Electric vehicles in Iceland: improving the electricity grid to accommodate for EV growth by 2050

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Abstract

Currently, the transport sector is responsible for 21% of global CO2 emissions with road transport accounting for the majority. In order to achieve global climate goals, it is of paramount importance that the road transport sector is electrified. Consequently, the electrification of transport is a pillar in the Icelandic climate plans. Through the electrification of transport the Icelandic government aims to reduce GHG emissions, dependency on foreign oil imports, and make progress towards achieving carbon neutrality by 2040. In order to explore the impact of EVs on the Icelandic grid, three EV growth Scenarios were developed based on population projections and future vehicle ownership. It was found that in 2050, the electricity demand from EVs will increase the general electricity demand by 0.7 to 1.1 TWh depending on the Scenario, leading to a general electricity demand of 7.8 to 8.2 TWh compared to 5.2 TWh in the Reference Scenario. The electricity demand is mainly located in the Capital Region which is inhabited by almost 65% of the total population. Moreover, EVs impact not only electricity demand but also power system stability and reliability of the electricity grid. Analysis of the reliability of the Icelandic grid made evident that the current grid is not able to cope with this increase without additional generation capacity. At present, the available transmission capacity is limited and the ageing infrastructure is susceptible to adverse weather conditions. This is studied in the West Fjords extensively since this region experiences the weakest reliability and security of electricity supply. Electricity supply in this region is severely affected by adverse weather conditions, not self-sufficient in electricity generation, and depends on one transmission line for almost 40% of the region's electricity imports. It is argued that the current strategies to reinforce the grid will not be sufficient in this region and that more localised solutions are needed. Through a multi-criteria analysis a hydropower plant, V2G technology, and micro-grid with distributed energy resources were assessed on their ability to improve the reliability and security of electricity supply and to accommodate for future electricity demand increases. It was found that local electricity generation and distribution combined with utilising the balancing and ancillary services from EVs would improve the reliability and security of electricity supply in the West Fjords by 2050.

Key words: Electric vehicles; population projections; vehicle projections; electricity demand; grid reliability; security of electricity supply; V2G technology; micro-grid with DER; MCA; Iceland

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Six years ago my sustainability journey started with my first lecture on climate change. Throughout the years I slowly came to the topic of electricity access, starting with my bachelor's thesis and now culminating in this master's thesis. As such, I would like to thank all the lecturers whose courses I have followed over the years at both Leiden University College and Utrecht University for teaching me to be curious and motivating me to explore sustainability challenges. By the same token, I would also like to thank the friends I have made along the way for their support.

Finally, I would like to end by expressing my gratitude to my parents, Rob and Ria. Thank you for supporting me and always believing in me.

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List of Abbreviations

AC	Alternating current
AS	Index of Reliability
BEV	Battery Electric Vehicle
CAIDI	Customer Average Interruption Duration Index
DC	Direct current
DER	Distributed Energy Resources
DSO	Distribution System Operator
EC	European Commission
EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWh	Gigawatt hour
HEV	Hybrid electric vehicle
ICEV	Internal Combustion Engine Vehicle
KM	System Minutes
km	kilometre
kV	kilo volts
kWh	kilowatt hours
MCA	Multi criteria analysis
MWh	megawatt hours
O&M	Operation & Maintenance

OV Orkubú Vestfjarða

PHEV Plug-in Hybrid Electric Vehicle

RES Renewable energy sources

SAIDI System Average Interruption Duration Index

SAIFI System Average Interruption Frequency Index

SI Statistics Iceland

SMA Average Power Curtailment per Disturbance

SMS Average Outage Duration Index

SRA Power Interruption Index

SSO Power Energy Curtailment Index

TSO Transmission System Operator

TWh Terawatt hour

V2G Vehicle-to-grid

Chapter 1 - Introduction

1.1 Background

Globally, the transport sector is responsible for about 25% of total energy consumption, and 23% of total energy related greenhouse gas (GHG) emissions (Anagnostopoulou, 2018; Sustainable Mobility for All, 2017). In addition, the transport sector is a significant contributor to the pollution of water, soil, and air accounting for 21% of global CO2 emissions (Holden et al., 2020; Ritchie, 2020). In the coming decades the increase in electric vehicles (EVs) will replace "a large share of conventional vehicles" and cause a "dent in the carbon dioxide emissions from road transportation" (Project Drawdown, n.d.). To illustrate, the International Energy Agency expects that the global EV stock will grow to 245 million vehicles by 2030 under its most sustainable projections, or to 140 million vehicles only taking into account policies that are currently in place (IEA, 2020c).

The electrification of transport is one of two pillars of the 2018 Icelandic Climate Change Action Plan, aiming for an emission reduction in this sector of 21% by 2030 compared to 2005 emissions (Ministry for the Environment and Natural Resources, 2020). Iceland intends to "build a low carbon economy in the near future" and since nearly all of the domestic energy is already produced by renewable sources, the sector with the most GHG reduction potential is the transportation sector (Ólafsdóttir, 2017). Currently, road transport is the second largest source of GHG emissions in Iceland, accounting for about 20% of total emissions (Ministry for the Environment and Natural Resources, 2020). Considering that Iceland does not produce its own fossil fuels, it is dependent on foreign oil imports which at present account for 16% of total primary energy use (Ministry for the Environment and Natural Resources, 2018b; OECD, 2020). The imported petroleum products are almost exclusively used in the transport and fishery sectors (Orkustofnun, 2009). Furthermore, CO2 emissions in the road transportation sector have increased by 87% since 1990, mainly due to population growth, increase in numbers of cars per capita, more mileage driven, and an increase in the share of larger and heavy vehicles in the domestic vehicle fleet (Environmental Agency of Iceland, 2020). Through the electrification of transport, Iceland can decrease its dependency on foreign oil imports, significantly reduce CO2 emissions, decrease the need for additional investments in gas or biofuel stations, reduce urban pollution, and take a significant step towards the larger goal of achieving carbon neutrality across all sectors by 2040 (Andwari et al., 2017; Government of Iceland, n.d.-a; Kester et al., 2020).

However, in order to accommodate the widespread roll-out of EVs a highly reliable electricity grid is needed with a limited occurrence of disruptions to the delivery of electricity to end-users. The Icelandic transmission system operator (TSO) Landsnet points out two causes for system disruptions and power outages throughout their annual performance reports: demanding and adverse weather conditions, and an increase in load on the grid (Landsnet, 2015; Landsnet, 2019a). Moreover, the Icelandic grid is unique because it is an isolated grid meaning that the electricity grid is not interconnected to other national grids, and can not rely on this connection for load planning and balancing support. An increase of EVs — and thus subsequent additional loads— will surely increase the disruptions unless the grid is improved and strengthened (Landsnet, 2015). An additional challenge is to ensure a reliable and secure supply of electricity across all regions in the country. The West Fjords region (in the northwest of Iceland) experiences the weakest security of electricity supply in the country with frequent disruptions and transmission losses (Government of Iceland, 2019). To guarantee a secure and reliable energy system, investments have to be made in generation capacity, system flexibility, and grid infrastructure (Boßmann & Staffell, 2015). Studies have been carried out on comparing grid infrastructure reinforcement strategies such as overhead versus underground cables, and which would be more (cost-)effective (Naderian et al., 2017). The question that this thesis will examine is whether the investments and construction of new infrastructure connecting these areas to the national grid is worth it, or whether decentralised options would be more beneficial and (cost-)effective. Consequently, challenges can be expected from an increase in EVs, and the necessary development of added infrastructure such as charging stations around the country, unless effective grid strategies and solutions are implemented. This thesis will explore the main bottlenecks of the Icelandic grid and how the grid solutions Vehicle-to-Grid (V2G) technology and a micro-grid with distributed energy resources (DER) can improve the reliability and security of electricity supply in the West Fjord in order to accommodate for future EV growth and subsequent electricity demand.

1.2 Research Context

Most studies have based growth forecasts of EVs on historical growth scenarios of conventional combustion engine vehicles, mainly focussing on metropolitan and urban areas, or on the global level (Hertzke et al., 2018; Perujo & Ciuffo, 2009; Sierzchula et al., 2014; Slowik & Lutsey, 2017; Wang et al., 2019). The problem with such scenarios is that they assume growth scenarios to be universally applicable. Moreover, these forecasts do not take into account the possibility of large disrupting global events that change the expected growth pathways, nor do they reflect regional differences in growth scenarios (Woodward et al., 2020). These two factors show the need for more localised EV growth forecasts instead of forecasts based on global trends. Additionally, detailed and concentrated projections on EV growth are also needed to estimate when and where charging infrastructure is necessary (European Environment Agency, 2016b). This is important because the lack of sufficient and adequate charging infrastructure is seen as one of the primary obstacles in the widespread roll-out of EVs (Sierzchula et al., 2014; Slowik & Lutsey, 2017; Wang et al., 2019; Zhou et al., 2015).

The European Environment Agency (2020) predicts that additional generation is needed to accommodate for the growing numbers in EVs across the European Union, with electricity consumption increasing from 0.03% in 2014 to 9.5% in 2050. Engel et al. (2018) argue while the increase in EVs will most likely not cause a significant increase in overall power demand, it will more than likely "reshape the electricity load curve". However, it should be noted this conclusion was based on taking only Germany as a case study, and assuming a maximum share of 7% of battery electric vehicles in the total passenger vehicle fleet in 2030, and a maximum share of 40% by 2050 (Engel et al., 2018). Hensley et al. (2018) propose that current power systems can handle the increase in demand as long as the EVs are charged off peak, but that the usage of fast chargers will actually have adverse consequences on power systems.

The challenges associated with increasing demand can be alleviated by either increasing the capacity of the grid, or by improving its capability to handle demand increases (European Environment Agency, 2016b; van Leemputten et al., 2020). Initiatives to increase the grid's capability are for instance smart technologies such as V2G-technology (U.S. Department of Energy, n.d.; Virta, n.d.). Similarly, the Alternative Fuels Directive (Directive 2014/94/EU) proposes that "in order to contribute to the stability of the electricity system" EVs should make use of intelligent metering at (re-)charging points. However, this statement assumes that making use of intelligent metering measures is financially and technically possible everywhere. Smart technologies such as V2G enables EVs to play a role in balancing the energy on the grid by functioning as distributed sources of energy. V2G is seen as a multi-faced solution as its bi-directional character would allow for smart charging, but also for supporting the grid by de-charging when demand exceeds supply (van Leemputten et al., 2020). However, there is currently no information of its use in Iceland. Studies point towards a number of limitations to using V2G such as its limited smaller-scale use, insufficient efficiency, and general assumptions regarding charging patterns (van Leemputten et al., 2020). Furthermore, implementing control and communication systems such as smart grids, also highlight a new level of vulnerability to power systems: communication systems need electricity to function, and electricity systems need communication systems to function (Wilbanks & Fernandez, 2013). A disruption in either of these systems can therefore cause a domino effect of failures. Likewise, distributed generation supported by micro-grids can be a vital part of ensuring electricity access to areas which currently lack access, or have weak security of electricity supply (Astarloa et al., 2017). Nevertheless, distributed resources such as photovoltaic systems and battery energy storage are more expensive at smaller scales, and in many locations their distributed deployment is likely to be inefficient (Pérez-Arriaga & Knittel, 2016). Exceptions are locations where networks are exceedingly congested or are seeing rapid increases in electricity demand according to Pérez-Arriaga & Knittel (2016). Other measures to improve the grid's capability to handle increasing demand are for instance grid extension or reinforcement measures that are currently already being carried out in order to improve the grid's resilience to the consequences of climate change. These measures include replacing overhead lines by underground cables to mitigate the direct and indirect impacts of extreme weather events, and reducing the number of costumers served by a single overhead-circuit (Braun & Fournier, 2016; Climate-ADAPT, 2020; Wilbanks & Fernandez, 2013). The measures are additional to grid extension measures, but the grid extension measures are generally not cost-effective for remote locations (Fürsch et al., 2013). Complete grid defection, meaning a complete disconnection from the main electricity grid, is also not seen as a cost-effective measure in most areas (Pérez-Arriaga & Knittel, 2016). Equally important to mention is the fact that while the impacts of EV growth on both electricity demand and the ability of the power grid to accommodate this growth has been studied in a plethora of countries with connected grids, much less is known about the effects on isolated grids.

To summarise, the question that arises is whether only smart technologies or physical reinforcement measures, or a combination of both, will ensure the reliability of the power system and improve the security of electricity supply in areas where this is currently not guaranteed. These areas often have inadequate levels of security of electricity supply due to either not having any access to the grid, or there is a connection to the grid but its supply is weak and variable. This thesis will fill the existing knowledge gap by synthesising previously studied approaches by means of a case study in Iceland, and particularly in the northwestern West Fjords region. The selected solutions will be assessed on their suitability and potential to improve the reliability and security of electricity supply in a remote location such as the West Fjords.

1.3 Research Questions

In order the address the aforementioned problems, this thesis will answer the following research question:

> **How can the Icelandic electricity grid be improved in order to enhance its reliability and accommodate the expected growth in electric vehicles by 2050?**

To answer the main research question, the following sub-questions will be answered:

1. What is the expected EV growth and additional electricity demand in Iceland up to 2050?

2. What is the spatial distribution of EV growth and additional electricity demand?

3. How reliable is the Icelandic electricity grid currently?

4. Which areas in the West Fjords are most vulnerable to electricity disruptions?

5. What are the currently proposed strategies to improve reliability and electricity security of supply?

6. What are the main criteria (grid)solutions have to meet in order to improve security of electricity supply in the West Fjords?

7. To what extent do the proposed solutions meet the criteria devised to improve security of supply in the West Fjords?

This thesis follows the following structure: first, Chapter 2 will discuss the main methodological approach, followed by an overview of the key concepts. Second, sub-questions 1 and 2 will be answered in Chapter 3, followed by sub-question 3 in Chapter 4 and sub-question 4 in Chapter 5.

Lastly, the remaining sub-questions 6 and 7 will be discussed in Chapter 6. Each of the Chapters will start with a brief introduction, explain the methodological approach that was followed in order to answer each sub-question and concludes with a discussion of the results. Thirdly, the overall results of the sub-questions and the limitations to this thesis and recommendations for future research will be summarised into a final discussion in Chapter 7 followed by the conclusion in Chapter 8.

Chapter 2 - Methodology

2.1 Research framework

In order to answer the main research question and the subsequent sub research questions, mixed methods were used. The methodological approach included using both quantitative and qualitative methods. A schematic overview of this thesis' research framework can be seen in Figure 1. Each of the boxes indicate the corresponding sub-question, and the blue links reflect the structure of the thesis.

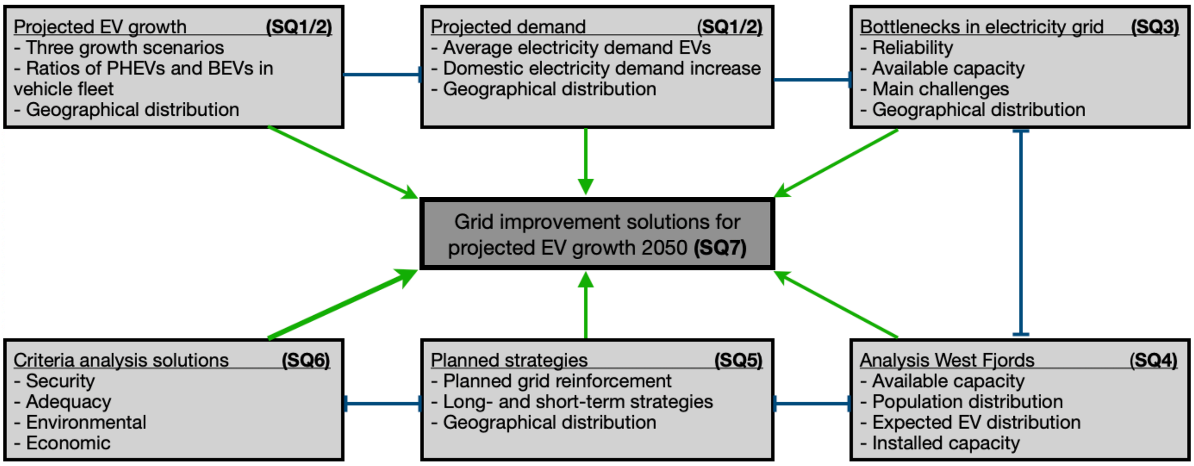


Figure 1 - Schematic overview of the research framework with each box showing the data needed to answer the 7 sub-questions.

The quantitative research data used in this thesis were primarily retrieved from the National Statistical Institute of Iceland Statistics Iceland (SI), Landsnet, and Orkubús Vestfjarða (OV). The qualitative research data used were retrieved from consulting agencies, academic journals, and other forms of grey literature such as technical papers, working papers, and white papers**.** A case-study design was used in order to allow for a deeper understanding of how the growth of EVs impacts the reliability and security of electricity supply in practice. The case-study focussed on Iceland, and more specifically on the West Fjords. Iceland is a developed country located in the North Atlantic Ocean with a population of about 350,000 people (SI, 2020b). Its economy is built upon the aluminium, tourism, and fisheries sectors, and more recently on data storage and processing (OECD, 2021).

There are four additional factors that make Iceland an interesting subject for a case study in the context of EV growth and its effect on the reliability and security of electricity supply. Firstly, almost all of Iceland's electricity is generated by renewable energy sources (RES). Hydropower provides about 73% of domestic electricity demand and the remaining 27% is generated by geothermal power (Askja Energy, n.d.-b). However, while the country is self-sufficient in generating its electricity demand, it is fully reliant on fossil fuel imports to fuel its vehicle fleet, marine vessels, and airplanes since there is no domestic production (Askja Energy, n.d.-c). Secondly, Iceland has had the highest per capita electricity consumption in the world almost uninterruptedly for the past two decades. Iceland grew from one of the poorest nations in Europe to one of the wealthiest due to an explosive growth in the manufacturing sector. The country started to utilise its renewable resources in the 1960s, producing electricity at low prices giving way to the growth of highly electricity intensive industries such as the aluminium production sector, and more recently attracting data centres (OECD, 2019). Consequently, recent data show that electricity consumption per capita in Iceland is about 55,000 kWh/capita, compared to an EU average of about 6,000 kWh/capita (Askja Energy, n.d.-c). Thirdly, the Icelandic electricity grid is an isolated grid which means that there is no connection to any other national grid. As a result, the country is fully dependent on its own generation facilities to meet the electricity demand since it is not possible to participate in international electricity trade (Pérez-Arriaga et al., 2017). According to Pérez-Arriaga et al. (2017), the ageing transmission network frequently reaches its transmission capacity at present, which will happen more frequently in the future due to increasing load and adverse weather conditions. Lastly, Iceland is a leading nation in EV adoption, with the share of EVs in vehicles sales exceeding 50% in 2020, compared to an EU average of 10% (IEA, 2021). Since Iceland does not have an adequate public transport system (no rail network, and sporadic bus stops outside of the Capital Region), the only way to make the transport sector more sustainable is through EVs. To achieve a sustainable transport sector the Icelandic Government has created a conducive environment for EV growth through multiple tax incentives, a proposed ban on the registration of new internal combustion engine vehicles (ICEVs) after 2030, in addition to the combination of relatively low electricity prices and high fossil fuel prices (EAFO, n.d.-a; Wappelhorst & Tietge, 2018; Ministry for the Environment and Natural Resources, 2018).

2.2 Key concepts

EVs and demand

In this thesis the following typology for EVs will be used: battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and (non plug-in) hybrid electric vehicles (HEVs). BEVs are purely driven by an electric motor, do not have a fossil fuel engine or generator, and its battery is recharged by the electricity grid (CAA, n.d.; SEAI, n.d.). PHEVs run on electricity for a range of typically 32 to 48 kilometres, and on gasoline or diesel for longer trips with its on-board battery recharged by the grid (CAA, n.d.; Woodward et al., 2020). HEVs are similar to PHEVs in that both vehicles have an internal combustion engine in addition to an electric motor, but the difference is that the batteries in HEVs are charged by on-board operations, and not by the electricity grid (CAA, n.d.). For this reason HEVs were excluded in this thesis. Since PHEVs and BEVs have different electricity needs, the vehicle mix of a country has different effects on future changes in electricity demand as will be made evident Chapter 3.

The rate of EV growth is an additional factor in assessing the impacts of EVs on electric power systems. If the roll-out of EVs happens too quickly, power systems will not have adequate time to adapt, and outages and disruptions can be expected to occur frequently. If the roll-out of EVs happens more gradually, electric power systems will have more time to anticipate increases in electricity demand and prepare accordingly. Kester et al. (2018) argue that distribution system operators (DSOs) in Nordic countries can handle EV loads "as long as their introduction does not peak". This is reflected in the European Environment Agency (2016b) report on EVs, stating that there are two approaches: either a complete charging infrastructure network is built in one go, or the necessary infrastructure is built as demand increases over time. However, Kester et al. (2018) and the European Environment Agency (2016b) seem to assume that the security of electricity supply in the discussed countries is already high, and that the speed of the implementation of charging infrastructure is the only challenge for power systems relating to the roll-out of EVs. This point of view generalises the challenges associated with the widespread roll-out of EVs. Therefore it is necessary to delve deeper into the dimensions of security of electricity supply in order to create a deeper understanding of the subsequent challenges of EV adoption. The effects of the roll-out of EVs and the subsequent solutions that are needed to accommodate for the increase in EVs will be discussed in Chapter 6.

Security of Electricity Supply

The concept of security of electricity supply encompasses both electricity access, and the frequency of power outages (Astarloa et al., 2017). As mentioned, virtually everyone in Iceland is currently connected to the grid, so the main focus will be on the latter aspect.

The concept of security of electricity supply can be explained by using the following four dimensions (Pérez-Arriaga et al., 2017):

1. **Strategic energy policy:** ensures long-term availability of energy resources, both reliable supply that meets environmental constraints, and physical existence of supply.
2. **Adequacy:** ensures the existence of adequate available capacity, both expected and installed to meet the projected demand.
3. **Firmness:** supply infrastructure is available when needed. Firmness depends mainly on operation schedules of installed capacity (e.g. fuel supply contracts, maintenance schedules, reservoir management)
4. **Security:** achieved by readiness of existing network and generation capacity to respond to load requirements when necessary. Level of security depends of operating reserves, and operational procedures set by system operator.

Capacity is defined here as the "rated continuous load-carrying ability of generation, transmission, or other electrical equipment" (UCTE, 2004). Using the four dimensions to analyse the reliability and security of supply will show the current challenges in the Icelandic grid. Moreover, the four dimensions have to be taken into account when assessing the impact that future grid solutions have on improving security of electricity supply. In this thesis the concept of grid reliability is one of two focal topics and, as will be explained in Chapter 4, consists of two elements: adequacy and security. From this point onwards, since the dimensions of strategic energy policy and firmness are inherent to reliability, both dimensions were included in the elements of adequacy and security.

Iceland's electricity market

Figure 2 shows an overview of the Icelandic electricity market. The state-owned electricity producer Landsvirkjun holds the largest share of generated electricity in the country, followed by Reykjavík ON, HS Orka, and Orkusalan. Most of the power companies are publicly owned, except HS Orka which is partially publicly owned. All end-users, both general and power-intensive, are free to choose their own electricity supplier, who in turn either generate the electricity themselves or buy from other producers (Askja Energy, n.d.-a; Næss-Schmidt et al., 2018). The generated power is then transmitted by the TSO Landsnet, owned by Landsvirkjun (64%), Icelandic State Electricity (23%), Reykjavík Energy (7%) and the West Fjords Power Company, Orkubú Vestfjarda (6%) (Orkustofnun, 2011; Zheng & Breitschopf, 2020). Landsnet transmits about 20% of the generated electricity to the five DSOs, and the remaining 80% directly to the power-intensive industry and other large users. Of the power-intensive industry the aluminium sector is the largest electricity consumer, which will be discussed in more detail in Chapter 3, and Landsnet's responsibilities will be discussed more extensively in Chapter 4. In turn, the TSO and the DSOs are supervised and monitored by the National Energy Authority, Orkustofnun. Orkustofnun's other responsibility is to provide licenses for the exploitation and development of mineral and energy resources (Orkustofnun, n.d.-d).

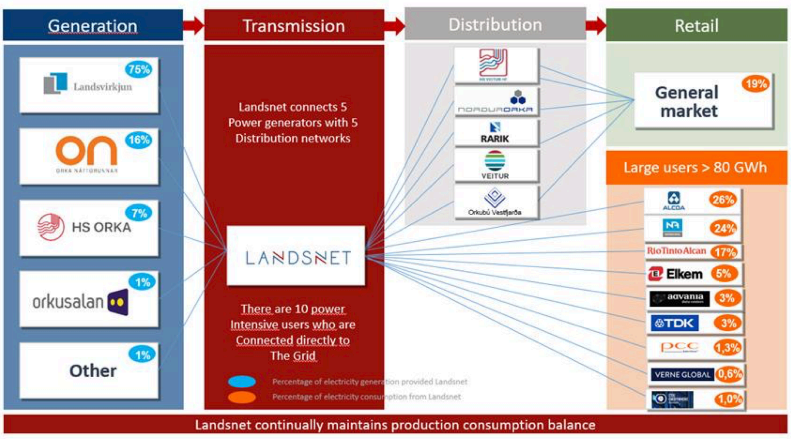


Figure 2 - Structure of the Icelandic electricity sector consisting of generation facilities, transmission, distribution, and end-users. Source: Zheng & Breitschopf, 2020

A license is needed for every power plant with a generation capacity of 1 MW or more, and has to be approved through the Master Plan for Nature Protection and Energy Utilisation, which is a Government framework that investigates whether the proposed power plant is in accordance with environmental criteria (Naess-Schmidt et al., 2017). Seeking approval for power plants through the Master Plan is a lengthy process and takes a minimum of 3 years due to the thorough analysis and stakeholder involvement.

Criteria Analysis

The goal of this thesis is to find out how the reliability and security of electricity is impacted by EVs, and what the possibilities are for implementing V2G technology and installing micro-grid solutions in terms of improving reliability. For this purpose, a multi criteria analysis (MCA) was carried out in Chapter 6 to highlight the strengths and weaknesses of the three selected options to improve reliability and security of electricity supply in the West Fjords. The selected options were a proposed hydropower plant Hvalárvirkjun, V2G technology, and a micro-grid with distributed generation. The MCA consisted of eight criteria classified into four categories (security, adequacy, environmental, and economic) that were based partly on the concept of security fo electricity supply, and on previous assessments conducted by Landsnet.

Chapter 3 - Population, vehicle, and electricity demand projections up to 2050

3.1 Introduction

This chapter will focus on the first and second sub-question on future EV growth and subsequent additional electricity demand up to 2050, and its distribution. For this purpose, three different EV growth Scenarios were developed up to 2050 ranging from Fast to Slow EV growth. The three EV Scenarios were based on two building blocks: future population projections and population distribution, and future vehicle projections and vehicle distribution up to 2050. This chapter will first discuss the methodology followed for the population projection and distribution (Section 3.2.1), vehicle projections and distribution (Section 3.2.2), the three EV Scenarios (Section 3.2.3), and finally for the electricity demand (Section 3.2.4). The results for the population projections and distribution follow in Sections 3.3.1 and 3.3.2, and the results for the vehicle projection and distribution will follow in Sections 3.3.3 and 3.3.4. Lastly, Sections 3.4 and 3.5 will discuss the results of the EV Scenarios and the projected electricity demand up to 2050.

3.2 Methodology

3.2.1 Population projections

The first step in creating the EV Scenarios was projecting the future population. The quantitative data needed for the population projections up to 2050 were retrieved from SI and graphed using R Studio. SI has published annual population projections since 2010 and the most recent projection was published in 2020. The data from the most recent projection consisted of the number of Icelandic inhabitants on the 1st of January for each year and forecasts for the population from 2020 up to 2069 using a low, medium, and high growth scenario. The growth scenarios were based on information on "population, births, deaths, migration and projected average life expectancy for the coming years" (SI, n.d.-c). In thesis, the medium growth projection was used because it was based on current predictions on GDP and unemployment rates. This will be explained in more detail in the next Sections.

The data for the current distribution of the Icelandic population were retrieved from SI and consisted of the number of inhabitants in 2019 distributed across 192 municipalities (SI, 2021b). The individual municipalities were categorised according to the 8 official regions: Capital region, Southern Peninsula, Western region, the West Fjords, Northwestern region, Northeastern region, Eastern region, and the Southern region (see Figure 3).

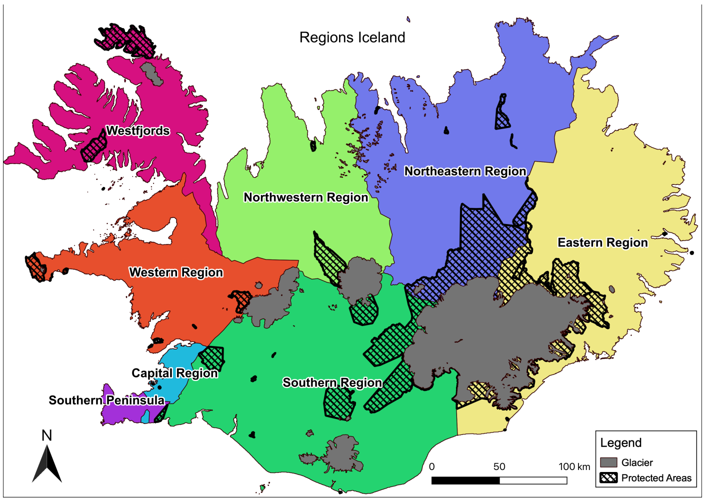


Figure 3 - Regions of Iceland, including glaciers and protected areas. The protected areas include national parks and nature reserves. Data source: DIVA-GIS, n.d.; National Land Survey of Iceland, 2018b

While the current distribution of the population is known, the SI projection did not project the future population on a municipal level that is needed to project the distribution of EVs and subsequent electricity demand by 2050. As such, the population distribution in 2050 was based on the future population projection by the European Commission (EC) which did provide a distinction between rural and urban population growth, in combination with the SI projection. The SI projection is still the leading projection since it was published more recently than the EC projection.

The EC projected a 2019 population of 356,991 inhabitants: 228,231 inhabitants in the Capital Region, and 128,760 inhabitants in the rural region as can be seen in Table 1 (Eurostat, 2021). In 2050, a total population of almost 490,000 inhabitants was projected by EC which indicates a growth rate of 37% compared to 2019.

Table 1 - Population projections from the European Commission and Statistics Iceland compared (Eurostat, 2021; SI, 2021b)

	European Commission			Statistics Iceland		
	2019	**2050**	**Increase (%)**	**2019**	**2050**	**Increase (%)**
Capital Region	228,231	317,270	39	-	-	-
Rural	128,760	172,032	33.6	-	-	-
Total	356,991	489,302	37.1	356,991	430,610	20.6

In contrast to the EC projections, SI projected a lower total population of 430,610 inhabitants in 2050 under a medium population growth scenario at a growth rate of 20.6%, which represents a difference of 16.5 percentage points from the EC projection. In order to discern the future population distribution for this thesis, the percentage point difference between the EC and SI 2050 projections was used leading to a growth percentage of about 22% for the Capital Region and of about 17% for the rural regions compared to SI's 2019 population. Important to note is that the growth rate for the rural regions includes all areas besides the Capital Region. The generalisation that the population outside of the Capital Region will grow at the same rate, from small towns to relatively big cities might not reflect true future migration or growth patterns. However, since there was no future population projection available on a more detailed level the assumption that there are two growth rates was necessary in order to project the future distribution. Furthermore, it was assumed that the municipalities that currently have 0 inhabitants will not be inhabited over the remainder of the projection period, and that glaciers and national parks will neither increase or decrease in size. The same growth rate was assumed for both individual urban nuclei as for municipalities as whole, because urban nuclei are often the only cities or settlements in a number of municipalities. This will be further explained and visualised in Section 3.3.2. The population distribution was visualised on a city and municipal level by using QGIS which is an open source Geographic Information System that is used to create, analyse, and visualise geospatial data (QGIS, n.d.). Additional data and shapefiles on cities and urban nuclei, power plants, roads, transmission lines, and land ice were retrieved from several sources such as Askja Energy, Orkustofnun, Open Data Iceland, and the National Land Survey of Iceland.

3.2.2 Vehicles

The second step in the EV Scenarios is to project the total number of passenger vehicles in 2050. Passenger vehicles are defined here as privately owned cars that can carry up to 8 passengers (SI, n.d.-d). Data from SI on the number of passenger vehicles per 1,000 inhabitants were available from 1950 to 2020 (SI, n.d.-d). The passenger vehicle rate per 1,000 inhabitants was used here instead of for instance the total number of passenger vehicles, because the rate per 1,000 can be used to project the future amount and distribution of vehicles more accurately according to the future population per region and municipality. For this reason, extrapolating the total amount of passenger vehicles from 1950 to 2050 would not accurately represent vehicle ownership since it might not be in line with the population growth. For years, Iceland has been among the global leaders of the number of passenger vehicles per 1,000 inhabitants: it was estimated that the number of passenger vehicles per 1,000 inhabitants was 731 in 2020 (Knoema, 2015; SI, 2018; SI, n.d.-d). To illustrate, the 2019 European Union average of passenger vehicles per 1,000 inhabitants was 569 according to the European Automobile Manufacturers Association (EAAA, 2021).

