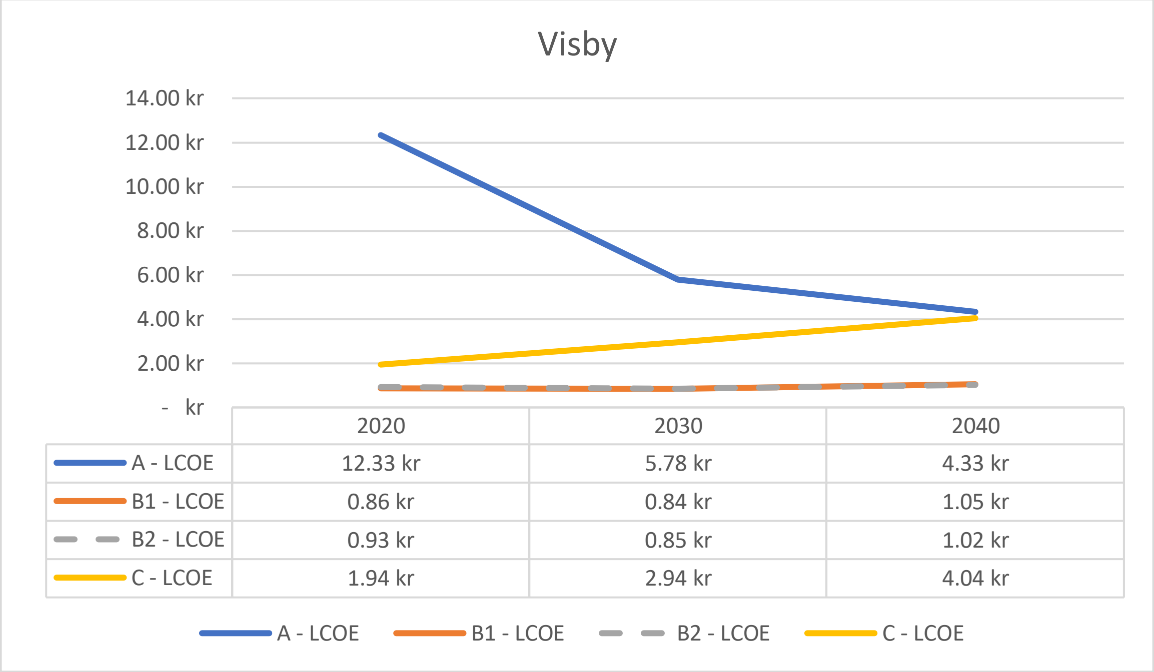
Moreover, Figure 13 presents the LCOE for all systems located in Östersund. In Figures 13-14, the LCOE is presented for each modelled system in the respective years and shown the table below the graph, and in the graph with its respective colour code. The LCOE is drastically reduced in the 2030 and 2040 case for system A whereas the LCOE for system C is increasing over the same time period. System A is still the most expensive alternative whereas the prosumer systems B1 and B2 is the cheaper alternative during all years.



	2020	2030	2040
A - LCOE	16.42 kr	7.55 kr	5.71 kr
B1 - LCOE	1.11 kr	1.23 kr	1.54 kr
B2 - LCOE	1.17 kr	1.21 kr	1.48 kr
C - LCOE	1.68 kr	2.55 kr	3.49 kr

Figure 13. LCOE for all systems in Östersund in the years 2020, 2030, and 2040.

Additionally, LCOE for each scenario located in Visby is presented in Figure 14. The graph show similar patterns to the LCOE for the Östersund scenarios. However, in year 2040, the off-grid system, system A, is close to grid parity with only a 0.29 SEK / kWh difference in the LCOE. Noteworthy is that the LCOE for systems B1 and B2 is still the economically advantageous alternatives.



	2020	2030	2040
A - LCOE	12.33 kr	5.78 kr	4.33 kr
B1 - LCOE	0.86 kr	0.84 kr	1.05 kr
B2 - LCOE	0.93 kr	0.85 kr	1.02 kr
C - LCOE	1.94 kr	2.94 kr	4.04 kr

Figure 14. LCOE for all systems in Visby in the years 2020, 2030, and 2040.

Another essential aspect to consider is the cost by each component for the modelled systems. Consequently, Figure 15 presents how much of the NPC each technology represents in the 2020 and 2040 scenarios for system A in Östersund. The hydrogen system, consisting of the hydrogen tank, fuel cell, and electrolyser represents over 80 % of the cost in 2020. The same system in Visby is not presented since the result is very similar in a percentage share aspect of the NPC, the same goes for the 2030 case seeing as the difference between 2030 and 2040 is not significant. Noteworthy is that the cost of the hydrogen tank represents over half of the NPC for system A in 2040.

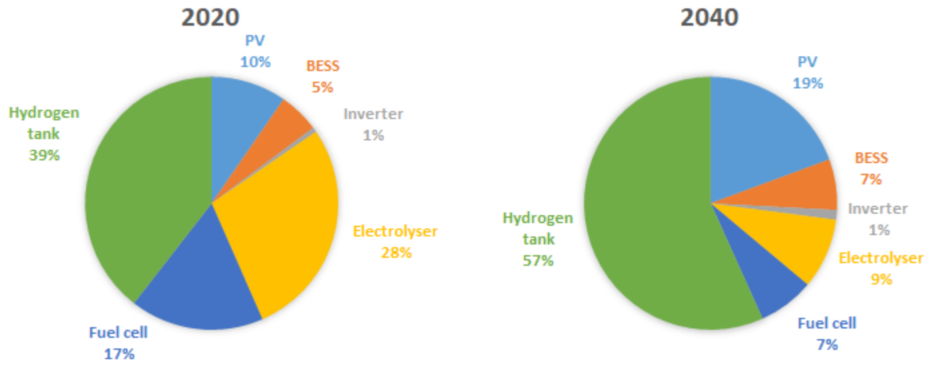


Figure 15. Cost by component as percentage of NPC for system A in Östersund, in the years 2020 and 2040.

Lastly, Figure 16 displays the cost by component for system B2 in Visby in the years 2020 and 2040. During the project lifetime, NPC for PV, BESS, and inverter is close to half of the cost when investing in 2020. Whereas, the same system is 28 % of NPC when the investments are done in 2040. With the decreasing technology costs together with rising grid costs, by 2040, grid costs represents 72 % of the NPC, compared to 43 % of the total NPC for the same system in 2020.

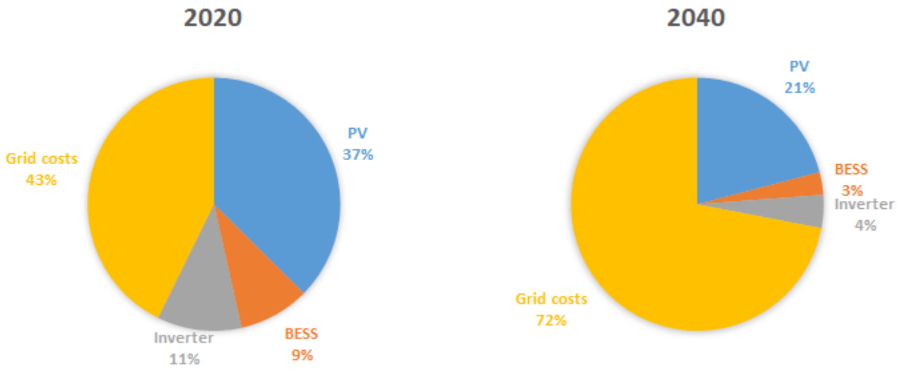
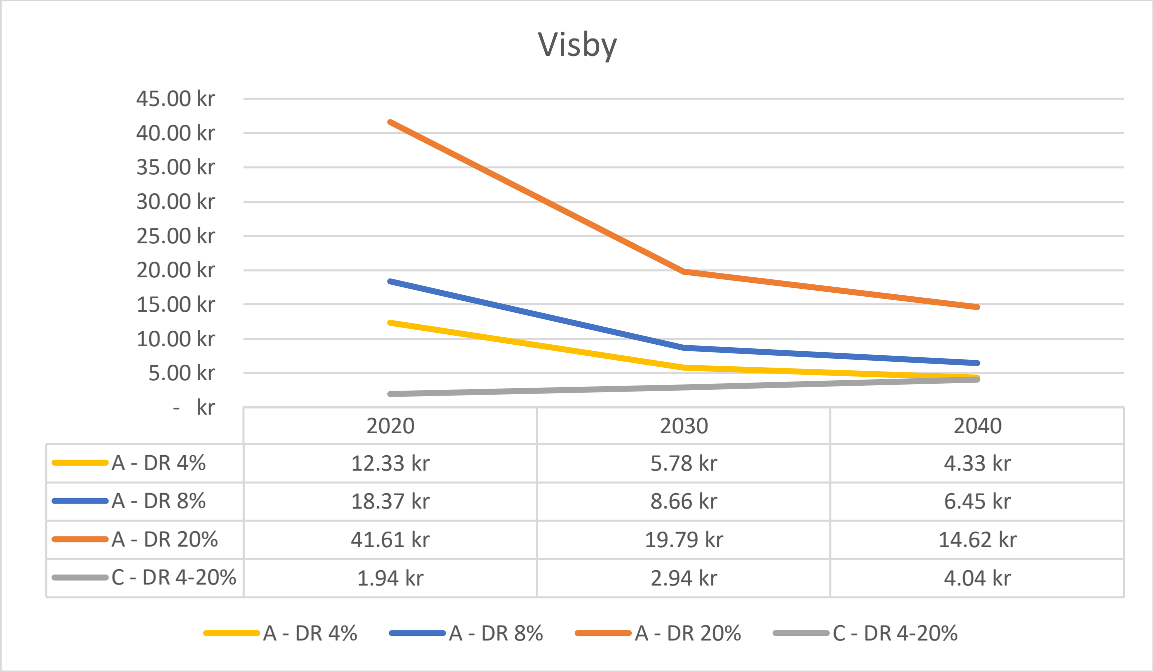


Figure 16. Cost by component as percentage of NPC for system B2 in Visby, in the years 2020 and 2040.

