Report for Umhvørvisstovan

Project: Modelling of the Faroese power system

Report

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Modelling of the Faroese power system

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Executive Summary

Faroe Islands aims to phase out existing oil-fired power and to have a fossil free electricity generation by 2030. This places some new challenges on the system as current system consists of primarily fossil thermal power production with the advantage that it can be used to balance the system while the replacement is primarily wind power which cannot. This creates a risk for imbalance in the system that must be handled. Another complicating factor is that decarbonisation occurs in all sectors, and as electrification is one of the primary solutions there is also a high likelihood of a very strong electricity demand development further increasing possible imbalance in the system.

Therefore, this project has investigated what it would take to balance the Faroese system in three future scenarios with different demand development and wind development. The analysis is based on extreme cases of high wind and low demand and high demand and zero wind to fully cover the range of situations that can happen.

All scenarios gave a generation deficit for the high load low wind case. The first scenario with a total electricity demand of 715 GWh had a lack of 100 MW, the second scenario with a total electricity demand of 960 GWh had a lack of 215 MW, and the third scenario that also had a total electricity demand of 960 GWh had a lack of 100 MW, but the deficit was lower in Scenario 3 than in Scenario 2 due to the assumptions of 25% demand flexibility and 70 MW additional storage.

A generation surplus was also shown in two of the scenarios. In scenario 1 and 2 there was no storage, which meant that in a high wind low demand case, there was almost 90 MW generation surplus for scenario 1, and 65 MW for scenario 2, that had to be curtailed. However, in scenario 3, both battery storage and pumped hydro was added which was able to balance the generation surplus in this scenario. This shows the potential of storage options as they can both help with generation surplus and deficit.

However, in conclusion, none of the three scenarios will fully cope with the assumed increase in demand with the planned development of wind and storage. One solution would be to add more storage than defined in the scenarios (30 MW battery storage and 70 MW pumped hydro in scenario 3). This could solve the problem of balancing the grid in combination with an increase in demand flexibility.

The study also showed that the grid will need investments to be able to cope with the demand and supply developments. The major bottlenecks are found in the north-eastern part of the system. The investments needs are spanning from 0.8 MEUR for OHL with the lower demand development in Scenario 1 to 5 MEUR for cables in Scenario 2 & 3 with the higher demand development.

1 Background

The Faroe Islands aims to phase out existing oil-fired power and to have a fossil free electricity generation by 2030, in other terms a decarbonisation of the power system. Wind power, supplemented by solar, will account for the greatest part of the renewable power generation growth. Different and more power generation will require reinforcements on the electricity grid, especially on the high voltage level.

In 2020, AFRY conducted a feasibility study, "*Reform av kraftsystemet på Færøyene"*, for Umhvørvisstovan (US). The purpose was to identify market principles for the power market that would be a good fit for the Faroe Islands system.

As continuation, AFRY will in this project provide an understanding of the implications of different potential future levels of fossil-free generation and increased electricity demand as the Faroese energy and power system is decarbonised. The technical aspects of the Faroese power system are investigated, with the purpose to secure that sufficient grid investments enable new power generation concessions and electrification.

The key players of the Faroese energy market which are mentioned and referred to in this report are listed in Table 1 below, together with their role and abbreviation.

Table 1: List of mentioned actors

Actor	Abbreviation	Role
Umhvørvisstovan	US	Faroese Environment Agency
Elfelagið Streymoy-Eysturoy-Vágar	SEV	Grid Owner, System Operator and Electricity Generation Owner on Faroe Islands
Vindrøkt and Effo		Wind Power Owner at Faroe Islands
Bakkafrost		Salmon producer and owner of biogas plant
Magn		Soon to be - Wind Power Owner at Faroe Islands

In the following sections, the methodology used in this study is presented (section 1.1) after which the objectives (section 1.2) and key characteristics and trends of the Faroe Islands power system are described (section 1.3).

1.1 Methodology

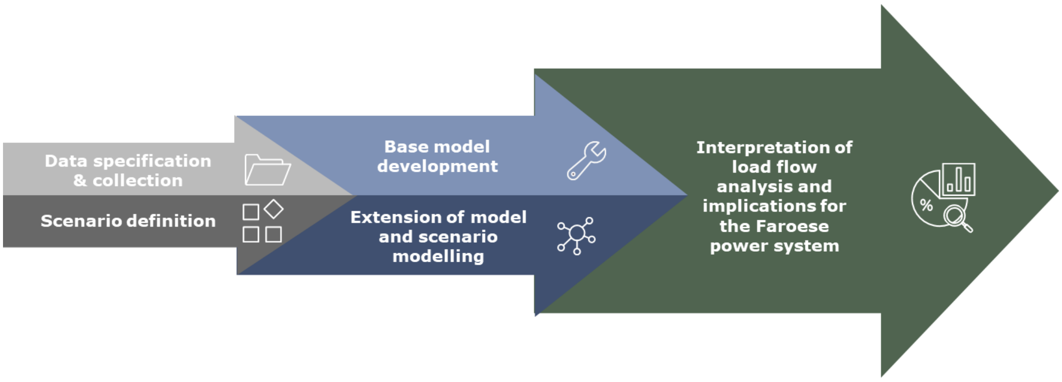
While electrification and decarbonisation of the Faroese energy system will require grid investments on all voltage levels, the focus of this study will be at the high-voltage transmission grid. The development of the lower-voltage distribution grid will depend on a number of factors related to new and transformed end-use and requires a much more detailed grid planning tool with associated data than what will be realistic and useful for the energy authority. Thus, for this project the 60 kV system will be modelled and analysed. The model is static and represents a snapshot of the Faroese power system That implies that only electric power and capacity at a certain point in time can be assessed and not energy (time series).

The demand and generation developments in the isolated system at Suðuroy are described and the planned connection to the main 60 kV grid will be considered for the scenario analysis of the future power system. Only large-scale electricity generation is considered in the developed scenarios. Small-scale generation such as domestic solar PV is neglected as these are connected to the local distribution grid with limited impact on the national transmission system.

For the power system modelling a commonly available platform (PSS/E) is used with proven capabilities for grid analysis and an open structure and wide access to competent advisory support both on development and use of the model. This will ensure that the model can be operated in-house, or open tenders for consultancy assistance can be issued by US.

The analysis follows a three-step approach, see Figure 1. First, the status quo of the Faroese power system is analysed (section 1.3) and the future scenarios defined in dialogue with US (section 2.1). In the second step, the base model is developed, followed by an extension of the model and the actual scenario simulations (chapter 3). Lastly, the simulation results are interpreted and potential implications for the Faroese power system derived (chapter 4).

Figure 1: Method



Other relevant topics and challenges for the operation of island power systems with a high share of non-synchronous generation are discussed in 5. Recommendations and conclusions will be summarised in chapter 6. A model manual for the usage of the model in the modelling environment PSS/E is provided in Annex B.

All simulations are performed for the most critical operation conditions for the future power system:

- **Operation in high load with zero wind generation**: Operation with no wind and high load, i.e. high demand from e.g. industries, indicate a time where no electricity from wind is generated but the system still requires a lot, e.g. during cold days.
- **Operation with high wind generation (maximum capacity) and low load**[1]: Operation with high wind generation and low load indicate a time where the system doesn't require electricity, but the generation is still high due to good wind conditions.

[1] Low load is assumed with 60% of peak load

1.2 Objectives of the study

Several challenges are arising when striving towards a fossil-free power system, especially in case of isolated systems such as the Faroes power system. Whereas larger, interconnected systems often benefit from the ability of surrounding systems to absorb or provide additional power, increasing the system stability, the operation of isolated systems need to be carefully planned and generation and load need to stay in balance within the system to ensure security of supply.

As mentioned before, in this study, the focus is set on static analysis of electric power and load flow analysis. The analysis will try to answer the following questions relevant for the operation of the Faroese future power system:

Generation-Demand Balance:

1) Will there be sufficient electricity generation, also in low wind situations, to meet the increasing demand (under consideration of storage and load flexibility)? If not, how much generation deficit occur in the defined scenarios and what are alternative measures to cope with this deficit?
2) Are the, in the investigated scenarios, defined levels of pumped hydro reservoirs (0-70 MW) or batteries (0-30MW) sufficient as measures to handle generation surplus in low load hours with high RES generation or will there be a need for wind curtailments? How much additional storage would be required to avoid the curtailment of wind?

Electricity grid:

3) In which parts of the 60 kV grid will grid constraints ("bottlenecks") occur and what is the investment need for grid reinforcement to guarantee security of supply?

Throughout the report these questions will be answered. Consequently it will build the backbone of the presented simulation results, analysis, and conclusions. Thus, some of the terms and assumptions are introduced below:

- Generation capacity deficit occur when the load is higher than the total generation in the grid or that area. In contrast, generation capacity surplus occurs when the total generation is higher than the total load. In order to reach a balanced system, the load (and losses) need to be in balance with the level of generation.
- For the investigation of potential bottlenecks in the future Faroese power system it is important to consider that usually power systems are dimensioned in a way so that even in these events security of supply is guaranteed. Even in these cases power lines should stay within their current limits. Consequently, the analysis within this study presented in section 4.3 consider capacity constraints in case of a (N-1) event in the simulated cases. A high-level approximation to assess N-1 cases without doing contingency analyses is to apply a rating factor of 150%[2].

1.3 The power system of Faroe Islands

The Faroe Islands consist of 18 islands with a total population of 53 500 inhabitants[3]. Tórshavn is the capital where roughly a third of the population is resident, located in

[2] AFRY assumption based on industry experience
[3] https://www.faroeislands.fo/ and US

the south on Streymoy island. Faroe Islands is a self-governing nation with responsibilities and independent power within the realm of Denmark.

The local economy is heavily dependent on the fishing- and salmon farming industry, which accounts for ~20% of the island gross value and employ around 15% of the working population[4]. Other industries of importance are financial services, tourism, telecommunication and harbour[5].

One of Faroe Islands political decisions is to decommission fossil fuels and invest in renewable sources. This is presented in the form of a target of 100% fossil free electricity generation by 2030[6] and 50% lower oil consumption in heating by 2025[6]. To be able to reduce the fossil fuels an extensive wind development is being planned.