Using the available data for 1950-2020 a power regression was carried out for the years 2014-2019, leading to the following regression equation:

$$PV\ rate = 659.83 \times t^{0.752} \quad \text{[eqn. 1]}$$

with $R^2 = 0.9478$.

Equation 1 was used to extrapolate the passenger vehicle rate for 2021-2050. The year 2020 was excluded from the regression since it would not accurately reflect vehicle ownership due to the impact of the COVID-19 pandemic. To demonstrate the impact, during 2020 a 44.5% decline in vehicle sales was reported in Iceland, which for a large part can reasonably be attributed to the pandemic and its effects on consumption such as increasing unemployment rates and restrictions (Focus2-Move, 2021). Furthermore, extrapolation using the years 2014-2019 was preferred over using GDP per capita as a function of passenger vehicle ownership through the widely used Gompertz function (see Dargay & Gately, 2001; Lu et al., 2017 and Wu et al., 2014) In this case, the Gompertz function in Dargay and Gately (2001) was used for comparison and showed very different values for the period 2000-2019 than reported by SI. Consequently, it was concluded that calculating passenger vehicle ownership according to economic forecasts would not accurately reflect future vehicle ownership. Additionally, it was assumed that the number of vehicles per 1,000 inhabitants would increase up to the vehicle saturation rate. Dargay et al. (2007) argue that the global vehicle saturation rate (meaning the maximum level of vehicles per 1,000 people) is 850 vehicles per 1,000 people. Since the number of vehicles per 1,000 inhabitants in Iceland is already high, 850 vehicles per 1,000 inhabitants seems plausible and was consequently used as the saturation level for this projection. The resulting values from this projection were multiplied by the population in the medium population growth scenario in order to calculate the total amount of passenger vehicles up to 2050.

Besides the total amount of passenger vehicles up to 2050, it is important to know how the vehicles are distributed. It is unlikely that the vehicle fleet will be distributed evenly across the country. Determinants of vehicles ownership include whether the owner lives in an urban area with adequate public transportation modes, or in a rural area where owning a vehicle is a greater necessity, and the income level of the owner where a higher level of income often results in owning one or more cars (Caulfield, 2012). The distribution of passenger vehicles in Iceland was calculated by using the most recent vehicle ownership rates published by the City of Reykjavik for 2019. The dataset distinguished three vehicle ownership rates reflecting the capital, the Capital Region, and the rest of the country. In 2019, the passenger vehicle ownership rate in Reykjavík was 701 per 1,000 inhabitants, 688 per 1,000 inhabitants in the Capital Region, and 965 per 1,000 inhabitants in the rest of the country (City of Reykjavík, 2020). However, using these values would not reflect car ownership for all municipalities across the country, especially for larger urban nuclei such as Akureyri in the north and Reykjanesbær in the southwest, for example. To illustrate, the Capital Region consists of 6 municipalities (besides Reykjavík) that are classified as urban nuclei, and have a large variation in the number of inhabitants ranging from 36,975 in Kópavogur to 238 in Kjósarhreppur (SI, 2021b). Therefore, to more accurately reflect vehicle ownership in urban nuclei located outside of the Capital Region, the Capital Region vehicle ownership rate of 688 passenger vehicles per 1,000 was applied to municipalities and urban nuclei with more than 5,500 inhabitants. Thus, the classification used for vehicle ownership rates was as follows in 2019: the Reykjavík area (128,793 inhabitants), the Capital Region (99,438 inhabitants), the urban areas (54,741 inhabitants), and the rural areas (74,019 inhabitants).

In order to calculate the passenger vehicle rate for 2050 according to the four individual areas in the classification above and in line with population projections, the growth rate of the overall passenger vehicle rate was used. According to the regression equation the vehicle rate reached the saturation level of 850 passenger vehicles per 1,000 inhabitants in 2044. Thus, the passenger vehicle rate of 850 per 1,000 inhabitants in 2050 represents a 13.94% growth rate compared to the 2019 rate of 746 vehicles per 1,000 inhabitants. This growth rate was applied to the four categories in order to find out the vehicle ownership rates by 2050 and resulted in the following rate per 1,000 inhabitants: 799 for Reykjavík, 784 for the Capital Region and urban areas, and 1,100 in the rural regions. For the same year the population was calculated to be 157,864 in the Reykjavík area, 121,883 for the Capital Region, 70,078 in the urban regions, and 80,784 in the rural regions. The vehicle distribution was subsequently calculated by multiplying the vehicle ownership rate by the population of a given municipality, and visualised on a municipal and city level using QGIS.

3.2.3 EV Scenarios

The three EV Scenarios were developed by combining the results of the previous sections. The starting point for constructing the PHEV and BEV ratio in the EV fleet was data for 2020 when the Icelandic passenger vehicle fleet consisted of a total of 269,615 vehicles of which about 5% were EVs (EAFO, n.d.-b; SI, n.d.-d). In that year, the EV fleet consisted of 5,499 BEVs and 9,698 PHEVs, with the share of PHEVs in the vehicle fleet having been larger the number of BEVs since 2017 (EAFO, n.d.-b). However, since 2019 the year-on-year BEV growth has been outpacing the year-on-year PHEV growth, and it can be expected that the number of BEVs will exceed the number of PHEVs in the vehicle fleet in the coming years. The three EV Scenarios developed for this thesis assumed different scenario-specific growth increases regarding the EV fleet based on several assumptions. First, each Scenario assumed a vehicle fleet turnover rate with scenario-specific consequences. The current Icelandic vehicle fleet turnover rate is 4.5%, which means that 4.5% of the total vehicle fleet is renewed every year (Hafstad, 2020). In Scenario 1 (Fast EV growth) it was assumed that the vehicles would be replaced by EVs and not by internal combustion engines vehicles (ICEVs). Scenario 2 assumed that up to 2030, half of the vehicles would be replaced by ICEVs and the other half by EVs. Scenario 3 assumed that up to 2050 half of the vehicles would be replaced by ICEVs and half by EVs. Second, a scenario-specific reduction in the PHEV year-on-year growth was assumed, ranging from an annual decrease of 50% to a decrease of 12.5%. Lastly, the first two Scenarios assumed a ban on the registration of new ICEVs after 2030, in line with Government plans (Ministry for the Environment and Natural Resources, 2018a).

3.2.4 Electricity demand

The subsequent additional electricity demand associated with the three EV growth Scenarios was calculated by using the basic forecasting equation suggested by Gryparis et al. (2020):

$$Electricity\ demand = E_{ev}\ (kWh)\ \times\ M_{annual}\ (km)\ \times\ N_{vehicles} \qquad \text{[eqn. 2]}$$

with:

E_{ev} = Average electricity consumption EV [kWh]

M_{annual} = Average annual mileage [km]

$N_{vehicle}$ = Number of EVs in vehicle fleet

The following assumptions were made in order to calculate the electricity demand for the three EV Scenarios:

1. The average electricity consumption for BEVs was estimated to be 0.194 kWh/km and will remain constant up to 2050 (Electric Vehicle Database, n.d.). Based on estimates by the IEA an electric driving share of 70% was assumed for PHEVs, which means an average electric consumption of 0.136 kWh/km (IEA, 2020a).

2. The annual mileage in kilometres in Iceland will follow OECD estimates for passenger vehicles transport demand, with an annual increase of 0.7% up to 2030 followed by an annual increase of 0.8% up to 2050 (ITF, 2017). This meant that the annual passenger vehicle mileage will increase from 12,665 km in 2020 to 15,926 km in 2050 (Samgöngustofa, n.d.). No difference was assumed between the total annual mileage between BEVs and PHEVs, nor possible differences between urban and rural mileage since that information was not available.

To put the electricity demand from EVs in the EV Scenarios into perspective, the general electricity demand up to 2050 was projected. The most recent data on electricity demand in Iceland was published in 2019 and retrieved from the Icelandic National Energy Authority to function as a starting point for the projection (Orkustofnun, 2020b). In an electricity demand forecast for Iceland carried out by Pérez-Arriaga et al. (2017), non power-intensive demand increased annually by 2.8% until 2020 and by 2% from 2020 up to 2030. The latter growth rate was also used here in order to project general electricity demand up to 2050. The power-intensive industry was not included in the demand projection because it would not accurately reflect the electricity demand from the population. This will be explained more extensively in Section 3.5.

From here on, the electricity demand in the non power-intensive industry will be referred to as ‘general consumption’, and electricity demand including the power-intensive industry will be referred to as ‘total consumption’. To compare the general electricity demand increase in the three EV Scenarios a Reference Scenario was included based on a baseline scenario. The Reference Scenario was based on a ‘slow progress’ forecast developed by Orkustofnun that assumed an annual demand growth rate of 0.7% because of lower expected economic growth, leading to a general consumption of 5,200 GWh and a total demand of 22,170 GWh by 2050 (Landsnet, 2021e).

Even though future general electricity demand increase resulting from further electrification and digitalisation will to a great extent be offset by improvements in energy efficiency in most advanced economies as proposed by the IEA (2019), in the case of Iceland it was expected that the growth in the service sector and the non-intensive industry will further increase electricity demand contrary to most advanced economies. Moreover, Faisal et al. (2018) found that urbanisation is one of the strongest drivers of electricity consumption in Iceland, followed by trade and economic growth. As shown in the Section 3.2.1, the urban population in Iceland is expected to grow at a higher rate than the population in rural areas, and thus justifies the increase in electricity consumption as a result of urbanisation used in this projection. Because future electricity demand distribution including the contribution of EVs was not available, it was calculated by combining the future population, vehicle, and demand projections. The total number of vehicles in 2050 informed the increase in electricity demand for the EV Scenarios, while the combination of future population projections and the resulting general electricity demand projections enabled the calculation of electricity demand per capita. Through the demand per capita, the electricity demand distribution was calculated.

3.3 Results and discussion

3.3.1 Population projections

The starting point for the SI population growth scenarios is the year 2020 with a population of 364,134. As can be seen in Figure 4, the population is expected to increase compared to current levels for all three scenarios: the low growth scenario will result in a population of 386,317 inhabitants by 2050, 430,610 inhabitants under a medium growth scenario, and 479,139 inhabitants under a high growth scenario (SI, 2021d).

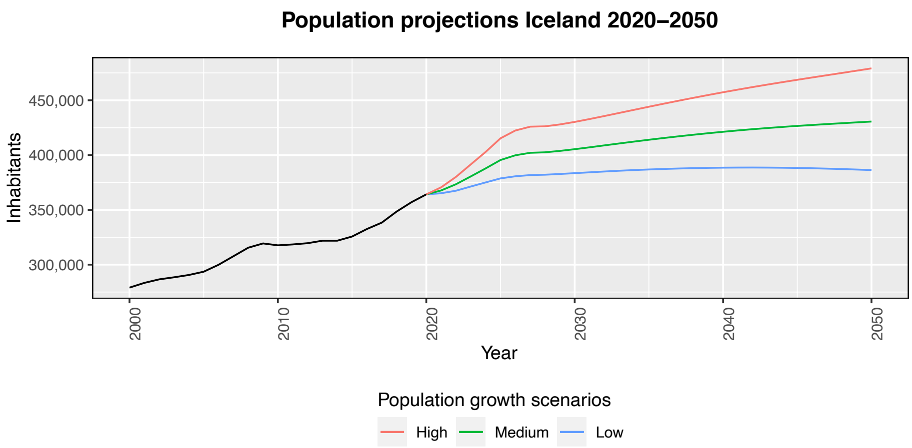


Figure 4 - Population growth scenarios Iceland 2020-2050 with historical population depicted in black line. Data source: SI, 2021d, SI 2021e.

SI explains that the population increase will largely be caused by high net migration (SI, 2010). In general, population growth can be attributed to two factors: total net migration (immigrants - emigrants), and natural change (births > deaths) (Giannakouris, 2010). In the SI projections the high growth scenario assumes a larger amount of births than deaths for the entire projection period, while the medium growth scenario expects the number of deaths to overtake the number of births after 2060, and the low growth scenario expects the number of deaths to overtake the number of births by 2037 (SI, 2020b). In addition to net migration and natural change, the three scenarios were based on different assumptions on unemployment rates and GDP growth. As Figure 4 shows, an accelerated growth up to the year 2026 is followed by a brief period of stabilised growth from 2027-2028. After 2028, population growth continues for the high and medium scenarios up to 2050, and continues for the low growth scenario up to 2040, after which its population decreases until the end of the projection. The change in growth after 2028 in each of the scenarios can be ascribed to each individual scenario assuming a scenario specific migration rate and a decrease in the annual population growth rate, as well as different assumptions regarding unemployment rates and GDP growth (SI, 2020b). SI indicates that "economic factors have a strong effect" on migration rates, which is why unemployment and GDP values are important factors for each scenario (SI, 2015). The low growth scenario was based on the assumption that no GDP growth will occur in conjunction with high levels of unemployment; the medium growth scenario was based on current statistical predictions on unemployment rates and GDP growth; and the high population growth scenario was based on GDP growth double that of current predictions in combination with low levels of unemployment (SI, 2015).

Yet, while long-term population projections can be helpful for policy makers and research purposes, its limitations have to be considered. According to Vanella et al. (2020) "as the length of the projection horizon increases, so does the uncertainty". The growth scenarios discussed here were based on highly interconnected factors which are difficult to accurately predict. For example, migration flows depend on a variety of elements such as economic circumstances in both the receiving and the sending country, the reputation of the country of destination, the cost of migration, attitudes to immigration laws and immigration in general, in addition to immigration policies among others (Skirbekk et al., 2007). In turn, these elements are further impacted by a variety of external factors, emphasising the inherent uncertainty and complexity of long-term projections. Another key point to note is that the SI population projection only projected population growth on a national level. The differences in population growth that can be expected in the more densely populated areas like the Reykjavík area and the city of Akureyri compared to population growth in the less densely populated rural areas were not addressed. This limitation will be further addressed in the next Section.

3.3.2 Population distribution

The Icelandic population distribution in 2019 can be seen in Figure 5. In this Figure the population distribution per municipality can be seen, as well as the location and population size of its cities and urban nuclei. The transmission line shows the main transmission grid, not the complete electricity grid that includes the distribution system. Furthermore, the red stars display the main power plants connected to the national grid. Iceland is one of the most sparsely populated countries in the world, and there are considerable differences in population sizes across the country (SI, 2020a). Both of these factors are reflected by the 2019 SI data: of the 192 municipalities in the dataset, 83.3% of the municipalities had fewer than 1,000 inhabitants: 62.5% of the municipalities had 0 inhabitants, and 20.8% had more than 0 but fewer than 1,000 inhabitants. The most populous municipality was Reykjavík with a population of 128,793 inhabitants, which corresponds to a share of 35.19% of the total Icelandic population. The least populous municipality was Arneshreppur located in the West Fjords, with a population of just 40 inhabitants. Additionally, about 25% of the country falls under formal protection in the form of three national parks and more than 120 other protected areas, which further limits the available areas where people live (Government of Iceland, n.d.-c). The largest of the national parks in Iceland is the Vatnajökull National Park located in the centre of the country. The Park covers about 14% of the total Icelandic area and spans across three regions (Government of Iceland, n.d.-c). Specifically in the Eastern region it can be seen that the population is distributed far away from the national park, with the exception of Höfn located to the southeast of the park.

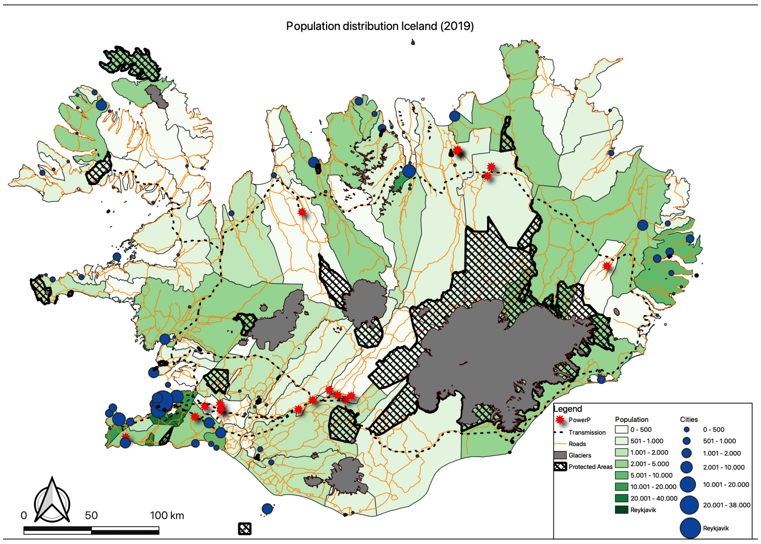


Figure 5 - Population distribution Iceland in 2019. Data source: National Land Survey of Iceland, 2018a, 2018b; SI, 2021b; SI, 2021c; Orkustofnun, n.d.-b; Orkustofnun, n.d.-c.

The majority of the population is concentrated in the Capital Region and the Southern Peninsula. In 2019 almost 64% of the total Icelandic population lived in the Capital Region and a further 8% in the Southern Peninsula. Moreover, from Figure 5 it becomes clear that a substantial amount of municipalities only have one urban nucleus and as such justifying the use of the same growth rate for municipalities and urban nuclei. In most municipalities (except for the landlocked municipalities) the population is concentrated near the coast. This also holds true for the city of Akureyri, located in the Northeastern region. After the cities and urban areas in the Capital Region, the city of Akureyri is the fourth largest municipality with almost 19,000 inhabitants, and thus nicknamed the Capital of the North. Its relatively large population can be attributed to the fact that some of the largest fish processing centres in the country are located in the city (Akureyrarbær, n.d.).

The West Fjords region is the least populated region with about 7,000 inhabitants, accounting for only 2% of the total Icelandic population. The West Fjords' population has seen a declining trend since the 1980s, caused by its inhabitants migrating to larger cities such as Reykjavík or Akureyri for better economic opportunities (Iceland Mag, 2016). This trend still holds for younger people, as Zhang and Bryant (2020) argue that the migration rates are higher for young people in the West Fjords than for young people in other regions of the country. This means that younger people in the West Fjords are more eager to migrate to for instance the Capital Region than younger people in other regions of the country. However, it is possible that (internal) migration rates into the West Fjords will increase in the coming years. One example of a pull factor for the West Fjords is the proposed expansion of the Icelandic aquaculture sector. The continued development of, for instance, open-cage salmon farming could positively affect migration rates into both the West Fjords and the Eastern region, where most new farms will be located (Iceland Chamber of Commerce, 2020).

The 2050 population distribution can be seen in Figure 6. The Capital Region population is expected to increase by almost 23% and the remaining regions by about 17%. As expected, the Capital Region remains the most populous area in Iceland in this projection, with a population of almost 280,000. The Capital Region consists of 7 municipalities, of which Reykjavík will remain the most populous in 2050 with 157,864 inhabitants compared to 128,793 inhabitants in 2019.

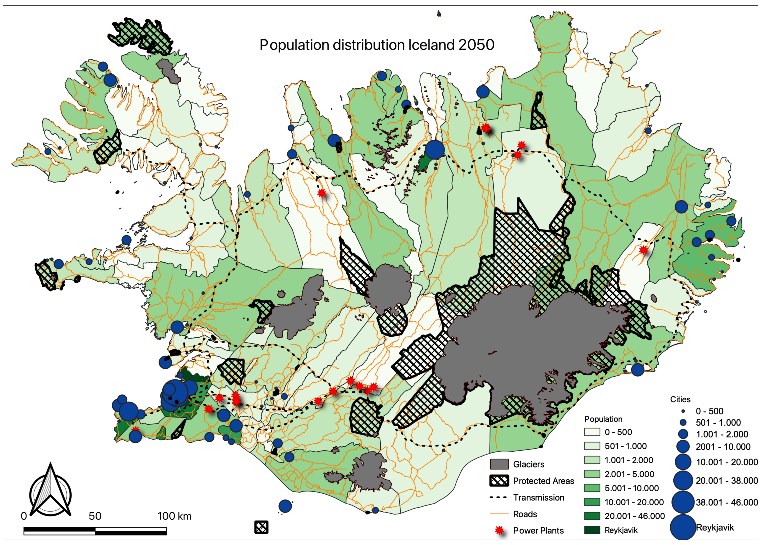


Figure 6 - Population distribution Iceland in 2050.

The two most populous municipalities outside of the Capital Region, Akureyri in the Northeastern region and Arborg in the Southern region will have a population of 22,174 and 11,113 inhabitants, respectively. Furthermore, the Capital Region is the only region where the share of the total population is expected to increase compared to 2019: the Capital Region's share of the total population increased by 1.04 percentage points in 2050. The share of the population living in the remaining regions all fell by 0.06 to 0.24 percentage points compared to 2019 levels. As mentioned in Section 3.2.1, this is a result of the assumption that there were two population growth rates: one for the Capital Region and one for the rest of the country. This meant that the 7 municipalities in the Capital Region would grow at the same rate until 2050, and that the remaining 65 inhabited municipalities with varying populations were clustered together and essentially form one rural area with a uniform growth rate.

3.3.3 Vehicle projections

The projection for the passenger vehicle rate per 1,000 inhabitants can be seen in Figure 7**.** As can be seen, the maximum value of 850 vehicles per 1,000 inhabitants was reached after 2043. In 2043, the number of vehicles per 1,000 inhabitants reached a value of 849, after which the projection reached a plateau of 850 vehicles per 1,000 inhabitants continuing up to the end of the projection. The increase to 850 passenger vehicles signifies an increase of almost 14% over the 2019-2050 period.

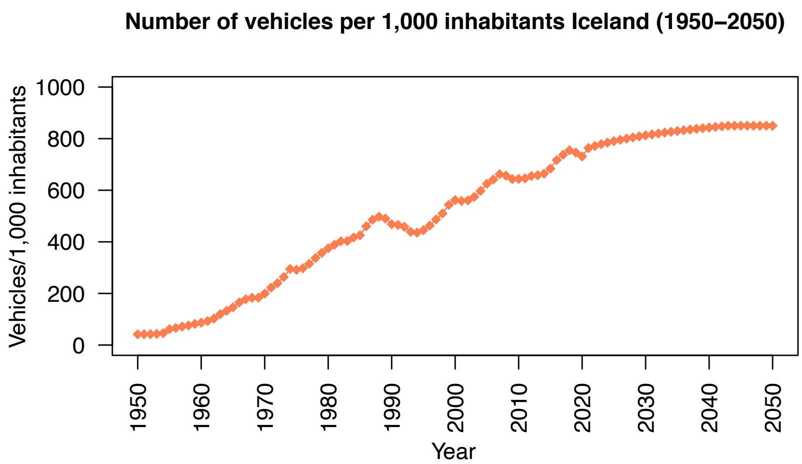


Figure 7 - Number of passenger vehicles per 1,000 inhabitants 1950-2050. Based on: SI, n.d.-d

Figure 8 shows the total number of vehicles as a result of the total population each year and the corresponding passenger vehicle ownership rate, resulting in about 366,000 passenger vehicles by 2050. It should be noted that this includes all passenger vehicles, meaning both EVs and ICEVs such as gasoline and diesel vehicles.

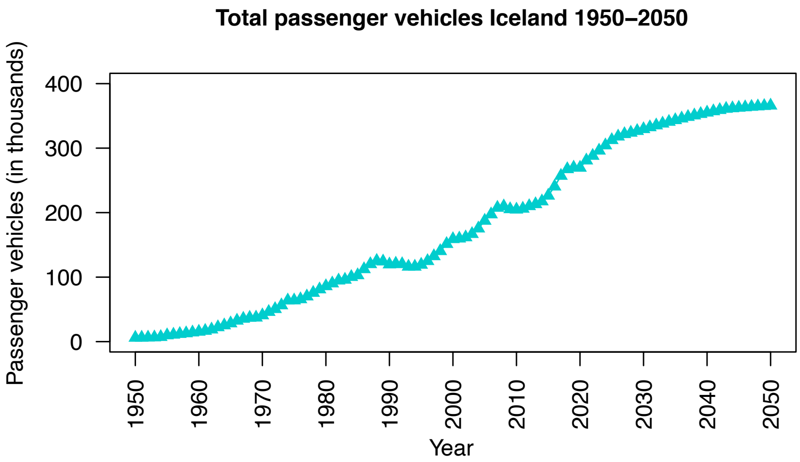


Figure 8 - Total passenger vehicles in Iceland 1950-2050. Based on: SI, n.d.-d; SI, 2021d

While it can be argued that the emergence and popularisation of ride-sharing services and shared cars will reduce private car ownership in the future, its impact on private car ownership so far is negligible (Heinonen et al., 2021). In Iceland, private vehicle ownership is expected to continue to dominate in the coming decades. Heinonen et al. (2021) found that private car ownership is deeply embedded in Icelandic culture and has historically been seen as a status symbol, in addition to Iceland being a highly car-oriented country. This is not in the least exacerbated by highly dispersed rural communities and the lack of adequate public transport possibilities outside of the Capital Region (Bjarnason, 2014; Keeling, 2020; Strætó, n.d.). A survey carried out by SI in 2014 reflects the inadequacy and attitude towards public transportation in Iceland: only 17.8% of the participants answered that they used public transport regularly, with 67% of the participants preferring to travel by their own vehicle, and 5.5% of the participants listing bad or inadequate access as their reason not to travel by public transport (SI, n.d.-b). Therefore, unless public transport is improved significantly with the intention to dissuade people from travelling by their own vehicle and to start travelling by public transportation, the dominance of private vehicle ownership can be reasonably expected to continue.

3.3.4 Distribution of vehicles

The passenger vehicle distribution can be seen in Figures 9 and 10. In order to display the distribution of passenger vehicles in 2050, the 2050 population was used in combination with the passenger vehicle rate per 1,000 inhabitants in 2050. This resulted in a total amount of passenger vehicles in Reykjavík of 90,283, 68,413 in the Capital Region, 37,661 in the urban areas, and 74,018 in the rest of the country in 2019. The distribution of the vehicles can be seen in Figure 9. This amounts to a total number of passenger vehicles of 267,786 which differs from the 269,825 total passenger vehicles in 2019 published by SI. The discrepancy of 2,039 vehicles between the SI statistic and the estimate here are most likely due to using average vehicle ownership rates for different classifications of municipalities as explained before.

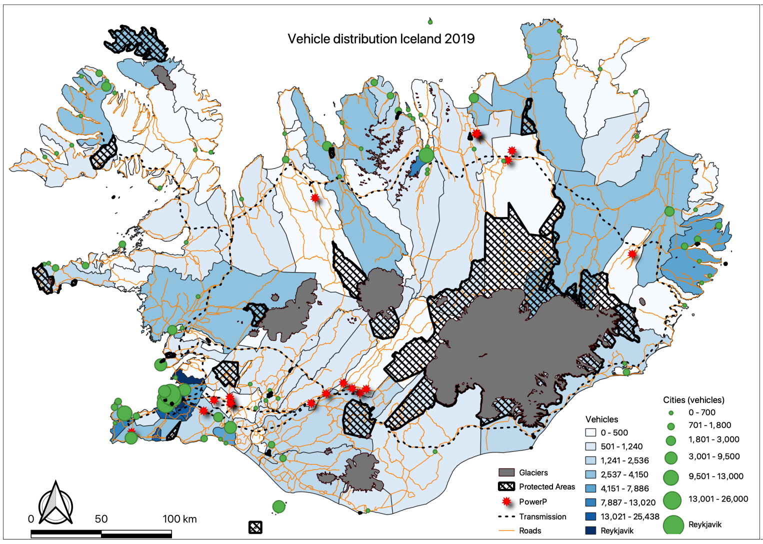


Figure 9 - Vehicle distribution in 2019, with distribution displayed on municipality level and on city level.

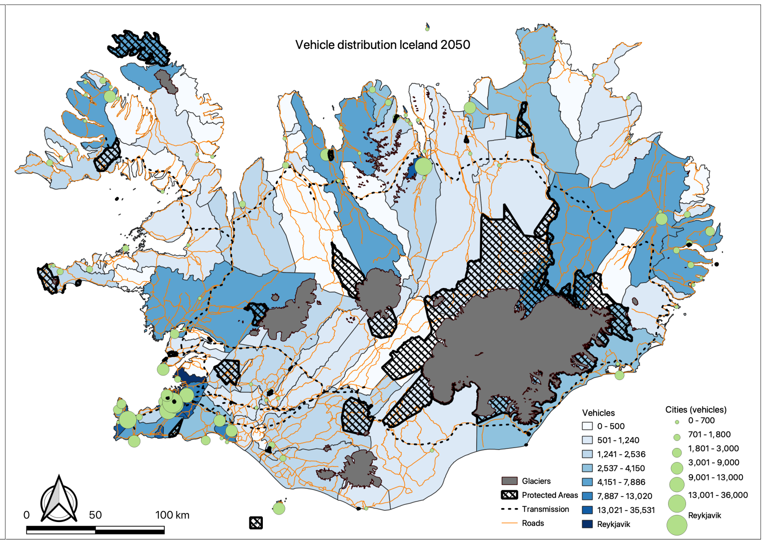


Figure 10 - Vehicle distribution in 2050, displayed on municipality level, and on city level.

In 2050, the total number of passenger vehicles were projected to be distributed as follows: 126,090 in Reykjavík, 95,546 in the Capital Region, 54,935 in the urban areas, and 88,824 in the rural areas, and can be seen in Figure 10. This amounted to a total of 365,395 vehicles in 2050, which signifies a discrepancy of 624 vehicles from the projection in the previous Section. Again, this could be due to using average passenger vehicle rates and the average growth rates for the municipalities and urban nuclei.

The amount of vehicles was calculated by using a classification distinguishing rural areas from urban areas. The population threshold for an urban area used here of 5,500 inhabitants deviates from how the Nordic countries usually define an urban area. According to Nordregio, a prominent Nordic research centre, the definitions for urban areas differ between Nordic countries. An urban area in Iceland, Sweden, and Denmark generally constitutes any place that has more than 200 inhabitants, which would make most of Iceland's municipalities urban areas, whereas Norway maintains a definition for an urban area as a place that has more than 2,000 inhabitants (Smas & Grunfelder, 2016). Moreover, Nordic countries maintain different urban-rural classifications compared to OECD or EU standards due to their low population densities. The European Commission classifies an area as an urban centre when it has a density of at least 1,500 inhabitants per km^2 and a population of at least 50,000, as an urban cluster when an area has a density of at least 300 inhabitants per km^2 and a population of at least 5,000, and areas that do not meet either of these criteria are classified as rural (Eurostat, 2018). Since the population density in Iceland is about 3 inhabitants per km^2 and 468 inhabitants per km^2 in Reykjavík, the most densely populated city in the country, classifications proposed by for example the European Commission would not be applicable in this instance (European Commission, 2018; City of Reykjavík, n.d.).

3.4 EV Scenarios

As can be seen in Figure 11, Scenario 1 assumed that the vehicle fleet would be fully electric in 2031, Scenario 2 achieved a fully EV based fleet in 2048, and the assumptions for Scenario 3 resulted in a fleet that would consist of a share of 66% EVs.

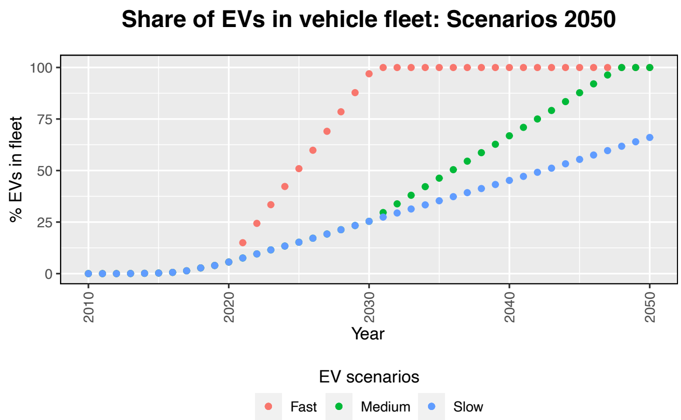


Figure 11 - Share of EVs in the vehicle fleet according to the three developed EV growth Scenarios (2010-2050)

The assumptions on which the individual Scenarios were built can be seen in **Table 2.**

Table 2 - Assumptions for the three EV Scenarios.

	Scenario 1 Fast Growth	Scenario 2 Medium Growth	Scenario 3 Slow Growth
Annual fleet turn over rate	10%	4.5%	4.5%
ICEV phase out	Up to 2030: phase out After 2030: ban on new registrations	Up to 2030: replaced vehicles 50% EV, 50% ICEVs After 2030: ban on new registrations of ICEVs	No ban on new registrations. Up to 2050: 50% of vehicles replaced by ICEVs and 50% replaced by EVs
Decrease year-on-year PHEV growth	50%	25%	12.5%

The following three sections will describe the results of the assumptions and how the vehicle fleet changes over the years up to the end of the projection period.