7.6 Sensitivity analysis and modelling limitations

A sensitivity analysis was performed on the variable that influenced the LCOE of system A the most, the Discount Rate (DR). In the above scenarios, the DR was set to 4 % based on a study that investigated DR in energy system optimisation models through a literature review and, suggested a DR between 4-5 % (García-Gusano et al., 2016). However, previous scholars have implied that consumers behaviour sometimes correspond to significantly higher implicit discount rates (Jaffe et al., 2004; Meier and Whittier, 1983). Hence, sensitivity cases were conducted with the DR set to 8 % and 20 % for system A and C in all modelled years. Results for the NPC in system A remained unchanged, however, the LCOE is affected. As for system C, the LCOE is unaffected whereas the NPC is slightly lower in the cases with the DR adjusted. Hence, the grey line in Figure 17 represents the LCOE of system C with DR 4 %, 8 %, and 20% since it remains unchanged. Furthermore, when the DR is set to 8% and 20%, grid parity is reached is not reached in any case, as seen in Figure 17.



	2020	2030	2040
A - DR 4%	12.33 kr	5.78 kr	4.33 kr
A - DR 8%	18.37 kr	8.66 kr	6.45 kr
A - DR 20%	41.61 kr	19.79 kr	14.62 kr
C - DR 4-20%	1.94 kr	2.94 kr	4.04 kr

Figure 17. Sensitivity analysis with adjusted DR for systems A & C.

Moreover, previous studies mention that one of the key determining factors of a consumers willingness to go off-grid was the desired reliability of the system (Hittinger and Siddiqui, 2017; H. Liu et al., 2019). In other words, if the capacity shortage is allowed at a higher degree, system costs were reduced drastically (ibid.). In the above scenarios, the reliability factor was set to 5 % for system A, resulting in a reliability factor of 95 %. However, there was no unmet load in the optimal solutions presented.

Furthermore, a sensitivity analysis was performed to investigate this factor. Noteworthy is that if only the reliability factor is changed in the system A case, the optimal solution resulted in the same optimal solution as presented in Table 8. This is due to the constraint set to the hydrogen tank where the initial tank level is 50% of the tank capacity and the end-year level has to equal or exceed this level. This constraint was considered crucial to the system, if it is not used, the system is optimized with the hydrogen tank level empty at the end of the year, which, implicitly, suggests that the system is only dimensioned to be self-sufficient for 1 year. Therefore, the reliability factor is concluded to not have an impact on the system A, off-grid case.

Another factor that was considered to affect the outcome of the unchanged reliability factor sensitivity analysis was the lower limits for the hydrogen system in system A. These lower limits was set based on the data gathered during the research context and empirics phase in order to model a realistic setup of the system components. Thus, the lower tank limit was set to 180 kg, which, is equivalent to 6 000 kWh, to at least cover the winter load for the Visby location (5 327 kWh). Additionally, the lower limits for both the fuel cell and electrolyser was set to 5kW based on the benchmark projects and additional data gathering on available products. Consequently, if these lower limits are adjusted, there could possibly be a system that can still meet the demand profile in the modelled locations with a lower NPC and LCOE. However, these were not investigated due to the initial assumptions regarding the hydrogen system.

8 Discussion

The aim of this chapter is to discuss the results from the analysis and modelling chapters , both separately and together, along with the prior knowledge in the research field of off-grid applications. Furthermore, this chapter is presented on the basis of the proposed sub-research questions with the goal of getting closer to a final conclusion of this study.

8.1 What are the drivers and barriers for off-grid electricity production in Sweden?

The situation of exploring drivers and barriers for innovations to disseminate in a developed system, such as the electricity system, have been found to be complex because of its many influential variables (Geels, 2004,2002; Unruh, 2000; Kemp et al., 1998; Hughes, 1987). This work indicates that there is a lot of different variables to consider which the empirical findings also suggests. However, it is also arguable that implications from this work display interesting differences and new insights on the scholarly level.

One of the greatest drivers for self-sufficiency could be that off-grid applications are adopted by the actual consumer/user and therefore market-driven. Having this in mind, it is arguable that off-grid and other applications where adoption decision lies in the hands of the final user adds another dimension to the original socio-technical system (STS), technological innovation system (TIS) and multi-level perspective theory (MLP). The aforementioned theories are highly developed towards understanding the co-evolutionary process between infrastructures, organizations, and institutions that create a complex lock-in of technologies. Historically, this makes sense because the only means of receiving electricity has been through state-regulated centralized electricity systems. However, today, the ground rules and dynamics are changing where the consumer can break into the system and create their own path of supplying electricity without being a part of the system. Therefore, from analyzing the empirical findings of this work, it is arguable that the impact of existing infrastructures, institutional setups, and organizations towards the deployment of off-grid applications are not as influential as the theories suggest. In conclusion, when it comes to complete off-grid applications, it is the technology itself that will serve as the biggest barrier or driver for deployment because of its independence from the larger system together with the final consumer having the larger role.

Suurs et al. (2009) and Bergek et al. (2008) proposed different *components* and *functions* within a technological innovation system (TIS) necessary for its performance and departing from these, a handful of drivers and barriers have been identified. From the analysis, it is evident that the component of *actors* is not only the actors with a thriving interest in off-grid applications, but also the incumbent actors with a more conservative market interest. Aligned with the findings from Parag and Sovacool (2016), that is, how prosumers compete with incumbents and existing infrastructure from enabling another path of supplying a household with electricity. It is arguable that because of off-grid applications nature of challenging the core business of the incumbents, it might represent one of the biggest barriers for deployment unless the incumbents find value in supporting the innovation.

There is evidence that self-sufficient households can bring net utility if coupled with the grid. However, the net utility is mostly discussed as a driver from a prosumer perspective and not off-grid. Prosumers and an electric sharing economy could address the social, economic and environmental challenges by diversifying the electricity supply (Parag and Sovacool, 2016; Skopik and Wagner, 2012). Concretized drivers, such as peak shaving from Bost et al. (2016), reduced transmission losses, an increased reliability proposed by Starke et al. (2019) and Y. Liu et al. (2019), and a reduced need for transmission grid upgrades from (Y. Liu et al. (2019) were all drivers highlighted from the interviews to apply to the Swedish context as well.

Despite the possible net utility, components in terms of *networks* and *institutions* are limiting the potential value for operating a self-sufficient household towards the grid in Sweden and thus, implicitly, favours an off-grid scene instead. Here, limitations, such as regulations of sharing electricity, appropriate prosumer markets, and the stable networks between policymakers and incumbents, are most visible from the empirical findings. Fifteen years ago, Hvelplund (2006) projected that such issues could exist in the future, that is, how markets that nourish the energy system from the integration of local electricity would be a key objective to fulfil. Bergek et al. (2008) and Suurs et al. (2009) emphasises the need for stable networks and from the analysis, it was found that major networks have been established between policymakers and incumbents. Such historical and strong networks are according to IEA (2014) governing the incumbents and serve as a barrier for new networks to establish between innovations and policymakers that could push for innovative markets that reaps the benefits of household electricity production. Consequently, a concise suggestion can, therefore, be presented as; the t*echnology* of household electricity production is here and it will certainly evolve which serves as a great driver for deployment but the barriers are the context the technology will be placed in.

Moreover, much of the literature emphasizes the idea that off-grid households can support the system, as well as form smaller interconnected systems to mitigate issues within the existing system configuration, meaning that there is an existing demand for new applications. Hence, exploring the different *functions* within the TIS of off-grid applications, it is arguable that a *market formation* for self-sufficiency in Sweden is close because of the demand for new applications. However, there is a tough barrier to overcome the resistance of incumbents who wants to exploit alternative solutions rather than supporting off-grid applications. Departing from the aforementioned finding from IEA (2014), explaining how the market regulations have historically governed monopoly utilities, TSO´s and DSO´s, together with findings from Palm (2017), that solutions for household electricity production are purchased by the final user which results in poor market design, it is arguable that the inert market formation is causing a slow diffusion of off-grid applications.

Here, it also is arguable that the observed literature pointing out the importance of surviving the early stages of deployment with the help of governmentally driven incentives are of importance for off-grid applications. Otherwise, the technology will not be able to compete with the incumbents and reach the mainstream market of the majority, leading to a technology “valley of death”(Grubb, 2004). Nevertheless, once again, it shows that the real driver for off-grid applications is the individuals, such as pioneers and enthusiasts, striving to push the technological frontier and prove its functionality through *entrepreneurial activities* and not the incumbent actors who seek business opportunities within it.

When discussing the larger system and the dynamics between the different levels of analysis it is evident that the existing system is stable, but the surrounding environment and external events are creating pressure for change. *First*, on the *regime level*, findings from this work argue that windows of opportunity exist for new applications, such as off-grid, because of issues in the current infrastructure. On the other hand, Sweden is argued to have one of the most sustainable electricity systems in the world and a large share of individual household systems could lead towards increased system costs, societal imbalances, and well-fare losses.