The electricity demand today is more than 400 GWh and US estimates it to significantly increase the next couple of years. As for many other Nordic locations, the power consumption is higher during the fall and winter months and in 2020, the peak load in the main area was measured to 63 MW in November[7].

The high voltage electricity grid (60 kV), illustrated in Figure 2 together with installed generation, consists today of one system on the northern islands. See Table 16 in Annex A for each line rated power. Sandoy is connected to the main system on the 20 kV voltage level. On Suðuroy there is an isolated 20 kV system. Plans for establishing an interconnection between them are currently being evaluated.

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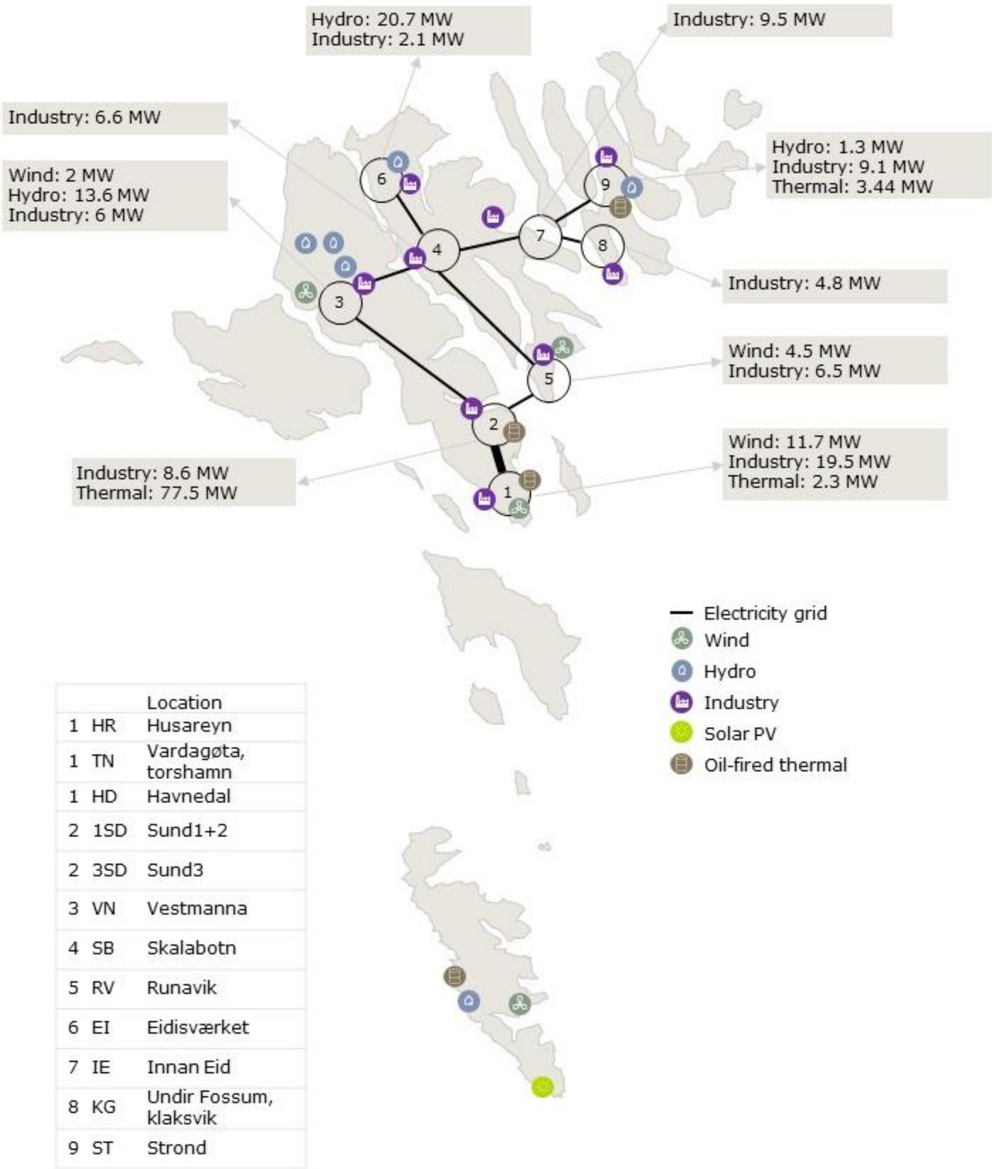
[4] https://www.faroeislands.fo/economy-business/economy/
[5] https://hagstova.fo/en
[6] https://www.faroeislands.fo/economy-business/energy/
[7] https://www.sev.fo/english/the-power-supply-system/

Figure 2: Faroe islands map – status quo



Note: Industry refers to load included in the model by SEV, what type of load on each location is not known but assumes to be industrial load.

Today, the Faroe Islands has a power supply with approximately 30% hydro power, 15% wind power and 50-60% oil-based thermal power.

Faroe Islands has currently 3 oil-fired thermal power plants in operation, two are connected to the northern system and one is located on Suðuroy[8], all owned by SEV. Total installed capacity is ~100 MW, where heavy fuel oil and some diesel are the used sources. The highest generation is during summer since hydro and wind have their peak during the winter months. The largest thermal power plant is located in Sund. Together with the hydro power, the thermal power contributes to balancing the power system.

[8] https://www.sev.fo/english/the-power-supply-system/

Consequently, fossil fuels still play an important role for Faroe Islands. Road traffic and numerous industries, e.g. the fishing industry have historically been dependent on fossil fuels. However, charging infrastructure, supporting e-mobility, is currently being developed indicating a shift towards an electrified vehicle fleet. Already there are around 130 charging poles on the Faroe Islands, including both public and private charging. Additionally, the use of space heating with electric heat pumps is also increasing. Furthermore, all industry segments are expected to electrify their business in the future, which is one of the reasons why the electricity demand expects to increase substantially.

There are six hydro power plants, all owned by SEV, with a total installed capacity of 39 MW[9] on Faroe Islands, where all have the possibility to serve as a storage. The largest plant is located in Eiði with three turbines. Studying the generation over one year, the highest generation occurs during the winter months[10].

Until 2021 there were three wind farms on the Faroe Islands located in Vestmanna, Neshagi and Húsahagi, with a total installed capacity of ~18 MW. Since February 2021, an additional wind farm has been installed at Porkeri, Suðuroy with a total capacity of 6.3 MW[11]. Additionally, three new wind farms have been committed, 25,2 MW in Hoyvíkshagi, 18 MW in Eiði and 18 MW in Flatnahaga. The wind farm located in Vestmanna and the newly committed one in Hoyvíkshagi is owned by the private companies Vindrøkt and Effo[12], the new wind farm in Flatnahaga by Magn and the other ones are owned by SEV.

The highest generation occurs during the winter months when the wind profile has better power generation conditions. The political target of fossil free electricity points out the direction of the future power system on Faroe Islands, indicating that a continued wind power development is necessary in order to reach the target. Additionally, there is a great potential for offshore wind at the Faroe Islands that currently is being investigated.

Recently, the local salmon producer Bakkafrost invested in Faroe Islands first biogas plant, named FÖRKA[14]. Tidal energy is another source of electricity generation that's currently being investigated. Together with Minesto, SEV is performing a project on the Faroe Islands to evaluate the potential[15].

Since 2019, SEV operates one solar power plant on Suðuroy[7,16]. Additional, US operate two small-scale solar PV units and some small-scale solar PVs are installed on roofs of private households[12]. According to US, there are more progressive plans to establish additional solar power with an installed capacity of 30-60 MW.

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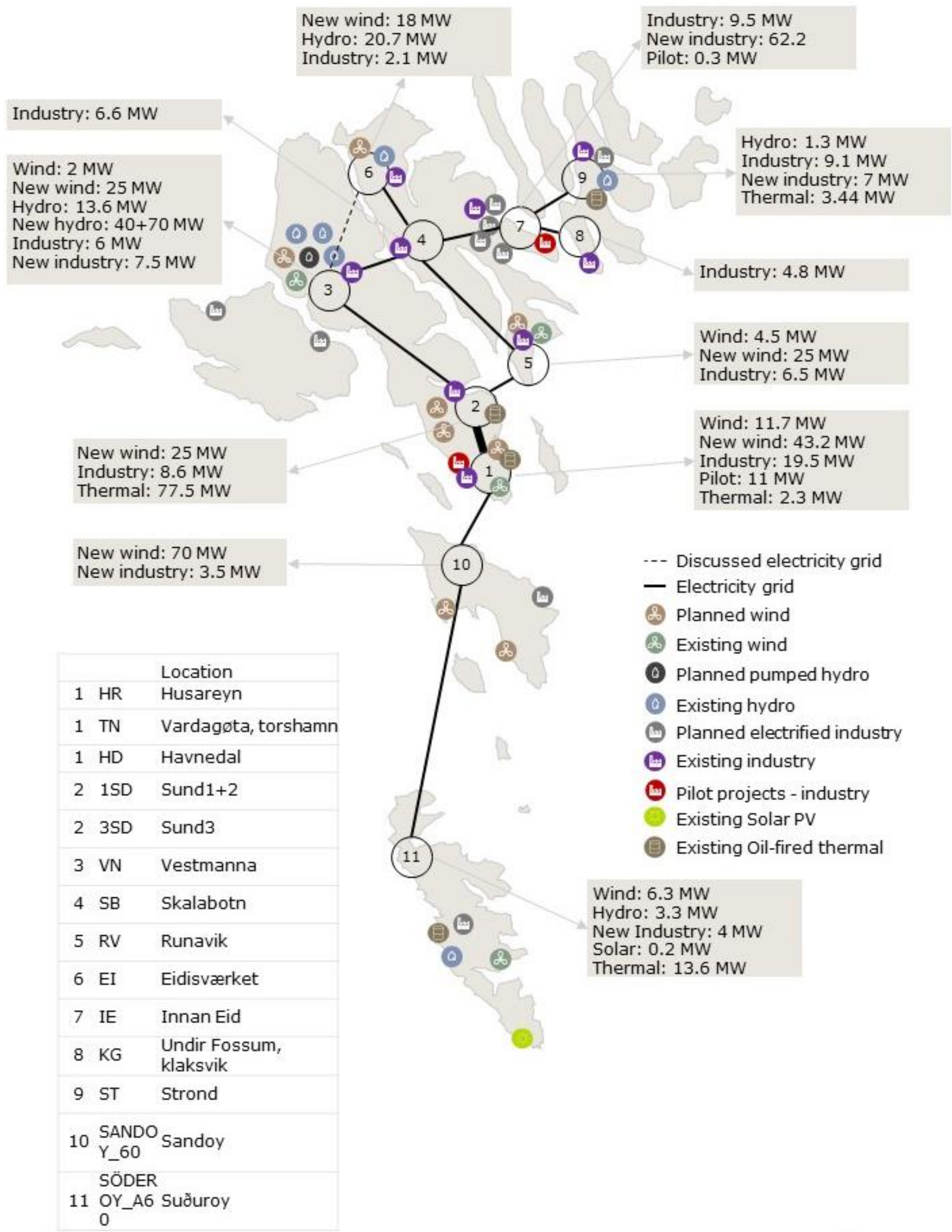
[9] 36 MW included in the model
[10] Data from US: Elproduktion 2020 hovedner
[11] https://local.fo/seven-turbine-porkeri-wind-farm-inaugurated/
[12] Nordic council of ministers: *Energy in the west Nordics and the Artic* (2018) and US
[14] https://www.niras.com/projects/biogas-from-bakkafrost/
[15] https://www.sev.fo/english/projects/minesto-tidal-energy-project/
[16] https://www.faroeislands.fo/the-big-picture/news/first-solar-panel-park-in-faroe-islands-activated/