3.4.1 Scenario 1: Fast Growth

Scenario 1 assumed that EV growth would peak before 2030 in order to electrify the national passenger vehicle fleet shortly after 2030 with an annual fleet turnover rate of 10%. In this Scenario, it was assumed that in order to phase out ICEVs by 2030, only these vehicles would be replaced by both BEVs and PHEVs. Furthermore, the year-on-year PHEV growth decreased annually by 50%, which led to a year-on-year growth of below 1% after 2025. Consequentially, after 2025 the vehicle turnover rate applied only to PHEVs in order to be replaced by BEVs. Thus, the number of PHEVs decreased in accordance with the annual fleet renewal rate of 10%, as can be seen in Figure 12.

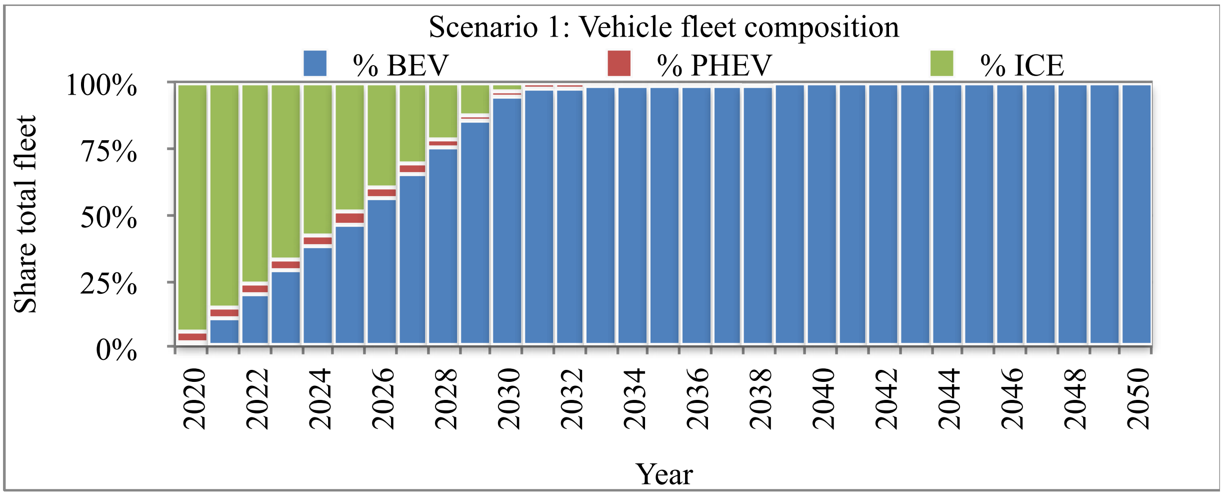


Figure 12 - Vehicle fleet composition for Scenario 1, with shares of BEV, PHEV, and ICEV of total vehicle fleet (2020-2050).

3.4.2 Scenario 2: Medium Growth

Scenario 2 is based on policies the Icelandic Government plans to carry out in the coming decades in order to make the transport sector more sustainable. Therefore, this Scenario used the average 4.5% fleet turnover rate mentioned before and assumed that a ban on new registrations of ICEVs will be implemented and starting in 2030. This means that before 2030, the new vehicles in the fleet would still consist of ICEVs in addition to EVs, as can be seen in Figure 13. Moreover, the year-on-year growth in PHEVs decreased by 25%, which resulted in a year-on-year growth of below 1% in 2033 after which the number of PHEVs decreased in accordance with the turnover rate of 4.5%, to be replaced by BEVs. As a result of these factors, the vehicle fleet will be fully EV based in 2048.

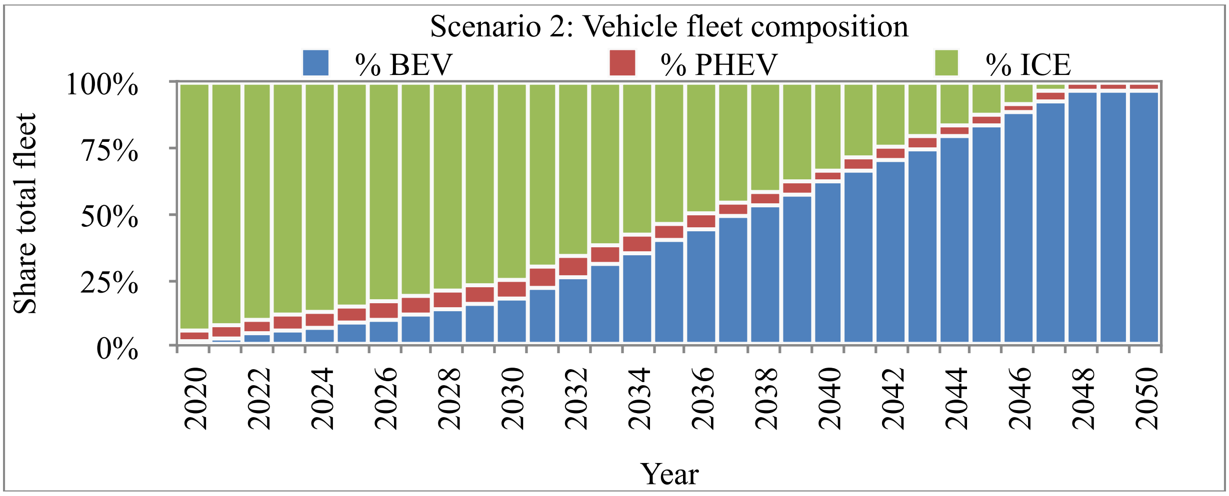


Figure 13 - Vehicle fleet composition for Scenario 2, with shares of BEV, PHEV, and ICEV of total vehicle fleet (2020-2050).

3.4.3 Scenario 3: Slow Growth

Scenario 3 reflect a business-as-usual scenario with a 4.5% fleet turnover rate, no ban on the registration of new ICEVs after 2030, and a decrease in PHEV year-on-year growth of 12.5%. The assumptions meant that the share of ICEVs in the national passenger vehicles still decreased, but slower than in Scenario 2 and that the national fleet would not be fully consist of EVs in 2050. As can be seen in **Figure 14**, the share of PHEVs increased —unlike the previous two Scenarios— to a share of about 20% of the total vehicle fleet in 2050. The share of BEVs in the vehicle fleet reached about 45% in 2050, and contrary to the previous two Scenarios the share of ICEVs remained relatively large at about 34%.

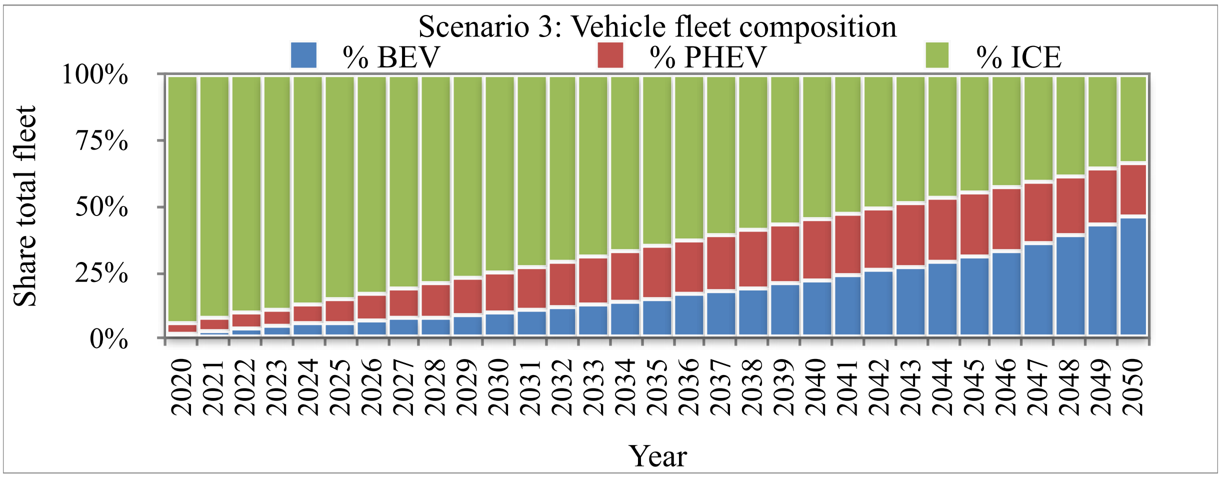


Figure 14 - Vehicle fleet composition for Scenario 3, with shares of BEV, PHEV, and ICE of total vehicle fleet (2020-2050).

In all Scenarios the number of ICEVs decreased up to 2050, which in turn decreases Iceland's dependency on foreign oil imports. Phasing out fossil fuels in the transport sector is one of two pillars in the Icelandic Climate Action Plan, since road vehicles are the largest consumers of imported oil and it is the only non-renewable energy source used in Iceland (Ministry of Environment and Natural Resources, 2018a; Ottensen & Kjartansdottir, 2015). A decrease in the share of vehicles that primarily on oil to be replaced by EVs is not only environmentally beneficial, but also economically beneficial. Firstly, the introduction of EVs in a vehicle fleet will only bring environmental benefits if the electricity used is produced from renewable sources. Since Iceland's electricity is almost exclusively produced by RES this will be more environmentally beneficial than to continue to use fossil fuels in transport. Secondly, EVs are economically beneficial to both owners and in terms of Government spending. For example, refined petroleum products are the leading import product in Iceland with $605 million worth of imports in 2019 (OEC, n.d.). Since the imported oil is only used in transportation, decreasing the number of vehicles that rely on petroleum products would significantly ameliorate Iceland's vulnerability to oil price volatilities, its reliance and expenditure on imports can be minimised (Shafiei et al., 2014).

3.5 Electricity demand

The resulting general electricity demand resulting from the three Scenarios can be seen in Figure 15. As can be seen, the electricity demand for all three Scenarios is 0.03 TWh in 2020. Over the next ten years, the electricity demand in Scenario 1 grew to 0.84 TWh due to the combination of a high annual vehicle turn-over rate and the decrease in PHEV year-on-year growth. The electricity demand in Scenarios 2 and 3 reached 0.2 and 0.18 TWh, respectively, for the reason that in both Scenarios ICEVs were still introduced up to 2030, and a slower decrease in year-on-year PHEV growth.

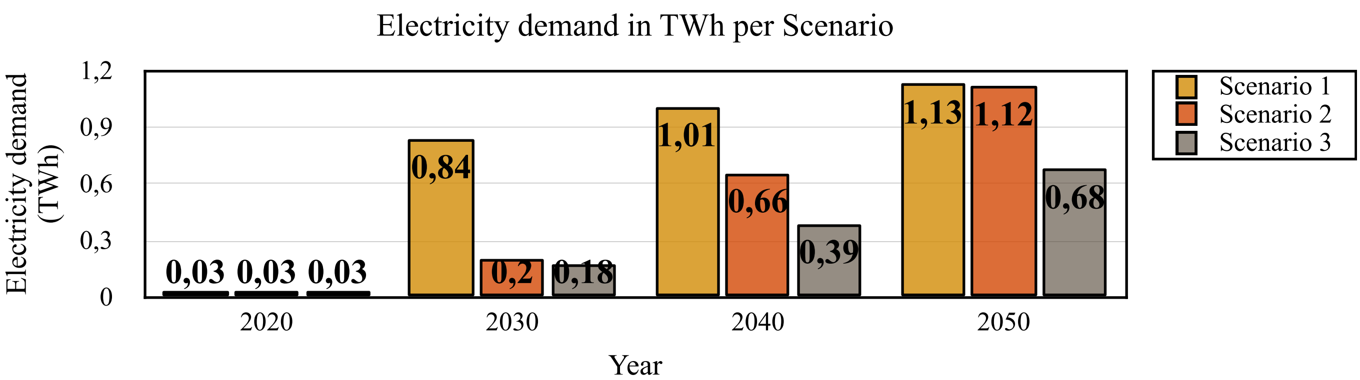


Figure 15 - Electricity demand in the three EV Scenarios.

As can be seen, the electricity demand growth in Scenario 1 slowed down from 2030-2040 compared to 2020-2030 due to the introduction of BEV having peaked before 2030. The growth after

2030 is solely due to the remaining PHEVs being replaced by BEVs. The reverse is true for Scenario 2, where a ban on new registrations of ICEVs after 2030 caused a faster growth in electricity demand in the 2030-2040 than in 2020-2030 during which such a ban was not yet in place. Contrary to the previous two Scenarios, the electricity demand in 2040 is relatively low in Scenario 3 due to the fact that both ICEVs and PHEVs were still being introduced after 2030. Finally, the electricity demand for the first two Scenarios reached 1.13 and 1.12 TWh by 2050. During this period, all newly introduced vehicles were BEVs in Scenario 2, causing the growth from 2040-2050. The electricity demand in Scenario 3 is low due to only 66% of the fleet consisting of EVs by 2050.

To put the general electricity demand from the EV Scenarios into perspective, Figure 16 shows the general electricity demand projection up to 2050, not including the power intensive industry. The electricity demand of the power intensive industry increased from about half of total demand between 1990-1997, 60-70% between 1998-2007, to about 80% since 2008 (Zheng & Breitschopf, 2020). The statistics made available by the National Energy Authority of Iceland, Orkustofnun, subdivide the power intensive industry into 5 categories: aluminium smelters, ferroalloy industry, aluminium foil industry, data centres, and other industries. The most recent data from 2019 show that the aluminium smelters were responsible for the largest share of electricity demand in this industry with 82.5%, followed by data centres with 6.5%, about 6% in the ferroalloy industry, 3% in the aluminium foil industry, and the remaining in the 'other industry' category, accounting for a total sector electricity demand of 15,146 GWh (Orkustofnun, 2020b).

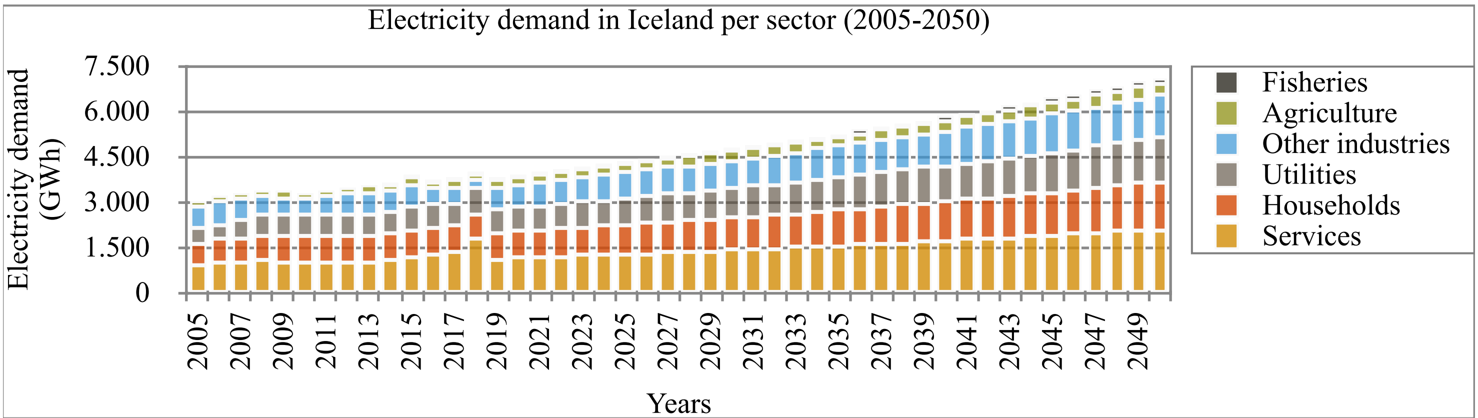


Figure 16 - Electricity demand up to 2050 excluding power intensive industry and EV Scenarios. Based on: Pérez-Arriaga et al., 2017; Orkustofnun, 2020b

The substantial share in demand of the power intensive industry is one of the reasons why Iceland has had the highest electricity consumption per capita for the past 20 years. In 2019 the electricity consumption per capita in Iceland was 56,828 kWh/capita, almost double that of Norway which followed with 26,492 kWh/capita (Our World in Data, n.d.). The low price of electricity generated from the country's abundant hydropower sources created a conducive environment for the rise and thereafter expansion of industries that demand large amounts of energy, such as the aluminium industry, starting in the 1960s (Askja Energy, n.d.-c; Zambrano-Monserrate et al., 2016). Since then Iceland has attracted a number of manufacturing and production industries to settle in Iceland and it can be expected that the industry's development will continue as long as electricity prices do not become too high. Moreover, power-intensive industries such as aluminium smelters are often built with its own adjoining power plant for its energy supply. Here, a reinforcing feedback mechanism can be seen: the more electricity is produced the more heavy industry will be developed, and the more the heavy industry sector grows the more electricity will have to be produced. This means that as long as there is a demand for heavy industry it can reasonably be expected that electricity consumption will continue to increase. If the share of the power intensive industry would not be taken into account the electricity consumption per capita would be about 10,678 kWh/capita in 2019, as opposed to 56,828 kWh/capita. Therefore, the power-intensive industry was only included in this analysis for comparison, since including it in the projections would not accurately reflect the electricity consumption of the Icelandic population, but rather the consumption of the whole country.

As a starting point in the Scenarios, the general electricity demand in 2020 was projected as 3,918 GWh which accounts for about 20% of the total electricity demand of 19,488 GWh. To illustrate, this results in a per capita general electricity demand of 10,759 kWh/capita, and 53,518 kWh/capita when taking into account the total electricity demand. The electricity demand from EVs in 2020 is the same for all three Scenarios: 39.03 GWh, or about 1% of general demand. In 2050, general demand was calculated to be 7,098 GWh using the methodology described in Section 3.2.4, excluding the EV Scenarios, resulting in mean a general demand per capita of 16,483 kWh/capita.

Table 3 - The general consumption, consumption per capita, and EV demand in 2050

	General consumption (GWh)	Electricity consumption (kWh/capita)	EV demand (GWh)	EV demand share of general consumption (%)
Reference Scenario	5,200	12,076	-	-
Scenario 1	8,228	19,108	1,123	13.7
Scenario 2	8,219	19,087	1,121	13.6
Scenario 3	7,777	18,061	679	8.7

In Table 3, the EV Scenarios are included in the general electricity consumption in 2050, leading to the EV demand as a percentage of general consumption of 13.7% in Scenario 1, 13.6% in Scenario 2, and 8.7% in Scenario 3. Moreover, in Table 3 the effect of EVs on both the resulting general electricity consumption and the electricity consumption per capita can be seen. Based on this information the geographical distribution of general consumption was calculated for each of the Scenarios in 2050, which can be seen in Figures 17-19. Table 4 shows the regional differences in electricity demand in more detail.

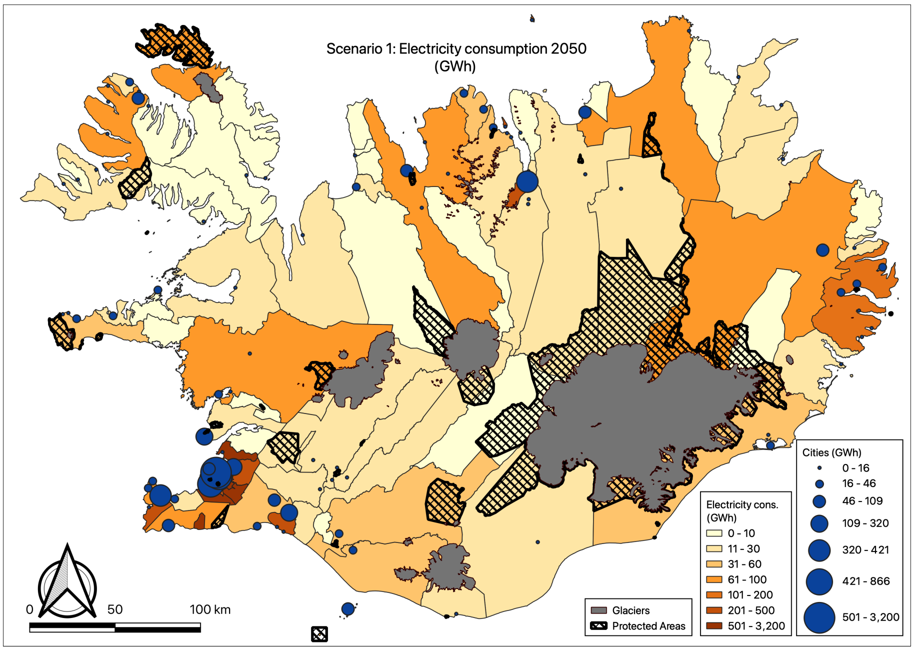


Figure 17 - Electricity consumption in 2050 for Scenario 1

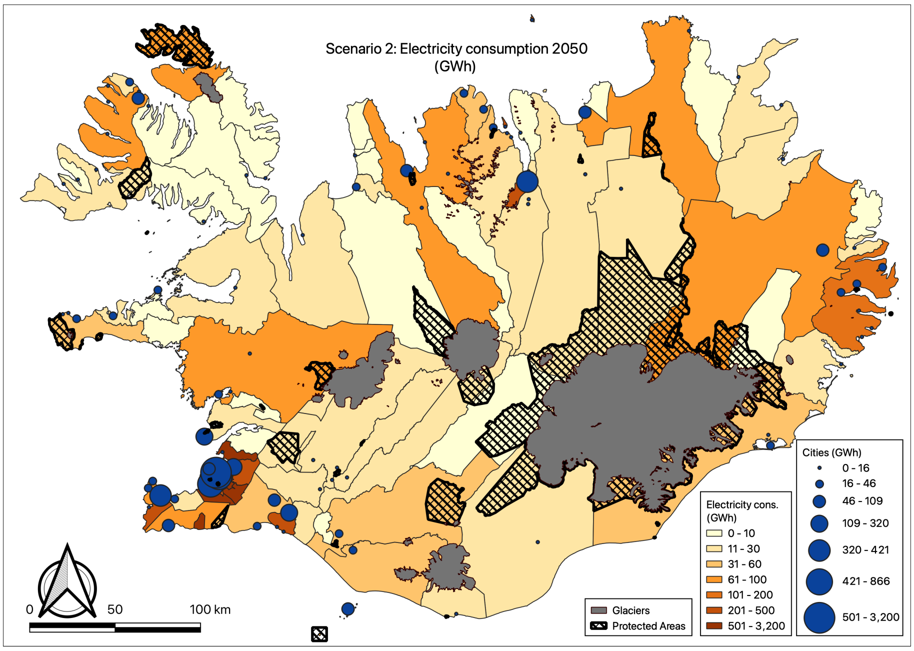


Figure 18 - Electricity consumption in 2050 for Scenario 2

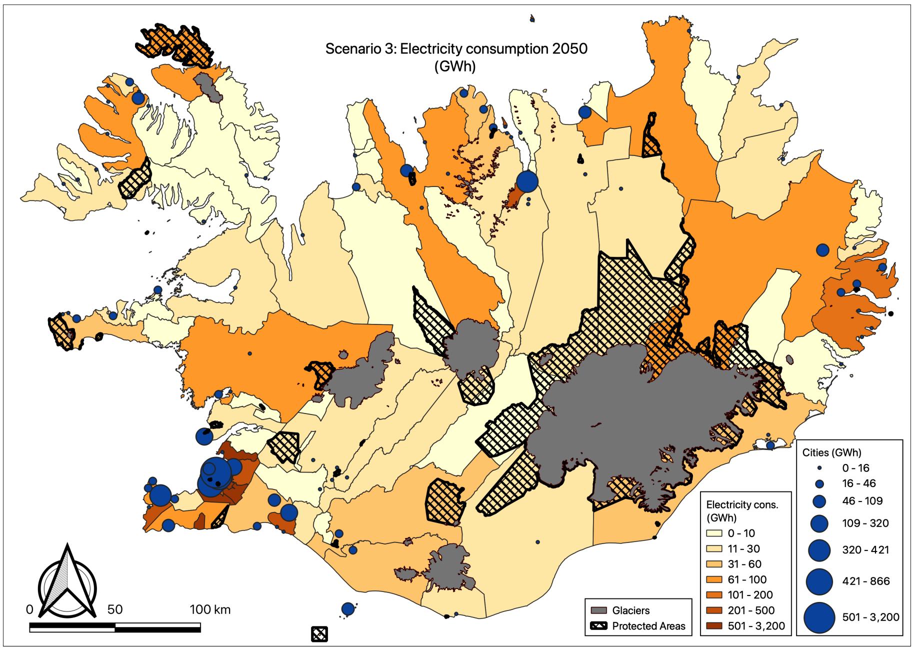


Figure 19 - Electricity consumption in 2050 for Scenario 3

As can be seen in Table 4, the highest general electricity demand can be found in the most populous regions. The majority of the Icelandic population lives in the Capital Region resulting in an electricity demand of 5 - 5.3 TWh according to the three EV Scenarios. The lowest demand can be found in the West Fjords, with an expected demand of 149 - 158 GWh in 2050.

Table 4 - General electricity demand according to Region in 2050.

	Scenario 1 (GWh)	Scenario 2 (GWh)	Scenario 3 (GWh)	Reference Scenario (GWh)
Capital Region	5.346	5.339	5.052	3.378
Southern Peninsula	607	606	573	384
Western Region	370	369	349	234
West Fjords	158	158	149	100
Northwestern Region	162	162	153	102
Northeastern Region	682	681	644	431
Eastern Region	239	239	226	151
Southern Region	666	665	629	421

Chapter 4 - Grid reliability

4.1 Introduction

This chapter addresses the third sub-question on how reliable the Icelandic grid currently is. The grid's reliability was assessed through both qualitative methods and quantitative methods, with the intention to identify the main bottlenecks in the national grid. This chapter will follow the following structure: first, the main characteristics of a power system will be discussed, followed by a more detailed account of power system reliability including a regional focus on the West Fjords. Finally, the main challenges to grid reliability will be summarised as well as future challenges.

4.2 Methodology

The overarching methodological approach for this Chapter was a literature review. Through a literature review, relevant information was found that was necessary to identify the main bottlenecks in the Icelandic grid. This information was retrieved from both academic sources as well as working papers by consulting agencies, and governmental agencies. The reliability of the grid was analysed using six reliability indicators. Data necessary for the reliability indicators were retrieved from the TSO Landsnet and the data for the reliability indicators to compare the Icelandic grid to other national grids were retrieved from the World Bank. Lastly, the data used for the analysis of the West Fjords were retrieved from the West Fjords DSO Orkubús Vestfjarða (OV).

4.3 Results and discussion

4.3.1 Grid characteristics

In order to identify the main bottlenecks in the Icelandic electricity grid, it is important to first create a deeper understanding of the electricity grid. Electricity grids are crucial in ensuring electricity supply security since they enable the flow of electricity from generation facilities to end-users (IEA, 2020b). More extensively, a grid system commonly consists of transmission and distribution networks, overhead lines and underground cables, transformers, substations, electrical protection and metering equipment, control systems, and control and communication systems (Ward, 2013). Ward (2013) further distinguishes the transmission network as parts of the grid system which operate at high voltages (> 100 kV) that are needed to transmit large volumes of power over long distances between load centres and power stations, and distribution networks as parts of the grid system that operate at lower voltages used to transmit smaller amounts of power over shorter distances. Besides the transmission and distribution networks the grid consists of two other components: load and generation, and can be seen in Figure 20 (Galli, 2013). In this Figure, it can be seen that after the electricity is generated in a generating station, the high voltage (often 100 kV - 700kV) transmission lines transmit the electricity to a substation which "steps down" the voltage to a lower voltage (often 33 kV - 66 kV) so that distribution lines can transmit the electricity from said substations to customers (Sedano & Brown, 2004).

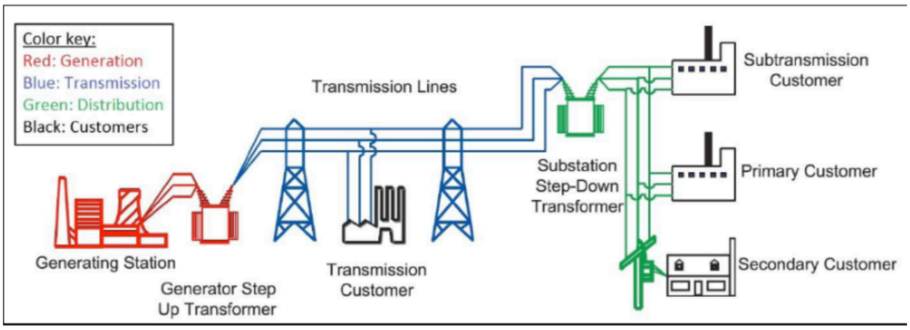


Figure 20 - Overview of traditional electric power system (Karagiannis et al., 2017)

4.3.2 Grid characteristics: Iceland

Following Figure 20, the Icelandic grid consists of three components: generation, transmission, and distribution. Firstly, nearly 100% of Iceland's electricity is produced from renewable sources with 75% from hydropower and 25% from geothermal power (Orkustofnun, n.d.-a). Since the National Power Company Landsvirkjun operates the majority of the hydropower plants it is the main supplier of electricity in the country (Government of Iceland, n.d.-b). After the electricity is generated in generation facilities, the electricity is then transmitted to a transformer which "steps up" the voltage in order to be transmitted by the high voltage transmission system.

Secondly, the transmission system transmits the electricity to the power intensive industry and distributors (see Figure 21). Traditionally, the Icelandic transmission standards have been designed around the power-intensive industry because of the necessity of a reliable and secure supply of electricity to mainly the aluminium smelters in order to prevent damage to equipment (Rikardsson, 2014). The operation of the transmission system entails connecting customers to the system, providing electricity in compensation for electricity losses in the system, supplying reactive power for the system to utilise transmission capacity and guarantee voltage quality, ensuring that the system operates in a reliable manner, providing a forecast on projected electricity demand, and plans for developing the transmission system (Electricity Act, No. 65/2003).

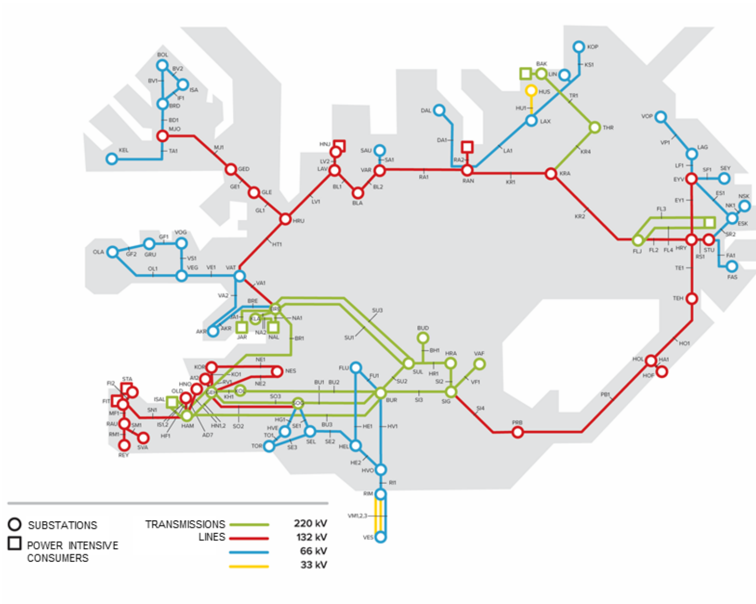


Figure 21 - The Icelandic transmission grid owned by Landsnet (Landsnet, n.d.-e)

Landsnet as the TSO, in addition to owning the main substations and 3,400 km of transmission lines, is responsible for a reliable power system and security of electricity supply (Askja Energy, n.d.-d; CEER, 2020). Its responsibilities were established in the 2003 Electricity Act and are as follows (Electricity Act, No. 65/2003):

> **1.** Co-ordinating supply and demand as regards electricity so that discrepancies between agreed purchase and actual use can be met, and entering into contracts with producers in connection therewith.
> **2.** Ensuring adequate supply of spinning reserves in the operation of the system.
> **3**. Determining processes of use where power measurements are not conducted.
> **4.** Measuring the delivery of electricity into and out of the transmission system in accordance with the applicable government regulation, documenting measurements and submitting records to the parties in question for the purpose of enabling financial settlement in relation to trade in electricity.
> **5**. Supplying public authorities, customers and the public with the information necessary to assess whether the company is performing its obligations and to ensure non-discrimination in trade in electricity.

To clarify point 2: there are two types of reserves: non-spinning and spinning reserves, or so-called contingency reserves that fall under ancillary services used by grid operators (U.S Department of Energy, 2011b). Ancillary services make sure that there is a continuous flow of electricity through offering balance support and are necessary to ensure a stable and secure supply of electricity (Mütlin, 2021). In general, reserves are the capacity that operators have as a back up in case of disruptions in power plants or if additional supply is needed. Non-spinning reserves are responsive loads that can be responsive within a certain specific time period but not yet started up, and spinning reserves are responsive loads that are operating at the same frequency as the grid and that can be responsive within a shorter timeframe (U.S Department of Energy, 2011b; Blumsack, n.d.-b).