Second, on the technological *niche level*, it is arguable from the findings, emphasized from both the respondents and the modelling part of this work, that the technology is possible to install and run but too expensive compared to existing technologies. Additionally, findings visualize a large gap between the current system configuration and off-grid. However, findings are also arguing for a future with system developments toward decentralized production that could benefit household electricity production. This, together with findings that off-grid applications could benefit from relational synergistic developments in other markets, as well as progression in terms of business models, infrastructure, and market demand for household electricity production, could altogether act as a driver for deployment.

Third, as the MLP theory suggests that *landscape developments* influence the socio-technical regime, this work suggests that the goal of achieving 100 % renewable electricity production together with current times of uncertainties could accelerate the pressure on the existing regime. Opening up for innovations to take place where the renewable production goal could leverage from off-grid applications and also increase the security of the system.

8.2 What is the economic rationale of investing and running off-grid and partially off-grid applications today and within the future?

Based on the techno-economic analysis performed through modelling different systems and scenarios in Chapter 7, it is safe to say that, as of today, there is no economic rationale of investing in a fully off-grid household in Sweden. With the Nordic weather conditions and solar radiation profiles, a long-term storage solution is required. This supports the assumption from RISE (2018) that Sweden is a challenging country for self-sufficient applications. Further, this study investigated the technology and economic characteristics of a hydrogen solution, which, is still in a low state of Manufacturing Readiness Level (MRL) and Technology Readiness Level (TRL). Consequently, the literature also emphasizes the low electricity prices in Sweden which is shown when comparing the different scenarios (Palm, 2017). There is a significant cost difference between the same household located in Östersund and Visby mainly due to the lower average temperature in Östersund, which results in a higher demand profile and consequently larger system requirements.

Furthermore, if the cost reduction of hydrogen technology follows the same path as Solar PV has done, which, is stated both in literature and empirics (Wang et al., 2018). The economic rationality of investing in an off-grid system will significantly increase over the coming decades and, eventually close in on grid-parity by 2040, especially in the Visby location. However, for this to occur, the LCOE of staying connected to the grid will have to continue to rise with basic trends as assumed in this study. Noteworthy is also that the future development of network charges, grid tariffs, and energy tax is still considered a key uncertainty. In fact, the spot price can also be considered as key uncertainty based on how the future electricity develops.

Partially off-grid systems are shown to be the most economically rational systems in both locations across all years considered in this study, whether it consists of only a PV system or an additional BESS. Even though grid parity is near in the 2040 scenario, the option of staying on the grid as a prosumer is more promising. Which, as both literature and empirics suggest, is also more favourable for the system as a form of net utility (Muqeet et al., 2019; Zhang et al., 2018, 2019; Espe et al., 2018; Lavrijssen and Carrillo Parra, 2017; Parag and Sovacool, 2016).

A wide range of technical and economic data was considered as impact variables when conducting the modelling part to strengthen this part of the study. Varying from cost-related data of components, electricity prices, and component characteristics of several technologies. However, there are several limitations to this part of the study that had to be excluded due to the time constraint and complexity which may have affected the outcome. Moreover, reliability is mentioned as a key impact variable in other off-grid studies, although, these studies did not investigate a hydrogen storage solution situated in Nordic conditions (Gorman et al.,2020; H. Liu et al., 2019; Hittinger and Siddiqui, 2017). Hence, the off-grid system in this study was dimensioned after a demand profile simulated in a high energy-efficient household with one key constraint, that the end-year tank level had to equal or exceed the initial tank level that was set to half-full. This resulted in a system that did not suffer from capacity shortage; hence, reliability was not a factor that could be analyzed without resizing the components and the system setup.

HEMS and other smart devices that monitor and regulate electricity usage are also impossible to simulate with the program used in this study which is considered to be essential for a modern off-grid house. Additionally, the available rooftop area is mentioned in previous studies as a limitation to the potential of leaving the grid (DiOrio et al., 2020; Gorman et al., 2020; Hittinger and Siddiqui, 2017; Kantamneni et al., 2016; Khalilpour and Vassallo, 2015; H. Liu et al., 2019). In the off-grid system based in Östersund, the minimum requirement for PV panels was 30 kW, which could be considered unrealistic on a house with 130 m^2 of living area. Lastly, inflation is used over the modelled project lifetime, however, this study has not considered currency inflation when predicting technology and electricity price costs that are used as inputs for years 2030 and 2040.

8.3 Why would a potential adopter invest in off-grid applications?

From this work, it is arguable that the modelling part regarding the costs of running an off-grid household could increase the knowledge of why a potential adopter would take an investment decision. The analysis showed that having profitability as the main motive for adoption today is unrealistic which is further strengthened from the modelling. To invest in an off-grid application results in an LCOE several times higher than the LCOE for grid-connected electricity. This is aligned with the argument from Noppers et al. (2014), that is, how *instrumental motives* are the relative advantages in terms of the technology´s functional use in relation to costs. Hence, this work shows that individuals making investment decisions based on cost-related relative advantages are probably not finding any interest in off-grid applications. However, as Nygrén et al. (2015) suggest that most potential adopters of RETs are interested in lowering electricity bills and eliminate other costs, which, is certainly limiting the overall demand for off-grid applications with the currently low profitability.

On the other hand, potential adopters can find other relative advantages than cost reduction, such as, increased reliability, independence, and control (Michelsen and Madlener, 2013). Additionally, environmental concern and a strive towards producing green electricity can be seen as motives (Mundaca and Samahita, 2020). Which, altogether, can influence the adopter decision-making process (Rogers, 2010). Moreover, the findings indicate that the influential attributes of *compatibility, observability, and trialability* for adopting an innovation according to Rogers (2010) is highly relevant for off-grid applications and possibly fulfilled. Empirical findings show that observability in terms of peer effects are key for making off-grid applications a social norm which, according to Mundaca and Samahita (2020), is considered as a milestone for the innovation to launch in numbers. Nevertheless, the innovation possesses a lot of *complexity,* referring to Rogers (2010), which limits the potential adopter group because of the need for having a piece of technical knowledge.

Furthermore, despite finding that off-grid applications, as of now, are far too expensive, there is a potentially drastic cost reduction within the upcoming 20 years. This study concludes that, in order for the innovation to reach the larger social groups and not only the small group of *innovators*, a need for cost reductions exists. Having this cost reduction in mind, it is arguable that the larger social groups that are driven by economic advantages, derived from Rogers's diffusion curve (Rogers, 2010), could find value in off-grid applications and become a potential adopter.

Hence, findings from this work, having the adopter motives and economic rationale in mind, displays a concretized picture to the decision of being an On-grid, off-grid or partially off-grid consumer. Partially off-grid makes sense for the consumers who are striving for profitability and low costs. Because of partially off-grid always being lower in costs than complete off-grid, it is arguable that complete off-grid only makes sense for the consumers with the desire of being self-sufficient, independent, or a part of the technological frontier. Lastly, since partially off-grid is cheaper than On-grid, within a project life time of 25 years, it is possible that being an On-grid consumer is, therefore, driven by the minimal need for consumer engagement or non-existing motive for self-sufficiency. In conclusion, findings from this work point toward a much-related adoption scene as presented in the theory and, therefore, it is arguable that further studies of having the presented theory as a base could increase the reliability of these findings.

8.4 How could a transition of the Swedish electricity system form with off-grid applications?

The presented theory suggested several transitions pathways having household electricity production in mind, in addition, further studies of models based on an estimation of costs and technological development was essential to establish further knowledge (Defeuilley, 2019; Hojčková et al., 2018). Accordingly, this study presents several different modelled scenarios of household electricity production that can support certain pathways. Additionally, it is arguable that the numerous insights of the Swedish electricity system from this study can tie these suggested pathways towards the Swedish context. Nevertheless, without speculating in different pathways of change, findings from this study point towards a scene where innovations, such as off-grid applications, challenge the existing system and puts pressure on the current configuration, as well as incumbents, to form a system that is best for everyone involved. Otherwise, if incumbents operate without having the consumer perspective in mind and strive towards a balanced development between producer-consumer, they might lose business because of the dissatisfied customers' possibility to supply themselves with electricity. It is also arguable that another pathway may form towards centralized renewable production as within the suggested *re-arrangement* (Defeuilley, 2019) or *Super-grid* (Hojčková et al., 2018) pathway. However, to investigate such a scenario lies beyond the objective of this study but is highlighted as a possible scenario, both in the literature and from the respondents.

However, departing from the findings in *Chapter 7, Modelling,* where it was found that off-grid applications, especially in the northern parts of Sweden, will probably be unable to reach-grid parity until beyond 2040. It is arguable that a transition highly influenced by off-grid applications are unrealistic. Hence, the third *off-grid pathway* from the analysis chapter emphasized by Defeuilley (2019) and Hojčková et al. (2018), is not supported by this work. This is also aligned with the findings from Energiforetagen (2019) and Swedish Energy Agency (2016), where a large scale off-grid deployment leading to an electricity system characterized by household electricity production was not a feasible option for the Swedish electricity system. Also, it is possible that this ties back to the aforementioned discussion, derived from Rogers's (2010) innovation theory, that off-grid applications must possess a higher level of attributes for the potential adopters to take-off. Meaning that, as of now, off-grid applications will probably not create any changes to the system. On the other hand, the modelling showed that grid-parity is about to be reached in Visby by 2040. This, together with other influential aspects could serve as a fundamental base for deployment, such as government support and global trends of household electricity production (Defeuilley, 2019; Energiforetagen, 2019; Hojčková et al., 2018; Energimyndigeten 2016), as well as external events (Geels, 2004, 2002). Altogether, leading towards an increased share of self-sufficiency in Sweden.