2 Scenario Description

In this chapter, the three scenarios and the assumptions behind them are introduced. Three scenarios were defined in cooperation with US. In order to establish reasonable scenarios, the current status of the power system was thoroughly studied (see section 1.3) and served as a base during the development.

In Figure 3, the existing and planned investments are illustrated together with a simplified electricity grid. Existing industry refers to load included in the model by SEV, what type of load on each location is not known but assumed to be industrial. Planned electrified industry are known industries with plans to electrify some of their business. The two listed pilot projects are a small district heating network in Leirvík and a fish farming boat outside of Tórshavn.

Figure 3: Faroe Islands map including the electricity grid, electricity generation and industries



Note: Exact location, length and type of the new connections is not known in detail. Existing industry refers to load included in the model by SEV, what type of load on each location is not known but assumes to be industrial load.

2.1 Defined scenarios

As described above, three scenarios were chosen to investigate the impact of different generation and demand levels to the grid.

Table 2 summarises the three scenarios and compares them to today's characteristics of the Faroese power system. The three scenarios and the assumptions supporting the figures are described in the following section. In addition, a summary of the assumption's origin is listed in Annex A.

Table 2: Figures for today and the three future scenarios

Electricity demand [GWh]	Peak load[17] [MW]	Flexibility [%]	Wind power[18] [MW]	Hydro power [MW]	Thermal power [MW]	Add. battery storage [MW]
Status quo[19]						
371	70	-	18	36	83	-
Scenario 1: Increased demand with flexibility						
715	170	25	206	36	0	-
Scenario 2: Increased demand with more wind and no flexibility						
960	240	0	250	36	0	-
Scenario 3: Increased demand with more wind, flexibility and storage						
960	240	25	250	36 + 40[20]	0	30

Note: All figures for Status quo are allocated to the northern system, e.g. the new wind farm at Porkeri, Suðuroy is not included in the table, since the connections is not constructed yet. However, in the scenarios, the connection is assumed to be established and thus the figures are allocated to the entire system.

Overall, the scenarios originate from the assumption that the fossil free target will be reached and that the electricity demand will increase significantly in the years to come. The wind levels considered in the scenarios are chosen to meet the increasing demand and thus to enable reaching the fossil free target.

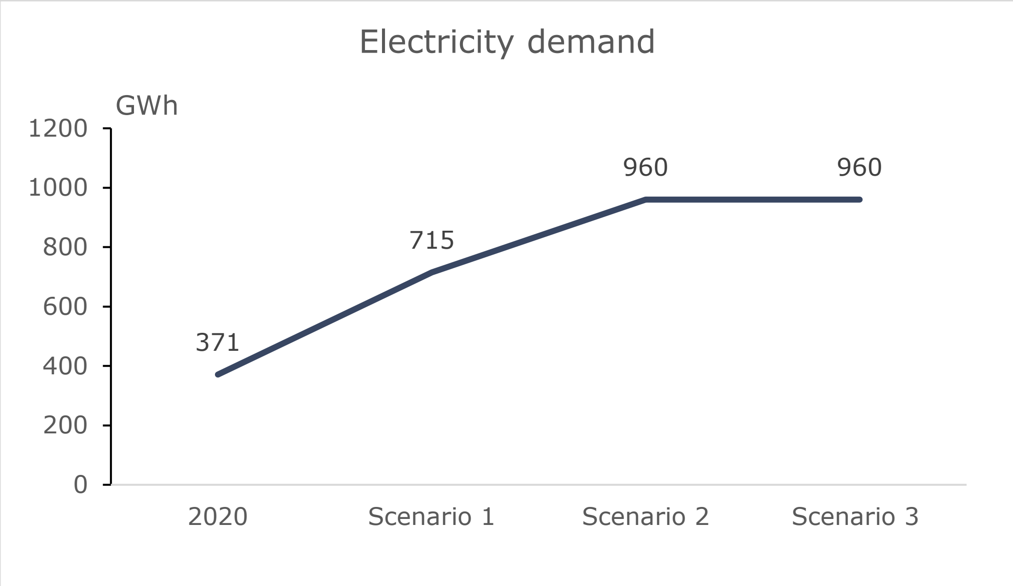
2.2 Electricity demand

In all scenarios, the electricity demand increases, illustrated in Figure 4.

In scenario 1, the demand is almost doubled compared to 2020 and for the two other scenarios the demand is even beyond that, approaching 1 TWh. The demand assumptions originate from the knowledge of the political decisions and the increased electrification of society, together with numerous discussions and an agreement with US.

[17] Peak load calculated based on electricity demand forecast and assumed full load hours, see 2.3 for more details on peak load calculation
[18] All wind power assumed to be onshore
[19] US, SEV. Figures for 2020
[20] Additional 40 MW generation capacity and 70 MW pump capacity

Figure 4: Electricity demand [GWh]



2.3 Installed capacity and peak load

In terms of peak load, different sources mention values between 60-70 MW, where 70 MW is used as the status quo, since it's originates from the PSS/E model from SEV. For the scenarios, peak load was calculated by dividing the electricity demand with the full load hours, i.e. the number of hours/year it would need to run at its rated power to generate the same amount of electricity that it generate during a year, assumed to be around 4000h[21].

A great increase in wind development, illustrated in Figure 5, is assumed in all scenarios with all sites located onshore. The assumptions regarding the wind development originates from already known investments, like establishment of 25 MW wind power from Vestas near Tórshavn[22] and several studies[23,24,25] along with agile discussions with US.

As presented before, investments in offshore wind is currently being investigated in several forums. These discussions are not considered in the scenarios. The costs for the offshore grid connection would likely to be borne by the developer and owner.

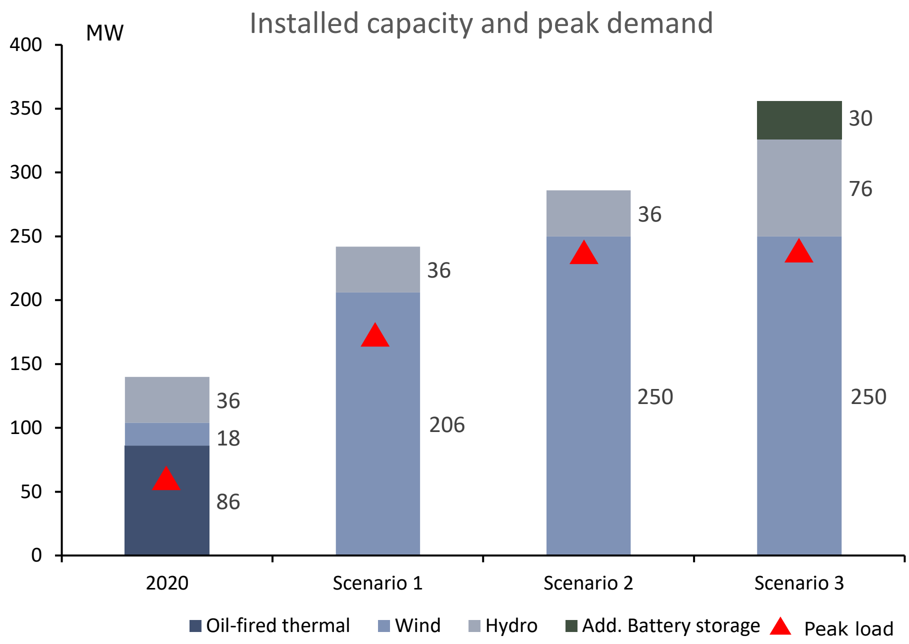
In scenario 3 an additional hydro power is added, including 40 MW generation capacity and 70 MW pump capacity in Vestmanna (Mýrarnar and Heygadalur). The additional hydro generation and pump capacity is in the same range as other studies (2025 levels)[26,27], specified in agreement with US.

In scenario 3, which investigate in detail the impact of available flexibility in the grid, additional 30 MW of battery storage is considered. The level of battery capacity which is planned to be connected to the Faroese power system, mainly as stabilisation of

[21] Based on AFRY industry and modelling experience
[22] https://www.evwind.es/2021/04/15/vestas-to-expand-wind-power-capacity-in-the-faroe-islands/80373
[23] Norconsult: *100% fornybar kraft Pumpekraft, vind og sol* (2018)
[24] Helma: *100% Sustainable Electricity in the Faroe Islands - Expansion Planning Through Economic Optimization (2021)*
[25] Dansk Energi: Teknisk notat (2017)
[26] EA Energy analysis (2018)
[27] Dansk Energi - Energilagring på Færøerne - Teknisk opsamlingsrapport (2018)

wind production, was discussed with US. As of today, it is not decided where these battery storage facilities will be installed. Within this report connections points for batteries and their impact on power flows in the grid and implications for the future grid operation will be presented and discussed to support the identification of connection points which seem to give the most value for the power system operation.