Lastly, the transmission system delivers the high-voltage electricity to substations where the voltage is stepped down in order to be able to be transmitted by distribution systems to smaller customers such as households. In contrast to the transmission system of which there is only one, there are five distribution networks covering a total network length of 22,000 km that transmits electricity to consumers in their respective distribution zones (Askja Energy, n.d.-a; CEER, 2020).

4.3.3 Definition of reliability

The primary function of an electric power system is to "supply its customers with electric energy as economically as possible with an acceptable degree of reliability", according to Billinton and Allan (2003, p. 511). The system's reliability can be defined as consisting of two elements: security and adequacy (see Figure 22). An electric power system should be able to withstand sudden disturbances and thus prevent instability, voltage collapse, and frequency exceeding limits (security); and it should be able to supply the electricity demand of customers at all times by means of adequate generation, distribution, and transmission facilities (adequacy) (Sedano & Brown, 2004; Heylen et al., 2018). A third element that is often included is resilience. Resilience can be seen as long-term reliability since its definition as the ability of a system to "adapt to changing conditions and withstand and rapidly recover from disruptions" indicates a sustainable and long-term reliable grid (U.S Government, 2017, p. 4-4).

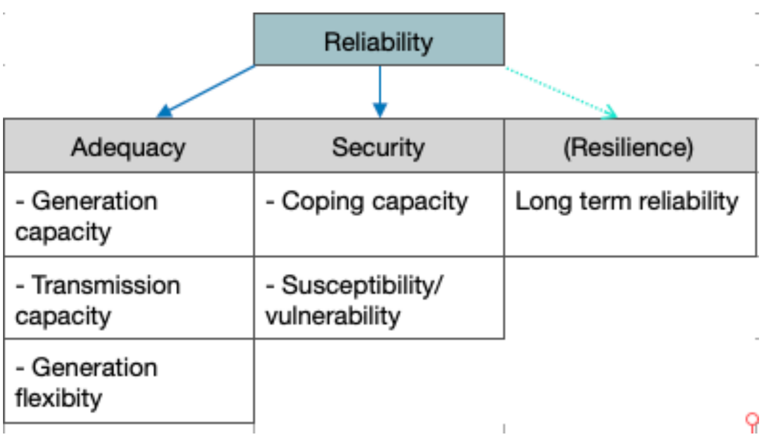


Figure 22 - Power system reliability. Based on: ABB Review, 2019; Accenture, 2020; Ciapessoni et al., 2020; Heylen et al., 2018; The U.S Department of Energy, 2016b

As can be seen in Figure 22, the security element consists of the two factors of coping capacity and susceptibility. The coping capacity indicates the ability of a TSO and DSO to mitigate adverse effects of an unwanted event (for example a disturbance) and the ability to return to its normal state, while the susceptibility indicates a power system's vulnerability to threats located outside of the system itself (Heylen et al., 2018). It is important here to demarcate the definition of a power system disturbance. Landsnet defines a grid disturbance as "an unexpected event that can cause automatic or manual disconnection of a unit in the transmission system or in the event of a failed reconnection after a malfunction", and each disturbance can consist of multiple faults (Landsnet, 2015). If nothing is done to mitigate the disturbance, a power outage can follow. A power outage is a complete loss of power as a result of a disturbance or failure in a part of the power system such as transmission lines or power stations (ABB, n.d.-b). The causes of disturbances in the Icelandic grid will be discussed in detail in Section 4.3.4.

Moreover, there are three hierarchy levels covering the power system's functional zones through which its reliability can be assessed (Kumar et al., 2018). The first level is concerned with generation facilities, the second level focusses on generation and transmission facilities, and the last level covers the complete system from generation, transmission to distribution (Heylen et al., 2018). However, as Heylen et al. (2018) also note: due to the increasing shares of RES distributed by the system the clear demarcation between the three hierarchy levels is fading. Additionally, analyses covering the third hierarchy level are rarely carried out due to the complexity and interconnectedness of the power system. Thus, in order to simplify, the main challenges to a reliable delivery of electricity can be divided into two domains: challenges in the transmission system, and challenges in the distribution system (Sultan & Hilton, 2019). In order for grids to function properly, electricity supply and electricity demand have to continuously be in balance. If this balance is not maintained faults can occur and can even lead to cascading failures or blackouts. For example, the ability of a transmission systems to deliver power in a reliable manner can be stressed by a rapid increase in load (Sedano & Brown, 2004). For illustrate, during harsh winters a rapid increase in the use of electric heaters can overload the power system. To meet demand generators will increase generation up to a certain safety limit. However, when demand is too high for a generator to keep up with, the generator will shut down in order to prevent overloading. If this process is repeated in too many generators a cascading failure can occur. A cascading power failure occurs when one part of the power grid fails, and the power load is transferred to another part of the power grid (ABB, n.d.-b). The same can occur in transmission lines if its transmission capacity is exceeded. If this continues to happen because parts of the grid are shut down in order to prevent overloads, a ripple effect can occur which can lead to a complete grid collapse (ABB, n.d.-b). If imbalances like this happen too quickly or the imbalance becomes too large for the system to cope with it can can lead to blackouts, operational risks, and an increase in outage minutes unless the transmission capacity is increased in order to accommodate for the increase in load (Government of Iceland, 2019).

Furthermore, a reliable grid reduces the use of fossil fuels in Iceland. In the case of a disruption event where the connection of a given costumer to the electricity grid cannot be restored in time back-up generators that often run on diesel fuel are needed to provide electricity (Ministry for the Environment and Natural Resources, 2018b). Thus, a highly reliable grid with sufficient generation flexibility leads to a reduced need for backup generators and as a result less demand for fossil fuels, as well as indicating the reliability of electricity delivery.

Although the Icelandic grid is regarded as one of the most reliable in the world, the Icelandic Government argues that balancing electricity supply and demand and thus ensuring security of electricity supply is an ongoing priority which faces significant challenges (Heimsmarkmidin, n.d.; Orkustofnun, n.d.-e). As can be seen in Figure 23 the level of security of supply differs geographically with the weakest security of supply found in the Northeast and the West Fjords. The security of supply and reliability is weakest in the West Fjords region with 17 disturbances and 403 outage minutes in 2020, followed by the Northeastern region with 6 disturbances and 176 outage minutes. In Figure 23, only the disturbances with the primary fault occurred in Landsnet's system are included and the outage minutes were calculated based on the primary distribution load per region (Landsnet, n.d.-c). One of Landsnet's security of supply targets each year is to keep the total amount of outage minutes below 50, which was achieved in only half of the 8 regions in 2020 (Landsnet, n.d.-c).

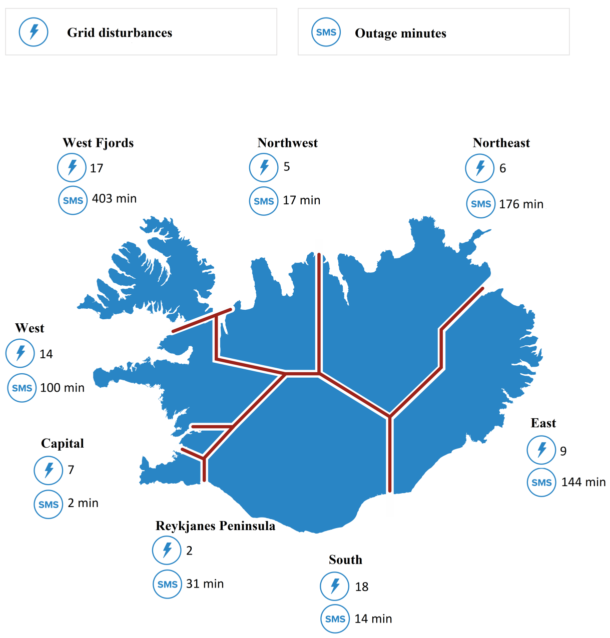


Figure 23 - Overview of disturbances and outages minutes for general users in 2020 reflecting the security (disturbances) and adequacy (outage minutes) aspects of reliability (Landsnet, n.d.-c)

4.3.4 Indicators reliability transmission system

Landsnet uses 6 indicators in its annual performance report in order to quantify the reliability and security of supply of the power system. Landsnet has a legal obligation to fulfil and meet the first three indicators (the Power Interruption Index, Average Outage Duration Index, and System Minutes) as set out in the Electricity Act (no. 65/2003) and the Ministry of Industry's Regulation on electricity quality and security of supply (Ministry of Industry, 1048/2004). Furthermore, the targets set for the Power Interruption Index and Average Outage Duration Index, and the System Minutes indicator have to be approved by the Icelandic National Energy Authority Orkustofnun, and are based on the annual primary load curtailments due to primary faults in Landsnet's system (Landsnet, n.d.-c). The primary load consists of two types of load: the power intensive user load, and the distributors load which means the general users. The indicators below will mention whether which type it used in its calculations, where necessary.

The security of supply indicators are as follows (Landsnet, n.d.-a; Landsnet, n.d.-d):

1. Power Interruption Index (SRA): ratio of the aggregate power curtailment and the peak load on the system, and is calculated as follows:

$$SRA = \frac{\Sigma P_i}{P_{max}} \; MW \,/\, MW \; per \; year \qquad \text{[eqn. 3]}$$

with:

P_i = Curtailed power in curtailment/disturbance *i* [MW]

P_{max} = Annual maximum power feed into transmission system in [MW]

Figure 24 shows that in 2020 the majority of the grid disturbances were caused by faults in other connected systems. The index is calculated using the amount of curtailed power, which is power that cannot be generated due to security reasons (Heylen et al., 2018). Here, the other connected systems include the power-intensive users, distributors, and producers, and the resulting disturbances can be caused by both energy users or energy producers (Landsnet, 2015). Landsnet's annual target of keeping this indicator below 0.85 was achieved since the SRA was 0.21 in 2020 for primary faults in Landsnet's system.

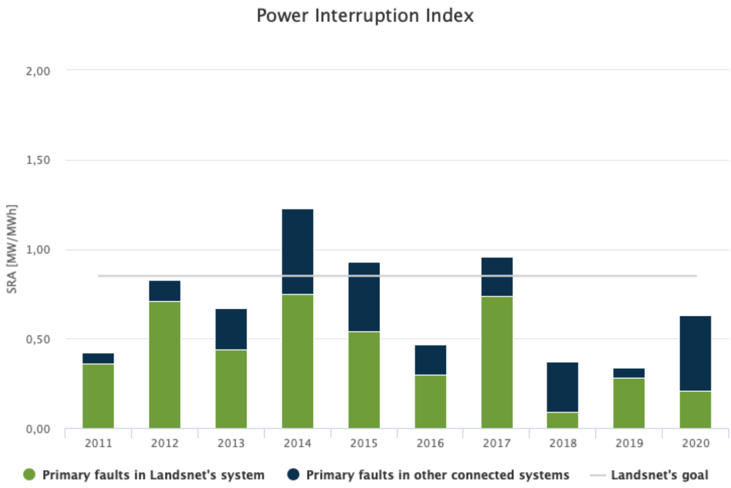


Figure 24 - SRA index in MWh / MW for 2011-2020. Y-axis should read MW / MW year instead of MW / MWh Source: Landsnet, n.d.-d

2. Average Outage Duration Index (SMS): ratio of the sum of curtailed energy and total energy delivered, and is calculated as follows:

$$SMS = \frac{\Sigma E_i}{E_{total}} \times 8760 \times 60 \; minutes \; / \; year \qquad \text{[eqn. 4]}$$

with:

E_i = Energy curtailed due to disturbance [MWh]

E_{total} = Total energy delivered to customers [MWh]

In other words, the SMS indicator shows the average duration of an outage. As can be seen in Figure 25, the SMS index for 2020 was 12.45 minutes, fulfilling Landsnet's annual goal of a maximum of 50 outage minutes. Figure 25 shows the SMS index for the entire primary load. As mentioned, the security of supply differs per region which can be seen in Figure 26 which shows the SMS index for the distributors load. As can be seen, the SMS index was highest in the West Fjords region in 2020 with 403.41 minutes, followed by the Northeastern region with 175.5 minutes. The index yielded the lowest result in the Capital Region with 2 outage minutes in 2020. The variation across regions in the average outage minutes for 2016-2020 that can be seen, is caused by several outliers that skew the average. For in stance, the 2016-2020 average outage minutes for general users is highest in the Northeastern region. This can be attributed to the large amount of outage minutes in this region in 2019 (2,776 minutes) which influences the average.

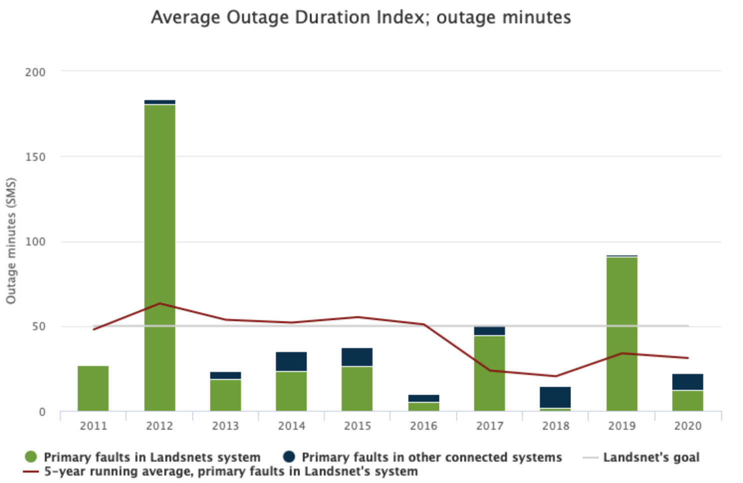


Figure 25 - SMS index in minutes for 2011-2020. Source: Landsnet, n.d.-d

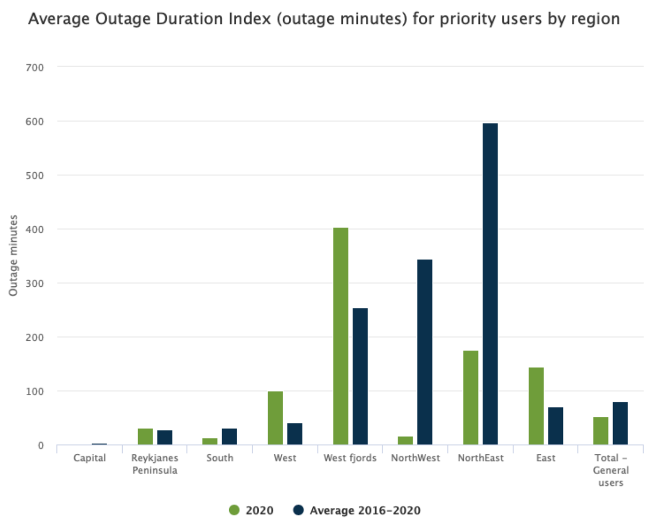


Figure 26 - Outage minutes for general users according to region with the green bars representing the outage minutes in 2020, and the blue bar representing the average for 2016-2020. Source: Landsnet, n.d.-a

3. System Minutes (KM): indicates the severity of a specific curtailment, and is calculated as follows:

$$KM = \frac{E \times 60}{P_{max}}\ minutes \qquad \text{[eqn. 5]}$$

with:

E = Energy curtailed due to disturbance [MWh]

P_{max} = Annual maximum total power feed into transmission system in [MW]

Landsnet categorises the severity of a disturbance according to its duration: Category 0 disturbances last for less than 1 system minute, Category 1 disturbances last for less than 10 system minutes, Category 2 disturbances last for less than 100 system minutes, and lastly Category 3 disturbances last for less than 1000 system minutes. Figure 27 shows the frequency of each Category over the past 10 years. As can be seen the most frequent every year are the category 0 disturbances. In 2020, 30 Category 0 disturbances occurred, and 3 Category 1 disturbances. Landsnet's annual goal is to make sure that individual disturbances do not last longer than 10 system minutes, which was achieved in 2020.

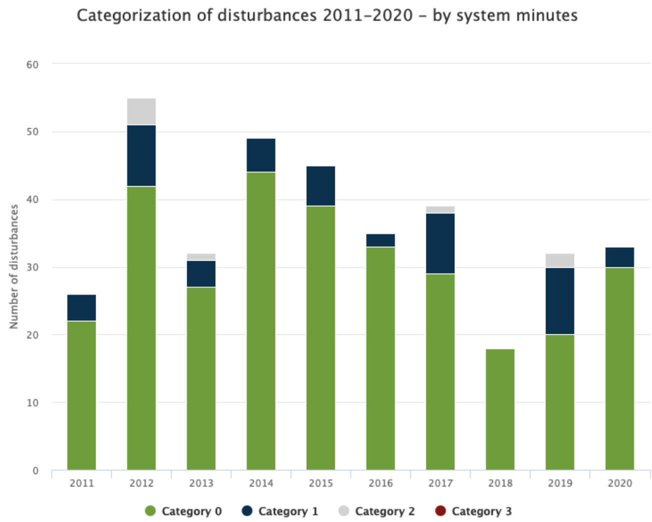


Figure 27 - Number of disturbances according to severity category. Source: Landsnet, n.d.-d

4. Power Energy Curtailment Index (SSO): ratio of curtailed energy if the load would have been unchanged during curtailment period and the total power of system, and is calculated as follows:

$$SSO = \frac{\Sigma\ T_i \times P_1}{P_{max}}\ MWh\ /\ MW\ year \qquad \text{[eqn. 6]}$$

with:

P_i = Power curtailment in disturbance i [MW]

T_i = Duration of disturbance [hours]

P_{max} = Annual maximum total power feed into transmission system [MW]

Figure 28 shows the SSO index over the past 10 years. The green line show the curtailment index for disturbances whose primary fault is in Landsnet's system, and the grey line shows all disturbances that affect Landsnet's system. In 2020 the SSO index for primary faults in Landsnet's system was 0.35 and 0.49 for all disturbances that affect Landsnet's system.

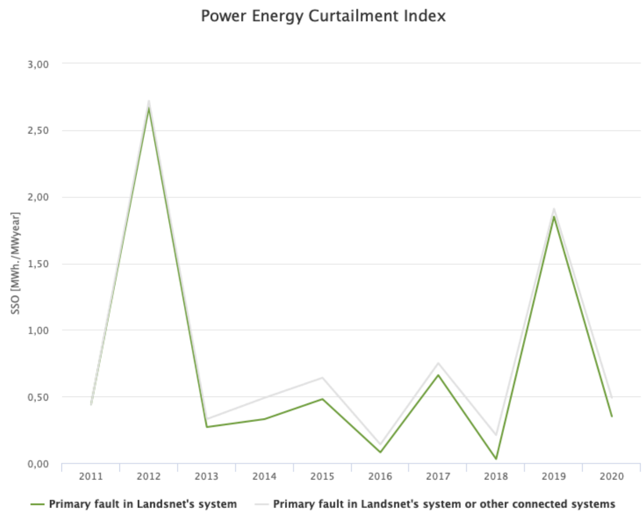


Figure 28 - SSO index for 2011-2020. Source: Landsnet, n.d.-d

5. Average Power Curtailment per Disturbance (SMA): indicator of average power curtailment during each disturbance, and is calculated as follows:

$$SMA = \frac{\Sigma\, P_i}{N}\ MW\ /\ disturbance \qquad \text{[eqn. 7]}$$

with:

P_i = Power curtailment in disturbance i [MW]

N = Number of disturbances

Figure 29 shows the SMA index over the past 10 years. Here it can be seen that in 2020 the average curtailment per disturbance was 13.77 MW per disturbance where the primary fault occurred in Landsnet's system and 36.98 MW on average per disturbance where the primary fault occurred in Landsnet's system or other systems.

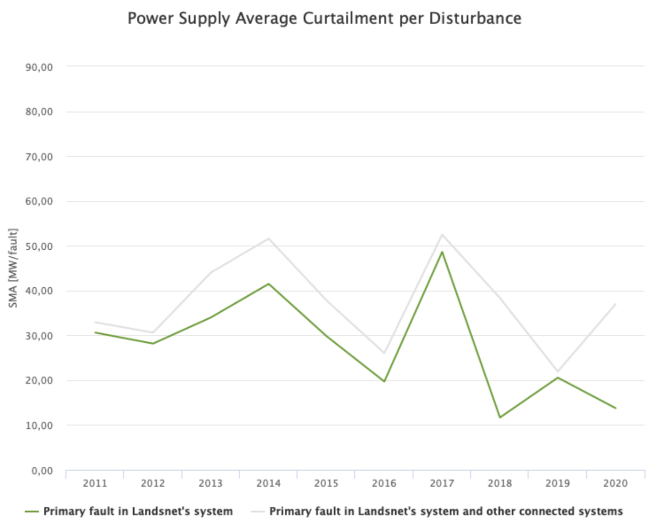


Figure 29 - SMA index for 2011-2020. Source: Landsnet, n.d.-d

6. Index of Reliability (AS): ratio of total customer hours subtracted by the total interrupted hours per year, and is calculated as follows:

$$AS = \frac{8760 - duration\ of\ outage}{8760} \quad \text{[eqn. 8]}$$

with:

Duration of outage = Average Outage Duration Index (SMS) indicator

This indicator can be converted into percentages as can be seen in Figure 30. Landsnet's goal for this target is to ensure a reliability of $> 99.9905\%$ for primary load users. Landsnet states that equals to 0.833 curtailed hours, or 50 outage minutes per year. Figure 30 shows that the reliability indicator for disturbances from Landsnet's system was 99.998% for primary load users in 2020, and 99.996% for disturbances in the entire system and thus both achieving Landsnet's annual target.

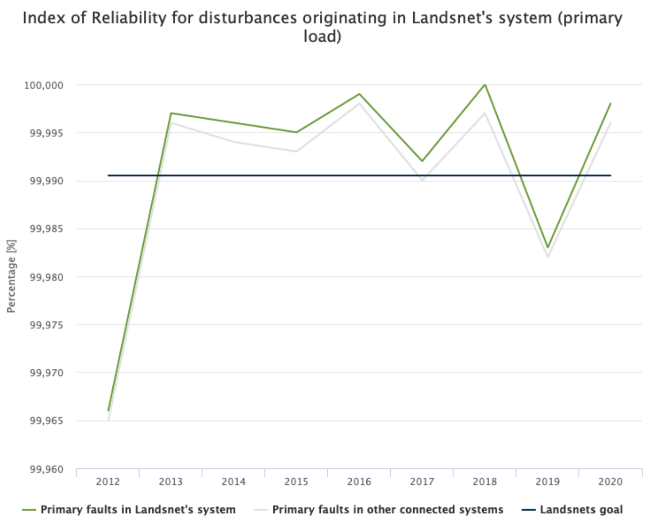


Figure 30 - AS Index for 2012-2020. Source: Landsnet, n.d.-d

These six reliability indicators shows that the Icelandic transmission system is relatively reliable, with faults in the entire transmission system being higher than faults where the primary fault in located in Landsnet's own system. Most of the faults in the transmission system are located in the transmission lines and cables, followed by faults in substations (see Figure 31). Landsnet reported 48 grid faults in 2020 caused by problems in transmission lines and cables, of which 46 occurred due to problems in (overhead) transmission lines and 2 due to issues originating in underground cables (Landsnet, n.d.-b). As can be seen in the Figures above, indicators can be highly variable from year to year. This can be explained by instances of harsh weather conditions that cause relatively long outages in some regions of the country. The effect of weather conditions can be seen in Figure 32.

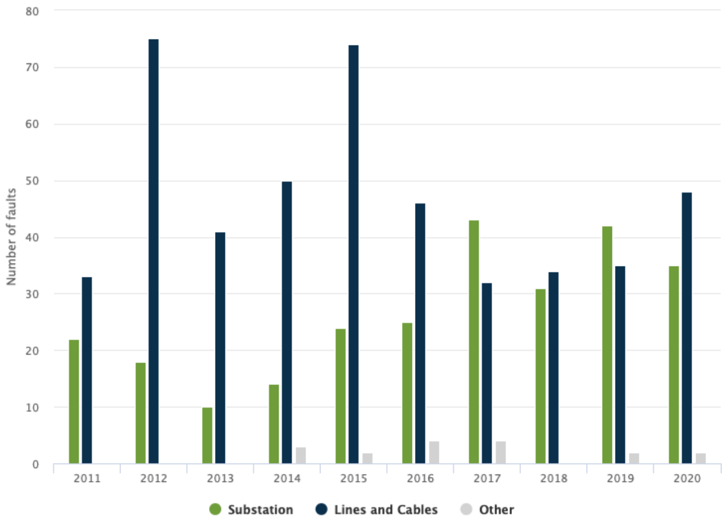


Figure 31 - Number of faults in the transmission system. Source: Landsnet, n.d.-a.

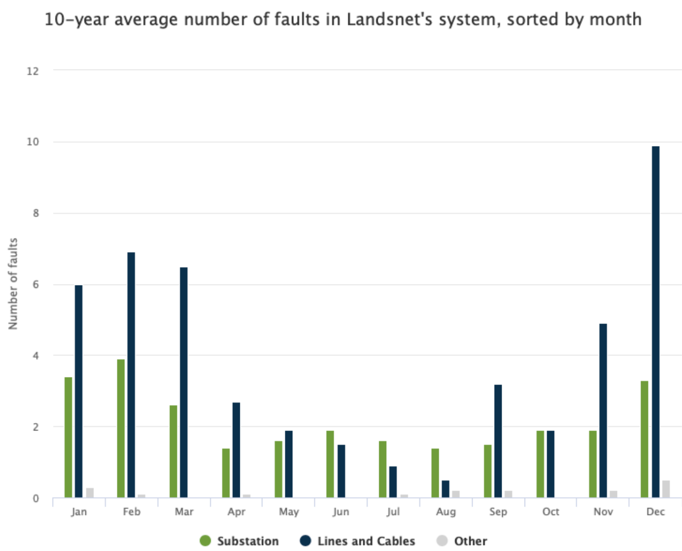


Figure 32 - Number of faults in the transmission system according to month in the year. Source: Landsnet, n.d.-a.

Figure 32 shows the average number of faults according to the month of the year for the past 10 years. It can be seen that the most amount of faults originating transmission lines and cables occur from November to March, with the maximum amount of faults occurring in December. From this Figure, it can be assumed that the primary cause of the faults in transmission lines and cables can be attributed to harsh weather conditions. Not only does icing, wind, precipitation, and debris resulting from extreme winter weather conditions impact the transmission lines themselves, the weather conditions also make it more difficult for maintenance and repairs to be carried out by designated technicians (Landsnet, 2015). This is in accordance with Figure 33, where the number of faults in the transmission system are categorised according to cause. As could be seen in Figure 25 and in several of the previous indicators, weather conditions were especially harsh in 2012 when icing caused lines to sag, and heavy snowfall caused severe damage to transmission infrastructure mainly in the North by damaging 50 power towers on several transmission lines (Landsnet, 2013).

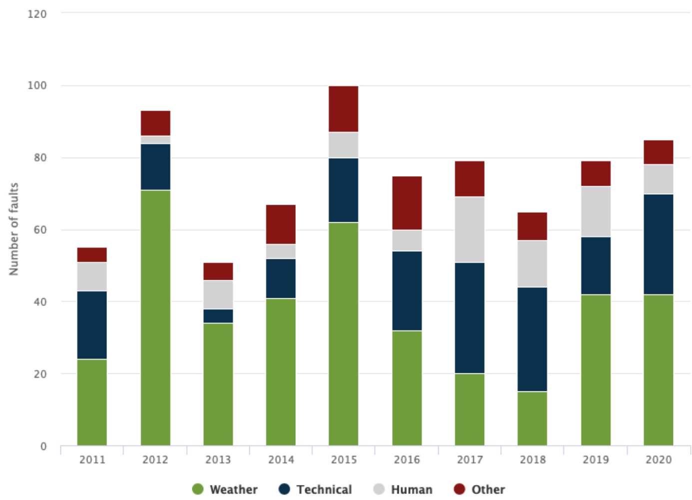


Figure 33 - Number of faults in transmission lines and cables according to cause. Source: Landsnet, n.d.-a.

Conversely, most of the faults occurring in substations are caused by technical issues, followed by human causes and weather conditions (Landsnet, n.d.-d). Since electricity still needs to be supplied to customers during disturbances and faults in the transmission system, distribution utilities have access to a collection of back-up power generators. Besides supplying electricity to customers during disturbances and faults, the back-up generators also assist in supplying to primary load during times when maintenance on the transmission system is carried out (Landsnet, n.d.-d). In Figure 34, the power generated by the back-up power generators can be seen during 2012-2020.

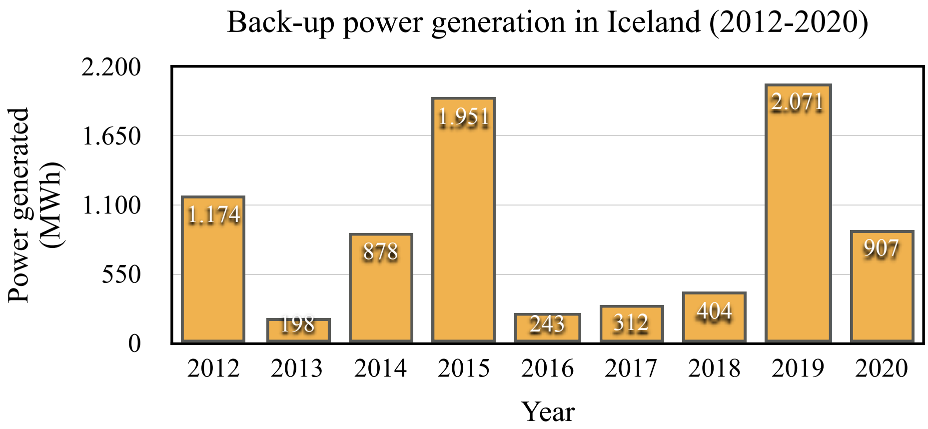


Figure 34 - Back-up power generation per year since 2012 in MWh. Based on: Landsnet, 2013; Landsnet, 2017; Landsnet, n.d.-b

From the indicators and the previous Figures it can be concluded that on average the overhead transmission line are most often the cause of grid disturbances due to adverse effects of weather conditions. As Figure 35 shows, the most problematic voltage level are the 66 kV lines, with an outlier in 2012 where the cables and lines with 33 kV voltage level experienced the most faults per 100 km of cable and line lengths.

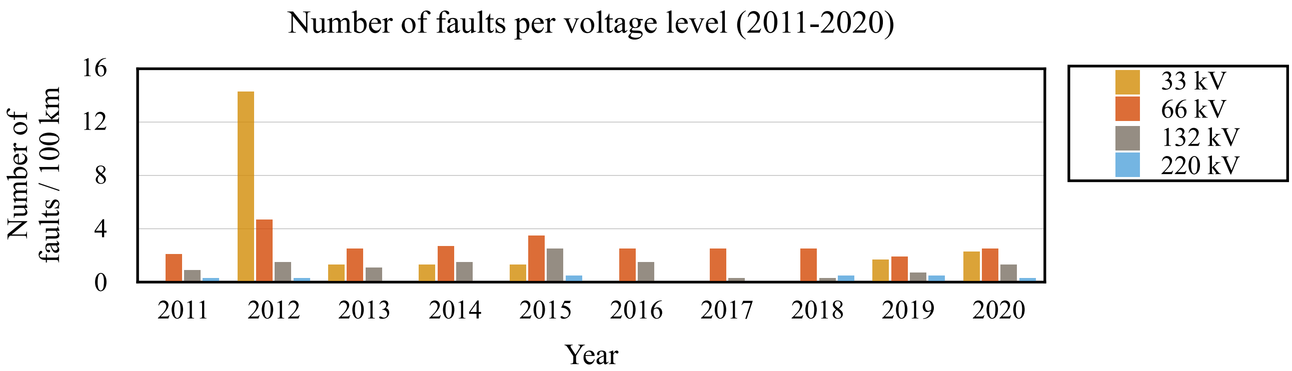


Figure 35 - Number of faults per 100 km of lines and cables per year for 2011-2020. Data source: Landsnet, n.d.-b

The lower voltage lines are mostly located in more remote areas, which are more often than not the areas that already experience low levels of security of supply (see Figure 21 and Figure 23). One of these regions is the West Fjords region, where the distribution network functions at a voltage of 66 kV. The next section will discuss the security of supply and reliability in this region.

4.4 West Fjord's security of supply and reliability

To assess the reliability of electricity delivery a more detailed look into regional distribution systems is necessary. The reason for this is that reliable delivery of electricity is a result of both the transmission system, and the distribution system. As mentioned before, the West Fjords region experiences the most amount of outage minutes and frequent disturbances on a regular basis. This has led to the Ministry of Industries and Innovation announcing a working group in June 2021 to asses the main bottlenecks in the generation, transmission, and distribution of electricity in the region as well as exploring whether improving the connection to the main transmission network would increase security of supply more, or whether decentralised options would be more beneficial (Ministry of Industries and Innovation, 2021). However, prior to the publication of the findings of the working group it is possible to identify the weaknesses in the West Fjords regarding electricity security of supply and its reliability. Therefore, this section will answer the fifth sub-question "What areas in the West Fjords are most vulnerable to electricity disruptions?".