There is, however, findings from this work that indicate how a transition towards an increased share of partially off-grid households having the role of prosumers can be seen as reasonable, both from the perspective of the individuals and the system. As mentioned in the discussion regarding the economic rationale of investing in off-grid, partially off-grid households are the most beneficial in terms of both costs for the individual household and net utility for the system. Consequently, the second transition pathway from the analysis chapter, namely the *incremental* *change* (Defeuilley, 2019)*, Smart-grid* or *prosumer* (Hojčková et al., 2018) pathway, can be seen as interesting. Despite the acknowledged benefits to the system of having prosumer households, the legal frameworks for energy sharing are limiting the potential value of acting as a prosumer. However, as Ei is working on a revised proposition for this, it is possible that prosumer households will gain momentum and start to form changes within the Swedish electricity system (Ei, 2020).

8.5 What is the impact of policies and regulations

From analyzing and discussing the many drivers and barriers, potential adopters, and economic rationale behind off-grid applications. It is evident that policies will affect the necessary transition of the electricity system to meet the renewable production goal and mitigate the existing issues of the electricity system. Hence, a final discussion regarding *policy implications* can be seen as valuable. First and foremost, findings illustrate how Sweden is in an early stage of its learning curve regarding household electricity production compared to many other countries. This means that Sweden can learn a lot from how other countries have developed their policies regarding self-sufficiency and also prevent the more undesirable effects to occur, such as decreased utility demand (utility death spiral) and societal imbalances. The overall components found from which policymakers can manage to avoid this are *grid tariffs, subsidy schemes,* and *regulations.* Nevertheless, how these components should be formed are much depending on the desired outcome.

Firstly, assuming a household with the ability to operate independently from the grid. Here, respondents argue that the structure of the *grid tariffs* are important since they can incentivize people to either be a part of the system or not. Morstyn et al. (2018) state that self-sufficient households unable to find incentives from being a part of the grid will probably decouple from the grid. This is a problem with the structure today according to the respondents since the larger proportion of tariffs are fixed and thus it is costly to stay connected to the grid even if the household mostly produces its electricity. Hence, if it is desired to incorporate the household to the system and take part of the many system benefits, there is a need to satisfy the intentions of the household (Linnenberg, 2011). In addition, findings suggest that it can be seen as important to limit the level of fixed tariffs, as well as, make sure that feed-in tariffs mirror the actual value of supporting the grid with electricity.

Also, household storage solutions are in its early phase of deployment and, arguably, there are some flaws in the tariff and subsidy structure with regard to storing energy. Respondents argue that investment aids only serve to optimize the single household and the study from Heinisch et al. (2018) shows that, in the least cost optimization operation, a PV-battery household would prefer electricity from the grid. This is further in line with findings from Sandahl (2019) and Palm (2017) showing that PV-storage households are incentivized to rather sell excess electricity than to store it.

Moreover, this work point towards grid-parity within 20 years and from the concept of grid-parity, explained by Breyer and Gerlach (2013) as a cost-competitive model, it is evident that *subsidies* for household electricity production once grid parity is reached should not be constructed to “over” incentivize potential off-grid households. Otherwise, consumers might find it uninteresting to stay connected to the grid because they can generate a large profit (Karneyeva and Wüsthagen, 2017). On the other hand, most of the investigated studies, as well as the empirical findings, show that it is of great importance to make sure that once the market of self-sufficient households have flourished and the society is relying on it, one cannot simply stop the subsidies since households are not interested in giving away their electricity for free. Such measures have created major problems with grid defection and utility death spiral (Hittinger and Siddiqui, 2017).

Also, to limit the decreased utility demand with self-sufficient households, policies could be developed to help the utility and network operators to find sources of revenues from the future small scale prosumers rather than increasing the energy prices and network tariffs which further is assumed to be the main driver of grid defection and utility death spiral (Khalilpour and Vassallo, 2015). On the positive side, it is also argued from the empirical findings that the Swedish society could have the potential of acting to what's best for the society as a whole, and policymaking is much driven by non-biased objective authorities.

In conclusion, the empirical findings are much related to the findings from Hittinger and Siddiqui (2017), that net metering policy, residential solar adoption, grid-tariff designs and electricity prices are all interrelated. Grid defection makes economic sense if a household face both unfavourable feed-in tariffs or net metering policies and high electricity bills as the high electricity bill make self-generation profitable and the lack of a feed-in tariff justifies the grid defection.

9 Conclusion

This chapter presents the theoretical contributions and practical implications of the study followed by its limitations and suggestions for future research. The overall purpose of this study was to increase the understanding of off-grid applications in the Swedish context by exploring both its techno-economic and socio-technical aspects.

By answering the underlying sub-research questions in *Chapter 8, Discussion*, it brought further insight to answer the main research question which aims to serve the purpose of this study. Consequently, the main research question, presented below, is responded to in this chapter.

"What are the prerequisites for off-grid applications to be used in the Swedish electricity system and by (its existing) consumers?"

With assumptions based on continuous cost increases for grid-connected electricity and a strong belief in heavy cost reductions for off-grid systems, Sweden will move towards a grid parity for self-sufficient households. Moreover, the empirical results of this study show that as of today, there are several existing barriers for off-grid applications to be adopted in the Swedish electricity system. From an economic perspective, there is a low rationale to invest in such a system for existing grid-connected consumers, and, it is not easily embraced and implemented into the current system. Additionally, with the high reliability of the grid and low cost of electricity, it is hard for disruptive technology to establish traction. One the other hand, with the prerequisite that the individual household plays a major role in the decision-making process and how the individual could hold a lot of different motives for adoption, a driver for an off-grid deployment exists. Further, with several sustainability targets on the agenda and an increased awareness of renewable energy in society. It can be concluded that, transformations are underway and prerequisites could change rapidly due to policymaking and technological development which could lead to off-grid and partially off-grid households playing a bigger role in the electricity system, especially within the coming two decades.

9.1 Theoretical contribution

This study raised the subject of household electricity production in the Swedish electricity system which, historically, been studied mostly in regards to households possessing the ability to support a share of their electricity demand from Solar PV and in some cases Solar PV plus batteries. Consequently, studies that design and run models on off-grid households in Sweden based on available components are limited. Therefore, by exploring households having the possibility to operate self-sufficient to a greater extent or even completely, the study has broadened the understanding of different levels of household electricity production.

Transition pathways have been studied by scholars for years, both in regards to a specific country or not, as well as, with or without the aim of exploring off-grid applications. From having these pathways as a backbone, this study applied the existing knowledge towards the Swedish context. Further, as discussed in *Chapter 8.4, How could a transition of the Swedish electricity system form with off-grid applications,* it is a great contribution from this work to fill the research gap of studies connecting the socio-technical change to techno-economic projections and thus being able to narrow down the potential transition pathways. It was argued from the existing literature how actual technology developments along with scenarios of what it may cost will make it possible to draw a stronger conclusion about what is possible in a specific context, which in this study was set to the Swedish electricity system. That being said, this work has contributed to the academic field of socio-technical systems successfully by displaying the possibility of combining the socio-technical systems theory with techno-economic projections.

Moreover, this study explored the idea to combine broad socio-technical systems and innovation theories with theories that explain the potential adopters decision-making processes. It was found that, when investigating dynamics in a large electricity system consisting of different actors, institutional setups, and complex infrastructures, the system theories are well-acknowledged and supported by scholars. However, in the case of household electricity production and its dynamics, as discussed in *Chapter 8.1, What are the drivers and barriers for off-grid electricity production in Sweden*, it somehow falls outside the original boundaries of the system theories because of the different characteristics where the final user have a larger role than expressed. Hence, this study contributed to developing and displaying a fruitful combination of existing theories that could work in favor of exploring novel technologies in socio-technical systems where the final decision lies in the hand of the user and with less impact from incumbent actors, institutional setups, and existing infrastructure.

9.2 Practical implications

It can be concluded that, from this study, there is a low probability that the Swedish electricity market will undergo radical changes in the near future due to an increased share of off-grid households. However, within the coming two decades, if technology costs continue to drop whilst electricity prices rise as projected, grid parity is considered to be inevitable. Additionally, with an increased adoption level, the complexity of investing in a fully off-grid system will decrease as it becomes more available and a potential market is developed. Therefore, incumbents and stakeholders must have such a scenario in mind when planning for the future to avoid decisions that could incentivize households to decouple from the grid.

From investigating how household electricity production evolved in other countries, as well as connecting it to the Swedish context, this study provided several practical implications that could aid actors in the Swedish electricity system to create as many system-benefits as possible if household production were to become increasingly popular. As mentioned, large-scale grid defection is not desirable for many parties, therefore, once grid-parity starts to become inevitable, it is important to create an opportunity to allow households into the electricity system but without necessarily disconnecting. To favor such a configuration, implications show that tariffs*,* subsidies*,* and regulation*s,* together with business models emphasizing the bi-directional flow of electricity between households as well as the grid, must be shaped in a way that creates value for both consumers and actors on the market.