Figure 5: Installed capacity and peak load [MW]



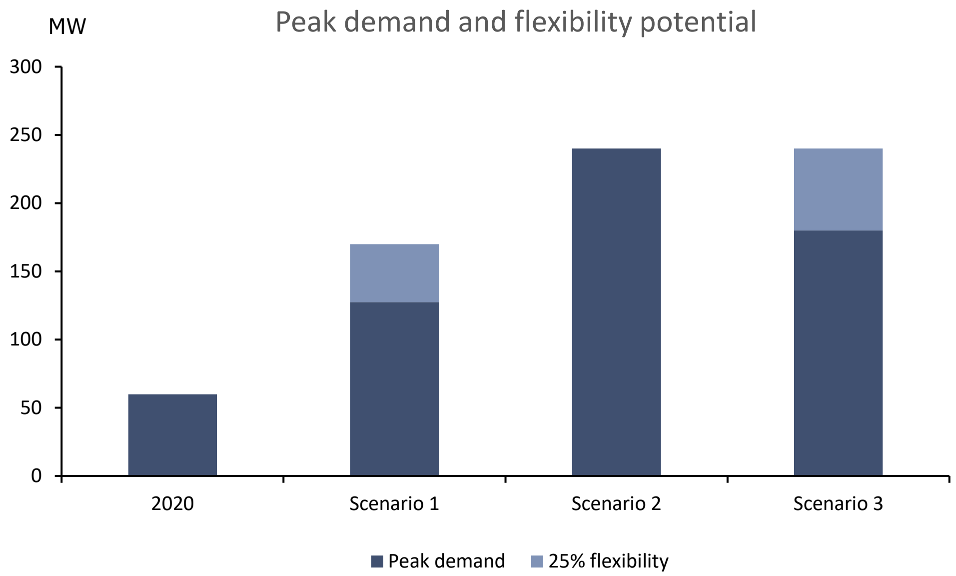
2.4 Flexibility

Demand flexibility within the power system refers to the possibility to be flexible with electricity usage, e.g. decrease/move some of the electricity demand (peak shifting). If the electricity demand is high during a period with low wind, flexibility have the possibility to lower the peak load and thus minimise the need of adding oil-fired thermal power in the system, see Figure 6

Based on AFRY's experience, a potential flexibility of 15-40% (ca 40% in Norway, 15-30% in the other Nordic countries) of the maximum demand in Nordic countries is possible[28]. Examples of flexible loads are hydro pumped storage, electric vehicles, district heating, heat pumps and some operations in industries. On Faroe Islands ~10% of households have a heat pump. AFRY assumes in this study 25% flexible load for the Faroe Islands considering the flexible loads available.

[28] AFRY - Market-based flexibility procurement for Nordic DSOs (2021)

Figure 6: Flexibility [%] and peak load [MW]



In summary, for the Faroe Islands to reach its target of a fossil free electricity generation, a huge energy transition of the power system needs to be achieved. The scenarios presented in this chapter display three different potential outcomes. The simulation, presented in 3.2, present the result, i.e. what each scenario would imply for the Faroese power system as a whole.

3 Modelling of the Faroese power system

To be able to analyse the impact of electrification and RES integration on the Faroese power system a system model including all electricity network assets, loads and generation need to be developed. This model can be utilised to simulate the scenarios as introduced in 2.1, and also be used to reflect other scenarios when updating parameters.

In the following chapter, first, the status quo model development is described together with characterisation of the status quo of the Faroese power system. Subsequently, the model adaptions and extensions towards the 2030 grid configuration are outlined and the scenario simulations presented.

3.1 Status Quo model development and simulations

As described in section 1.1 a model of the Faroese power system is developed in a simulation environment with proven capabilities for grid analysis and an open structure and wide access. The status quo model development considering todays grid characteristics is described in section 3.1.1 followed by the simulation results for the status quo model (section 3.1.2.1 and 3.1.2.2).

The status quo modelling and simulations are based on the generation and load levels as presented in Table 3.

Table 3: Status quo load and generation levels in Faroese power system

Electricity demand [GWh]	Peak load [MW]	Flexibility [%]	Wind power[29] [MW]	Hydro power [MW]	Thermal power [MW]	Add. battery storage [MW]
Status quo[30]						
371	70	-	18	36	83	-

3.1.1 Model development

One of the main goals of this project is to enable US to build an own view on Faroe Islands future power system. For this a detailed model of the power system considering transformers, overhead lines (OHLs) and underground cables of the Faroese power system is needed. As described before, this study will focus on the 60 kV voltage level of the system. This section describes the development of the model.

As modelling environment for this grid study, the simulation software PSS/E is used. Before conducting the simulation, grid data was received and reviewed to learn about the topology of the grid. The grid model and data were provided by SEV. PowerFactory DigSilent is used for grid modelling within SEV, so, for this project, the grid model was exported and converted to a compatible file format for PSS/E (.raw).

[29] All wind power assumed to be onshore
[30] US, SEV. Figures for 2020

A separate single line diagram representing the 60 kV-grid was provided which includes all the relevant busses listed (see Annex C). The assessment of data quality and consistency revealed the following issues:

- The grid model given by SEV and the pdf-file with the single line diagram has different annotations.
- The model and single line diagram (SLD) miss information on generation and load type.
- The model does not provide any information on reactive power production of the wind generation units[31].
- Capacity of installed generation as well as peak load as implemented in the model does not fully match SEVs publicly available information. No changes are done to the already implemented generating units and loads in the model to fit publicly available information assuming that SEV is likely to implement these types of data accurate in their model.

To be able to receive a full picture of the model and the information on the Faroese power system as described in section 1.3 and in the scenario description in section 2.1, a comprehensive mapping exercise was required. The mapping of all provided bus notations can be found in Annex A**Error! Reference source not found.**, including the name of each power grid station, their abbreviations and bus numbers in PSS/E.

As mentioned above, the installed capacities of generation units and loads were kept at the same levels as in the model provided by SEV for the base case.

The provided grid model consists of voltage levels ranging from 60 kV down to 10 kV. However, as the 60 kV grid is the voltage level that is focused on in this study, the model has been aggregated to the 60 kV level. A simplified SLD of the Faroese power system as used for this study is illustrated in Figure 7.

When performing power system studies a swing bus is used as reference point for the model and to balance the active and reactive power in a system. It is used to provide for system losses by emitting or absorbing active[32] or reactive power[33] to and from the system. In all analysis in this report active power in form of load flows is in focus. Voltage stability, highly related to reactive power, is neglected.

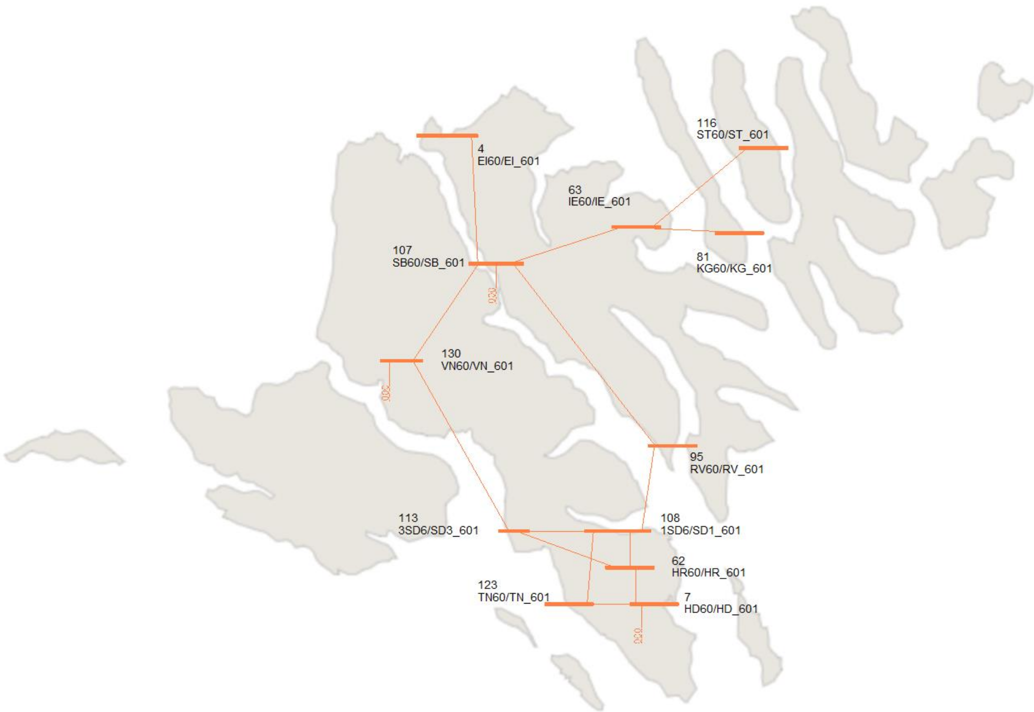
As the Faroes power system is an isolated system the swing bus does not reflect realistic operation conditions as there are no surrounding systems which can absorb or provide additional power. Instead, the power absorbed or provided by the swing bus can indicate an existing energy surplus or deficit in the system which need to be solved by appropriate mitigation measures to ensure security of supply. Exemplary measures could be the up- or downregulation of generation units, activation of hydro storage, battery units or demand flexibility. The role of these different measures and their implications, especially for the future system operation, are discussed in chapter 4.

[31] As this study is focused on the active power flows this can be neglected. However, if other issues such as loss level or voltage shall be investigated with the model this information will need to be complemented in PSS/E (see section 5.4 for more details).

[32] Active power is the power which is actually consumed or utilised in an AC circuit. It is measured in Megawatts (MW).

[33] Reactive power, measured in MegaVolt-ampere reactive (MVAR), exists in an AC circuit when the current and voltage are not in phase. Reactive power is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors and directly influences electric system voltage.

Figure 7: Simplified SLD of the Faroese grid with all 60 kV-buses indicated. Swing bus is located at Sund 1 (SD1).



Note: Sund 1 (SD1) and Sund 3 (3SD) are illustrated with a geographical distinction to be able to assess the connection between these nodes. Actually, the two nodes are placed next to each other what need to be considered when interpreting simulations results, especially as the swing bus is located at Sund 1 (SD1).