4.4.1 Reliability

The West Fjords' DSO OV reported both and increase in the consumption of reserve power, and an increase in the production of electricity using back-up generators in 2020 (OV, 2021). A more extensive look into the reliability of the West Fjords' distribution system is provided by the publication of the six reliability indicators in the previous section. Besides the six reliability indicators, the annual performance reports also include the widely used and well-established indicators to measure the reliability of a power system: the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI) indicators (Mishra et al., 2020; U.S. Department of Energy, 2016a). The SAIDI indicator reflects the annual average duration of outages experienced by a customer, and the SAIFI indicator reflects the annual average number of outages experienced by a customer (World Bank Group, n.d.-a, n.d.-b). The CAIDI indicator is the ratio between the SAIDI and SAIFI indicator, and shows the average outage duration a customer can experience per outage, or in other words, the time it takes for power to be restored for a give customer. Table 5 shows the six reliability indicators, as well as the SAIFI, SAIDI, and CAIDI indicators, compared to the indicators for Landsnet's transmission system in 2020. The data for the last three indicators were retrieved from the World Bank Group and will be more extensively discussed in Section 4.5.1.

Table 5 - Reliability indicators the Landsnet TSO and the West Fjords DSO in 2020 (Orkubús Vestfjarða, 2021; World Bank Group, n.d.-a, n.d.-b)

Reliability indicators	Landsnet (TSO)	West Fjords (DSO)
SRA (MW / MW year)	0.21 (target: < 0.85)	1.47 (target: < 3)
SMS (minutes / year)	12.45	107.8 (target: < 300)
KM 0 (< 1 min)	30	112
KM 1 (< 10 min)	3	15
KM 2 (< 100 min)	0 (target: 0)	1 (target: < 3)
KM 3 (<1000 min)	0 (target: 0)	0

Reliability indicators	Landsnet (TSO)	West Fjords (DSO)
SSO (MWh / MW year)	0.35	1.81
SMA (MWh/ disturbance)	13.77	0.53
AS (%)	99.998	99.97950
SAIFI	0.41	2.40
SAIDI (hrs)	0.63	2.97
CAIDI (hrs)	1.54	1.24

The reliability indicators for Landsnet indicate the reliability scores for primary faults located in Landsnet's own transmission system. As can be seen, the majority of the indicators yield a lower score in the West Fjords than in Landsnet's transmission system. It should be noted here that the indicators are compared between a TSO and a DSO. The majority of disturbances in electricity delivery occur in distribution systems and are more often than not a result of weather conditions, while the remaining disturbances in the transmission system are more infrequent but result in more widespread outages affecting a larger amount of customers (U.S Government, 2017). If a disturbance is severe enough a power outage can follow (Silverstein et al., 2018).

There are two factors that should be taken into account when looking at Table 5. Firstly, the differences in results show that these indicators should be treated with caution. The TSO indicators report an average over the whole country and does not show regional differences. This becomes clear when looking at the SMS indicator, which is a reflection of the average duration of a disturbance. It can be seen that whilst the average outage duration per year is 12.45 minutes in the transmission system, it is 107.8 minutes per year in the West Fjords' distribution system. The opposite is true for the SMA indicator which shows that the average load reduction per disturbance is higher in Landsnet's system than in OV's system. Secondly, not included in the indicators are the total number of disruptions in both the distribution system, and disruptions in Landsnet's system that impacted the electricity supply to the West Fjords' distribution system. As OV explains in their annual performance report, there were a total of 222 disturbances in the distribution system in 2020 (compared to 160 in 2019), and 19 disruptions in Landsnet's own transmission system that hindered the supply to the West Fjords' distribution system (OV, 2021). OV did not publish the locations of the 222 disturbances in 2020 but a report by Landsnet (2019b) on the security of electricity supply in the West Fjords reported that most faults during 2009 - 2018 occurred in the Keldeyri, Bolungarvík and Ísafjördur/Breididalur substations and are especially prone to disturbances during years with harsh weather conditions such as in 2012.

4.4.2 Operational challenges

Figure 36 shows the electricity system in the West Fjords. As can be seen, OV operates 12 diesel back-up power generators with a total capacity of about 18 MW, and 8 hydropower plants with a total capacity of about 17 MW (OV, 2021). The largest of the hydropower plants is the Mjolka plant with an installed capacity of 11.2 MW. The smallest of the plants is the Myrarárvirkjun plant located in the north with a capacity of 0.06 MW. In addition to the 8 hydropower plants operated by OV, there are 4 plants co-owned by OV and Landsnet with a total installed capacity of about 4 MW (see Appendix A for a complete overview of installed capacity). No geothermal plants are deployed to generate electricity in the West Fjords.

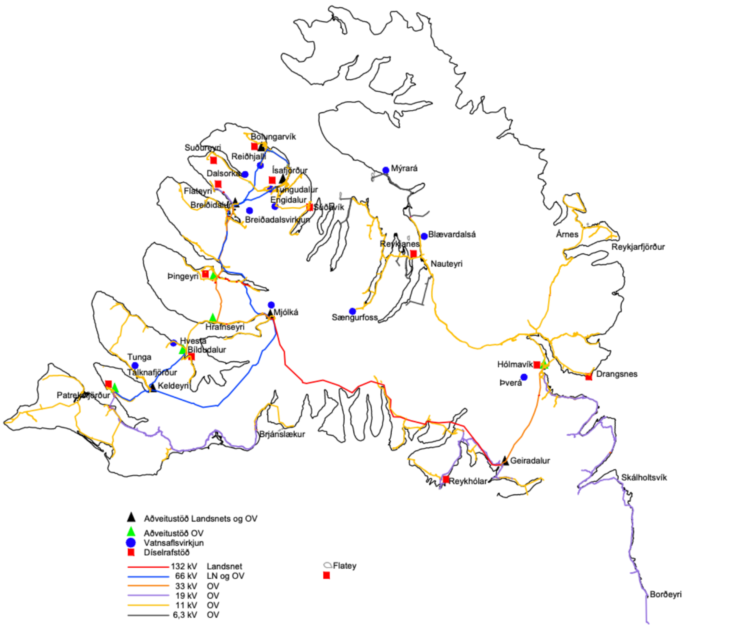


Figure 36 - West Fjords distribution network: black triangles show substations of both Landsnet and OV, green triangles show OV substations, blue marks show hydropower plants, and red marks show diesel back-up generators. Source: OV, 2021

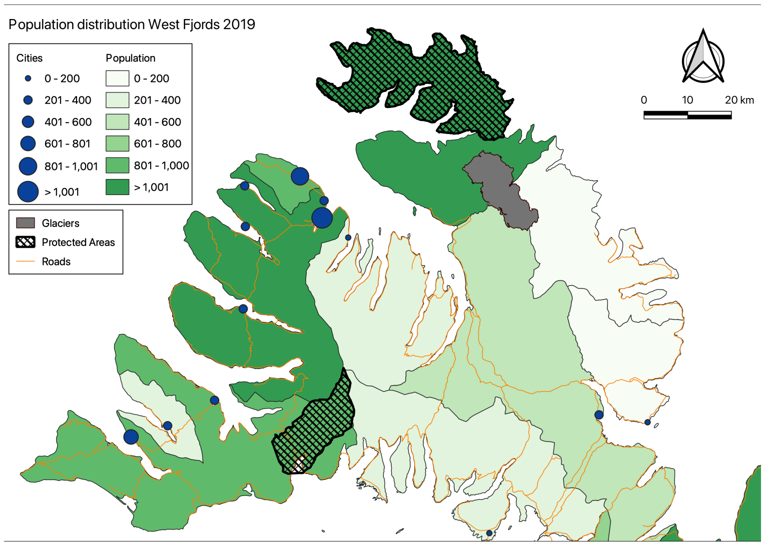


Figure 37 - Population distribution in the West Fjords (2019).

Figure 37 shows the 2019 population density in the West Fjords. This Figure shows that the Keldeyri, Bolungarvík and Ísafjördur substations located in the northwest of the region that experience the most amount of disturbances are located in the most densely populated areas.

The majority of the distribution system consists of overhead transmission lines. A substantial share of the distribution network in the region consists of underground cables, deviating from the trend throughout the rest of the country where underground cables are less common. The reason for this is that the West Fjords consists of rough and mountainous terrain which limits the available areas where transmission equipment can be built, and what type of equipment can be used (Logadóttir, 2017). In addition, Landsnet mentions two operation challenges in the West Fjords in its 2018-2027 development plans (Landsnet, 2018b). The first operational challenge is that the West Fjords' distribution system is a radial grid. There is only one transmission line connecting the 66 kV West Fjords distribution system and the 132 kV main transmission system, namely the West Line which can be seen in Figure 36 as the red line in the centre in the southern part of the region (Landsnet, 2018b;

OV, 2020). The fact that there is only one connection to the main transmission system, the Mjólkárvirkjun substation, makes a ring connection that is necessary for establishing a N-1 criterion impossible. The N-1 criterion means that if one part of the system fails the supply of electricity is not interrupted (ABB, n.d.-b; Landsnet, 2018b). However, this is only an option if there is more than one transmission line, because if the primary transmission line, in this case the West Line, fails its operation needs to be taken over by another component, in this case another transmission line.

The second challenge is the frequent disruptions in the distribution system. The newly installed back-up generators only partially alleviate the stress on the distribution system, but mainly in the northern part of the region and not in the southern part (Landsnet, 2018b). Besides these two challenges, a third challenge is that the region is not self-sufficient. Even though there are 12 hydropower plants in the West Fjords, the region does not generate enough electricity in order to be self-sufficient and needs to import about 40% of electricity via the West Line from other parts of Iceland in order to meet the region's demand (GREBE, 2016; OV, n.d.). This shows that any disruption in the West Line is detrimental for the electricity supply to customers in the region.

Thus, seeing as the region is already not self-sufficient and that a secure delivery of electricity heavily depends on the region's West Line, the additional projected demand will likely to hinder the reliable delivery of electricity in the populous parts of the West Fjords region. In addition to these operational challenges, the principal problem as argued before are harsh weather conditions. The cascade of problems that weather conditions can cause can be illustrated by way of the winter conditions in 2019. As could be seen in Section 4.3.4, the winter of 2019 was especially harsh leading to a record of back up power generation, the second highest amount of system minutes, and second lowest score for the reliability index in the past 9 years. These numbers show the susceptibility of both the distribution and transmission system to weather conditions. The increase in extreme weather events resulting from climate change will only make matters worse if nothing is done in order to increase the reliability and resilience of both the transmission and distribution system.

4.5 Discussion

4.5.1 International comparison

In order to compare the reliability of the Icelandic grid to other grids, the SAIDI and SAIFI indicators have to be used since Landsnet uses its own reliability indicators that are not used internationally. The data for the indicators were retrieved from the World Bank, since Landsnet does not publish data necessary for the calculations. It should be noted that the data used mostly focusses on businesses, and not necessarily on household customers. However, it does give a general indication of the reliability of each national grid.

Table 6 shows the SAIDI, SAIFI, and CAIDI indicators for Iceland and 9 other countries. The countries used for comparison are the Nordic countries (Denmark, Sweden, Finland, Norway), and countries where the share of electricity generated from renewable sources is also high such as Albania, Paraguay, and Costa Rica. The countries of New Zealand and Cyprus are included as these are isolated grids (not interconnected to any other grid) like Iceland. As can be seen in Table 6, even though the three indicators are used to indicate the reliability of a power system they should not be used separately. For example, Finland ranks first in both the SAIDI and SAIFI indicator, but ranks fifth in the CAIDI indicator. Conversely, Paraguay and Albania score worst in both the SAIDI and SAIFI indicators, but score second and sixth for the CAIDI indicator, respectively. In other words, low scores for the SAIDI and SAIFI indicators might still give a relatively high value for the CAIDI indicator, as well high scores for the SAIDI and SAIFI indicators resulting in a low CAIDI score.

Table 6 - Reliability indicators in 2020 and share of electricity generated from RE sources in 2020 in the last column (Based on: Our World in Data, 2021; World Bank Group, n.d.-a, n.d.-b)

Country	SAIDI (hrs)	SAIFI	CAIDI (hrs)	Share (%) RE
Iceland	0.63	0.41	1.54	99.99
Denmark	0.50	0.50	1	78.21
Sweden	0.61	0.66	0.92	67.62
Finland	0.20	0.16	1.25	49.94
Norway	1.50	1.30	1.15	98.79
Albania	33.46	22	1.52	100
Paraguay	21.9	22.80	0.96	100
Costa Rica	0.54	0.21	2.57	99.84
New Zealand	3.77	2.14	1.76	81.12
Cyprus	0.55	0.22	2.5	11.19

The data for Iceland shows that a customer experienced an average outage duration of 1.54 hours per outage in 2020. This is the longest duration of all the Nordic countries and higher than the countries with 100% share of electricity produced by RES (Albania and Paraguay), but lower than the two other countries with isolated grids (New Zealand and Cyprus). This shows the inaccuracy of using the CAIDI indicator alone to assess grid reliability: both Albania and Paraguay for example perform worse than Iceland on both the SAIDI and SAIFI indicator, but have a lower CAIDI score. Comparing the SAIDI, SAIFI, and CAIDI scores for the West Fjord's distribution system, it can be seen that the SAIDI indicator is almost 5 times higher in the West Fjords than in Iceland, and the SAIFI indicator is almost 6 times higher in the West Fjords than in Iceland.

There are a multitude of factors that influence the reliability of a power system. It does not solely rely on an operator's ability to cope with adverse weather conditions: it relates back to the security and adequacy aspects of reliability. To illustrate, in the case of Albania, the country fully relies on hydropower for its electricity generation, but in dry years electricity demand exceeds supply and electricity has to be imported from other countries (OST, 2018). However, next to the dependence on only one source of electricity generation, the distribution network is deemed to be inadequate, electricity losses are high (accounting for 21.7% of total electricity consumption in 2019), no forecasting of electricity demand is carried out, and there is a general lack of real-time information (IRENA, 2021). All of these factors reflect the need for more generation flexibility and a more varied and diverse generation capacity in order to balance supply and demand better, and goes beyond grid reliability solely being affected by weather conditions. This also holds true for Paraguay, where hydropower supplies 100% of the domestic electricity demand by using only 35% of the domestic installed hydroelectric capacity and consequently exporting the remaining generated electricity (IHA, 2019). So even though there is a hydroelectric surplus in Paraguay, again, the inefficiency and high losses in the transmission and distribution networks combined with a lack of strategic energy planning impact the reliability of the power system (Pappis et al., 2021). These two examples show that it is not possible to meaningfully assess the reliability of a power system only based on the three indicators. Additionally, the consequences of climate change are especially dire for countries that fully rely on hydropower for electricity generation such as Paraguay and Albania, and for instance Norway. For the first two countries, the effects of climate change can lead to reduced runoff and precipitation, and changes in the seasonality and variability of river flows and precipitation which can reduce hydropower production (ESMAP, 2009; Rivarola Sosa et al., 2011). Whilst Norway might seem similar to Iceland, the hydropower plants in Norway depend on snowmelt and precipitation, while hydropower plants in Iceland solely depend on glacier melt and are thus less susceptible to the consequences of climate change, such as droughts (Zheng & Breitschopf, 2020)

Another key point is that the importance of a reliable electricity supply has an additional dimension in Iceland. The largest share of electricity is consumed by the power intensive industry, and for this sector it is of paramount importance that the generation capacity can meet demand at all times. Any disruption can be detrimental for the power intensive industry and its equipment, even if the disruptions are short. For this reason, power intensive industry plants are often built with their own power plants in close vicinity. This is different from most countries where the largest share of electricity is consumed by for instance the residential sector such as in Albania and Paraguay, and thus adding new generation capacity is not the most urgent matter (IRENA, 2021; Pappis et al., 2021).

4.5.2 Main reliability challenges

Most of the literature on the reliability of a power system discusses the impact that increasing the share of renewable energy can have on the grid, with less focus on systems that already have a high share of renewable energy in the electricity generation mix such as Iceland (see: Accenture, 2020; Singh et al., 2019; World Economic Forum, 2021). However, in general the reliability of a power system is mainly determined by its ability to balance supply and demand. When an imbalance between supply and demand occurs the stability of the power system is impacted. An imbalance can cause voltage collapse, loss of synchronism, overloads, or frequency deviations, and can consequently lead to system instability and as a result power outages (Ourahou et al., 2020). Of these, voltage and frequency control are the two most important to manage in order to maintain system stability. In isolated systems such as Iceland the impact of voltage fluctuations are more severe and frequency excursions are larger than in interconnected systems, according to Merino et al. (2014). Landsnet sets strict limits for frequency quality that are controlled by regulatory power. The frequency of the Icelandic power system is 50 Hertz (Hz) and deviates when the balance between supply and demand changes. The frequency must be kept within a certain limit in order to function well and this is achieved by matching the electricity entering the grid exactly with the electricity exiting the grid, since alternating current (AC) electricity cannot be stored in the grid. The frequency limit for the Icelandic grid is 1% on either side of the system frequency of 50 Hz for 99.5% of the time, and 4-6% on either side of 50 Hz for 100% of the time (Landsnet, 2017). The limits are managed through frequency regulation/regulatory power where either generation output is decreased (down regulation) or increased (up regulation) depending on the situation (Blumsack, n.d.-a). When frequency regulation is not a sufficient measure for a given situation, the reserves mentioned before (part of the ancillary services) have to be used.

The same holds true for the delivery voltage in a power system: if the voltage is too high, this can overload the connected equipment. If the voltage is too low, the connected equipment will not be able to function properly and can lead to voltage collapse (Sedano & Brown, 2004). The delivery voltage quality limits in Iceland are measured annually at 6 points of delivery across the grid, and must be within a +10/-10% of each point's rated voltage (Landsnet, 2017). As was mentioned as one of the responsibilities of TSOs, adequate reactive power is needed in order to maintain voltage quality. The necessary regulatory power needed for voltage and frequency control can be supplied by other grids in interconnected grids. For this reason, TSOs of isolated grids are looking more into using technologies such as battery storage, micro-grids, and V2G to provide ancillary services such as frequency control, voltage control, and emergency services, since assistance from other grids is not an option (Banshwar et al., 2017; Khooban et al, 2016; Yang et al., 2015). Another main challenge to the reliability of the Icelandic grid is that the transmission capacity is inadequate. According to Pérez-Arriaga et al. (2017) the Icelandic transmission network is ageing and frequently reaches its transmission capacity which will be exacerbated by increasing demand in the future.

4.5.3 Future challenges

To conclude this chapter, as is made clear by reliability indicators above, the most pressing issues are grid disturbances in transmission lines and cables that are mainly caused by adverse effects due to weather conditions. In the future, extreme weather events resulting from climate change will only exacerbate the frequency of disruptions and it effects, even more so than can already be seen. Reflecting back on the two elements that make up the concept of reliability, it can be concluded that the main issue here is in the transmission facilities and capacity (adequacy) and exposes the inadequacy in the security aspect's coping capacity and susceptibility of the power system. Future challenges will only further stress the ability to maintain power system stability.

Table 7 shows a summary of the electricity demand (general and total) in 2019 in the West Fjords and in Iceland, as well as the projected demand in 2050 according to the three EV Scenarios. The electricity consumption in 2019 amounted to 163 GWh in 2019 in the West Fjords, and the installed capacity of 34.65 MW is about half hydropower and half fossil fuel. OV's own hydropower plants and fossil fuel generators generate about 91 GWh of electricity.

Table 7 - Demand in the West Fjords and in Iceland in 2019 with total electricity demand, electricity generation and installed capacity, and future demand according to the EV Scenarios and the Reference Scenario. (Source: Landsnet, 2021a; OV, 2020; Orkustofnun, 2020a, 2020b)

	2019				**2050**				
	General Electricity demand (GWh)	**Total electricity demand (GWh)**	**Electricity generation (GWh)**	**Installed capacity (MW)**	**Scenario 1 general demand (GWh)**	**Scenario 2 general demand (GWh)**	**Scenario 3 general demand (GWh)**	**Reference general demand (GWh)**	**Planned capacity (MW)**
West Fjords	88	163	91	35	158	158	149	100	55
Iceland	3,812	18,958	19,489	2,923	8,228	8,219	7,777	5,200	

As could be seen from the West Fjord's analysis, new generation capacity has to be installed in order for the region to be self-sufficient and increase the security of electricity supply. OV currently generates only 60% of the region's electricity demand and therefore the installed capacity will not be sufficient to accommodate for the EV Scenarios, nor the Reference Scenario, in the future. Moreover, while real-time load forecasting is paramount for the reliable operation of the grid, the increase in EVs will create a more volatile load profile that will become more and more difficult for TSOs to accurately forecast load (Alizadeh et al., 2010). Furthermore, the region's distribution equipment is vulnerable to adverse weather conditions, and 40% of its electricity demand needs to be imported through the only line that connects to the main transmission grid, the West Line. Both factors will become increasingly more threatening to a reliable distribution system and security of electricity supply. It is imperative for new measures to address the two elements of power system reliability: security and adequacy (see Figure 22). The next chapter will focus on the current and planned strategies to improve grid reliability and security of electricity supply.

Chapter 5 - Grid strategies

5.1 Introduction

This Chapter will answer the 5th sub-question: "What are the currently proposed strategies to improve reliability and electricity security of supply?". In 2020 the Icelandic Government published its first long-term Energy Policy consisting of plans up to 2050. In this Future Vision report the following two long-term goals are mentioned: "Energy security has been achieved through a supply of varied renewable energy options and sound infrastructure" and "[t]he energy network is smart and flexible, with no waste". (Ministry of Industries and Innovation, 2020, p.9). As shown in the previous chapter, achieving these two objectives mean that the power system needs to be improved. This chapter will build upon the previous chapter by creating an overview of what is currently being done in order to improve the power system, and what still needs to be done in order to accommodate for future electricity demand increases.

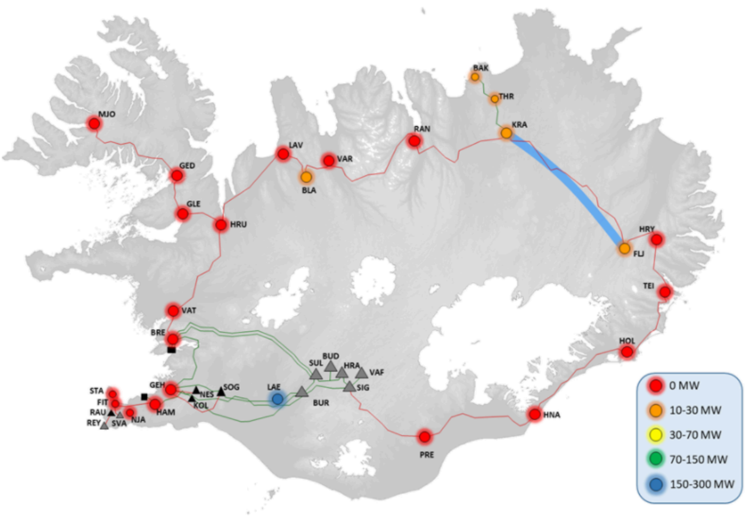
5.2 Methodology

A literature review was carried out in order to find out what the currently proposed strategies are to improve the reliability of the grid and to improve the security of electricity supply, and to synthesise the strategies into an overview. The reviewed literature consisted of government documents, policy documents, and reports published by the West Fjords' DSO OV and the TSO Landsnet. The primary sources were the OV 2020 annual performance report and the long-term development plan report and short term action plan by Landsnet.

5.3 Results and discussion

5.3.1 Capacity building strategies - short term (2021-2023)

Landsnet is continuously working to increase the reliability and the security of electricity supply through grid reinforcement strategies. The most widely used ways to reinforce the grid are to build new high voltage lines and substations, replacing transmission lines with higher voltage transmission lines, replacing substation equipment for optimal grid operation, upgrading conductors, and adding transformers in substations in order to be able to handle higher loads (Ciupuliga, 2013). These measures are all included in the strategies proposed by Landsnet with the intention to increase transmission capacity.



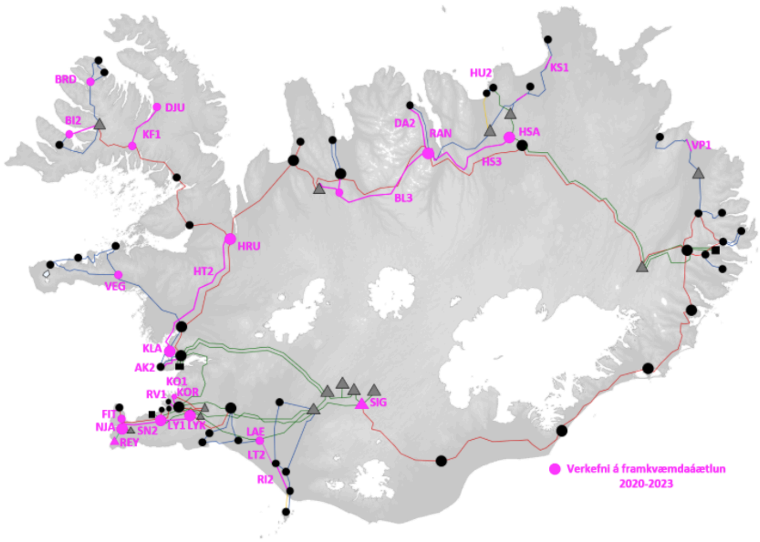


Figure 38 - Available transmission capacity in points of delivery. The West Line in the West Fjords can be seen as the connection between the MJO and the GED substations. Source: Landsnet, 2021e

Figure 39 - Planned strategies that will start construction in 2020-2023. Source: Landsnet, 2021f.

As can be seen in Figure 38, there is little to no available transmission capacity to add to points of delivery on top of peak demand. In this context, the point of delivery is the connection where the transmission system supplies electricity to the distribution system. This means that there is no possibility to increase the supply of electricity without overloading the point of delivery. In addition to inadequate available transmission capacity, the harsh weather conditions necessitate measures that reduce the vulnerability of transmission equipment to such conditions. In order to increase capacity, Landsnet's roadmap provides an overview of the planned strategies that are expected to start construction in 2021-2023 (see Figure 39). The initial action plan for 2021-2023 was changed by adding four new strategies as a result of the winter in 2019 (Landsnet, 2021a). The consequences of the 2019 winter discussed in Chapter 4 changed the priorities of the 2021-2023 action plan. The harsh winter conditions in 2019 caused severe damage to substations and transmission lines due to strong winds, icing, and snow. In a report prepared by Landsnet the following conclusions were drawn as a result: N-1 connections are vital in order to increase security of electricity supply and reliability, transmission capacity between regions needs to be increased by 15% (to 500 MW), and back up generators are a crucial part in ensuring security of supply during disruptions resulting from weather conditions (Landsnet, 2020). The N-1 connections are a recurring strategies in plans and policy documents by the Icelandic Government, Landsnet, and OV. In the context of the Icelandic transmission grid, the N-1 connections refer to connection that implement the N-1 security criterion discussed in Section 4.4.2

The newly added strategies in the current action plan aim to decrease the vulnerability of transmission to weather conditions by reinforcing transmission lines or renovating substations. In addition to these new plans, a more extensive overview of the planned strategies can be seen in Table 8. The strategies in Table 8 only include plans that will start and finish construction within the timeframe of 2021-2023 (for complete list see Appendix B). Most of the short-term strategies are planned in the West Fjords and in the Southern Peninsula, and none are planned in the Southern Region that will start and finish construction between 2021 and 2023. The combined costs of the twelve strategies in Table 8 is at least €95 million and including only strategies that will start and finish construction in the next two years. The most expensive strategy is the construction of the new Njarðvíkurheiði substation in the Southern Peninsula due to the amount of new equipment that will be installed. This strategy was also one of the four strategies that was added after the 2019 winter. The other three new strategies are the Reykjanesvirkjun substation expansion, the Breiðadalur substation renovation, and the Hrútatunga substation upgrade.

Table 8 - Planned strategies that will start and finish construction during 2021-2023. Names of transmission equipment and region are added to the plans to enable identification on Figure 2. Based on: Landsnet, 2021a

Plan	Construction	Strategy	Goal	Costs
Húsavík point of delivery (HU2 - *N*)	2021-2021	New point of delivery	Current transmission line is the oldest in the transmission system, new delivery point improves reliablity, N-1 connection	€ 747,166
Vopnafjörður line 1 (VP1 - *NE*)	2021-2021	Reinforce regional transmission line by replacing part of it with underground cable	Decrease vulnerability to weather conditions, increase security and reliability	€ 3,328,288
Southern Peninsula line 2 (SN2 - *SP*)	2021-2022	New 220 kV transmission line between the Capital Region and the Southern Peninsula	Enables N-1 criterion	€ 15,819,557
Reykjanesvirkjun substation expansion (REY - *CR*)	2021-2022	30 MW substation expansion	Increase transmission capacity	€ 2,153,198
Breiðadalur substation (BRD - *WF*)	2021-2022	Renovate ageing substation	Improve reliability northern West Fjords	€ 3,192,439
Hrútatunga substation (HRU - *WF*)	2021-2023	New substation and upgrade transmission equipment	Increase transmission capacity and reliability	€ 7,879,212
Njarðvíkurheiði substation (NJA - *SP*)	2021-2023	New substation with 220 kV switchgear, 220/132 kV transformers	Increase transmission capacity and reliability	€ 31,734,208
Rangávellir transformers (RAN - *N*)	2022-2022	Increase voltage 132/66 kV	Increase transmission capacity and security of supply in Eyjafjörður	€ 2,961,497

Plan	Construc-tion	Strategy	Goal	Costs
Suðurfjörður West Fjords reinforce-ment (*WF*)	2022-2023	Transmission system rein-forcement by mesh connec-tion in Breiðadalur, Mjólkár and Keldeyrar	Improve reliability in southern West Fjords	€ 16,390,120
Vegamót substation (VEG - *W*)	2022-2023	Renovate substation	Improve reliablity Snœfellsnes	€ 2,608,291
Straumsvík switch (*SP*)	2022-2023	New substation equipment	Maintain reliability of Lyk-lafells line 1	€ 747,166
Korpa substation (KOR - *CR*)	2022-2023	New substation to replace ageing substation	Improve security of supply in Reykjavík	€ 8,171,286

5.3.2 Strategies in the West Fjords

The three strategies for the West Fjords region in Table 8 will be carried out by Landsnet to improve the transmission system. To improve the distribution system in the West Fjords, OV carries out its own strategies to improve the reliability and security of electricity supply. Grid reinforcement strategies are needed in distribution systems in order to provide secure and reliable connections for end-users and to be able to operate the distribution grid in a satisfactory manner. Both points are threatened by increasing loads, ageing infrastructure, inadequate transmission capacity, and growing restoration times (EURELECTRIC, 2013). In recent years, the introduction of smart grid technology has greatly improved the amount of outage minutes and restoration time in the West Fjords (Vestfirdir, 2019). However, the effects are substantial in the southern part of the region, but less so in the northern part of the region (Landsnet, 2019b).

The most recent performance report from 2020 announced strategies that will start construction in 2021 that consist of the construction of new underground cables in the northeast, southeast, and northwest; construction of a new transformer in the southwest; and renovating substations in the northwest (OV, 2021). In addition, installing back-up power generators are continuously included in OV's annual strategies because of the limited amount of alternatives. Back-up power generators generated 892 MWh of electricity in 2020 as opposed to 97 GWh generated by hydropower plants, being especially important as the main source of electricity in Flatey, an island off the south coast of the region (OV, 2021).