9.3 Limitations and Future research

This study consisted of two major parts, empirics gathered and analysed through interviews, with the intention of contributing to the socio-technical perspectives. In addition, a modelling part was performed to investigate the current and projected cost to run an off-grid system whilst comparing the economics of both prosumer- and grid-connected households, to strengthen the techno-economic part. Furthermore, delimitations had to be set for both parts of the study, which could have affected the reliability and outcome. Both parts of the study were considered necessary, however, it can be argued that it could have been two separate studies that would have allowed more depth to each part.

There is a variety of terminology used in the case of off-grid, prosumer, and self-sufficient households which, in many cases are referred to as synonyms. As a result, this impeded the ability to cover the complete area of literature on the subject. Additionally, technological development of BESS and hydrogen technology moving forward at a high pace, the same goes for the context that these technologies are utilized within. Consequently, this has been taken into consideration during the time of the study and up to date literature and data have been gathered where possible, which, does not imply that it is the latest findings published might still be irrelevant. Also, this study looked at hydrogen storage within the household premises, an alternative solution could be to import hydrogen and have a smaller tank, which, would lower the biggest cost of the system.

It is difficult to develop statistical generalizability with the results of this study, however, it has contributed when discussing and comparing it with previous studies in the same area. The choice of respondents may have affected the outcome of the gathered empirics with biased responses and views of the potential off-grid adoption, which is shown in the empirics. Consequently, this makes replication of the more socio-technical part of the study hard to replicate. The lack of integrating actors, in terms of TSOs and DSOs because of the finite timeframe, could have limited the general opinion in the empirical findings. Nevertheless, the modeling part of the study is considered to be fully replicable with the presented approach and assumptions considered in all scenarios.

Furthermore, the electricity system is a complex mechanism, especially when considering the impact of new applications, this study has considered a variety of factors. However, it is recognized that this is only the tip of the iceberg and future research is necessary. Another area to investigate is what the Swedish electricity system will require in the future and, thereafter, see how off-grid households could contribute from extensive energy systems analysis. Additionally, this study analysed off-grid single-family households, future researchers could investigate multi-family households or off-grid neighborhoods. Lastly, a more in-depth modelling part where real prosumer households with smart systems and the ability to manage demand curves could be investigated together with a deeper analysis of the future tariff-system.

References

Abdin, Z., Webb, C., Gray, E., 2015. Solar hydrogen hybrid energy systems for off-grid electricity supply: A critical review. Renew. Sustain. Energy Rev. 52, 1791–1808.

Alvesson, M., Sköldberg, K., 2008. Tolkning och reflektion: vetenskapsfilosofi och kvalitativ metod. Studentlitteratur.

Andersson, B.A., Jacobsson, S., 2000. Monitoring and assessing technology choice: the case of solar cells. Energy Policy 28, 1037–1049.

Baker, P., 2016. Benefiting Customers While Compensating Suppliers: Getting Supplier Compensation Right. Regul. Assist. Proj. RAP Bruss. Belg.

Battery University, 2019. BU-413a: How to Store Renewable Energy in a Battery – Battery University [WWW Document]. URL https://batteryuniversity.com/learn/article/bu_413a_storing_renewable_energy_in_a_battery (accessed 2.1.20).

Bauwens, T., 2016. Explaining the diversity of motivations behind community renewable energy. Energy Policy 93, 278–290.

Baxter, P., Jack, S., 2008. Qualitative case study methodology: Study design and implementation for novice researchers. Qual. Rep. 13, 544–559.

Bayliss, C.R., Hardy, B.J., 2012. Chapter 27 - Smart Grids, in: Bayliss, C.R., Hardy, B.J. (Eds.), Transmission and Distribution Electrical Engineering (Fourth Edition). Newnes, Oxford, pp. 1059–1074. https://doi.org/10.1016/B978-0-08-096912-1.00027-7

Bell, E., Bryman, A., Harley, B., 2018. Business research methods. Oxford university press.

Bergek, A., 2002. Shaping and exploiting technological opportunities: the case of renewable energy technology in Sweden. Chalmers University of Technology Goteborg.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Res. Policy 37, 407–429. https://doi.org/10.1016/j.respol.2007.12.003

Blaikie, N., 2003. Analyzing quantitative data: From description to explanation. Sage.

Blomkvist, P., Hallin, A., 2015. Methods for engineering students, First Edition. ed. Studentlitteratur AB.

Bogdan, R., Biklen, S., 2006. Qualitative research in (validation) and qualitative (inquiry) studies. It Method-Appropr. Educ. Introd. Theory Methods.

Bost, M., Gährs, S., Aretz, A., 2016. Prosuming aus sozial-ökologischer Perspektive. Ökol. Wirtsch.-Fachz. 31, 23–25.

Bray, R., Woodman, B., 2019. Barriers to Independent Aggregators in Europe.

Breyer, C., Gerlach, A., 2013. Global overview on grid-parity. Prog. Photovolt. Res. Appl. 21, 121–136.

Candas, S., Siala, K., Hamacher, T., 2019. Sociodynamic modeling of small-scale PV adoption and insights on future expansion without feed-in tariffs. Energy Policy 125, 521–536. https://doi.org/10.1016/j.enpol.2018.10.029

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. Energy Res. Soc. Sci. 37, 175–190.

Chesser, M., Hanly, J., Cassells, D., Apergis, N., 2018. The positive feedback cycle in the electricity market: Residential solar PV adoption, electricity demand and prices. Energy Policy 122, 36–44.

Ciuciu, I.G., Meersman, R., Dillon, T., 2012. Social network of smart-metered homes and SMEs for grid-based renewable energy exchange, in: 2012 6th IEEE International Conference on Digital Ecosystems and Technologies (DEST). Presented at the 2012 6th IEEE International Conference on Digital Ecosystems and Technologies (DEST), pp. 1–6. https://doi.org/10.1109/DEST.2012.6227922

Collins, J., Hussey, R., 2014. Business research methods. 4. Uppl.

Cone, C., 2018. Battery Energy Storage Systems (BESS) - Worthwhile Investment? [WWW Document]. Renew. Energy World. URL https://www.renewableenergyworld.com/2018/08/23/battery-energy-storage-systems-bess-worthwhile-investment/ (accessed 2.13.20).

Cornwall, A., Jewkes, R., 1995. What is participatory research? Soc. Sci. Med. 41, 1667–1676.

Crabtree, B.F., Miller, W.L., 1999. Doing qualitative research. sage publications.

Cresswell, J., 2014. Research Design: Qualitative, Quantitative, and Mixed Methods Approaches-John W. Creswell.

de Heer, H., 2015. The Independent Aggregator. USEF.

Defeuilley, C., 2019. Energy transition and the future (s) of the electricity sector. Util. Policy 57, 97–105.

Denzin, N., 1970. Strategies of multiple triangulation. Res. Act Sociol. Theor. Introd. Sociol. Method 297, 313.

DiOrio, N., Denholm, P., Hobbs, W.B., 2020. A model for evaluating the configuration and dispatch of PV plus battery power plants. Appl. Energy 262, 114465.

Dosi, G., 1982. Technological paradigms and technological trajectories. Res. Policy 2, I47-62.

Ei, 2020. Ren energi inom EU - Ett genomförande av fem rättsakter. Swedish Energy Markets Inspectorate (Ei), Eskilstuna.

Ei, 2018. Tariffutformning för ett effektivt utnyttjande av elnätet [WWW Document]. Eise - Energimarknadsinspektionen. URL https://www.ei.se/sv/Projekt/Projekt/tariffutformning-for-ett-effektivt-utnyttjande-av-elnatet/ (accessed 5.5.20).

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manage. Rev. 14, 532–550.

Elskling, 2020. Förstå hur en elfaktura är uppbyggd [WWW Document]. URL https://www.elskling.se/exempelfaktura/ (accessed 5.5.20).

Energiforetagen, 2019. Färdplan fossilfri el – analysunderlag.

Energimarknadsbyrån, 2020a. Elräkningen [WWW Document]. Energimarknadsbyrån. URL https://www.energimarknadsbyran.se/el/dina-avtal-och-kostnader/elrakningen/ (accessed 5.5.20).

Energimarknadsbyrån, 2020b. Nätavgifter [WWW Document]. Energimarknadsbyrån. URL https://www.energimarknadsbyran.se/el/dina-avtal-och-kostnader/elkostnader/natavgifter/ (accessed 5.5.20).

Eryilmaz, D., Sergici, S., 2016. Integration of residential PV and its implications for current and future residential electricity demand in the United States. Electr. J. 29, 41–52.

Espe, E., Potdar, V., Chang, E., 2018. Prosumer communities and relationships in smart grids: a literature review, evolution and future directions. Energies 11, 2528.

Falcone, P.M., 2014. Sustainability transitions: A survey of an emerging field of research. Environ. Manag. Sustain. Dev. 3, 61.

Flick, U., 2014. An introduction to qualitative research. Sage.

García-Gusano, D., Espegren, K., Lind, A., Kirkengen, M., 2016. The role of the discount rates in energy systems optimisation models. Renew. Sustain. Energy Rev. 59, 56–72. https://doi.org/10.1016/j.rser.2015.12.359

Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environ. Innov. Soc. Transit. 1, 24–40.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Res. Policy 33, 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy, NELSON + WINTER + 20 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F.W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., Neukirch, M., Wassermann, S., 2016. The enactment of socio-technical transition pathways: a reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014). Res. Policy 45, 896–913.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Policy 36, 399–417.

Gorman, W., Jarvis, S., Callaway, D., 2020. Should I Stay Or Should I Go? The importance of electricity rate design for household defection from the power grid. Appl. Energy 262, 114494.