3.1.2 Status quo simulations

As introduced in section 1.1, two worst-case situations are simulated: high load with zero wind generation and a case with a low load combined with high wind generation. The low load is assumed to be 60 % of the peak load, which is assumed for all calculations in this study. Since these are two cases that will put a lot of stress into the grid due to deficit and surplus in generation compared to the load, each case will use an iterated solution in the following manner to obtain a balanced case:

- The initial solution will provide a view on the generation-demand balance in the situation and show the magnitude of the deficit or surplus in generation and where this imbalance is most significant in the grid.
- The following iterations of the simulation will be aimed to balance generation and load demand. As it would be required for operation of an isolated system such as the Faroese power system.

As no information about the reactive power generation or consumption of the wind farms are available in the power system model, the reactive power is assumed to be zero for the simulation.[34] As mainly active power flow is analysed in this study the impact of this assumption is neglectable.

[34] The reason for this assumption was because of the control method "fixed Q based on wind power factor" that each wind power plant (WPP) used, this factor was set to 1 meaning that only active power is generated.

After the assessment of the generation-demand balance in the system, grid constraints in the grid are investigated in a second step. For this, the loadings of underground cables and OHLs are evaluated based on load flow calculations. As mentioned above, the swing bus will generate or consume active power in case demand and generation are not balanced in the system. As this would affect the load flow in the system and by that affect line loadings, grid constraints are only evaluated in the balanced grid operation (the iterated solution of the model). The assessment of load flows and loadings has the aim to evaluate if the power system is dimensioned appropriately and to identify constraint lines which require grid reinforcement.

The load flow simulation results for today's system are presented in the following sections, including illustrations of the simplified SLD to visualise the calculated loading of the power lines. The loading is calculated in % of the rated values and is the amount of electric power transported via overhead lines or cables. Rated current indicates the power line is dimensioned for and that the power lines should be able to handle without any occurring damages. If higher capacity is needed, the power line needs to be dimensioned for that, by increasing the diameter of the power line (or increasing the number of conductor). Often, power lines are dimensioned for operation at a conductor temperature of 65°C in order to have some marginal to avoid high thermal loading during longer periods. In summary, higher power leads to higher heat exchange and operating temperature. The highest operation temperature is 90°C, if it is exceeded, the lifetime of the power line will decrease drastically

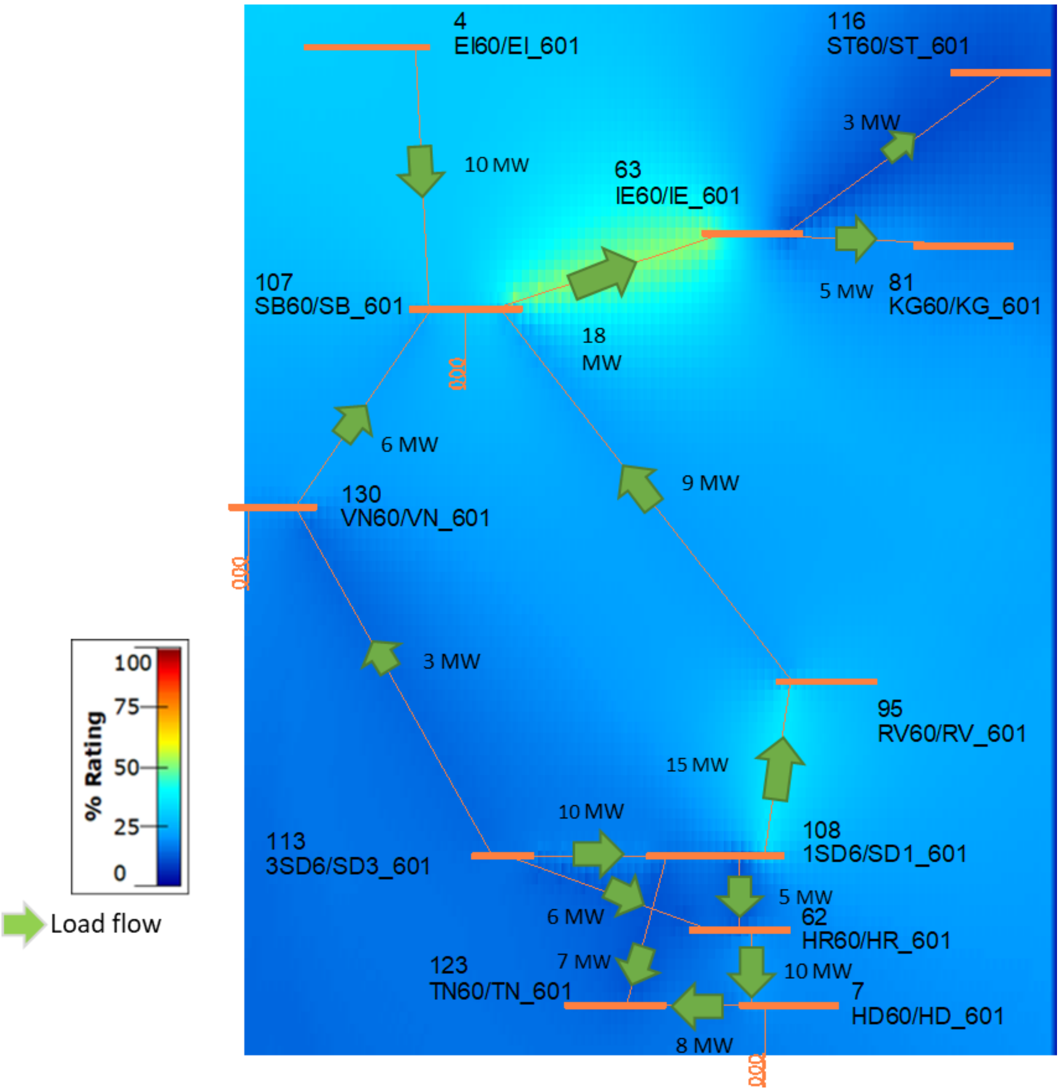
In the following the simulation results for both cases, high load and zero wind (section 3.1.2.1) as well as low load and high wind (section 3.1.2.2) are presented and discussed.

3.1.2.1 High load, zero wind

In this case with high load demand in the 60 kV grid, the load level is assumed to be 70 MW, while scaling down all the generation from wind to 0 MW. Thermal and hydro power is adjusted to about 71 MW to meet the load demand as well as to take account for system losses and bring the grid to a balanced state.

In Figure 8, the result of the load flow calculation is illustrated.

Figure 8: Simulation results obtained after load flow calculation



Note: The green arrows represent the direction and amount of active power in the grid. The heat map indicates which lines that are the most loaded.

Due to not having any wind power in this scenario, both thermal power and hydro need to be the main source of generating electricity. The placement of generating units are in Husareyn (HR60), Vestmanna (VN), Eidisværket (EI) and Sund (1SD + 3SD). The loads are located in Torshavn (TN60), Skalabotn (SB60), Innan Eid (IE60), Strond (ST60) and Undir Fossum (KG60). This explains why the power flow is moving to areas in the Southern and north-eastern part of The Faroese power system.

Simulation shows that the installed capacity of generation, combining thermal and hydro power, in today’s grid is enough for the current loads, while having some margin to an increase of the load in the future. However, in peak load situations in which wind is not blowing and even hydro power would not be available (e.g. low water levels after dry periods or during service period of the power plants) constraints to the grid operation can arise as the thermal power plants are not capable to fully cover todays peak load.

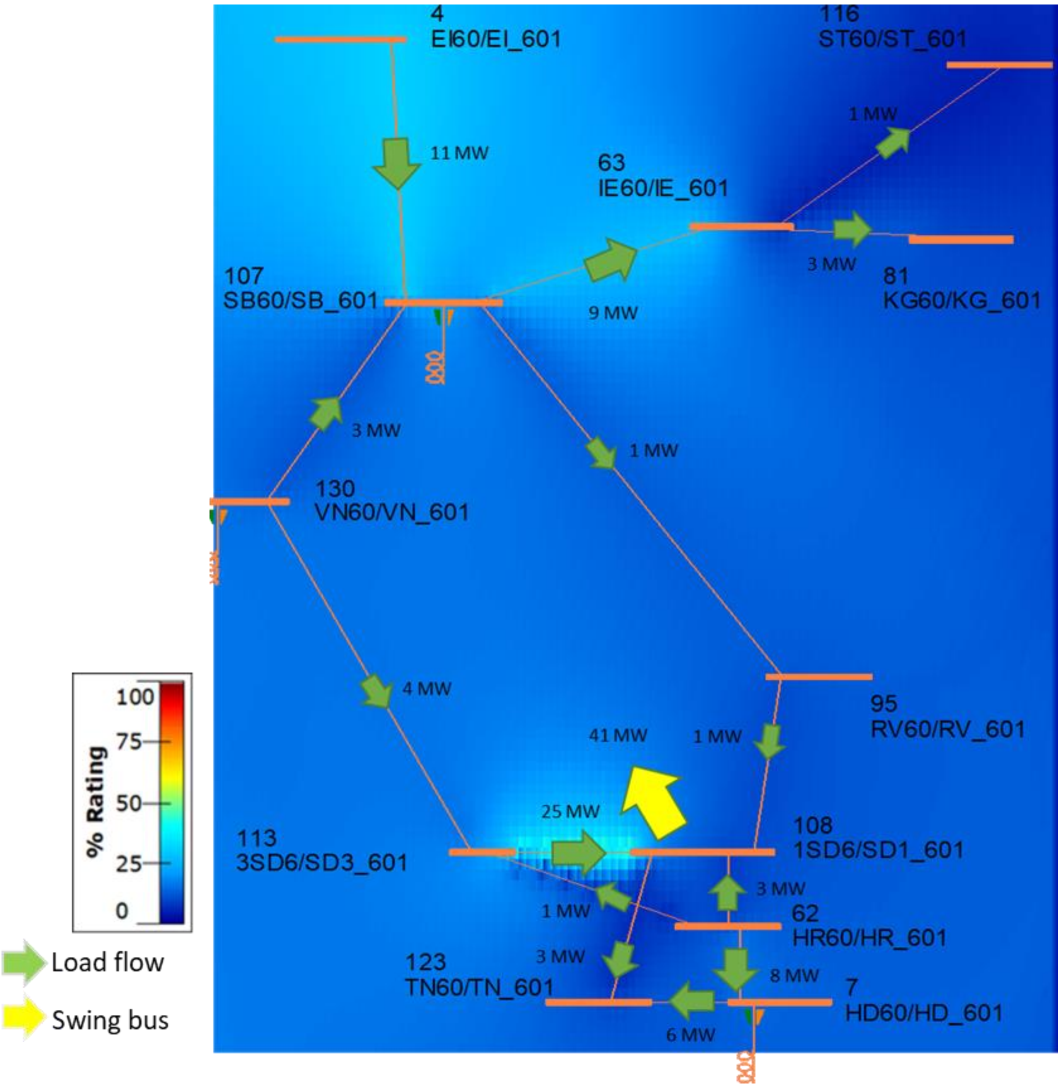
As seen in Figure 8, the lines between Skalabotn- Innan Eid and Runavik-Sund 1 are the highest loaded lines (52% and 37% of rated current), but still far from their current rating. The loading of all lines is within an acceptable range (up to 70-80% of rated current)[35] for today's grid topology.