There are several strategies that are considered in the West Fjords that would greatly improve the reliability and security of electricity, but require substantial investments. The first is the construction of a hydropower plant in the northwest of the region. OV (2021) stated that generation capacity has to be increased with 5 to 20 MW to be able to meet electricity demand. The previous Chapter showed that in 2019, an installed hydropower capacity of plants owned by OV of about 17 MW generated about 60% of the region's electricity demand. Thus, if only hydropower is taken into account in order for the region to be self-sufficient an installed capacity of about 31 MW was required for the 2019 electricity demand levels. The 14 MW of additional hydropower capacity that is needed in order for the region to be self-sufficient, shows that OV's estimate is currently sufficient to meet the region's electricity demand on its own. Be that as it may, this is an adequate estimate for current electricity demand. It should be taken into account that electricity demand will increase in the future and that this estimate will not be adequate anymore. The proposed hydropower plant Hvalárvirkjun in the northeast of the region would increase generation capacity by 55 MW and would be able to generate 320-340 GWh per year, but its construction has been contested in recent years on environmental protection grounds (Hafstad, 2019; HS Orka, n.d.; Landsnet, 2019b). Nevertheless, the plant has been included in the energy utilisation category in the Master Plan for Nature Protection and Energy Utilisation since 2013 (Rammaáætlun, n.d.-b). The Master Plan is an institutional tool that is used to "bride opposing views and interests regarding land use in areas rich in energy resources in Iceland", and has four categories for potential power plants starting with plant exploration in the power plant option, protection category, on hold category, to the energy utilisation category (Rammaáætlun, n.d.-a). The fact that the Hvalárvirkjun is in the last category indicates that all necessary processes and assessments have been carried out and that the power plant could theoretically be built, if it were not for the connection costs being a hinderance at the moment. The second strategy considered is to construct a new high voltage transmission line along the West Line from Hrútatunga to Mjólká and thus enable the N-1 criterion. At the moment, an N-1 connection is not possible in the West Fjords, because there is only one transmission line connecting the transmission system to the distribution system, namely the West Line. However, constructing the 160 km long transmission line would cost at least €80 million, and most likely increase the transmission costs (OV, 2021). The third strategy considered by OV is a new proposed power plant in the south of the region, which could increase generation capacity by 15-20 MW and enable a N-1 connection. Yet, this plan is again met with resistance due to environmental concerns: discussions are taking place whether this area should be designated as a national park and thus prohibit the exploitation of resources necessary for the power plant. These three proposed strategies are either still on hold pending approval after investigation if the plans are in accordance with environmental legislation, or because the plans require a substantial investment that cannot be financed at this time. As can be seen, all strategies focus heavily on enabling the N-1 criterion. The N-1 criterion features in most of the strategies since in a proposed piece of legislation, the Government expressed the goal to ensure the reliability and security of electricity for all end-users through establishing N-1 connections across the county (OV, 2021). Seeing as there is not one N-1 connection in the entire West Fjords region, it is not surprising that all strategies are focussed towards achieving that aim.

5.3.3 Capacity building strategies - long-term (-2030)

Besides the short-term strategies discussed in the previous Section, Landsnet's has a long-term ten year plan that aims to improve security of supply and reliability by extensive plans across the country. The ten year plan entails constructing a new 220 kV transmission line network that follows the blue line in Figure 41, ranging from the Southern Peninsula, through the Western Region to the Northwestern Region, and via the Northeastern Region to the Eastern Region. The total investment required for the construction of this network is estimated to be at least €611 million (Landsnet, 2021a). This new network will consist of the following five increments of 220 kV voltage lines (Landsnet, 2021b, 2021d):

1. Krafla line 3 (between Fljotsdalur and Krafla)
2. Holasandslina 3 (Krafla and Akureyri)
3. Blanda line 3
4. 220 kV transmission line Hvalfjordur - Hrutafjodur
5. 220 kV transmission line Hrutafjordur - Blanda

The construction of new transmission equipment that are necessary for these five transmission line increments can be seen in Figure 40. As can be seen in Figure 41, the available capacity will significantly improve compared to the capacity available in the previous section. The new available capacity was calculated based on additional capacity as a result of the above mentioned plans, and a scenario which projects a general electricity demand of about 4,700 GWh and a total electricity demand of 22,000 GWh by 2030 (Landsnet, 2021c). The general electricity demand used is about 900 GWh lower than Scenario 1 and 200 GWh lower than Scenarios 2 and 3 (see Section 3.5). Thus, even though the available capacity increases significantly it is likely that the measures proposed will not be enough for the projected electricity demand in this thesis.

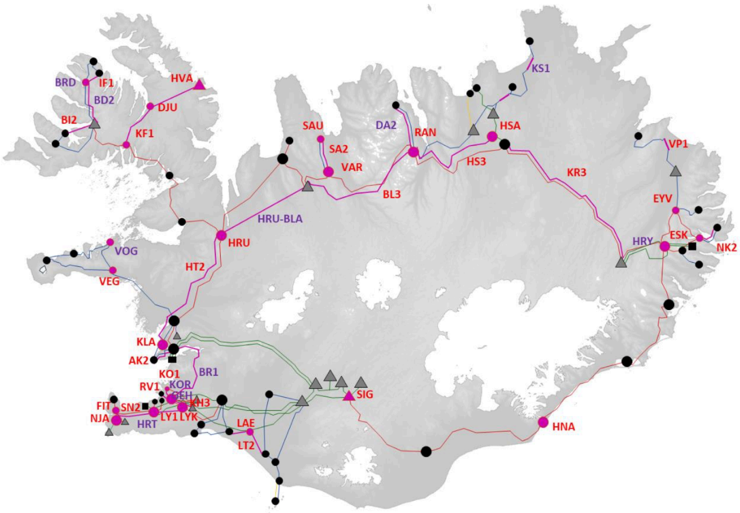


Figure 40 - Strategies in Landsnet's ten year plan can be seen in red. Source: Landsnet, 2020

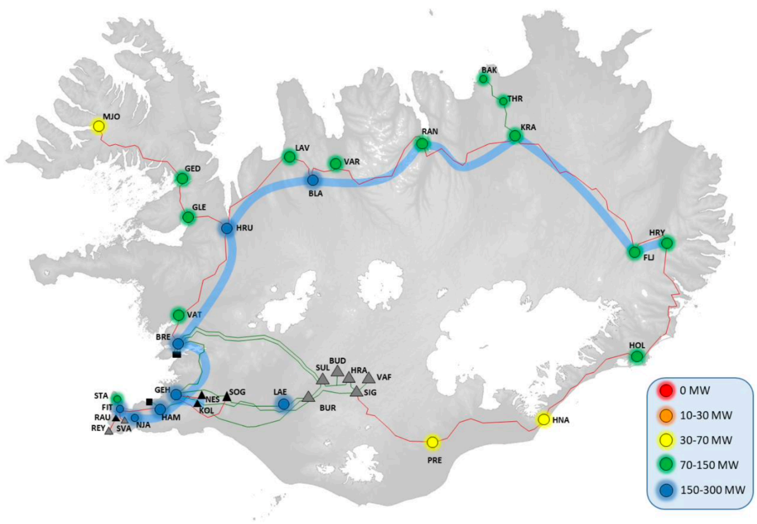


Figure 41 - Available capacity in delivery points in 2030 after the implementation of Landsnet's ten year plan strategies. Source: Landsnet, 2021b

While the goal of the ten year plan is to improve the reliability and security of electricity supply, Landsnet did not publish the estimated effects of all five strategies on the reliability indicators but only for strategies 1 and 2. It is estimated that the combination of lines 1 and 2, Krafla line 3 and Holasandslina 3, will decrease the SRA indicator by 11.5% (-0.097 MW/MW year) and the SMS index by 1.49 minutes compared to 2017 levels (Landsnet, 2021a). In 2017, the indicators yielded scores of 42.5 minutes for the SMS index, and 0.93 for the SRA index (Landsnet, 2018a). The reduction in the SRA indicator is mainly due to the Krafla line, and the improvement of the SMS indicator is due to the Holasandslina. Neither lines are expected to have a significant effect on the KM index. It can be argued that the effects of the combination of the two lines do not seem significant, however it should be noted that these two lines represent a part of the ten year plan located in the northeast of Iceland and do not indicate the total improvements of the reliability indicators as a result of the ten year plan. Moreover, on a regional scale the two lines will improve the amount of outage minutes in the region. This is necessary because the SMS indicator yielded the highest 5-year average score in the Northeastern region, out of all regions.

In case the short- and long-term strategies are not sufficient after 2030 and will not lead to adequate transmission capacity, Landsnet developed three scenarios that will be additional to the previous strategies. Table 9 shows that the first two strategies are in the Highland Line category and consist of constructing high voltage lines across the Highlands located in the centre of the country. The third strategy is in the Regional line category and aims to reinforce the transmission line between the Eastern region and the Southern Region.

Table 9 - Landsnet's three long term strategies of continued development to improve transmission capacity (2050) (Landsnet, 2021b, 2021c)

Highland Line	Regional Line
H.1: new 220 kV line across the Highlands + 50 km underground	**B:** Reinforcement/reconstruction of transmission line between Sigalda and Fljótsdal to 220 kV line
H.2: 150/300 kV direct current (DC) connection across the Highlands (200 km)	

Figure 42 shows the ten year plan (in grey) in addition to the Highland Line Category strategies (H.1 in solid green and H.2 in dashed green), and the Regional Line Category strategy (blue line). Landsnet carried out an MCA in order to discern which strategy is the most beneficial in terms of increasing security of electricity supply, improving reliability of the grid, and which are the most-cost effective and least adverse to the environment.

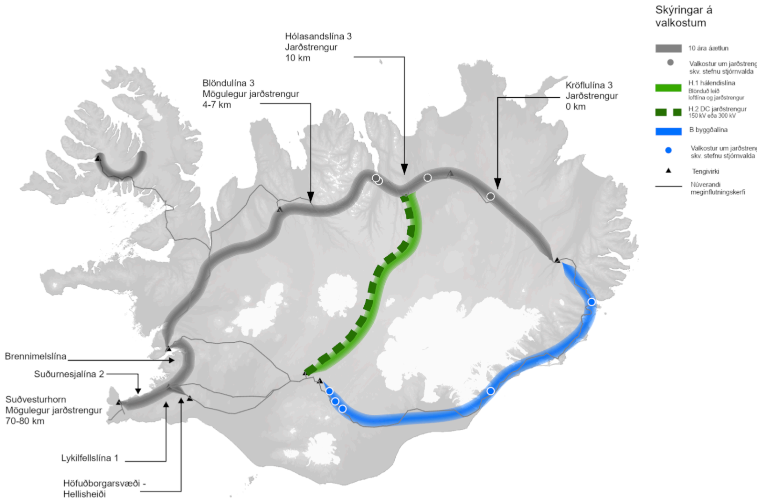


Figure 42 - Long-term strategies. Source: Landsnet, 2021c

Both of he Highland Line strategies are expected to have positive effects on the reliability and security of supply, with the greatest impact on the security of supply between the north and the east of the country. In turn, the Regional Line strategy will improve security of supply along the route of the transmission line, and provide new locations of local energy supply in the southeast and east (Landsnet, 2021c). The cost-effectiveness of each of the strategies is compared according to national economic costs and macro-economic benefits such as the discounted construction costs and the payback period. The costs and benefits are compared against a scenario where no additional reinforcements are carried out in the current system, and against the ten year plan. Again, the costs were calculated according to an electricity forecast which projects a general electricity demand of 6,700 GWh and a total electricity demand of 23,715 GWh by 2050. As Table 10 shows, under this scenario the total costs of construction is highest for the H.2 strategy at €332 million, and lowest for the ten year plan at €247 million. The difference in costs in the Highland Line strategies is that the H.2 strategy uses a DC transmission line which is more efficient, but also more expensive (Landsnet, 2021c). However, when looking at the national economic costs that include the costs due to transmission losses and restrictions, and operational disruptions the costs are highest for the ten year plan at €228 million, and lowest for the Regional Line strategy at €219 million. This strategy also has the highest amount of macro-economic savings compared to the current system at €213 million.

Table 10 - Overview of economic assessment of long term strategies during 2020-2050. Costs expressed in million €. Based on: Landsnet, 2021C

	Ten year plan	H.1	H.2	B	Current system
Transmission losses	213.34	210.90	210.90	209.70	226.77
Transmission limits	1.49	1.49	1.49	1.49	49.90
Improved utilisation power plants	-114.75	-114.75	-114.75	-114.75	0
Operational disruptions	127.61	125.97	125.97	122.71	155.24
Total	**227.69**	**223.62**	**223.62**	**219.14**	**431.91**
Benefits compared to current system	204.22	204.22	204.22	212.77	-
Discounted construction costs	247.03	260.42	332.30	323.33	-
Payback period	**37 years**	**37 years**	**46 years**	**44 years**	-

The environmental criteria are perhaps the most stringent, since every plan has to be assessed on whether the transmission lines are located in protected areas, or even too close to protected areas, and how much each plan impacts and changes the appearance of the environment. The main environmental concern regarding the Regional Line strategy is that the transmission lines will be constructed for a large part in nature conservation areas (Landsnet, 2021c). In turn, the main concern for the Highland Line strategies is that construction will be carried out in the Highlands, which are located in the centre of the country and are mostly wilderness areas. Plans to designate the entire Highlands as a national parks and thus a protected area could negatively impact future development of this strategy. However at present, the environmental impact is considered to be higher for the Regional Line strategy due to the existing designated nature conservation areas that are in close vicinity of proposed the transmission equipment.

5.4 Discussion

It is unlikely that the planned strategies described above will be sufficient long-term solutions to increase the reliability and security of electricity supply. According to Pérez-Arriaga et al. (2017) a reliable power supply is a result of strategic energy policy, that in turn is built upon the following three points:

1. **Adequacy:** ensure the existence of adequate generation and transmission available capacity, both expected and installed to meet the projected demand.
2. **Firmness:** supply infrastructure is available when needed. Firmness depends mainly on operation schedules of installed capacity.

3. **Security:** achieved by readiness of existing network and generation capacity to respond to load requirements when necessary.

All three points will be threatened by weather conditions and increasing demand even with the short- and long-term planned strategies. Additionally, neither the short-term strategies nor the long-term strategies explicitly take into account the impact of increase in EVs, subsequent electricity demand and charging. The charging of EVs makes for volatile loads. In other words, when EVs are charged in an uncontrolled manner a certain degree of volatility is introduced on the grid which makes frequency and voltage control more difficult.

One of the points of contention that is raised when looking at Landsnet's strategies is that the main approach is to extend and reinforce transmission lines. Extending and reinforcing transmission lines requires substantial investments and will almost certainly increase the cost of electricity transmission. Additionally, increasing the capacity of transmission lines alone will not increase reliability in the long-term. Ren et al. (2008) state that when transmission lines are reinforced in order to increase capacity, the immediate effect is that the grid will become more reliable since its capacity margin increased. However, on a longer timescale the power flows of the grid will eventually increase to take advantage of the increased margin, and thus reduce the capacity margin of the transmission lines again. In other words, increasing the capacity margin in transmission lines will eventually not be an adequate strategy to increase reliability. Moreover, the distance over which the electricity has to be transmitted also needs to be taken into account. Transmission losses increase in line with the distance over which it is transmitted. The strategies discussed involve electricity being transmitted over great distances, which increases the losses and increases the probability of voltage drops (Sedano & Brown, 2004). The voltage drops in turn have to be mitigated by equipment further incurring costs of transmission. Furthermore, an additional factor that necessitates continuous and consistent reinforcement measures is the lifetime of transmission equipment. Landsnet states that the expected lifetime of transmission lines is 50 years and 40 years for substations and its equipment (Landsnet, 2021a). In 2020, almost 16% of all transmission lines and cables already exceeded the lifetime of 50 years, and a quarter of the substations exceeded the 40-year lifetime (Landsnet, n.d.-a). For the remaining lines, cables, and substations the end of the lifetimes are approaching because most of the remaining infrastructure was built in the 1980s and 1990s. To illustrate, by the end of the time period of the long-term strategies almost all transmission equipment has had to be either completely replaced or reinforced. On top of this, the fact that electricity demand is not static, as in electricity demand will continue to increase in the next 30 years, will exacerbate the need for continual reinforcement measures in addition to the factors mentioned. In other words, the capacity margin, transport losses, and lifetimes of transmission equipment present a perpetual need for reinforcement under the circumstance of increasing demand, and will therefore not be a long-term solution for improving reliability and stability. Equally important, the question that arises is whether solutions on a national level such as the three strategies described above, will actually meaningfully improve the reliability and security of supply in regional areas. For example, in the event that the

West Line in the West Fjords is reinforced the supply from the transmission grid to the distribution system at the point of delivery in Mjolka will be improved, but that does not necessarily ameliorate the issue of reliability in this region. Beyond that point, the distribution system is still troubled by for instance weather conditions.

Likewise, only installing more smart grids is unlikely to overcome reliability and security of electricity supply issues. While the introduction of a smart grid in the West Fjords in 2015 significantly reduced outage minutes, it is not a silver bullet for all reliability problems. Smart grids can greatly reduce restoration times but will not single-handedly prevent disruptions. Disruptions will have to be prevented by different measures, such as shortening transmission distances by placing generation facilities in the vicinity of end-users through for instance DER, or installing a micro-grid. Integrating smart grid technology with EV charging, such as through V2G technology, could be beneficial through its bi-directional exchange with the grid. Technology such as V2G is needed because not only should the generation and transmission capacity increase as a result of increasing electricity demand, the power system should also be prepared for the changing nature of loads. V2G technology can help to manage the volatility from EV loads, and thus help maintain the stability and reliability of the power system.

Finally, the continued use of back-up power generators, and even installing new ones every year, is a concern that comes forward in OV's strategies. While back-up power generators greatly increase the reliability and security of electricity supply in some areas, it is contradictory to the climate neutrality plans put forth by the Government, Landsnet, and OV. All three parties aim for a carbon neutral electricity supply by 2030, which is not possible when using back-up generators that run on diesel fuel, no matter how relatively insignificant the contribution of these generators to the total electricity supply is. Additionally, according to Pérez-Arriaga et al. (2017) installing diesel generators will not adequately solve network congestion in the entire Icelandic grid, due to the costs associated with running the diesel generators. Because of the costs the generators would only be cost-effective to be used to mitigate severe curtailments.

To conclude this chapter, the desire put forward in the Energy Vision 2050 that energy security will be achieved across the country through a sound, flexible, and smart electricity grid, will not be achieved through the short- and long-term strategies discussed. While the strategies will most likely improve energy security on a national level, and improve the reliability indicators, it is doubtful that regional issues will be resolved. The next chapter will offer an overview of two grid solutions that will progress towards the objectives set out in the Energy Vision 2050. A regional focus on the West Fjords will provide insights into whether the proposed Hvalárvirkjun hydropower plant will be more beneficial in regards to increasing the reliability and security of electricity supply, compared to the grid solutions of V2G technology and micro-grids.

Chapter 6 - Grid solutions

6.1 Introduction

This Chapter will answer the 6th and 7th sub-questions on what criteria grid solutions have to meet in order to increase the reliability and security of electricity supply in the West Fjords, and to what extent the grid solutions meet the selected criteria. The former is concerned with the methodological aspect, and the latter is a result of the methodological approach. The purpose of this chapter is to acknowledge the issues that hinder a reliable and secure supply of electricity, and to discover how the impacts of these issues can be ameliorated. As has become evident from the previous chapters, the impact of adverse weather conditions on transmission equipment and the fact that the West Fjords region is not self-sufficient regarding electricity generation and therefore has to import 40% of its electricity supply from the main transmission grid over the West Line, hinder a reliable and secure supply of electricity. These two factors combined make the future reliance on the West Line as the main supply route of electricity from the transmission system more insecure. Therefore, this chapter will argue that in order to ensure a reliable and secure supply of electricity, localised solutions have to be implemented. The future challenges as a result of harsh weather conditions becoming more extreme and more frequent due to climate change, and that not only will the electricity demand in the region increase but that the nature of this demand will also change, require different measures than that are currently in place. Whereas conventional loads can be accurately predicted, EVs present a more volatile load which can impact the stability and reliability of the grid. This is an additional factor that needs to be taken into account when assessing possible grid solutions. In this Chapter, three options were analysed by way of an MCA in order to discover the strengths and weaknesses according to four categories that relate to the concept of reliability discussed in Chapter 4 and the four dimensions for security of supply proposed by Pérez-Arriaga et al. (2017). The three options are the Hvalárvirkjun hydropower plant discussed in Section 5.3.2 as a strategy in the West Fjords, and the two grid solutions V2G technology, and micro-grid with DER. The chapter will start with a more extensive look at the selected options, followed by the description of the methodology followed in the MCA and how the criteria were measured. Finally, the results will be discussed in reference to previous chapters and will conclude with recommendations on how to improve the reliability and security of electricity supply in the West Fjords region.

6.2 Methodology

6.2.1 MCA option selection

The options that were chosen for the MCA were found through a literature review and from Chapter 5. The Hvalárvirkjun plant came forward as a strategy in the West Fjords in Section 5.3.2 as the only serious contender in the region and has been included in the final category of the Master Plan since 2013. The two grid solutions, V2G technology and the micro-grid with DER, were selected since both are widely featured in literature on how to improve the reliability and security of electricity supply. In this case, V2G technology utilises the EVs for demand response and ancillary services, while the micro-grid with DER improves self-sufficiency in electricity supply in residential areas. The main characteristics of the three options will be explained in more detail here.

Hvalárvirkjun hydropower plant

The first option was the Hvalárvirkjun hydropower power plant. This plant is offered throughout the OV annual reports as a solution to the region's self-insufficiency in electricity generation. The location of the proposed 55 MW Hvalárvirkjun hydropower plant is in the northeast of the West Fjords region, with the following characteristics (HS Orka, n.d.; Vesturkerk, n.d.-a):

- 3 reservoirs and 5 dams
- Installed capacity: 55 MWe
- Head: 315 metres
- Flow: 20 m^3/s
- Generation: 320-340 GWh/year (for 5,818 hrs/year)
- Owners: HS Orka (70%) and Vesturverk developer (30%)

The location of the plant has caused tension between the local population and environmental groups and agencies. Whereas proponents of the plant see the generation capacity that the plant adds and the possible jobs created for locals as more important than the potential detrimental environmental impact associated with the development and operation of this power plant, environmental groups and planning agencies claim that the plant would "reduce the largest continuous uninhabited wilderness in the West Fjords by 14 percent or 226 km^2" (Hafstad, 2019; Vesturkerk, 2016). The potential environmental destruction has galvanised the plant's opponents since the announcement of the plant to undertake action against its development. Nonetheless, the plant has been included in the final category of the Master Plan and could therefore potentially be built, but construction has not started as of yet (Vesturkerk, n.d.-b). The introduction of this new hydropower plant would increase the region's generation capacity from the currently installed capacity of about 35 MW to 90 MW and would be able to fully meet the region's electricity demand. In addition to the generation capacity, Vesturverk explains that the plant will provide flexible power to the national grid and reduce the likelihood of power shortages which, according to Landsnet, will occur more often in the future if additional capacity is not installed (Vesturkerk, 2016).

Landsnet bears the responsibility for the construction of transmission equipment to transmit the electricity from the power plant to the end-user (Vesturkerk, 2016). In order to do this Landsnet has proposed a new point of delivery in Ísafjörður that would have to be constructed for the Hvalárvirkjun plant which in turn would enable the N-1 criterion, in addition to the new electricity producers having to pay an annual fee to Landsnet in order to guarantee that electricity prices will not increase for customers (Rammaáætlun, 2021). According to 2011 estimates, the construction of the plant itself would cost about €30 million and the connection costs were found to be €0.038 per kWh per year, ranking amongst the least cost-effective out of all plants assessed in the Master Plan (Rammaáætlun, 2011). This means that if the plant were to generate 340 GWh per year, the connection costs would amount to more than €13 million per year. These costs are the responsibilities of the owners, HS Orka and Vesturverk.

V2G technology

The second option for consideration was V2G technology. V2G technology can provide ancillary services and demand response through its bi-directional connection to the grid. At present, V2G technology is not being used in Iceland and the only research available on its application in the country is limited to theory, not practice. An example of this is that in a study concerned with the application of V2G technology in the Nordic countries, its use in Iceland was not brought up or even suggested by experts in the domestic energy and transport sector (Kester et al., 2018). In most places, the research on the use of V2G is often studied in relation to its ability to facilitate RES integration (see: Ota et al., 2011; Taljegard et al., 2019). However, since RES integration is not an issue in Iceland, its benefits lie in its load management ability, potential to function as back-up power and storage, and to stabilise the grid through frequency and voltage control**.** There is a considerable potential for EVs to provide these benefits, assuming that the EVs are used on average for an hour in the morning and an hour in the evening. This means that EVs are in use less than 10% of the day and that for the remaining >90% when the vehicle is not in use and connected to the grid, the EVs' flexibility can be used to provide grid services. Load balancing and power system stabilisation will become increasingly important as the number of EVs increase in the near future. Through load management, V2G technology can reduce peak load by load shifting and as a result alleviate stress on the power system (Kester et al., 2018). Figure 43 shows that besides peak shaving, V2G charging can fill load valleys and charge off-peak when grid capacity is high compared to uncontrolled charging when demand generally peaks (Sørensen et al., 2018).

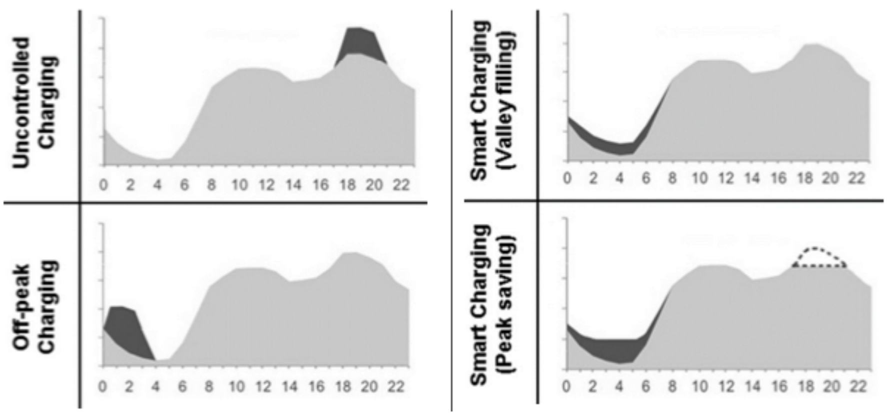


Figure 43 - Smart charging approaches EVs. (Source: García-Villalobos et al., 2014 in Sørensen et al., 2018).

Moreover, power quality can be maintained by frequency regulation (charging when frequency is rising and discharging when frequency is dropping) and through voltage support by providing reactive power (ABB, n.d.-a). Further, the ability to use EVs as back-up power and storage is advantageous especially in the West Fjords, since back-up diesel generators are an important part in the regional electricity supply due to frequent disruptions. Thus, replacing the back-up power generated by the diesel generators by power stored in EVs would therefore directly decrease the carbon footprint of electricity supply.

However, it should be taken into account that additional hardware and software are required to enable V2G technology as opposed to current forms of smart charging that make use of a uni-directional connection to the grid, such as V1G. Since electricity grids are AC and the battery in an EV is DC, all EVs require an adapter that transforms the AC from the grid into DC in order to be able to charge the EV battery. Fast chargers have this transformer built into the charging equipment so that the electricity that goes into the car is already DC and therefore does not have to be transformed in the vehicle itself (van Leemputten et al., 2020). Because the main characteristic of V2G is that it enables the injection of electricity back into the grid, another adapter is needed that transforms the battery's DC back into the grid's AC. The features of the smart charging ability and that electricity can be injected back into the grid in order to provide grid support is what makes V2G technology an extension of V1G, which only uses smart charging strategies. Currently, no EVs are equipped with this transformer on-board and thus have to be implemented in charging infrastructure, incurring additional installation costs.

Micro-grid with DER

The third and last option included in the MCA was a micro-grid with DER. A micro-grid can be defined as "a group of interconnected load and distributed energy resources within clearly defined electrical boundaries that act as a controllable entity with respect to the grid […] and can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode" (U.S. Department of Energy, 2011a). In other words, the main characteristics of a micro-grid are that it is local, smart, and independent solution (Wood, 2020). Generally, the longer the distance between the point of generation and the end-user becomes, the higher the power losses are. Decreasing the distance between generation and consumption by way of a micro-grid, decreases the losses associated with electricity distribution, and also reduces the susceptibility of transmission equipment to for instance harsh weather conditions (Gholami et al., 2015).

A micro-grid can operate both in island mode and in grid-connected mode. Connected to the main transmission grid, micro-grids can provide flexibility through enabling electricity exports and imports, ancillary services, and distribute the electricity received from the main grid (IRENA, 2019a; Yang et al., 2015). In isolated mode, so not connected to the main grid, micro-grids can provide electricity in remote locations where the development of new transmission lines are not cost-effective, or where power supply is unreliable with frequent outages as is the case in the West Fjords (IRENA, 2019a).

Generally, the technical and hardware requirements for micro-grids are a source of generation (for example: wind, hydro, or diesel generators), a storage option, advanced metering infrastructure for monitoring, micro-grid controllers, inverters, connection hardware to connect the main transmission grid to distribution grid, plug port, and software for control systems (IRENA, 2019a). In the West Fjords a number of diesel generators are already installed as became evident in Section 4.4. It was therefore assumed here that these generators would be the source of generation for the micro-grid to be used in combination with storage and small scale wind power. Wind power was chosen here as the generation technology over for instance small scale hydropower or geothermal, because the wind power potential in Iceland is severely under-utilised at the moment. According to Nawri et al. (2014), the annual wind conditions are not a limiting factor for wind energy production in Iceland —meaning that wind speeds are high enough for power production— and that "modest wind farms" have the potential to match small scale hydropower and geothermal plants. The reason why wind power is under-utilised at the moment is the lack of investments and support from energy producers. Due to the abundance of available hydropower and geothermal power sources, energy companies have historically never seen the need to invest in wind power (Askja Energy, n.d.-e). However, the introduction of wind power into the Icelandic generation mix can become a necessity in the future due to two reasons. First, hydropower in Iceland is dependent on river streamflows and glacial melt that exhibit a large annual variation with more flow in summer than in winter, while the annual wind power cycle follows the opposite variation cycle with higher wind speeds in winter than in summer (Nawri et al., 2014). In such a way, the two sources complement each other and can be an effective combination. Second, as a result of climate change glacial melting will be accelerated in the near future, which at first will increase hydropower generation but will decrease generation after peak run-off is reached due the loss of glacier mass causing decreasing flow (Sveinsson, 2016). Such a change is not expected for the wind cycle and thus wind power will likely become a necessity for the Icelandic generation mix in the future. More regionally, wind power has been studied as an alternative source of generation to reduce dependency on the main transmission grid in the West Fjords (Barajas, 2019). It is not possible to use geothermal resources in the region because there are no high temperature geothermal fields in the region, or in fact even close to the region (Mathews & Sowiżdżał, 2019).

The diesel generators are currently being used mainly for back-up power and located in the populated areas in the West Fjords. Two of the diesel generators are installed in the most densely populated area, which is also the area experiencing the most frequent electricity supply disruptions, with a total generation capacity of 15.1 MW (see Appendix A). Referring back to Section 4.4, the most populated cities are also the cities that experience frequent disturbances, namely Ísafjörður and Bolungarvík. By 2050, according to the projections in Chapter 3 this area in the West Fjords is expected to have the highest electricity demand and the most amount of EVs. According to Mathews & Sowiżdżał (2019) a Vestas 3.45 MW wind turbine could generate 10.4 GWh/year in Bolungarvík, the second most populated city, and two turbines located near the most populous city in the region, Ísafjörður, could generate 26.5 GWh/year. Therefore, in this MCA the micro-grid with DER as option 3 is located in the most populous area in the region, and will consist of two diesel generators and three large scale wind turbines with a total installed capacity of 25.45 MW.

6.2.2 Criteria selection

An MCA was used as a tool to translate the qualitative data on the two grid solutions and the Hvalárvirkjun power plant into a quantitative overview in order to discover the strengths and weaknesses of each option. The EC (n.d.) set out four steps that an MCA follows that will be explained in this section: define the objectives, evaluate the criteria, measure the goals, and assess the attributes. First, the objective reflects the end-goal of the MCA. Since the purpose of this thesis is to answer the question how the grid needs to be improved in order to accommodate for EV growth by 2050, two objectives were chosen. The primary objective is to increase the reliability and security of supply in the West Fjords in the context of EV growth. The secondary objective is to ensure that the West Fjords' electricity generation and distribution system is sustainable, in line with Government plans to achieve carbon neutrality by 2040.

The second step, the evaluation of criteria, required a set of criteria which indicate how that objective is achieved. Dodgson et al. (2009) argue that the grouping of criteria into categories or clusters can be helpful to create a structured overview of the different components that make up the overall objective. The reason for this is that in this way it can be verified whether a criterion actually helps achieving the objective and at the same time making easier to discern the most important factors that impact the objective. Thus, for this MCA four categories were created that reflect the most important factors discovered up to now in this research that are required in order to achieve the two objectives each consisting of individual criteria (see Table 11). The first two categories, security and adequacy, refer back to the definition of reliability discussed in Chapter 4 in addition to the dimensions of security of supply by Pérez-Arriaga et al. (2017). The last two categories, environmental and economic, refer to the criteria used by Landsnet to assess strategies as shown in Chapter 5. Likewise, the individual criteria in each category were partly based on Landsnet's criteria and partly on the dimensions of supply security by Pérez-Arriaga et al. (2017) and Heylen et al. (2018).

The third step denotes the goal of each criterion, or to put it differently the target of each criterion. As can been seen in Table 11, each goal indicates the whether it was desired that the options decrease or increase the criterion. Numerical data for each individual criterion were not always available, and therefore the goals were mainly qualitative and based on estimates retrieved from literature. This will be explained more extensively in the next section.