Griskevicius, V., Tybur, J.M., Van den Bergh, B., 2010. Going green to be seen: status, reputation, and conspicuous conservation. J. Pers. Soc. Psychol. 98, 392.

Grubb, M., 2004. Technology innovation and climate change policy: an overview of issues and options. Keio Econ. Stud. 41, 103–132.

Guerello, A., Page, S., Holburn, G., Balzarova, M., 2020. Energy for off-grid homes: Reducing costs through joint hybrid system and energy efficiency optimization. Energy Build. 207, 109478.

Guo, Y., Li, G., Zhou, J., Liu, Y., 2019. Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis. IOP Conf. Ser. Earth Environ. Sci. 371, 042022. https://doi.org/10.1088/1755-1315/371/4/042022

Haapaniemi, J., Haakana, J., Belonogova, N., Lassila, J., Partanen, J., 2018. Changing to Power-Based Grid Pricing-An Incentive for Grid Defections in Nordic Conditions? Presented at the 2018 15th International Conference on the European Energy Market (EEM), IEEE, pp. 1–5.

Hamari, J., Sjöklint, M., Ukkonen, A., 2016. The sharing economy: Why people participate in collaborative consumption. J. Assoc. Inf. Sci. Technol. 67, 2047–2059. https://doi.org/10.1002/asi.23552

Heinisch, V., Odenberger, M., Göransson, L., Johnsson, F., 2019. Prosumers in the Electricity System—Household vs. System Optimization of the Operation of Residential Photovoltaic Battery Systems. Front. Energy Res. 6. https://doi.org/10.3389/fenrg.2018.00145

Hekkert, M.P., Suurs, R.A., Negro, S.O., Kuhlmann, S., Smits, R.E., 2007. Functions of innovation systems: A new approach for analysing technological change. Technol. Forecast. Soc. Change 74, 413–432.

Herkert, J.R., 2005. Ways of thinking about and teaching ethical problem solving: Microethics and macroethics in engineering. Sci. Eng. Ethics 11, 373–385.

Hittinger, E., Siddiqui, J., 2017. The challenging economics of US residential grid defection. Util. Policy 45, 27–35.

Hojčková, K., Sandén, B., Ahlborg, H., 2018. Three electricity futures: Monitoring the emergence of alternative system architectures. Futures 98, 72–89.

Holmström, C., 2018. Energi- och miljöskatter [WWW Document]. Ekonomifakta. URL https://www.ekonomifakta.se/Fakta/Energi/Styrmedel/Energi-och-miljoskatter/ (accessed 5.5.20).

Hoogma, R., Kemp, R., Schot, J., Truffer, B., 2002. Experimenting for sustainable transport: the approach of strategic niche management. Routledge.

Hughes, T.P., 1987. The evolution of large technological systems. Soc. Constr. Technol. Syst. New Dir. Sociol. Hist. Technol. 82.

Huld, T., Müller, R., Gambardella, A., 2012. A new solar radiation database for estimating PV performance in Europe and Africa. Sol. Energy 86, 1803–1815. https://doi.org/10.1016/j.solener.2012.03.006

Hvelplund, F., 2006. Renewable energy and the need for local energy markets. Energy 31, 2293–2302.

IEA, 2019a. Solar Energy: Mapping the Road Ahead – Analysis. IEA, Paris.

IEA, 2019b. Energy storage – Tracking Energy Integration – Analysis. IEA, Paris.

IEA, 2014. Residential Prosumers - Drivers and Policy options (Re-Prosumers) 2014.

Inês, C., Guilherme, P.L., Esther, M.-G., Swantje, G., Stephen, H., Lars, H., 2019. Regulatory challenges and opportunities for collective renewable energy prosumers in the EU. Energy Policy 111212. https://doi.org/10.1016/j.enpol.2019.111212

IRENA, 2019. off-grid renewable energy solutions to expand electricity access: An opportunity not to be missed. International Renewable Energy Agency, Abu Dhabi.

IRENA, 2018. Renewable Power Generation Costs in 2017 [WWW Document]. URL https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf (accessed 11.26.18).

IRENA, 2017. Electricity storage and renewables: Costs and markets to 2030. International Renewable Energy Agency, Abu Dhabi.

IVA, 2016. Framtidens elanvändning [WWW Document]. URL https://www.iva.se/globalassets/info-trycksaker/vagval-el/vagvalel-framtidens-elanvandning-delrapport.pdf (accessed 1.23.20).

Jacobsson, S., Bergek, A., 2011. Innovation system analyses and sustainability transitions: Contributions and suggestions for research. Environ. Innov. Soc. Transit. 1, 41–57.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 2004. Economics of energy efficiency. Encycl. Energy 2, 79–90.

Jensen, R., 1982. Adoption and diffusion of an innovation of uncertain profitability. J. Econ. Theory 27, 182–193. https://doi.org/10.1016/0022-0531(82)90021-7

Jiang, Y., Kang, L., Liu, Y., 2019. A unified model to optimize configuration of battery energy storage systems with multiple types of batteries. Energy 176, 552–560. https://doi.org/10.1016/j.energy.2019.04.018

Kahn, H., Wiener, A.J., 1967. The Next Thirty-Three Years: A Framework for Speculation. Daedalus 96, 705–732.

Kantamneni, A., Winkler, R., Gauchia, L., Pearce, J.M., 2016. Emerging economic viability of grid defection in a northern climate using solar hybrid systems. Energy Policy 95, 378–389.

Karneyeva, Y., Wüstenhagen, R., 2017. Solar feed-in tariffs in a post-grid parity world: The role of risk, investor diversity and business models. Energy Policy 106, 445–456.

Kavlak, G., McNerney, J., Trancik, J.E., 2018. Evaluating the causes of cost reduction in photovoltaic modules. Energy Policy 123, 700–710. https://doi.org/10.1016/j.enpol.2018.08.015

Keay, M., Rhys, J., Robinson, D., 2014. Chapter 8 - Electricity Markets and Pricing for the Distributed Generation Era, in: Sioshansi, F.P. (Ed.), Distributed Generation and Its Implications for the Utility Industry. Academic Press, Boston, pp. 165–187. https://doi.org/10.1016/B978-0-12-800240-7.00008-4

Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. Technol. Anal. Strateg. Manag. 10, 175–198. https://doi.org/10.1080/09537329808524310

Khalilpour, R., Vassallo, A., 2015. Leaving the grid: An ambition or a real choice? Energy Policy 82, 207–221.

Koch, S., 2015. Chapter 2 - Assessment of Revenue Potentials of Ancillary Service Provision by Flexible Unit Portfolios, in: Du, P., Lu, N. (Eds.), Energy Storage for Smart Grids. Academic Press, Boston, pp. 35–66. https://doi.org/10.1016/B978-0-12-410491-4.00002-6

Kondziella, H., Bruckner, T., 2016. Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies. Renew. Sustain. Energy Rev. 53, 10–22. https://doi.org/10.1016/j.rser.2015.07.199

Kosonen, A., Koponen, J., Ahola, J., Peltoniemi, P., 2015. On- and off-grid laboratory test setup for hydrogen production with solar energy in nordic conditions, in: 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe). Presented at the 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), pp. 1–10. https://doi.org/10.1109/EPE.2015.7309428

Lavrijssen, S., Carrillo Parra, A., 2017. Radical prosumer innovations in the electricity sector and the impact on prosumer regulation. Sustainability 9, 1207.

Laws, N.D., Epps, B.P., Peterson, S.O., Laser, M.S., Wanjiru, G.K., 2017. On the utility death spiral and the impact of utility rate structures on the adoption of residential solar photovoltaics and energy storage. Appl. Energy 185, 627–641.

Lindahl, J., Stoltz, C., Oller-Westerberg, A., Berard, J., 2018. National Survey Report of PV Applications in Sweden - 2018 [WWW Document]. URL http://iea-pvps.org/ (accessed 2.3.20).

Lindorfer, J., Rosenfeld, D.C., Böhm, H., 2020. 23 - Fuel Cells: Energy Conversion Technology, in: Letcher, T.M. (Ed.), Future Energy (Third Edition). Elsevier, pp. 495–517. https://doi.org/10.1016/B978-0-08-102886-5.00023-2

Linnenberg, T., Wior, I., Schreiber, S., Fay, A., 2011. A market-based multi-agent-system for decentralized power and grid control. Presented at the ETFA2011, IEEE, pp. 1–8.

Liu, F., Zhao, F., Liu, Z., Hao, H., 2018. The impact of fuel cell vehicle deployment on road transport greenhouse gas emissions: The China case. Int. J. Hydrog. Energy 43, 22604–22621. https://doi.org/10.1016/j.ijhydene.2018.10.088

Liu, H., Azuatalam, D., Chapman, A.C., Verbič, G., 2019. Techno-economic feasibility assessment of grid-defection. Int. J. Electr. Power Energy Syst. 109, 403–412.

Liu, Y., Wu, L., Li, J., 2019. Peer-to-peer (P2P) electricity trading in distribution systems of the future. Electr. J., Special Issue on Strategies for a sustainable, reliable and resilient grid 32, 2–6. https://doi.org/10.1016/j.tej.2019.03.002

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Res. Policy 41, 955–967.

Marnay, C., Lai, J., 2012. Serving Electricity and Heat Requirements Efficiently and with Appropriate Energy Quality via Microgrids. Electr. J. 25, 7–15. https://doi.org/10.1016/j.tej.2012.09.017

Medelius-Bredhe, L., 2019. Debatt: Svenska kraftnät agerar utifrån elförsörjningens behov — men lösningarna kräver samverkan. SvK 2019.