3.1.2.2 Low load, maximum wind

In this case with low load demand in the Faroese grid, the load level is scaled down to 42 MW (60% of peak load). The reactive power on each load is scaled down with the same factor. The generation from wind power is set to its maximum of 18 MW. As described before, the first solution of the load flow model shall provide a view on the generation-demand balance in the simulated case without any additional balancing measures. Thus, generation from thermal and hydro power is kept on the same levels as in the original snapshot[36] provided by SEV and combined counts for 66 MW.

In Figure 9, an illustration of the result of the load flow calculation is presented.

Figure 9: Simulation results obtained after completed load flow calculation without balanced generation and demand



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[35] Grid should be dimensioned in a way that sufficient marginal is existing to ensure operation in N-1 case. Depending on cable types and placement configuration and dimensioned temperature of cables the rated current can differ. Assuming that SEV has considered this in the model, 70-80% is a valid high level assumption.

[36] Snapshot refers to generation and demand levels according to the from SEV provided grid model.

Note: The green arrows represent the direction and amount of active power in the grid. The yellow arrow represents where the excessive active power is being consumed. The heat map indicates which lines that are the most loaded.

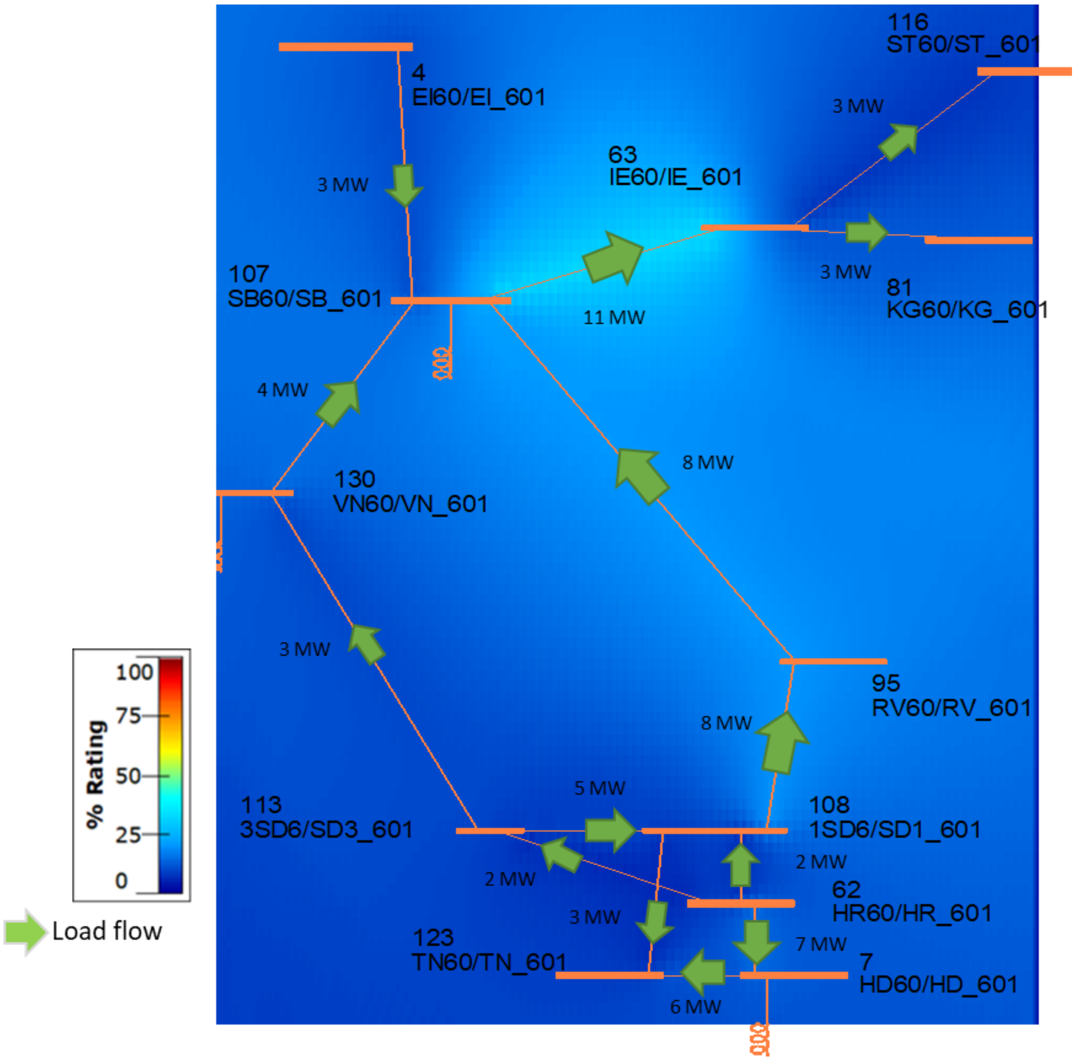
With a maximum generation of active power from wind, placed in Vestmanna (VN60), Husahagi (placed under HR60) and Neshagi (placed under RV), the power flow differs from the previous case. The electricity demand is still high in the north-eastern part of the grid, thus, significant power flows into that area can be observed.

With the addition of wind in Vestmanna, Neshagi and Husahagi, a generation surplus appears since the generation exceeds the demand. The excessive electricity is directed to the southern part of the grid and is absorbed by the swing bus in PSS/E at Sund 1 (1SD). Having a load demand of 42 MW and a generation of roughly twice the amount of active power that is necessary for the electricity demand, the swing bus absorbs around 41 MW.

To prevent this imbalance between generation and consumption, some generation planning needs to be implemented. The first step is to scale down or limit the generation from thermal and hydro power. As last measure the curtailment of wind power could be applied. Simulating the base case scenarios with today's preconditions in the grid the downregulation of thermal and hydro power plants is sufficient to ensure a balanced system operation.

Figure 10 illustrates the load flow results in the case of balanced generation and demand.

Figure 10: The result after completed load flow calculation with balanced grid.



Note: The green arrows represent the direction and amount of active power in the grid. The heat map indicates which lines that are the most loaded.

To simplify the regulation, it is assumed that all thermal and hydro power plants are scaled down with the same factor. To balance out the electricity surplus the thermal and hydro power plants are scaled down to about 36%. Wind power generation is kept on the same level. No actual market mechanisms for the regulation were considered as this would require a detailed market modelling of the situation. No grid constraints when simulating the case of low load and maximum wind can be observed. The highest loaded line is between Skalabotn and Innan Eid (33% of rated current) as demand in the north-eastern part of The Faroese grid is still relatively high compared to the rest of the grid and generation in the area was scaled down to balance the grid.

3.2 Model extension and scenario simulations

As introduced in chapter 0, the model is extended and configured to be able to simulate the scenarios specified in Table 2. The model used for the status quo simulations mentioned in section 3.1 is therefore used as the foundation for the grid model. New planned generation and loads, including their areas according to the scenarios, are implemented to the model.

The model is extended according to the grid topology and placement of loads and generation as illustrated in Figure 3. Both, Sandoy and Suðuroy are considered in the model and are assumed to be connected to the main grid via a 60 kV-cable starting from Husareyn/Kirkjubour. The technical data for the 60 kV-cable is provided by SEV, including the estimated cable lengths between the connection points. No other grid reinforcements until 2030 have been considered due to lack of available information. This implies that it is likely that many of the power lines will be highly loaded or even overloaded, implicating potentially very high loss levels in the grid. The loading of power lines and the loss levels in the modelled simulations and cases will be addressed in the following sections.

As the focus of the study is on active power and no other information about reactive power of the future loads considered in the scenarios it is assumed that the same ratio between active and reactive power is retained as in today's loads provided by SEV (reactive power 30 % of active power). Additionally, no information about reactive power generation or consumption for the planned generation are specified. Therefore, the assumption of zero reactive power exchange with the grid for the new generation units is used.

When adding the hydro that is located in Vestmanna with a generator capacity of 40 MW and 70 MW consumption during pump mode, it is modelled as a classic generator unit during generation and as a load when pumping water to the top of the water reservoir.

In a similar way the modelling of batteries is being implemented. During scenarios when the battery supports the generation by exchanging stored energy to the grid, it is modelled as a generator. When the battery is in the low load cases it needs to absorb power (recharging) it is then modelled as a load.

As described in section 1.2 there are a couple of key questions to be answered from the simulations:

- Is it possible to cope with the appearing generation deficits and surpluses in the most extreme operational situations with the level peak load, generation and storage as defined in the scenarios 1-3 in chapter 0? If not, which measures would be additionally required to balance the generation and demand in a way that security of supply of the Faroese island system can be guaranteed?
- Based on the balanced simulation cases, which power lines will be the bottleneck for the operation of the future Faroes power system? How big is the capacity deficit of these lines and which investments are required to reinforce the grid sufficiently?

To answer these questions the chosen scenarios have been simulated with the help of the extended grid model of the Faroese power system with the amendments and assumptions introduced above. With the help of the simulations the appearing generation deficits and surpluses could be quantified and mitigation measure were implemented to balance the grid so that there is no active power surplus or deficit in the grid. For this, first the units as defined in the scenarios were utilised as measure to adjust and reach the balanced state. If the scenario still could not be solved within the available resources, additional measures were implemented to obtain a balanced solution. This could be by either increasing or decreasing loads and generation or adding energy storages.