Lastly, the final step was the attribute which reflects whether the goals from the previous step were met. Again, since the targets were mainly qualitative, the extent to which the individual criterion met its own target was scored on a cardinal scale of measurement ranging from 1 to 5, based on qualitative metrics. A criterion received the (lowest) score of 1 when its goal was not at all met and a (highest) score of 5 when its goal was fully met. Thus, combining these four steps resulted in an overview of the aggregate score indicating the strengths and weaknesses of each of the options.

Table 11 - MCA for grid solutions in the West Fjords for the objective of increasing the reliability and security of electricity supply in the region to accommodate for future EV growth. Goal symbol indicated whether the goal is to increase or decrease criteria in order to achieve objective.

Category	Criteria	Goal	Attribute
Security	1. Susceptibility	↓	Received higher score if solution reduced susceptibility
	2. Coping capacity	↑	Received higher score if solution increased coping capacity
Adequacy	3. Generation flexibility	↑	Received higher score if solution increased generation flexibility
	4. Generation capacity	↑	Received higher score if solution increased generation capacity
	5. Transmission capacity	↑	Received higher score if solution increased transmission capacity
Environmental	6. Impact (construction, materials, extraction resources, infrastructure, location)	↓	Received lower score when environmental impact of solution was high
	7. Benefits (reduces carbon footprint electricity ie. reduces backup generators)	↑	Received higher score if solution was more environmentally beneficial than current system
Economic	8. Annualised costs	↓	Received lower score when annualised costs were high

6.2.3 Criteria measurement and context

In order to score the criteria certain parameters had to be set for every individual criterion due to the following three reasons: not all criteria could be assessed based on quantitative data, the options could not be assessed on the same absolute scale, and in order to discern the perspective of the stakeholders involved. Firstly, while criteria such as the generation capacity and installation costs could be ranked on a 1 to 5 scale because both could either be estimated or the data could be retrieved from literature, criteria such as environmental impact and susceptibility were more difficult to rank on an absolute scale because of their complexity and a lack of available data. Secondly, it had to be taken into account that the three options had different scales of impact: the generation capacity of a hydropower plant was naturally higher than the generation capacity of a smart charging technology, or a micro-grid. Assessing the three options on an absolute scale would overlook and minimise the benefits that each option could offer. Therefore, to counter the potential unfair assessment the criteria were assessed on a relative scale. Thirdly, the perspective of which stakeholder's interest the scores were based on needed to be clarified. As mentioned, the MCA was built upon two objectives, and as such the criteria were assessed from the perspective of the power system in the West Fjords, including both the West Fjords' DSO and the end-user. The manner and context in which the criteria were measured will be explained here.

A. Security

The criteria in this category refer back to the security aspect of the concept of reliability explained in Chapter 4, and were based on Heylen et al. (2018) who defined system security as "the ability of a system to handle disturbances" consisting of susceptibility and coping capacity.

The first criterion, susceptibility, indicates the level of vulnerability of the power system to threats originating from outside of the system. The susceptibility of the current transmission and distribution system was made evident in Chapter 4, showing that harsh weather conditions are detrimental to transmission equipment and thus hindering a secure and reliable supply of electricity, especially in the West Fjords. For this reason, options received a better score when it decreased the susceptibility of the system to adverse weather conditions.

The second criterion, coping capacity, is related to susceptibility in that it indicates the TSO and DSO's ability to manage an unwanted event originating from outside of the system and can be described as the response time to such an event, as was discussed in Section 4.3.3. This criterion in an extension of the previous, because if the the coping capacity of the system is not adequate and a threat cannot be mitigated the threat becomes an unwanted event and the power system has to be restored to its stable state. Examples of the coping capacity include the ability to provide power to energise key instrumentation and equipment during blackouts, battery load shedding in order to extend battery life, and having access to back-up generators to prevent blackouts (NEI, 2012). Also included is the ability to maintain stable operation by preventing voltage deviations or frequency excursions that can lead to outages if not mitigated. Thus, the options that can mitigate threats and can provide voltage support and frequency regulation received the highest score.

B. Adequacy

The criteria in the adequacy category were based on the second aspect of the concept of reliability and reflect the ability of a system to supply the electricity required by end-users. Brazil and de Hoog (2014) argue that there are three ways in which the increased uptake in EVs impacts the electricity grid and the ability of the power system to deliver the required electricity: peak load, voltage drop, and phase imbalances and power quality. First, the definition used for the first criterion, generation flexibility, is "the ability of a system to deploy its resources to meet changes in net load", and is determined by the "resources available and the magnitude, frequency, and duration of changes in the net load" (Lannoye et al., 2014). As such, the generation flexibility included how the system copes with the first consequence of EV uptake, the peak load.

The most recent data on peak load in the West Fjords is from 2018, when a peak load of 22.8 MW was reached, according to Landsnet (2019b). Regarding future EV growth and the impact on peak load, Engel et al. (2018) argue that while the electricity demand resulting from EVs is not necessarily the primary issue with EV integration, but that the change in the load profile is especially on a regional level. The Icelandic utilities' association Samorka (2020) noted a charging peak of 0.7 kW per EV around 19:00 every evening in Iceland, coinciding with the general load peak. During an average day, electricity demand peaks in the morning when people are getting ready for work, and later in the evening when people come home from work. Likewise, these are the times that people are most likely to charge their vehicles, especially after coming home in the evening. Since there was no data available on charging behaviour in the West Fjords, nor a distinction of charging behaviour between PHEVs and BEVs, this estimate was used to calculate the load added by all EVs during peak load in 2050. As can be seen in Table 12**,** during peak load at 19:00 in the evening, Scenarios 1 and 2 added about 5 MW of load, and the third Scenario added about 3.5 MW. However, assuming that it is likely that the peak found by Samorka will increase by 2050 due to the advances in charging technology, battery capacity, and the implementation of more fast chargers, the EV peak load added assumed a lower bound of 0.7 kW per EV and an upper bound of 1.4 kW. This resulted in an added peak of 10.9 MW in Scenarios 1 and 2, and 7.2 MW for Scenario 3.

When charging happens in an uncontrolled manner and an imbalance between supply and demand occurs, the increased uptake in EVs can lead to voltage deviations, frequency excursions and power losses, and as such can lead to power system instability. Thus, the generation flexibility criterion was scored regarding the extent to which options can balance load, provide voltage support and frequency control in order to increase flexibility and prevent system instability. The difference between this criterion and the coping capacity criterion in the previous category is that the coping capacity indicates the ability to mitigate threats on a longer time scale and refers more to physical threats while the flexibility criterion indicates the ability to maintain stability instantaneously.

Table 12 - Input data for the MCA in the West Fjords.

	2050		
	Scenario 1	**Scenario 2**	**Scenario 3**
BEVs	7,744	7,532	3,568
PHEVs	21	233	1,563
EV peak load (MW)	5.4 - 10.9	5.4 - 10.9	3.6 - 7.2
EV electricity demand (GWh)	23.97	23.78	14.40
General electricity demand (GWh)	158.13	157.95	149.46

	2050		
	Scenario 1	**Scenario 2**	**Scenario 3**
Share EV demand in region (%)	15.16	15.06	9.64
Hvalárvirkjun capacity (MW)	55		
Fleet EV storage capacity daily (MWh)	269.08	262.58	130.27
Micro-grid capacity (MW)	25.45		

The second criterion, the generation capacity, was scored on a relative scale. To asses the capacity of the EV fleet the following assumption were used (Electric Vehicle Database, n.d.; IEA, 2021; Söderbom, 2020; Steward, 2017):

- Average battery capacity of BEV: 60 kWh
- Average battery capacity of PHEV: 14 kWh
- DC-AC conversion efficiency: 90%
- maximum depth-of-discharge to preserve battery health: 80%

These assumptions led to a daily average storage capacity of 130 - 269 MWh depending on the EV Scenario, taking into account the daily fleet demand (see Table 12). In other words, after the daily driving demand the remaining 80.3% of the EVs available capacity can be used for V2G. In comparison, the hydropower plant has a generation capacity of 55 MWe and is able to generate 320-340 GWh/year, or on average 876 - 931 MWh daily. The installed capacity in the micro-grid with DER is 15.1 MW for the diesel generators that generated 959 MWh of electricity for back-up power in 2019 (see Appendix A). The wind turbines have a combined installed capacity of 10.35 MW and could generate 36.9 GWh per year. Thus, this criterion was scored on each option's relative generation or storage capacity.

The third criterion in this category, the transmission capacity, was scored based on the options' impact on the available transmission capacity. As argued by Pérez-Arriaga et al. (2017), the transmission capacity of the Icelandic grid has been far from adequate with inter-regional power flow exceeding the security limits put in place 28% of the time in 2014. The transmission capacity was expected to increase with the construction of new transmission equipment. Seeing as all large power plants have to be connected to the main grid, this would mean that the Hvalárvirkjun power plant would greatly improve transmission capacity, while at the same time enabling the N-1 criterion. The micro-grid only increased transmission capacity locally, and the V2G capacity was not expected to have a significant contribution.

C. Environmental

Similar to the options assessed in the Master Plan framework, an environmental category was included in this MCA. This category was divided into two criteria, impacts and benefits, in order to reflect the environmental damage inflicted by the options and to reflect the second objective of this MCA to ensure a sustainable electricity supply.

The environmental impact criterion was scored by estimating the extent of the environmental damage incurred if the given option was implemented, including the necessary construction and the operation of each option. The environmental impact of the Hvalávirkjun plant was made evident in Section 6.2.1, and the impact of the micro-grid with DER was determined by its use of diesel generators and the environmental impact of the wind turbines. It was assumed that the installation of the wind turbines required access roads and building sites while the construction of necessary turbine infrastructure would disturb the natural environment through for instance laying the foundation for the base of the turbine tower. Moreover, other environmental impacts of wind power have been well accounted for in academic literature, such as the effects on wild life, pollution, and noise (see for example Mann & Teilmann, 2013; Nazir et al., 2019). The assumption was that since only three turbines would be installed as opposed to a wind farm consisting of a large amount of turbines, the environmental impact from the turbines themselves would be minimal and that the diesel generators would have more adverse impacts. For the V2G option it was assumed that the installation of the charging infrastructure would lead to minimal impact. Yet, while EVs do not run on diesel or gasoline, one of the main arguments against EVs is that the batteries require a large amount of metals leading negative environmental impacts (Casals et al., 2017). However, in order to contain the scope of this research the complete life cycle of the EV battery was not taken into account, only the impact that the EVs have on the electricity supply and demand through V2G.

The environmental benefits were measured through estimating the reduction of the carbon footprint of electricity generation and use. The carbon footprint of electricity generation and use in this context is caused by the use of diesel back-up generators. For this reason, the potential of an option to reduce the carbon footprint was tied to two factors: reliability and self-sufficiency. Firstly, a reliable and secure supply of electricity decreased the use of back-up diesel generators. Secondly, the self-sufficiency of an option meant that fewer back-up diesel generators were needed. Consequently, if the option improved the reliability and self-sufficiency of the electricity supply then the option received a higher score.

D. Economic

The costs for each of the options were calculated by way of the annualised costs and were scored on a relative scale. The following equations were used (adapted from HOMER Energy, n.d.-a, n.d.-b):

$$Annualised\ costs\ = C_{npc}(i, R)\ \times\ a \qquad \text{[eqn. 9]}$$

where

$$a\ =\ \frac{i(1+i)^R}{(1+i)^R - 1} \qquad \text{[eqn. 10]}$$

with:

C_{npc} = net present costs including initial investment, Operation and Maintenance (O&M), fuel, and replacement [€]

i = discount rate [%]

R = project lifetime [years]

a = capital recovery factor

The resulting costs for each option can be in Table 13, and will be explained in more detail here.

1. As mentioned, the installation costs for the Hvalárvirkjun plant will be about €30 million and the operational costs include the annual connection costs amounting to €13 million a year, according to 2011 estimates. It was assumed that this estimate did not include the annual maintenance and operation costs of the actual hydropower plant itself. According to IRENA (2012), the average annual O&M costs are about 1.5% of the initial investment costs, resulting in an annual cost of €450,000 for the Hvalárvirkjun plant in addition to the annual connection costs leading to a total annual cost of €13.45 million for the plant owner. The lifetime of the plant was based on Pérez-Arriaga (2017) and discount rate was based on a hydropower study by Samorka (2016).

Table 13 - Annualised costs per option in € (thousands)

	Investment	O&M	Fuel	Replacement	Lifetime (years)	Discount rate	Capital recovery rate	Annualised costs
Hvalárvirkjun	30,000	13,450	-	-	50	7.5%	0.09	3,714
Micro-grid with DER	43,569	366	61	11,385	20	7.5%	0.09	4,735
V2G	8,541	427	272	17,083	10	7.5%	0.09	2,251

2. The installation costs for the second option, V2G technology, were two-fold: first, it was assumed that the charging infrastructure required would be private residential chargers installed at the owner's residence and not in communal public spaces such as parking lots. This means that the installa-

tion costs for the charging infrastructure are the responsibility of the owners. Assuming that one charger was installed for every EV at a cost of €1,100, the total initial investment cost was €8,541,500 (De Los Ríos et al., 2012; Nicholas, 2019). Important to note here is that it was assumed that a charging unit that enables V2G charging costs around the same as a conventional charging unit used for V1G. The maintenance costs were assumed to be 5% of the initial investment costs, and the fuel costs in this case indicate the costs of hardware degradation at 3% of the initial investment costs (Nicholas, 2019). With a lifetime of 10 years per charger, all chargers need to be replaced at least twice at the same costs of the initial investment. Additionally, the second part of the V2G costs were the annual fuel costs for the decline in battery health due to charging, at €0.034/kWh of battery capacity amounting to €15,808 for Scenario 1 (Calearo & Marinelli, 2020). Scenario 1 was used for the cost estimate to show the maximum costs that would be incurred.

2. The costs for the last option consisted of the micro-grid itself, the wind turbines, and the required infrastructure. The diesel generators are already installed and were therefore not included in the installation costs and the costs for the micro-grid itself depends on the capacity of DER installed. However, using the average costs for a community sized micro-grid including storage, generation sources, and infrastructure of about $2.1 million per installed MW, at a total installed capacity of 25.45 MW the micro-grid with DER would cost more than €43 million (Veckta, 2020). It should be noted that this estimate included the construction and cable infrastructure amounting to a cost of €32 million, assuming the wind turbines cost about €1.1 million per MW capacity (Blewett, 2020). The annual O&M costs for the micro-grid consisted of maintenance costs of €0.01258/kWh for the diesel generators and €20/kW for the wind turbines, amounting to a total cost of €365,590 (Adefarati et al., 2017). For the diesel generator fuel costs, it was assumed that 50% of the electricity generated in 2019 would be generated in the future due to improved reliability and the contribution from the wind turbines, for a cost of €126/MWh based on Pérez-Arriaga et al. (2017). The same discount rate was used for the micro-grid as for the hydropower plant and the lifetime of 20 years seen in Table 13 was based on the average lifetime of wind turbines (NREL, n.d.). An average lifetime of 20 years for the wind turbines means that all three turbines will have to be replaced before 2050 with a replacement cost of €11.4 million. Lastly, it was assumed that the micro-grid would not have to be replaced before 2050.

Criteria weighing

Considering the criteria above and that the purpose of this MCA was to highlight the weaknesses and strengths of all three options as opposed to create a ranking, it was decided that the criteria would be weighed equally. An additional factor that informed this decision was the data availability. For instance, the installation costs for the hydropower plant were available from the developer, while the costs for the remaining two options had to be estimated from literature and could therefore deviate from the actual costs in Iceland. Therefore, due to the lack of exact data for all criteria in the West Fjords, all criteria were assigned a weight of 1/8.

6.3 Results and discussion

6.3.1 MCA Results

Table 14 shows the results of the MCA according to the criteria scoring with a maximum possible final score for each option of 5. As can be seen, the V2G option received the highest final score of 4.3, followed by the Hvalárvirkjun hydropower plant with a score of 3.6. The micro-grid with DER option received the lowest score of all three options with a 3.4. Figures 44-47 show the electricity demand for the three EV Scenarios and the Reference Scenario for context. Due to the Hvalárvirkjun plant offered as a solution in the Master Plan, its scores will be compared to the two grid-solution options in this section.

Table 14 - Performance matrix for the Hvalárvirkjun hydropower plant and the two grid solutions with the weighted final score.

Criteria	Suscept-ibility	Coping capacity	Gen. flexibil-ity	Gen. capaci-ty	Trnsm. capaci-ty	Env. impact	Env. benefit	Ann. costs	Final Score
Hvalárvirkjun	2	3	5	5	5	2	4	3	3.6
V2G	5	4	5	4	2	4	5	5	4.3
Micro-grid	4	4	4	4	3	3	4	1	3.4

Security

The Hvalárvirkjun plant yielded the lowest scores in the security category of all three options, due to the distance that the electricity needs to be transmitted over (see Figures 44-47). The distance that the transmission infrastructure has to cover to reach the proposed connection point by Landsnet, increases the susceptibility of said infrastructure to adverse weather conditions. Likewise, the coping capacity of the plant received a score of 3, because if damage occurs in the transmission lines the power system might not have the ability to restore to a stable state in a short time due to the limited amount of transmission equipment available. Conversely, the V2G and micro-grid options received higher scores for this category because the transmission distance is substantially shorter due to the micro-grid generating electricity locally and the EVs can provide back-up power locally as well.

Adequacy

Contrary to the previous category, the Hvalárvirkjun plant yielded the highest scores possible in the adequacy category. This is due to the fact that the hydropower plant would provide significant flexibility due to its quick ramp up time and the ability to provide ancillary services (U.S. Geological Survey, n.d.). Similarly, as explained in the previous section the V2G and micro-grid options would also be able to provide flexibility, but less generation capacity. Moreover, important to highlight are the scores for the transmission capacity. The Hvalárvirkjun plant received the maximum possible score due to the new transmission infrastructure that would have to be constructed from the plant to the connection point, which at the same time would enable the N-1 criterion. The micro-grid would only increase transmission capacity locally, and V2G would have minimal impact on transmission capacity expansion.

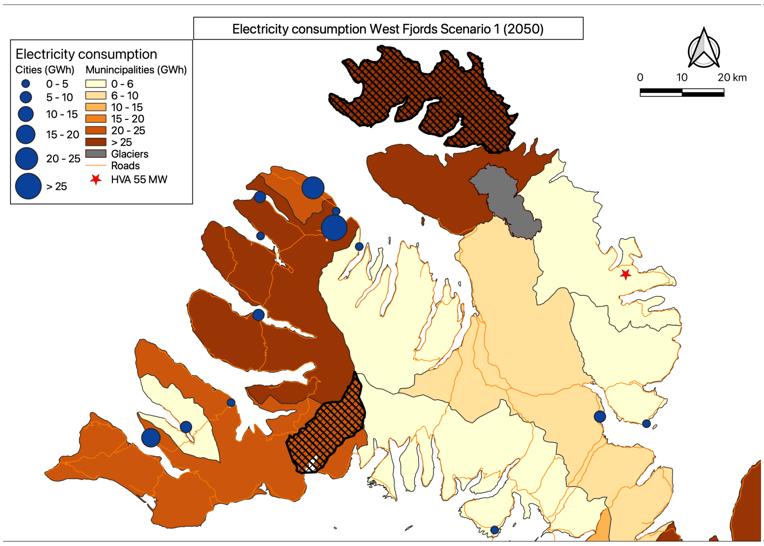


Figure 44 - EV Scenario 1 and the subsequent general electricity demand in the West Fjords in 2050.

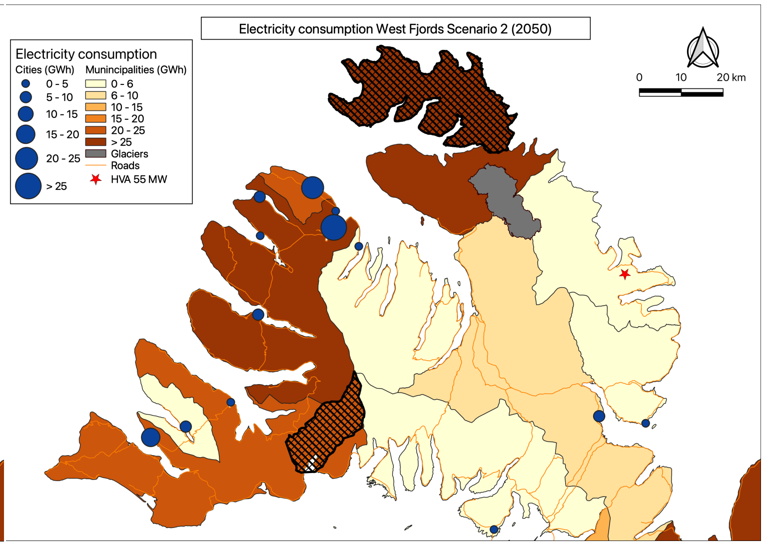


Figure 45 - EV Scenario 2 and the subsequent general electricity demand in the West Fjords in 2050.

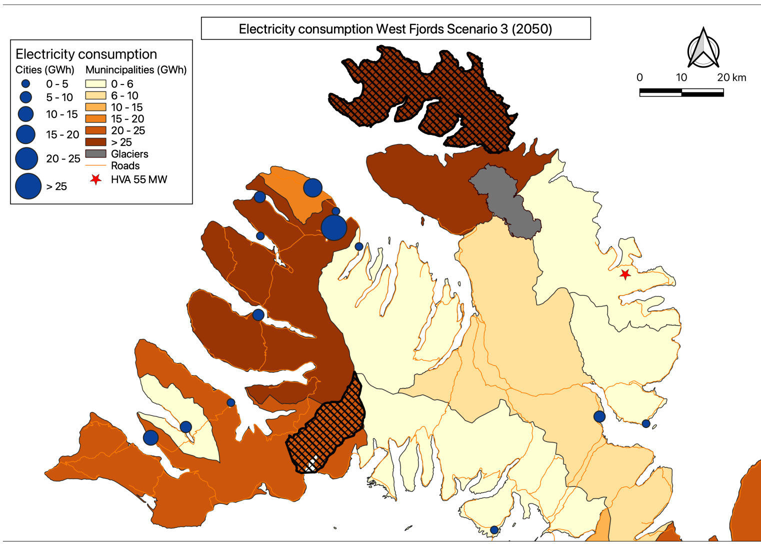


Figure 46 - EV Scenario 3 and the subsequent general electricity demand in the West Fjords in 2050.

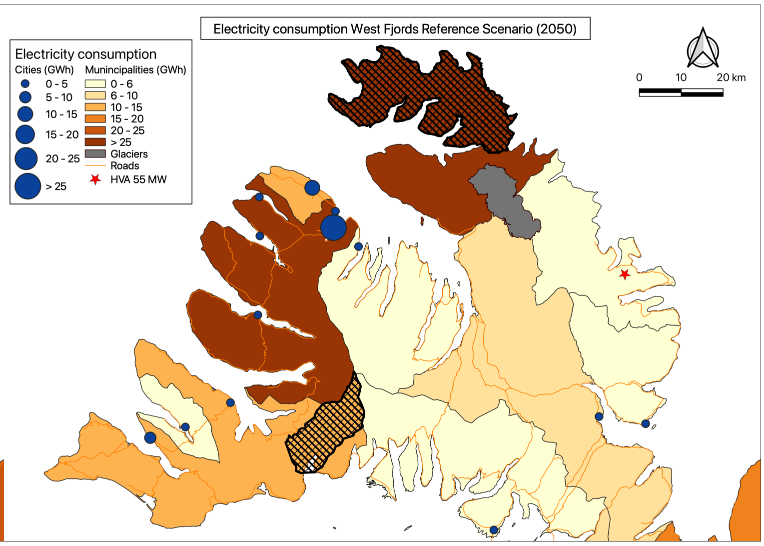


Figure 47 - Reference Scenario and the subsequent general electricity demand in the West Fjords in 2050.

Environmental

As mentioned, the Hvalárvirkjun plant has been contested on environmental grounds due to the sheer size of the plant: it is estimated that the plant would occupy about 14% of a currently undisturbed area. Moreover, not only the plant itself will impact the immediate environment, but also the access roads over which materials need to be transported and the construction site during the development of the plant. Based on this, the plant received a score of 2. On the contrary, the environmental benefit criterion received a higher score due to the newly installed generation capacity decreasing the need for back-up power generators. At present, the back-up generators are used when either a disturbance occurs in the West Line resulting in a lack of electricity supply, or when there is a disturbance in the regional distribution system. The Hvalárvirkjun plant would significantly decrease the reliance on the West Line, if it is still needed at all, and therefore decrease the use of diesel generators. The micro-grid option received an average score of 3 for this category, since the diesel generators are still used and the micro-grid and its wind turbines have to be constructed and installed, thus impacting the environment. Likewise, the use of diesel generators has a negative impact, but the electricity generated by the wind turbines has a positive impact on the environmental criterion. Therefore, due to the options having both negative and positive impacts the environmental criterion received a score of 3. The V2G option yielded the highest scores for the environmental criteria due to the little environmental impact of construction —the charger will be installed at the owner's residence— and due to the fact that no fossil fuels are used in either the driving or in the charging of the vehicle. Moreover, in the case of a disruption the stored electricity in the EVs battery can be used instead of the electricity generated by the diesel generators. It should be noted that the score would be significantly lower if the whole lifecycle of the battery would have been taken into account, due to the substantial environmental impact of manufacturing the EV's batteries as discussed in the previous section.

Economic

The costs of the three options were scored on based on the annualised costs. As can be seen, the micro-grid received the lowest score followed by the hydropower plant, while the V2G option received the highest score. The costs for the micro-grid were high due to the initial investment costs and the replacement costs. Costs for the hydropower plant resulted from a relatively high initial investment, but primarily from the high annual O&M costs. Lastly, the costs for the V2G option wer lower, despite having the highest replacement and fuel costs over the project lifetime. This is due to the fact that in the initial investment costs only the costs of the charging infrastructure were included.

Criteria weights impact

A sensitivity analysis was carried out in order to see what criterion has the most impact on the final aggregate score for each option. According to Dodgson et al. (2009) it is important to carry out such an analysis in order to "check the robustness of the analysis" (p. 44). The impact of each of the criteria on the final aggregate score can be seen in Figure 48 for the Hvalarvirkjun plant, Figure 49 for the V2G technology, and Figure 50 for the micro-grid option. The approach used was based on Mabin and Beattie (2006) by changing the weights of the individual criteria to find out the impact on the final score. Each Figure indicates the final score in the event that a criterion is weighted differently. For example, in Figure 48 if the generation flexibility criterion would be assigned a weight of 80% while the remaining criteria were assigned the remaining weight equally, then the final score would increase to 4.7.

As can be seen from **Figure 48**, the environmental impact and susceptibility criteria have the most negative effect on the final score and could decrease the score to 2.4 if the weight were changed. Conversely, the criteria in the adequacy category have the most positive effect and could increase the score to 4.7. The cost criterion has a negative impact but less pronounced than the susceptibility and environmental impact criteria, similar to the coping capacity criterion, and could decrease the score to 3.1

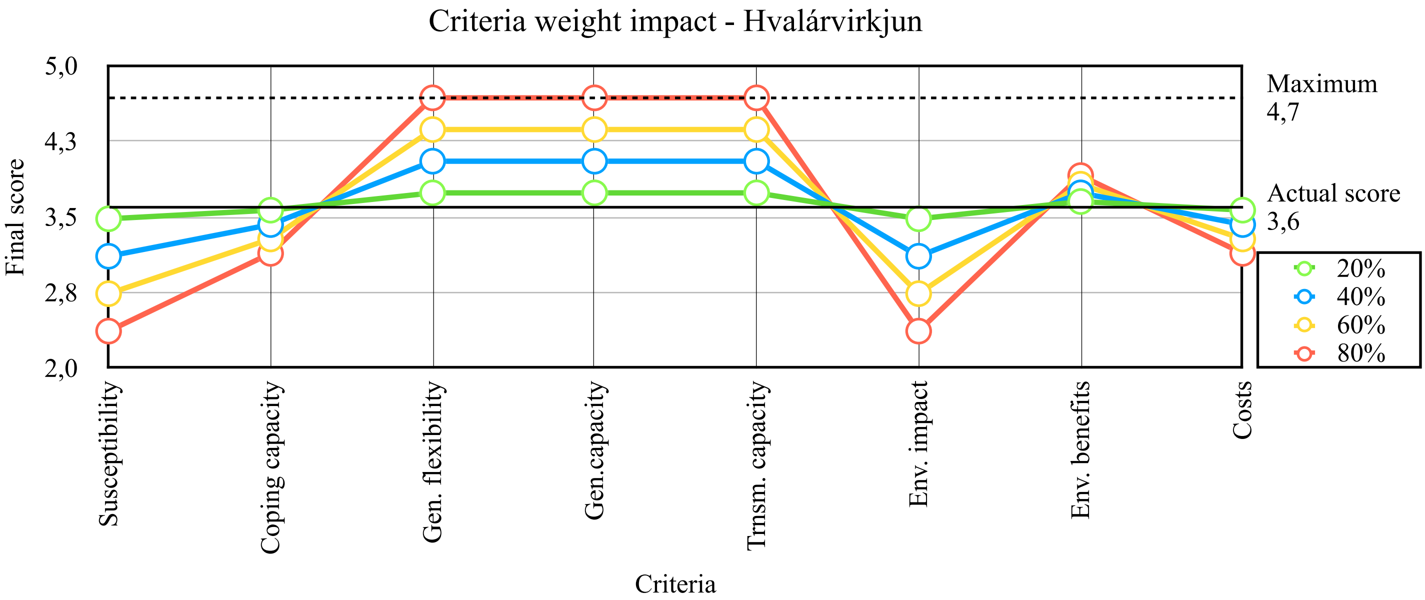


Figure 48 - Impact of change in weight for the Hvalárvirkjun option

Figure 49 shows the impact of the criteria weights on the final score for the V2G option. As can be seen, the transmission capacity criterion has the most negative effect on the final score and could decrease the score to 2.5. The coping and generation capacity, and the environmental impact have a negative impact on the final score, albeit small. The remaining criteria of costs, environmental benefits, generation flexibility and susceptibility all have the same positive impact and could increase the score to a maximum of 4.8.

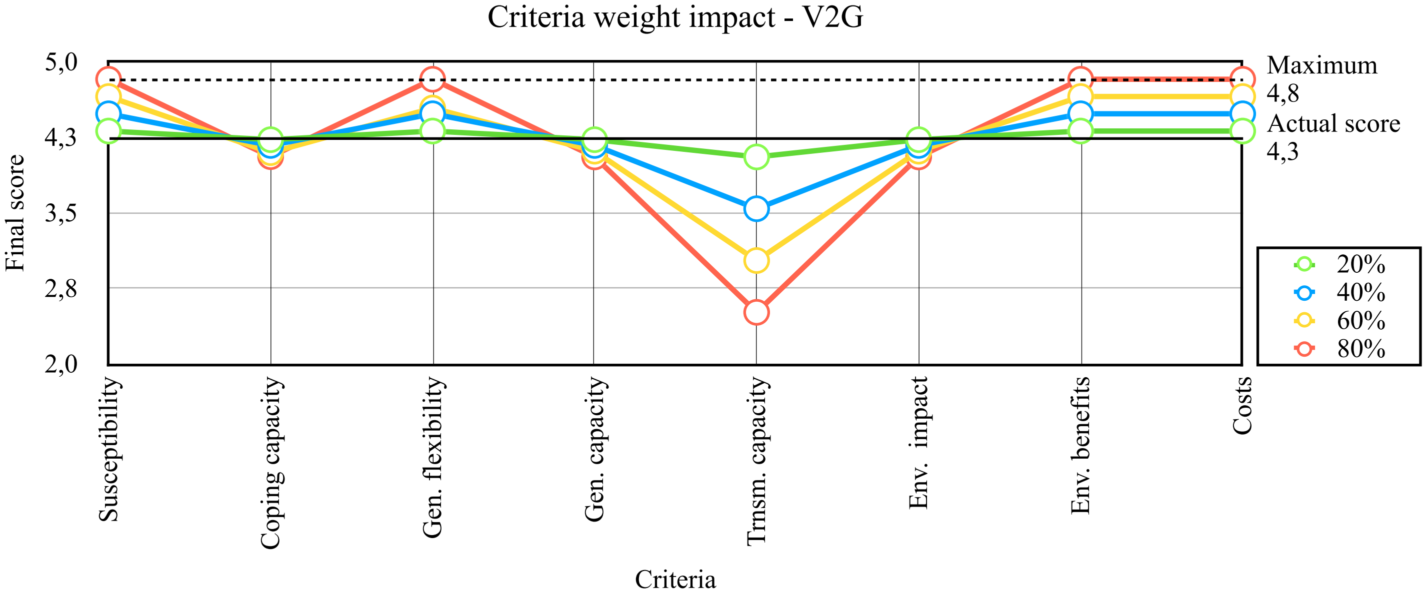


Figure 49 - Impact of change in weight for the V2G option

Lastly, Figure 50 shows the impact of the criteria weight on the final score for the last option, the micro-grid with DER. Contrary to the previous two options, minimal effects of the weights on the final score can be seen, except for the costs criterion which could significantly decrease the score to 1.5 out of 5. The maximum score can be improved by only 0.5 compared to the actual score of 3.4., due to the susceptibility, coping capacity, generation flexibility and capacity, and environmental benefits criteria. In addition to the cost criterion, only the transmission capacity and the environmental impact criteria indicate a negative impact if the weights of the criteria were to change.