Meier, A.K., Whittier, J., 1983. Consumer discount rates implied by purchases of energy-efficient refrigerators. Energy 8, 957–962.

Michelsen, C.C., Madlener, R., 2013. Motivational factors influencing the homeowners' decisions between residential heating systems: An empirical analysis for Germany. Energy Policy 57, 221–233.

Millet, P., Grigoriev, S., 2013. Chapter 2 - Water Electrolysis Technologies, in: Gandía, L.M., Arzamendi, G., Diéguez, P.M. (Eds.), Renewable Hydrogen Technologies. Elsevier, Amsterdam, pp. 19–41. https://doi.org/10.1016/B978-0-444-56352-1.00002-7

Mohanty, P., Muneer, T., Kolhe, M. (Eds.), 2016. Solar photovoltaic system applications: a guidebook for off-grid electrification. Springer, Cham.

Mongird, K., Viswanathan, V.V., Balducci, P.J., Alam, M.J.E., Fotedar, V., Koritarov, V.S., Hadjerioua, B., 2019. Energy Storage Technology and Cost Characterization Report (No. PNNL-28866, 1573487). https://doi.org/10.2172/1573487

Moradi, A., Vagnoni, E., 2018. A multi-level perspective analysis of urban mobility system dynamics: What are the future transition pathways? Technol. Forecast. Soc. Change 126, 231–243.

Morstyn, T., Farrell, N., Darby, S.J., McCulloch, M.D., 2018. Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nat. Energy 3, 94–101.

Mundaca, L., Samahita, M., 2020. What drives home solar PV uptake? Subsidies, peer effects and visibility in Sweden. Energy Res. Soc. Sci. 60, 101319.

Muqeet, H.A., Ahmad, A., Sajjad, I.A., Liaqat, R., Raza, A., Iqbal, M.M., 2019. Benefits of Distributed Energy and Storage System in Prosumer Based Electricity Market. Presented at the 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), IEEE, pp. 1–6.

New Energy World, 2014. FUEL CELLS AND HYDROGEN JOINT UNDERTAKING. Multi - Annual Work Plan 2014 - 2020. New Energy World.

Nissen, U., Harfst, N., 2019. Shortcomings of the traditional “levelized cost of energy”[LCOE] for the determination of grid parity. Energy 171, 1009–1016.

Noppers, E.H., Keizer, K., Bolderdijk, J.W., Steg, L., 2014. The adoption of sustainable innovations: Driven by symbolic and environmental motives. Glob. Environ. Change 25, 52–62. https://doi.org/10.1016/j.gloenvcha.2014.01.012

Nord Pool, 2019. System price and Area price calculations [WWW Document]. URL https://www.nordpoolgroup.com/trading/Day-ahead-trading/Price-calculation/ (accessed 5.5.20).

Nordling, A., 2017. Sweden’s Future Electrical Grid: A project report. IVA, Stockholm.

Nygrén, N.A., Kontio, P., Lyytimäki, J., Varho, V., Tapio, P., 2015. Early adopters boosting the diffusion of sustainable small-scale energy solutions. Renew. Sustain. Energy Rev. 46, 79–87.

Oberst, C.A., Schmitz, H., Madlener, R., 2019. Are Prosumer Households That Much Different? Evidence From Stated Residential Energy Consumption in Germany. Ecol. Econ. 158, 101–115. https://doi.org/10.1016/j.ecolecon.2018.12.014

O’hayre, R., Cha, S.-W., Colella, W., Prinz, F.B., 2016. Fuel cell fundamentals. John Wiley & Sons.

Palm, A., 2017. Residential solar photovoltaics deployment: barriers and drivers in space. Lund Univ.

Palm, J., 2018. Household installation of solar panels–Motives and barriers in a 10-year perspective. Energy Policy 113, 1–8.

Palm, J., Eriksson, E., 2018. Residential solar electricity adoption: how households in Sweden search for and use information. Energy Sustain. Soc. 8, 14.

Palm, J., Tengvard, M., 2011. Motives for and barriers to household adoption of small-scale production of electricity: examples from Sweden. Sustain. Sci. Pract. Policy 7, 6–15.

Parag, Y., Sovacool, B.K., 2016. Electricity market design for the prosumer era. Nat. Energy 1, 1–6.

Park, P., 2006. Knowledge and participatory research. Handb. Action Res. 2, 83–93.

Philipps, S., Warmuth, W., 2019. Photovoltaics Report. Fraunhofer Inst. Sol. Energy Syst. ISE 49.

Quintero Pulido, D.F., Ten Kortenaar, M.V., Hurink, J.L., Smit, G.J., 2019. The role of off-grid houses in the energy transition with a case study in the Netherlands. Energies 12, 2033.

Rao, K.U., Kishore, V., 2010. A review of technology diffusion models with special reference to renewable energy technologies. Renew. Sustain. Energy Rev. 14, 1070–1078.

Razzaq, S., Zafar, R., Khan, N.A., Butt, A.R., Mahmood, A., 2016. A Novel Prosumer-Based Energy Sharing and Management (PESM) Approach for Cooperative Demand Side Management (DSM) in Smart Grid. Appl. Sci. 6, 275. https://doi.org/10.3390/app6100275

Rip, A., Kemp, R., 1998. Technological change. Hum. Choice Clim. Change 2, 327–399.

RISE, 2018. Så kan solenergi produceras i nordliga förhållanden [WWW Document]. RISE. URL https://www.ri.se/sv/berattelser/sa-kan-solenergi-produceras-i-nordliga-forhallanden (accessed 5.12.20).

Rogers, E.M., 2010. Diffusion of innovations. Simon and Schuster.

Rotmans, J., Kemp, R., Van Asselt, M., 2001. More evolution than revolution: transition management in public policy. Foresight- J. Future Stud. Strateg. Think. Policy 3, 15–31.

Safari, M., Hardy, A., 2019. Expert Talk: Battery Storage in the Energy Transition [WWW Document]. EnergyVille. URL https://www.energyville.be/en/press/battery-storage-energy-transition (accessed 2.10.20).

Sandahl, D., 2019. Solar PV coupled with electricity storage in Sweden-The factors aiding the transition.

Sandén, B.A., Jacobsson, S., Palmblad, L., Porsö, J., 2008. Assessment of the impact of a market formation programme on the Swedish PV innovation system. Presented at the DIME International Conference "Innovation, sustainability and policy, pp. 11–13.

Saunders, Lewis, Thornhill, 2009. Research methods for business students, 5th ed. Pearson.

Scamman, D., Bustamante, H., Hallett, S., Newborough, M., 2014. off-grid solar-hydrogen generation by passive electrolysis. Int. J. Hydrog. Energy 39, 19855–19868. https://doi.org/10.1016/j.ijhydene.2014.10.021

SCB, 2019. Elnätspriser för olika typkunder, tidsserie [WWW Document]. Stat. Cent. URL http://www.scb.se/hitta-statistik/statistik-efter-amne/energi/prisutvecklingen-inom-energiomradet/priser-pa-elenergi-och-pa-overforing-av-el-nattariffer/pong/tabell-och-diagram/tabeller-over-arsvarden/elnatspriser-for-olika-typkunder-tidsserie/ (accessed 5.5.20).

Schleicher-Tappeser, R., 2012. How renewables will change electricity markets in the next five years. Energy Policy, Special Section: Frontiers of Sustainability 48, 64–75. https://doi.org/10.1016/j.enpol.2012.04.042

Schoemaker, P.J., 1995. Scenario planning: a tool for strategic thinking. Sloan Manage. Rev. 36, 25–50.

Scholz, R., Tietje, O., 2002. Formative scenario analysis. Embed. Case Study Methods Integrating Quant. Qual. Knowl. Sage Thousand Oaks CA 79–116.

Siemieniuch, C.E., Sinclair, M.A., Henshaw, M.J.Dec., 2015. Global drivers, sustainable manufacturing and systems ergonomics. Appl. Ergon. 51, 104–119. https://doi.org/10.1016/j.apergo.2015.04.018

Siyal, S.H., 2019. Techno-economic assessment of wind energy for renewable hydrogen production in Sweden.

Skatteverket, 2020a. Energiskatt på el [WWW Document]. Energiskatt På El. URL https://www.skatteverket.se/foretagochorganisationer/skatter/punktskatter/energiskatter/energiskattpael.4.15532c7b1442f256bae5e4c.html (accessed 5.5.20).

Skatteverket, 2020b. Mikroproduktion av förnybar el – privatbostad [WWW Document]. Mikroproduktion Av Förnybar El – Priv. URL https://www.skatteverket.se/privat/fastigheterochbostad/mikroproduktionavfornybarelprivatbostad.4.12815e4f14a62bc048f41a7.html (accessed 5.5.20).

SKM, 2020. SKM Elcertificate price history [WWW Document]. Sven. Kraftmäkling Elcertificate Price Hist. URL http://www.skm.se/priceinfo/history/ (accessed 5.5.20).

Skopik, F., Wagner, C., 2012. Novel Energy Saving Opportunities in Smart Grids Using a Secure Social Networking Layer, in: 2012 IEEE 36th Annual Computer Software and Applications Conference. Presented at the 2012 IEEE 36th Annual Computer Software and Applications Conference, pp. 557–566. https://doi.org/10.1109/COMPSAC.2012.75

Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Res. Policy 41, 1025–1036.