In the following sections the simulations of the different scenarios and cases is described in a bit more detail, including information on how generation and load balance has been realised. However, alternative measures and analysis of the results will be discussed more in chapter 4. It should be noted that alternative measures (e.g. different locations of generation units) might affect the simulations results, especially regarding utilisation of power lines and direction of flows. However, as for the scenarios 1-3 below different load and generations levels as well as different measures are considered to cope with the appearing challenges of generation deficit and surplus. The presented results give a good indication of the potential bottlenecks in the future Faroese power system.

3.2.1 Scenario 1

Scenario 1 represents a more conservative peak load development with a moderate wind build out until 2030, see Table 4.

Table 4 Demand and wind power assumptions for Scenario 1 (ref. Status quo)

Electricity demand [GWh]	**Peak load [MW]**	**Flexibility [%]**	**Wind power[37] [MW]**	**Hydro power [MW]**	**Thermal power [MW]**	**Add. battery storage [MW]**
Status quo[38]						
371	70	-	18	36	97	-
Scenario 1: Increased demand with flexibility						
715	170	25	206	36	0	-

In the following sections, the simulations and corresponding results for both cases, high load, zero wind and low load, high wind are discussed and illustrated.

3.2.1.1 High load, zero wind

According to Table 2 in this case the load is set to 170 MW but with a flexibility in load that makes it possible to lower the load level to 126 MW. In this case a specific operational situation is simulated in which wind is not blowing and thus wind power provides zero power to the grid. Considering the scenario as specified in chapter 0 and the goal of fossil free generation in 2030, the only generation that could be provided to the grid from hydro at that instance. However, todays hydro power plants as implemented in the scenario (36 MW) is not sufficient to meet the peak load.

Therefore, additional 99 MW predictable generation (e.g. batteries, hydro or thermal power plants) were implemented with a large share in Sund (1SD113/3SD108) and additional smaller sites in Strond (ST116), Torshavn (TN123), Suðuroy (SÖDEROY_A602301) and Innan Eid (IE60) to meet the load of scenario 1. Alternative solutions and measures to balance the grid in case of this high load scenario will be discussed and presented in 4.1.

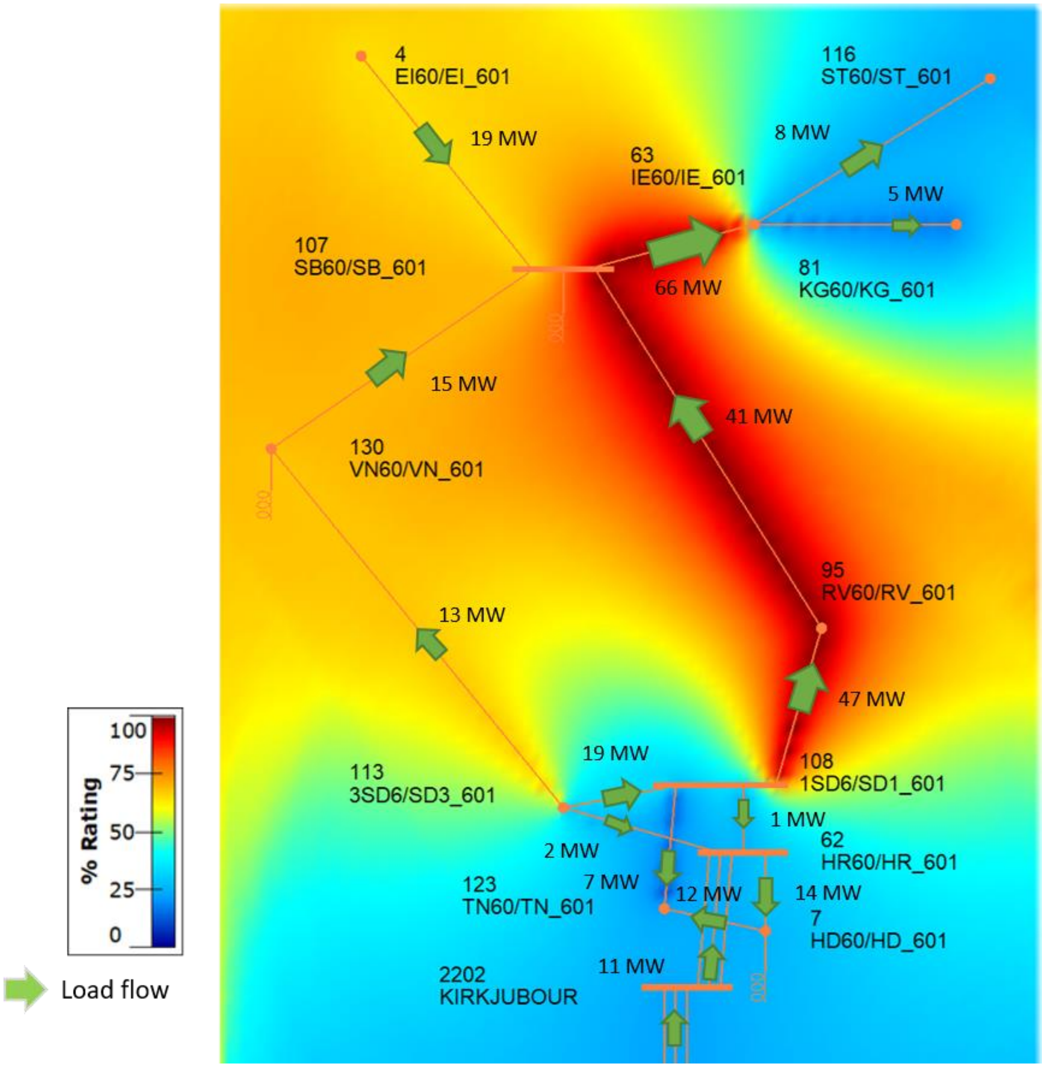
In Figure 11 the results of the simulation of the balanced case are illustrated with a heat map to indicate which lines that are being highly loaded (red - >100% loading, blue – <25% loading). It should be considered that the choice of the location of the additional generation units might impact the results of the load flow analysis and thus

[37] All wind power assumed to be onshore
[38] US, SEV. Figures for 2020

the loading of the power lines. However, the location was chosen based on the assumption that the electricity grid is dimensioned today after the location of the thermal generation unit implicating that reusing these sites for other types of generation or storage might be favorable. Additional locations have been chosen with the goal to optimise power flows where possible.

The newly added power lines towards Sandoy and Suðuroy are dimensioned for the peak load levels according to scenario 1. No risk for overloading of these power lines could be identified, therefore the figures presented below are focused on the main grid where the most interesting results are obtained.

Figure 11: Heat map including the line loadings in case of high load, zero wind power in scenario 1



Note: The green arrows represent the direction and amount of active power in the grid. The heat map indicates which lines that are the most loaded.

As seen in the figure the lines that are the highest loaded in normal operation are between Sund-Runavik (1SD-RV60, 117 % of MVA cable rating), Runavik-Skalabotn (RV60-SB60, 101 % of rating) and Skalabotn-Innan Eid (SB6060-IE60, 210 % rating). This is expected since the majority of the power flow is moving towards the north-eastern part of the grid where the highest load is located, and no generation is installed.

3.2.1.2 Low load, maximum wind

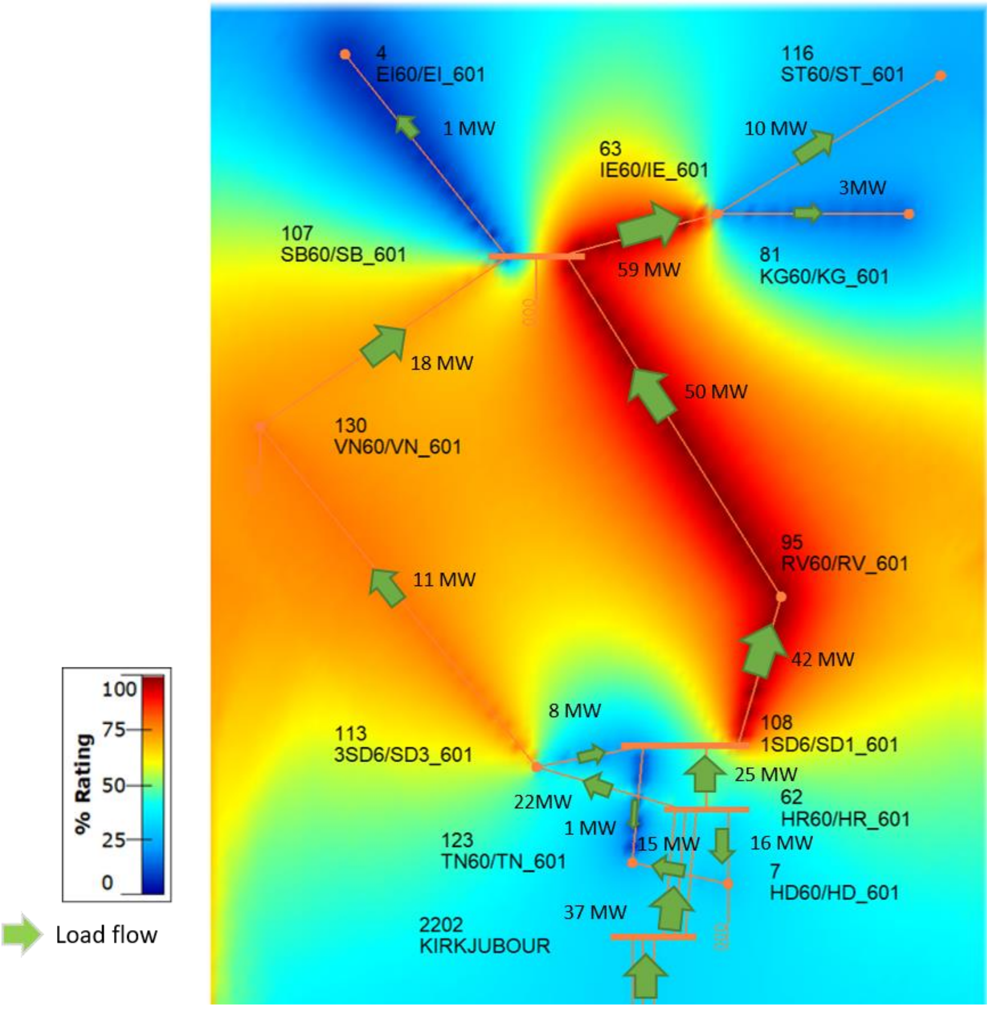
For the case with low load and wind generating on its maximum, a large surplus resulting from high wind power generation levels need to be addressed. In this simulation the curtailment of wind from 203 MW to 115 MW is assumed to meet the low load. Alternative measures (e.g. installation of battery or pumped hydro storage) are discussed and presented in more detail in section 4.1).