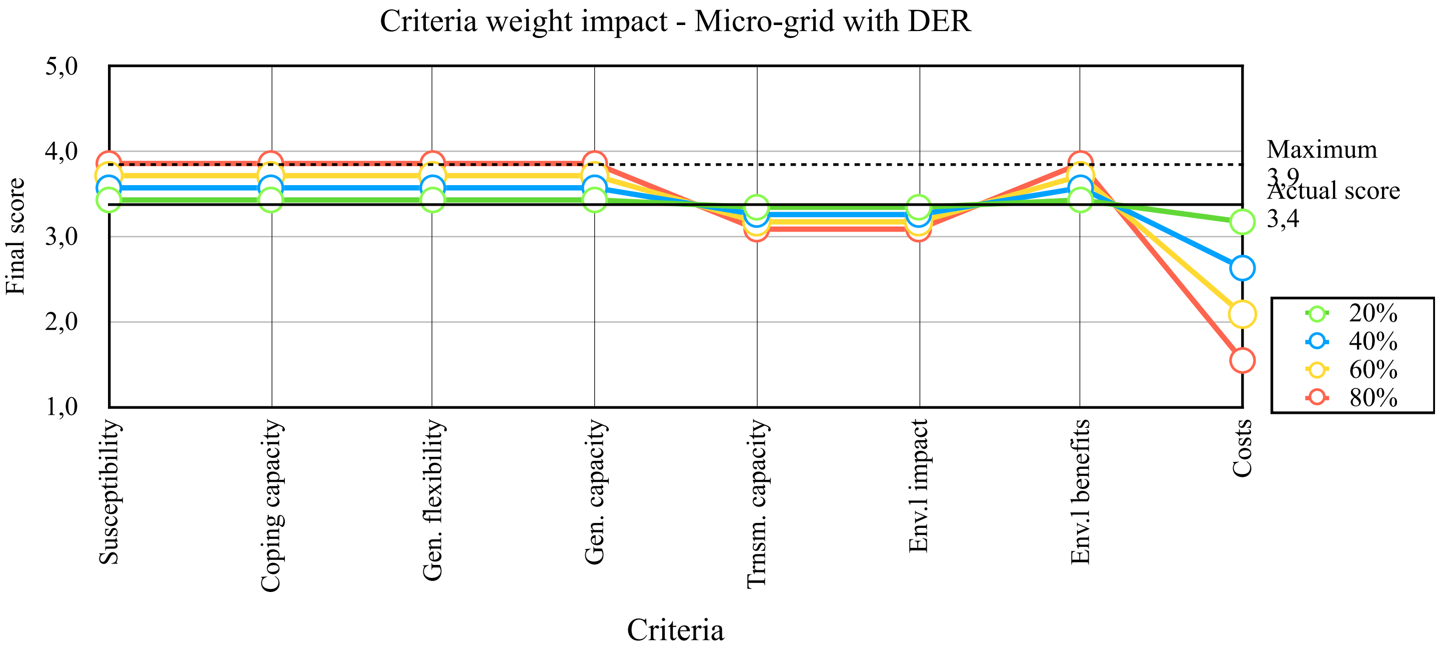


Figure 50 - Impact of change in weight for the micro-grid with DER option.

6.3.2 Discussion

The previous chapters have shown that the main factors that hinder a reliable and secure supply of electricity in the West Fjords are adverse weather conditions impacting transmission lines and equipment, insufficient installed capacity to meet the region's electricity demand, and the reliance on the West Line to meet 40% of the region's electricity demand. All three factors are expected to exacerbate the region's electricity supply insecurity and unreliability looking at future demand increases. As the three EV Scenarios show, the general electricity demand increases to 149 - 158 GWh by 2050 depending on the Scenario, compared to a general demand of 87 GWh in 2019. If the costs of the three options are compared to the West Fjords strategies suggested by Landsnet and OV in the previous chapter, it can be seen that even though the initial investment costs for the Hvalárvirkjun plant and the micro-grid with DER are higher than most of the short-term strategies, the options provided here are more extensive in improving the reliability and security of supply. Not in the least because all options decrease the distance over which the electricity has to be transmitted, contrary to the present situation where almost half of the region's electricity has to be imported over a 160 km long transmission line. For example, the strategy to reinforce the West Line will cost at least €80 million and will not substantially abate any of the three factors that hinder a reliable and secure electricity supply because adverse weather conditions will still impact the transmission infrastructure, the region's installed capacity will not increase, the distance over which the electricity has to be transmitted will not decrease, and the reliance on the West Line will even become stronger due to the belief that reinforcement will solve the reliability issues. The main results will be discussed in this section, by comparing the Hvalárvirkjun plant to the two other options.

Security

As can be seen, the Hvalárvirkjun plant yielded the lowest score in the security category. While underground cables would decrease the susceptibility of the transmission equipment, the West Fjords is a region characterised by its rough and mountainous terrain and as can be seen an emphasis on preserving nature causing the construction of underground cables to be difficult. At the same time, the coping capacity would not be significantly improved by implementing this plant, or in the worst case could even decrease. Heylen et al. (2018) explain that the coping capacity indicates how the power system copes with an unwanted event, restore the power system's function to a stable state and limit negative effects. Following this definition, the plant can actually decrease the coping capacity of the power system. To explain, any disturbances in the West Line causes problems in the West Fjords' electricity supply that cannot always be instantly mitigated by the region's back-up power. The dependence on the West Line would be shifted to the Hvalárvirkjun plant since it would be able to fully supply the electricity demand in the region, and thus instigating less focus on external back-up measures since the plant is expected to be able to fulfil the entire demand. This dependence, in combination with the increased susceptibility of the transmission equipment and less emphasis on back-up measures would impair the system's ability to restore to a normal stable state in case of severe unwanted events. The transmission equipment here is the main hindering factor because if the transmission lines are damaged, then any emergency or contingency plan from the plant itself would not make a difference. For this reason, the security scores for V2G and the micro-grid option yielded higher results. The distance that has to be covered by transmission equipment is substantially shorter than for the Hvalárvirkjun plant, and thus less susceptible to adverse weather conditions. Naturally, the V2G and micro-grid option do not completely mitigate the impacts of adverse weather conditions because of the shorter transmission distance, albeit a significant reduction in susceptibility. To illustrate, even though the Vesta wind turbines in the micro-grid option are equipped with de-icing systems, storms can still damage the turbines (Mathews & Sowizdzal, 2019). It should also be noted the wind turbines are dependent on whether or not wind speed are within safe operating limits. That is to say, the wind speed should exceed the cut-in speed but cannot exceed the cut-out wind speed. When the wind speed exceeds the cut-out wind speed, the turbines shut down in order to prevent damage. If the wind speed is lower than the cut-in wind speed, the turbines will not generate any electricity. The cut-in speed for the Vesta turbines used in the MCA is 3 m/s and the cut-out wind speed is 22.5 m/s, and according to Mathews and Sowizdzal the average monthly wind speed in Ísafjördur and Bolungarvík does not go below the cut-in speed, nor exceed the cut-out speed except during storms in the winter months (Vestas, n.d.). Nevertheless, due to the decreased transmission distance the micro-grid will be beneficial in the long-term. For example, it was found that for a local grid-connected micro-grid in New York distribution and transmission losses decreased by 6%, while at the same time selling excess electricity back to the main grid (IRENA, 2019a). This would be a win-win situation for the micro-grid option.

Adequacy

Contrary to the previous category, the hydropower plant yielded the highest possible scores in this category due to the added generation capacity and improvement of the generation flexibility. With the added installed capacity provided by the Hvalárvirkjun hydropower plant, more than enough electricity can be generated to meet the projected demand in 2050 in the West Fjords.

The generation capacity is not only important in relation to overall annual electricity generation, but also in relation to generation flexibility and how the option copes with daily peak load. In this case, the power plant should have sufficient capacity in order to meet the region's peak load since self-sufficiency is important in order to reduce the reliance on the West Line. As mentioned, peak load reached 22.8 MW in 2018 against a total installed hydropower capacity owned by OV of about 17 MW, resulting in a capacity margin of -25%, not including the installed capacity of diesel back-up generators. The capacity margin represents the power that is available on top of peak demand in case of unexpected disruptions. In recent years, it has been more attractive for energy producers to invest in the generation capacity for the power-intensive industry than for the general sector. As a consequence, the capacity margin for the general demand has decreased in recent years. To explain, according to Næss-Schimdt et al. (2017) in recent years the demand from the power-intensive industry has been increasing, and due to a difference in price premiums to supply to the power-intensive industry and to households it has been more rewarding for power producers to supply electricity to the former rather than the latter. When peak load increases faster than new capacity is installed, the capacity margin decreases further. At present, there is no agreement on a minimum capacity margin that is needed in order to ensure the security of electricity supply. However, for example, if a capacity margin of 20% is desired then in the event that the Hvalárvirkjun plant is installed and assuming that the installed hydropower capacity owned by OV at present is still in operation, then peak load can increase up to 57.6 MW.

Conversely, the V2G and micro-grid option cope with peak load differently. Neither of the options are expected to be able to fully meet electricity demand, but can manage peak load through smart controls. The micro-grid option has enough capacity to manage the current peak load for the entire region and it can therefore reasonably be expected that the micro-grid can cope with peak load in the most populous area of the West Fjords. To highlight the V2G option, its main characteristic is that it increases grid stability and that power flows are optimised at the distribution grid level (Ali et al., 2020). Uncontrolled EV charging can lead to peak load increases when owners come home from work and start charging simultaneously as explained before. By implementing V2G, charging would not start instantly but is moved to times when there is enough available capacity— such as at night— through load shifting and peak shaving in order to reduce peak load, adding significant generation flexibility. Correspondingly, during peak demand the EVs can provide grid support by discharging back to grid. Again, this is the benefit of using V2G as opposed to smart charging used at present which can manage charging but is not able to discharge back to the grid. As such, the flexibility of the EV fleet will be optimally utilised by using its batteries. The EV batteries can store generated electricity when supply exceeds demand, and thus reduce curtailments. If there is no storage option for the excessive generated electricity the grid operator has to shut down generation in order to maintain a stable frequency to prevent system instability (Mültin, 2021). As such, V2G-technology can be seen as a mitigation measure as opposed to an adaptation measure. While the other two options are installed to cope with the increased demand from EVs, through V2G technology the EVs themselves would be used to mitigate the demand through for the charging strategies described. However, for EVs to actually have an impact on grid services and to provide ancillary services a large quantity of vehicles is needed. The calculations used in this MCA are based on average battery sizes and time of use, and assume that every vehicle will participate. In reality, the storage capacity of EVs will most likely be lower due to losses and inevitable battery degradation, and the high initial costs for owners will mean that not everyone is able to, or wants to, participate. Therefore, the estimates provided should be seen as an indication of the theoretical potential rather than the true implementation potential.

Environmental

All three options have an impact on the environment on a different scale. In general, the threshold for environmental impact for an option is low. Electricity generation in Iceland is already 99% renewable, so if an option uses any non-renewable source for generation it has a high environmental impact compared to the generation portfolio already in place**.** Likewise, because nature preservation and protection is such an important factor in Iceland, the Government continuously designates new national parks and protected areas. The fact that there are so many areas that are currently not inhabited or built in cause any new option to disturb these areas through development and construction of for instance access roads, and as a result have a high environmental impact.

In the case of the three options, the environmental impact criterion yielded the lowest score for the hydropower plant. As mentioned before, the Master Plan framework was introduced in order to find a balance between the need to install new capacity to meet electricity demand and the need to preserve nature and wilderness areas. Since the Hvalárvirkjun plant is in the final category of the Master Plan and has been approved, this means that the plant's potential environmental damage is deemed not to be detrimental and that the plant is in fact needed in order to be able meet electricity demand. Yet, continuous efforts by environmental groups and local residents to stop the development of the plant show that not everyone agrees with this assessment.

Comparatively, the environmental impact of the V2G and micro-grid option are significantly lower. In the case of the V2G option, the chargers will be installed at the owner's residence and will therefore not require construction in undisturbed areas and the micro-grid is smaller in size than the hydropower plant and will as a result have a lower environmental impact. Likewise, the environmental benefits of the three options are mainly a result of whether the use of fossil fuels is reduced. In the case of the hydropower plant the environmental benefit is clear since it can provide all of the region's electricity, while the use of V2G would also reduce the need for back-up power due to load balancing and having storage capacity that can be used instead of the diesel generated back-up power. Not included in the MCA are the offset CO2 emissions by the EVs compared to an ICEV based fleet. According to calculations based on Samorka (2020) and the data used in Section 3.5, the fleet in the West Fjords could offset 26,818 metric tonnes of CO2 and 8,780,319 litres of gasoline in 2050.

Conversely, the micro-grid option makes use of the diesel generators while also consisting of wind turbines that can provide a substantial share of electricity. Therefore, the environmental benefit criterion received a score of 3 because it depends on how often the diesel generators have to be used, and whether the use of the generators can be offset by the use of the wind turbines. Moreover, if the perspective on environmental impact is extended the the manufacturing of the turbines, it was found a study on wind energy potential in the West Fjords that it could only take half a year for the wind turbines to repay the energy footprint generated during manufacturing (Barajas, 2019).

Economic

The criteria in the economic category were difficult to measure and to assess because of the different dimensions and the available data. First, the total costs of the hydropower plant are shared between the owner of the plant and the developer, and Landsnet being responsible for the costs for the transmission infrastructure. Second, the costs for the implementation of V2G technology are shared between the EV owners who are responsible for the initial charging infrastructure, and the grid operator who have to compensate the owners for using the EVs for the purpose of grid services. And third, the costs for the micro-grid with DER would most likely be covered mainly by the West Fjords DSO and partly by Landsnet due to transmission infrastructure. Moreover, while the costs for the hydropower plant were available, the costs for the last two options had to be estimated and were thus not necessarily accurate for Iceland. It should be noted that due to the complexity of breaking down the costs involved, cost incurred such as labour, planning and permits, carrying out environmental assessments, and transportation of the materials were not included due to data availability and to limit the scope of the economic category. However, after looking at the initial costs and the annual recurring costs, the benefits that the options can provide should not be overlooked. While the initial costs incurred on the EV owners in the V2G option are high, the long-term benefits largely offset the investment costs for both the grid operator and the owners: charging an EV is less expensive than using gasoline or diesel for a ICEV, and a reliable and secure supply of electricity means that the DSO has to pay for less back-up power.

Conclusion

As a result from the MCA in this chapter, and the evidence in the previous chapters it can be argued that the optimal solution would be a combination of all three options. Looking at the reliability and the security of electricity supply in the West Fjords at present, it can be argued that the security aspect ranks higher on the scale of importance than the adequacy aspect. As the previous two chapters have shown, the transmission and distribution infrastructure in Iceland is highly susceptible to adverse weather conditions. Even if generation capacity is increased to an adequate level, a susceptible transmission and distribution network will negate the benefits of adequate generation capacity. Therefore, a combination of local generation and shorter distribution distances would be most beneficial in the West Fjords to improve the reliability and security of electricity supply. Especially the combination of V2G technology in micro-grids could be beneficial for rural residential areas, since the EVs can be used as the storage option. While it should be acknowledged that the use of V2G technology has the potential to abate the problem of network congestion, it should be taken into account that using the EV battery in the manner that V2G technology requires could potentially degrade the capacity and the lifetime of the battery. It is also important to acknowledge what party will benefit most from the solutions put forward in this chapter. As explained in Chapter 4, Landsnet bears the responsibility to transmit generated electricity to DSOs who in turn distribute the electricity to end-users. Landsnet is the only entity that can build transmission equipment and facilities, but it is not the only entity that can build generation facilities. Thus, the more decentralised the power system becomes in the West Fjords through the implementation of more DERs and using EVs, the stronger the control measures have to become to effectively facilitate the expansion of local generation and distribution. Nevertheless, it is clear that a more efficient and reliable electricity supply benefits all parties involved and that a reliable and secure supply of electricity can be ensured provided that the DSO and TSO cooperate.

Chapter 7 - Discussion

7.1 Results

This thesis set out to find out how the electricity grid can be improved in order to accommodate for future EV growth in 2050, with a focus on the region with the least reliable and secure electricity supply in Iceland, the West Fjords. This section will summarise the results of the sub-questions briefly, before discussing the main limitations to this study and provide recommendations for future research.

Sub-questions 1 and 2: What is the expected EV growth and subsequent electricity demand and its distribution up to 2050?

The expected EV growth and subsequent electricity demand were projected up to 2050, by way of future population and vehicle projections. The Icelandic population is expected to increase to 430,610 inhabitants, and the total amount of vehicles is expected to increase to 366,019 passenger vehicles. Through the three EV Scenarios that were based on different assumptions on EV growth, it was found that the general electricity demand will increase to 8.2 TWh for the Fast Growth and Medium Growth EV Scenario and to 7.7 TWh for the Slow Growth EV Scenario by 2050, compared to a general electricity demand of 3.8 TWh in 2019. The share of EV demand in the general electricity demand in each of the Scenarios ranges from 8.7% in the Slow Growth Scenario, to 13.6 - 13.7% in the Medium and Fast Growth Scenarios, respectively. Most of the projected electricity demand was found to be concentrated in the Capital Region due to the size of its population, and less so in rural regions.

Sub-questions 3 and 4 : How reliable is the Icelandic grid currently and what areas are most vulnerable to electricity disruptions in the West Fjords?

Through Landsnet's six reliability indicators it was found that even though the Icelandic grid is reliable, there are stark regional differences. As the indicators made evident, the main obstacles to a reliable and secure supply of electricity across the country are adverse weather conditions and limited available transmission capacity. Moreover, the fact that the Icelandic grid is isolated and cannot rely on other grid for support makes the reliability of the electricity grid of paramount importance.

It was found that adverse weather conditions are especially harmful in the West Fjords, in addition to the region not being self-sufficient in electricity generation, and its reliance on the West Line for electricity imports. The most populous cities, Bolungarvík and Ísafjörður, are also the areas experiencing the most amount of disruptions. The increase in future electricity demand will further stress the distribution system in the West Fjords, and thus additional capacity is needed.

Sub-question 5: What are the currently proposed strategies to improve reliability and security of electricity supply?

The reliability of the grid is threatened by both the growing electricity demand, inadequate transmission capacity, and weather conditions. In order to alleviate future stresses on the electricity grid due to growing electricity demand and to increase transmission capacity, Landsnet carries out short- and long-term strategies which mainly focussing on grid reinforcement. The costs of the short-term strategies that will start and finish construction in the coming two years, amount to more than €95 million. Landsnet's long-term strategies either disturb the Highlands in the centre of the country which is an area that is at present relatively undisturbed, or would require construction near another national park in the south of the country. Due to the challenging construction environment, the total construction costs of the long-term strategies would range from €247 million to €332 million. As argued, in rural areas such as the West Fjords where outages are frequent and security of supply is weak, grid reinforcement strategies will not be adequate taking into account future electricity demand, and thus requiring more local solutions and generation capacity. However, plans for new large-scale capacity are continuously hindered due to the high initial costs and due to environmental concerns regarding the disturbance of nature areas. Moreover, Landsnet's strategy of installing more diesel generators in rural locations to provide electricity is not in line with the Government's goal of a carbon neutral electricity supply by 2030.

Sub-questions 6 and 7: What are the main criteria that grid solutions have to meet and to what extent do the grid solutions meet these criteria?

Through an MCA, the options of the proposed hydropower plant Hvalárvirkjun, and the grid solutions of V2G technology and a micro-grid with DER were assessed. The main criteria that the options had to meet were divided into four categories reflecting the concept of reliability used throughout this thesis, in addition to the dimensions of security of supply by Pérez-Arriaga et al. (2017). The categories were: security, adequacy, environmental, and economic. As a result of the MCA, the V2G option received the highest score of all three options with 4.3 out of 5, while the Hvalárvirkjun plant received a score of 3.6, and the micro-grid with DER received the lowest score of the options with 3.4. The V2G options scored well on all criteria except the transmission capacity criterion. The adequacy criteria yielded high scores for the Hvalárvirkjun option, but the option yielded low scores for the susceptibility and environmental impact criteria. The main criteria that caused the micro-grid option to have the lowest score were the high annualised costs. However, it was found that a combination of local large-scale generation combined with smart technologies such as V2G technology and the micro-grid would greatly improve the reliability and security of electricity supply in the West Fjords.

<u>Main research question: How can the Icelandic electricity grid be improved in order to enhance its reliability and accommodate for the expected growth in electric vehicles</u>

The main way in which the grid can be improved in order to enhance the reliability and and security of electricity supply is through reducing the transmission distance to decrease the susceptibility to adverse weather conditions. As a result of the MCA it was made evident that in rural regions such as the West Fjords, reliance on the main transmission grid will not be adequate in the future, and that more local and decentralised solutions are needed, such as smart technologies.

7.2 Limitations and recommendations

Since each of the Chapters included a discussion of its results and limitations, this section will briefly discuss the overall limitations and challenges for this thesis as well as recommendations for future research.

Projections and assumptions

Due to the fact that this thesis was built upon population and vehicle projections up to 2050 it is important to acknowledge the inherent uncertainties in such projections. Significant assumptions were made regarding rural and urban population growth rates, vehicle growth rates, driven mileage, EV efficiency, and as a result regarding the electricity demand increase. For instance, for the population distribution projection, it was assumed that the Capital Region population would increase by 22% and the rest of the country by 17% compared to 2019 population levels. Assumptions like this were necessary since a regional projection for the Icelandic population has either not been conducted recently, or it was not available. Using these growth rates mean that that larger cities outside of the Capital Areas are denoted as rural areas while they could be actually be classified as urban areas, such as Akureyri. Likewise, for the vehicle projections it was assumed that the passenger vehicle ownership rate would keep increasing up to a saturation level of 850 passenger vehicles per 1,000 inhabitants after which it would remain constant, which in reality might be different. Again, either vehicle projections have not been carried out before, or were not available. Moreover, the EV Scenarios, especially Scenarios 1 and 2, assumed that the usual factors that hinder the widespread roll-out of EVs, such as range anxiety or EVs being too expensive for prospective owners, would not play a significant role in Iceland due to the multiple incentives implemented by the Government. To repeat the argument made by Vanella et al. (2020) "as the length of the projection horizon increases, so does the uncertainty". For this reason, the conclusions drawn in this research are highly scenario specific and should be treated as such. Therefore, the following three recommendations for future research are made with regards to the projections for Iceland:

- In-depth research into inter-region migration rates in addition to rural population growth within regions

- Accurate projections for vehicle ownership rates in urban and rural areas

- Research into future EV and charging infrastructure efficiency in order to accurately mod el future electricity demand

Grid reliability and strategies

The grid reliability in Iceland was assessed by using the six reliability indicators published by Landsnet over the past 10 years. Even after all the available annual performance reports were exhausted, not all the data used for the indicators and for the visualisations provided by Landsnet were available. This was especially challenging when assessing whether future strategies would be adequate. The available results from the indicators were used to analyse future impacts of demand increases and additional loads. Because the projections used relied heavily on assumptions the outcomes should be seen as an indication rather than the actual accurate level of reliability. Nevertheless, the main outcome of the reliability indicators still stand: weather conditions and limited transmission capacity are the main problems for the transmission in Iceland.

Additionally, not all information on grid reliability and future strategies were available in English, and thus either had to be translated or were unintentionally missed. The limited data availability was especially challenging for the long-term strategies in Chapter 5 due to the technical nature of the strategies. Therefore, the following two recommendations for future research are made:

- Analysis of future grid reliability and effectiveness of short- and long-term strategies using expected electricity demand increases using for instance power flow tools

- Assessing the short- and long-term strategies based on exact data and not on translations

MCA assumptions

Regarding the MCA in Chapter 6, the criteria measurements were largely based on assumptions and the scoring was based on subjective assessments. The subjective basis of scoring was exacerbated due to the fact that the three options assessed were difficult to score consistently due to a limited amount of available information on the West Fjords beyond the information used in this thesis, and due to the different scales of impact. The majority of the information used for the analyses on the West Fjords had to be translated, which lead to mis-translations, or were unintentionally overlooked. This means that valuable information that could have helped with the MCA assessment and criteria was possibly missed. Moreover, regarding information availability for the options in the MCA, V2G technology is currently not used anywhere in Iceland and it was therefore difficult to assess its impacts or what the costs would be due to the absence of a frame of reference. Estimations regarding costs for for instance labour, material, permits, and environmental assessments were beyond the scope of this research and therefore not included. For the same reasons, the micro-grid with DER option was difficult to asses. Additionally, research into grid reliability and possible solutions is highly complex due to the intricacies of the power system and because of the many stakeholders involved. As such, in order to assess possible solutions for enhancing grid reliability and security of supply the following three recommendations are made:

- Extensive research into the suitability and usefulness of V2G in Iceland, and especially in rural regions. This includes cost estimates for the installation of chargers, costs for battery health and EV degradation, and environmental impact of the EV lifecycle. Moreover, research on the economic benefits for owners for providing storage and grid services is important to take into account, as well as the costs for the DSO and TSO.

- Research regarding the institutional framework in place, and how that affects the possibility to implement V2G and micro-grids with DER.

- The electricity generated by DER and the electricity injected back into the grid by EVs require a solid electricity market framework in order to be effective. This requires the cooperation between Landsnet, the power companies, and the distribution companies. Therefore, a closer look is required into the market workings in Iceland.

Chapter 8 - Conclusion

To conclude, this thesis focussed on grid reliability in a remote region of Iceland and how future electricity demand increases as a result of EVs will impact the reliability and security of supply. As such, the nexus between two pillars of modern life were investigated: transportation and a reliable and secure supply of electricity. While the limitations in this research should be acknowledged, the results are still applicable: in order to prepare and accommodate for future electricity demand increases due to the growth in EVs, decentralised and smart solutions are needed. The contribution of this thesis is that the impacts of EVs had not been investigated in the West Fjords before, nor in combination with future population and vehicle projections up to 2050. Additionally, the applicability of V2G technology has not been researched before in the context of the West Fjords.

Moreover, Iceland is a unique case in that nearly all of its electricity is already generated by RES and that it is the leader in electricity consumption per capita, and a frontrunner in EV adoption. The electrification of transport is one of two pillars in the Icelandic climate plan, and is therefore an important step towards achieving the country's climate ambitions to achieve carbon neutrality across all sectors by 2040. The research conducted in this thesis shows that while on a country level the power system could possibly cope with the increase in electricity demand due to the installing of new generation capacity being connected with the demand of the power-intensive industry, on a local level the electricity demand increase will present significant challenges to the reliability and security of electricity supply in the coming years. The challenges will become especially severe if demand increases faster than that new generation capacity is installed. The fact that adverse weather conditions are the primary obstacle to a reliable and secure electricity supply due to damage incurred to transmission infrastructure, shows that local and smart solutions to reduce transmission distance are needed. Impacts of weather conditions will become more and more important due to one of the consequences of climate change being an increase in extreme weather events.

For this reason, the findings of this thesis can prove to be useful in other countries, especially for other isolated grids, because the integration of RES and EVs will become more important in the coming years and the consequences of climate change such as adverse weather conditions will become a universal challenge for all countries. Iceland serves as an example of a country that fully integrated RES in the electricity grid and is making strides in the integration of EVs to achieve a carbon neutral economy, for which a reliable and secure electricity supply is crucial.

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Appendix A

Installed Capacity in the West Fjords 2019. (Based on: Orkustofnun, 2020a)

Location	Type	Owner	Year	Capacity (kW)	Generation (MWh)
Bildudalur	Fossil fuel	OV	1973	1,200	21
Blaevardalsa	Hydro	OV	1975	288	1,302
Bolungarvik	Fossil fuel	Landsnet	2014	10,800	955
Breidadalsvirkjun	Hydro	Smavirkjun / small scale	2012	456	3,921
Drangsnes	Fossil fuel	OV	1975	470	7
Engidalur (Fossavirkjun)	Hydro	OV	2015	1,200	5,464
Flatey	Fossil fuel	OV	2006	182	209
Flateyri	Fossil fuel	OV	1975	420	1
Fossa- og Nonhornsvaten	Hydro	OV	1937	1,160	1,000
Holmavik	Fossil fuel	OV	1990	1,400	50
Hvesta	Hydro	Smavirkjun / small scale	2004	1,430	6,119
Ísafjörður	Fossil fuel	OV	1976	4,300	4
Mjolka	Hydro	OV	1958	11,200	70,626
Myrara	Hydro	OV	1965	60	389
Patreksfjordur	Fossil fuel	OV	1964	4,300	30
Pingeyri	Fossil fuel	OV	1980	1,520	7
Pvera	Hydro	OV	1953	2,200	5,513
Reidhjall	Hydro	OV	1958	514	1,700
Rekjanes	Fossil fuel	OV		666	0
Reykjholar	Fossil fuel	OV		750	23
Saengurfoss	Hydro	Smavirkjun / small scale	1976	720	1,338
Sudavik	Fossil fuel	OV	1986	1,400	36
Sudureyri	Fossil fuel	OV	1975	720	1

Location	Type	Owner	Year	Capacity (kW)	Generation (MWh)
Tunga	Hydro	Smavirkjun / small scale	2001	144	614
Tungudalur	Hydro	OV	2006	700	4,252

Appendix B

Short term strategies. (Based on: Landsnet, 2021a)

Strategy	Construc-tion	Plan	Goal
Southern Peninsula line 2	2021-2022	New 220 kV transmission line between the Capital Region and the Southern Peninsula	Enables N-1 connection, will disturb lava flows
Húsavík delivery point	2021-2021	Construction of a new delivery point	Current transmission line is the oldest in the system, this delivery point will connect to industrial area - 11kV circuit breaker at Bakki substation
Vopnafjörður line 1	2021-2021	Reinforce regional transmission line by replacing part of it with underground cable	Less vulnerable to weather conditions
Reykjanesvirkjun substation	2021-2022	Install 30 MW substation	Increase capacity
Hrútatunga substation	2021-2023	New substation and upgrade transmission equipment	Increase capacity and reliability
Njarðvíkurheiði substation	2021-2023	New substation with 220 kV switchgear, 220/132 kV transformers	Increase transmission capacity and reliability
Breiðadalur substation	2021-2022	Renovate ageing substation	Improve reliability northern West Fjords
Vegamót substation	2022-2023	Renovate substation	Improve reliablity Snœfellsnes
Lyklafell substation	2022-2024	New 220 kV substation close to Capital Region	Alleviate stress on nearby substation that is the only deliver point in Capital Region
Lyklafells line 1	2022-2024	New high voltage 220 kV overhead transmission line connecting Lyklafell substation to Straumsvík substation	Replaces two ageing and inadequate lines
Straumsvík switch	2022-2023	New substation equipment	Maintain reliability of Lyklafells line 1

Strategy	Construction	Plan	Goal
Klafastaðir substation	2022-2024	New substation for power plant to alleviate pressure on other substation	Improve security of electricity supply and reliability to largest point of delivery in the system
Korpa substation	2022-2023	New substation to replace ageing substation	Improve security of supply in Reykjavík
Suðurfjörður West Fjords reinforcement	2022-2023	Transmission system reinforcement by mesh connection in Breiðadalur, Mjólkár and Keldeyrar	Improve reliability in southern West Fjords
Rangávellir transformers	2022-2022	Increase voltage 132/66 kV	Increase transmission capacity and security of supply in Eyjafjörður
Dalvík Line 2	2023-2024	New 66 kV underground cable between Dalvík and Akureyri	Strategy that was prioritised after 2019 winter
Blöndulína 3	2023-2024	New 220 kV line between Rangávellir and Blanda, new substations, new 132 kV underground cable	Increase transmission capacity and security of supply
Rimakots line 2	2023-2024	New 132 kV underground cable connection Westman Islands to Southern region	Strengthens connection to Westman Islands to increase security of supply
Hvalfjörður-Hrútafjörður	2023-2025	New 220 kV overhead line (91 km) connecting Klafastaðir substation and Holtavörðuheiði substation	Increase transmission capacity and security of supply
Ísafjarðardjúp new delivery point	2023-2025	New delivery point to connect to main transmission grid at Ísafjarðarjúp	Increase security of supply in the West Fjords
Fitjar substation	2023-2025	Install five new 132 kV switchgears and new 132 kV undergroud cable between Fitjar and Njarðvíkheiði	

Strategy	Construc-tion	Plan	Goal
IS3	2023-2024	New 220 kV overhead line be-tween Hamranes to Ísal	