Smits, R., 2002. Innovation studies in the 21st century;: Questions from a user's perspective. Technol. Forecast. Soc. Change 69, 861–883.

Sommerfeldt, N., 2019. Solar PV in prosumer energy systems - A techno-economic analysis on sizing, integration, and risk (Doctoral Thesis). KTH Royal Institue of Technology, Stockholm, Sweden.

Starke, M., Zeng, R., Zheng, S., Smith, M., Chinthavali, M., Wang, Z., Dean, B., Tolbert, L.M., 2019. A Multi-Agent System Concept for Rapid Energy Storage Development. Presented at the 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), IEEE, pp. 1–5.

Stern, P.C., 2000. New environmental theories: toward a coherent theory of environmentally significant behavior. J. Soc. Issues 56, 407–424.

Suurs, R.A., Hekkert, M.P., Smits, R.E., 2009. Understanding the build-up of a technological innovation system around hydrogen and fuel cell technologies. Int. J. Hydrog. Energy 34, 9639–9654.

SvK, 2015. ANPASSNING AV ELSYSTEMET MED EN STOR MÄNGD FÖRNYBAR ELPRODUKTION [WWW Document]. URL https://www.svk.se/siteassets/om-oss/rapporter/anpassning-av-elsystemet-med-en-stor-mangd-fornybar-elproduktion.pdf (accessed 1.23.20).

Swedenergy, 2019. Elbristen har många ansikten – Energiföretagen förklarar - Energiföretagen Sverige [WWW Document]. URL https://www.energiforetagen.se/pressrum/nyheter/2019/september/elbristen-har-manga-ansikten--energiforetagen-forklarar/ (accessed 1.26.20).

Swedish Energy Agency, 2020. Koppla batterier till solcellerna [WWW Document]. URL http://www.energimyndigheten.se/fornybart/solelportalen/batterier-kopplat-till-solceller/ (accessed 5.7.20).

Swedish Energy Agency, 2019a. Energiindikatorer 2019-Uppföljning av Sveriges Energipolitiska mål.

Swedish Energy Agency, 2019b. Energy in Sweden: An overview. Energy Swed. 2019 14.

Swedish Energy Agency, 2019c. Fortsatt möjlighet att söka stöd för energilager i hemmet [WWW Document]. URL https://www.energimyndigheten.se/nyhetsarkiv/2019/fortsatt-mojlighet-att-soka-stod-for-energilager-i-hemmet/ (accessed 5.12.20).

Swedish Energy Agency, 2019d. Fördjupning om löpande intäkter [WWW Document]. URL https://www.energimyndigheten.se/fornybart/solelportalen/vilka-stod-och-intakter-kan-jag-fa/fordjupning-om-lopande-intakter/ (accessed 2.11.20).

Swedish Energy Agency, 2019e. Stöd som du kan få vid investering [WWW Document]. Stöd Som Kan Få Vid Invest. URL http://www.energimyndigheten.se/fornybart/solelportalen/vilka-stod-och-intakter-kan-jag-fa/stod-vid-investering/ (accessed 5.5.20).

Swedish Energy Agency, 2018. Kraftig ökning av nätanslutna solcellsanläggningar [WWW Document]. URL https://www.energimyndigheten.se/nyhetsarkiv/2018/kraftig-okning-i-natanslutna-solcellsanlaggningar/ (accessed 2.11.20).

Swedish Energy Agency, 2016. Fyra framtider - energisystemet efter 2020.

Swedish Research Council, 2017. Good research practice 86.

The Swedish Association of Graduate Engineers, 2019. Hederskodex [WWW Document]. URL https://www.sverigesingenjorer.se/om-forbundet/sveriges-ingenjorer/hederskodex/ (accessed 10.3.19).

Tidd, J., Bessant, J.R., 2018. Managing innovation: integrating technological, market and organizational change. John Wiley & Sons.

Tradingeconomics, 2020. Sweden Inflation Rate | 1980-2020 Data | 2021-2022 Forecast | Calendar | Historical [WWW Document]. URL https://tradingeconomics.com/sweden/inflation-cpi (accessed 4.8.20).

Ulli-Beer, S., 2013. Conceptual grounds of socio-technical transitions and governance, in: Dynamic Governance of Energy Technology Change. Springer, pp. 19–47.

Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7

Wang, J., Wang, H., Fan, Y., 2018. Techno-Economic Challenges of Fuel Cell Commercialization. Engineering 4, 352–360. https://doi.org/10.1016/j.eng.2018.05.007

Wang, Z., Yu, X., Mu, Y., Jia, H., 2020. A distributed Peer-to-Peer energy transaction method for diversified prosumers in Urban Community Microgrid System. Appl. Energy 260, 114327. https://doi.org/10.1016/j.apenergy.2019.114327

Winnhed, P., 2019. Samling för nätkapacitet.

World Energy Council, 2015. 2015 Energy Trilemma Index: Benchmarking the sustainability of national energy systems. World Energy Council, United Kingdom.

Wright, G., Cairns, G., Goodwin, P., 2009. Teaching scenario planning: lessons from practice in academe and business. Eur. J. Oper. Res. 194, 323–335.

Xylia, M., Svyrydonova, J., Eriksson, S., Korytowski, A., 2019. 2019 Urban Energy Report. Beyond the tipping point: future energy storage. Sweco.

Yang, F., Roche, R., Gechter, F., Gao, F., Koukam, A., 2015. An agent-based approach for battery management systems. Presented at the 2015 IEEE Energy Conversion Congress and Exposition (ECCE), IEEE, pp. 1367–1374.

Zafar, R., Mahmood, A., Razzaq, S., Ali, W., Naeem, U., Shehzad, K., 2018. Prosumer based energy management and sharing in smart grid. Renew. Sustain. Energy Rev. 82, 1675–1684. https://doi.org/10.1016/j.rser.2017.07.018

Zhang, C., Wu, J., Zhou, Y., Cheng, M., Long, C., 2018. Peer-to-Peer energy trading in a Microgrid. Appl. Energy 220, 1–12.

Zhang, W., Wang, X., Huang, Y., Qi, S., Zhao, Z., Lin, F., 2019. A Peer-To-Peer Market Mechanism for Distributed Energy Resourses. Presented at the 2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia), IEEE, pp. 1375–1380.

Zhang, Y., Campana, P.E., Lundblad, A., Yan, J., 2017. Comparative study of hydrogen storage and battery storage in grid connected photovoltaic system: Storage sizing and rule-based operation. Appl. Energy 201, 397–411. https://doi.org/10.1016/j.apenergy.2017.03.123

Zohuri, B., 2019. Hydrogen Storage Processes and Technologies, in: Zohuri, B. (Ed.), Hydrogen Energy: Challenges and Solutions for a Cleaner Future. Springer International Publishing, Cham, pp. 257–279. https://doi.org/10.1007/978-3-319-93461-7_8

Appendix I

Hej,

Jag och min uppsatskamrat Jesper Björkman skriver examensarbete på företaget PowerCircle och hör av oss till er för att få ta del av er kunskap till vår studie.

Arbetet handlar om att undersöka vilka förutsättningar som krävs för att nuvarande nätanslutna elkonsumenter (i form av hushåll) ska komma att koppla bort sig från nätet och bli självförsörjande av elektricitet (alternativt fortfarande nätanslutna men till stor del självförsörjande s.k. prosumers). Denna fråga har en roll i en större spekulativ fråga där vi tittar på möjliga utvecklingsspår av elnätet och hur dessa off-grid hushåll och prosumers kan komma att påverka det nationella elsystemet i from av dess system, aktörer och konsumenter.

Vi utför en modellering av typhushåll baserade på dess geografiska placering i Sverige med olika scenarion för att se vad det är som kommer att påverka den ekonomiska rationaliteten i att bli självförsörjande. Variabler som påverkar resultatet komma vara kostnad och teknikutveckling av solceller och lagringstekniker MEN även prognoser av elpriser, tariffer, skatter och subventioner.

Vår modelleringen kommer trycka på vilka kostnader som krävs för att det ska vara lönsamt men för att förstå att andra aspekter kan påverka rationaliteten och utfallet av självförsörjande hus behöver vi er.

Nedan finns några frågor vi hoppas att ni vill diskutera med oss! Om möjligt tar vi gärna kontakt via Skype eller fysiskt möte men vi även tacksamma för svar via mail. Beroende på er bakgrund kan vi även fördjupa oss i specifika ämnen utöver dessa. Om ni inte har tid kanske ni möjligtvis har en kollega att vidarebefordra oss till?

Tack på förhand, Simon och Jesper!

Q. Vad anser du är anledningen till att frågan kring självförsörjande hushåll fått uppmärksamhet?

Q. Vad är drivkrafterna och barriärerna för att kunder ska bli självförsörjande av elektricitet? Exempelvis

- Från hushållets perspektiv
- Resp. dagens aktörer inom svenska elnätet

Q. Vad är dom potentiella fördelarna alternativt nackdelarna med att kunder kopplar sig off-grid eller delvis off-grid (kopplad till nätet men innehar solceller och BTM batteri)

- För elnätet (en aspekt att diskutera kan vara hushållens roll som flexibla laster i nätet)
- För marknadens aktörer
- För kundkollektivet

Q. Om sverige ska uppnå 100 % förnybar elektricitet, hur tror ni systemet kommer se ut då? Exempelvis

- Förändringar hos dagens aktörer
- Resp. individuella hushåll

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