The simulation results of this balanced case are illustrated in Figure 12. As in the high load, zero wind case, a load flow towards the north-eastern part of the grid can be observed. The highest loads are still located mostly in the north-eastern areas, although on lower levels compared to the high load scenario.

Compared to the high load case presented in section 3.1.2.1, no generation from hydro in Eidisværket (EI60) is implemented in this simulation. Thus, the direction of the power flow has changed compared to the high load results illustrated in Figure 12 to supply the remaining load in this area.

Additionally, the power line between Runavik and Skalabotn (RV60-SB60) is higher loaded compared to the high load scenario because of the wind power located at Runavik (RV60).

Figure 12: Heat map indicating the line loadings in case of low load, maximum wind power in scenario 1



Note: The green arrows represent the direction and amount of active power in the grid. The heat map indicates which lines that are the most loaded.

As seen in the figure the lines that are the highest loaded are between Sund -Runavik (1SD-RV60, 109 % of rating), Runavik-Skalabotn (RV60-SB60 ,127 % of rating) and Skalabotn-Innan Eid (SB6060-IE60 ,181 % rating). This is expected since the majority of the power flow is moving towards the north-eastern part of the grid where the highest load is located, and no generation is installed.

3.2.1.3 Scenario 1 summary

In scenario 1 a moderate increase of peak load as well as wind generation was assumed and introduced in chapter 0. As the defined scenario would lead to imbalances in the system in the worst-case situations of high load, zero wind as well as low load and high wind, mitigation measures had to be considered.
To obtain a solution the levels of generation and load are needed to be set to the same values presented in Table 5.

Table 5: Overview of generation deficit and surplus in the scenarios as well as mitigation measures chosen for scenario 1

Case	Generation deficit [MW]	Generation surplus [MW]	Measure
High load, zero wind	99	0	Additional (predictable) generation units/storage
Low load, high wind	0	88	Curtailment

According to the solution presented for scenario 1, additional 99 MW generation units/storage are needed to solve the solution and balance the system in the high load case what could be addressed with. Different measures are being discussed in more detail in section 4.1. To cope with the generation surplus of 88 MW in the low load case, wind curtailment was implemented in this simulation. Also for this measure different alternatives are discussed in section 4.2.

The differences in the cases between load and generation level is referred to system losses which are around 9 MW in the high load, zero wind and 12 MW in the low load, high wind case of scenario 1. The high system losses are a result of the high loading of the modelled power lines.

As it could be seen in both sections above, 3.2.1.1 and 3.2.1.2, high load, zero wind case and low load, high wind case, the power lines between Sund-Runavik (1SD-RV60), Runavik-Skalabotn (RV60-SB60) and Skalabotn-Innan Eid (SB6060-IE60) are the highest loaded and represent a bottleneck in the simulated scenarios with the chosen placing additional predictable generation units and other mitigation measures (such as curtailment). However, it is expected that even by choosing other measures the same power lines would represent a bottleneck as the highest loads remain in the north-eastern part of the grid. Installation of generation units or storage in the north-eastern areas however could ease the loading of the identified bottlenecks. More explanations and discussions around the impact of batteries and their location are presented in chapter 4 and 5.

3.2.2 Scenario 2

Compared to scenario 1, scenario 2 represents a more progressive peak load development with a more extensive wind build out until 2030, see Table 6 Neither additional pumped hydro, batteries or flexibility were originally considered in the scenarios.

Table 6 Demand and wind power assumptions for Scenario 2 (ref. Status quo)

Electricity demand [GWh]	**Peak load [MW]**	**Flexibility [%]**	**Wind power[39] [MW]**	**Hydro power [MW]**	**Thermal power [MW]**	**Add. battery storage [MW]**
Status quo[40]						
371	70	-	18	36	97	-
Scenario 2: Increased demand with more wind and no flexibility						
960	240	0	250	36	0	-

Below, the scenario simulations are presented in more detail for the two considered cases.

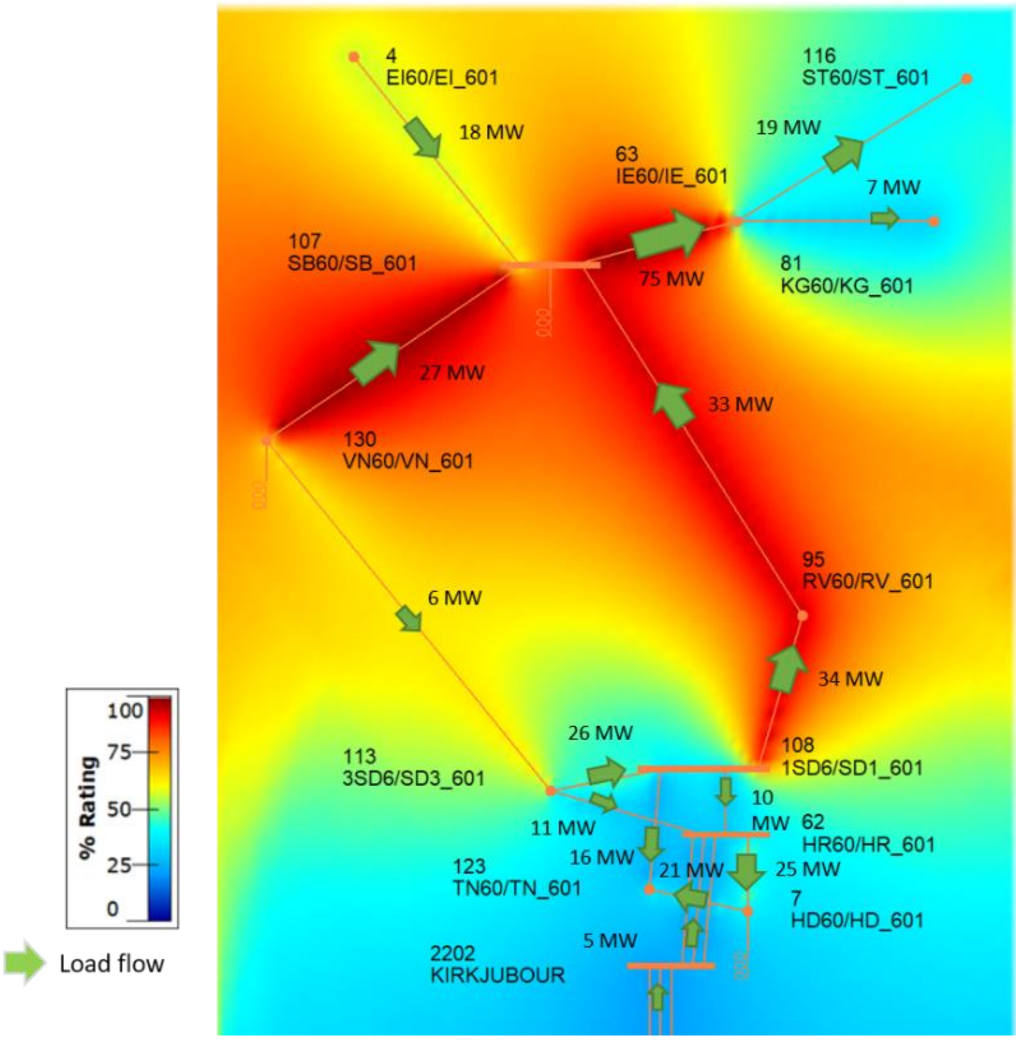
3.2.2.1 High load, zero wind

In this case a peak load hour is simulated with a total load of 240 MW with no possibility of flexible loads. It is assumed in this case that there is no generation from wind available (wind not blowing). Thus, the below presented results are based on the assumption that additional predictable generation such as batteries, hydro (or thermal) power plants of a total of 215 MW is implemented, exceeding the original defined levels of scenario 2. The sites for the additional generation are chosen as in scenario 1 in Sund (1SD113/3SD108), Strond (ST116), Torshavn (TN123), and Suðuroy (SÖDEROY_A602301) . Additionally, the 40 MW reservoir at Vestmanna (VN130) is considered as well as units at buses Innan Eid (IE60), Runavik (RV95) and Skalabotn (SB107). Also, here the location has been chosen considering existing grid preconditions and location of thermal power plants as well as an optimisation of the power flows and grid losses.

The result for the balanced case is presented in in Figure 13. Once again, the flow is towards the north-eastern parts of the grid. Although the loads considered in this scenario are much larger compared to scenario 1, the flow between Skalabotn-Innan Eid is not that much higher because of the battery placed at Innan Eid that minimises the flow of generation coming from buses before Skalabotn. For example, the battery placed at Innan Eid supports with generation close to the load and therefore also limits the need of transporting active power from other buses, i.e. minimising the flow in the grid.

[39] All wind power assumed to be onshore
[40] US, SEV. Figures for 2020

Figure 13: Heat map indicating the line loadings in case of high load, zero wind power in scenario 2



Note: The green arrows represent the direction and amount of active power in the grid. The heat map indicates which lines that are the most loaded.

As presented in Figure 13 above, the lines that are the highest loaded are between Sund-Runavik (1SD-RV60, 91 % of MVA cable rating), Runavik-Skalabotn (RV60-SB60, 88 % of rating), Skalabotn-Innan Eid (SB6060-IE60, 228 % rating) and Vestmanna-Skalbotn (VN60-SB60, 96 % of rating).

This is expected since the majority of the power flow is moving towards the north-eastern part of the grid where the highest load is located, and no generation is installed. The reason for why the loading over the line between Vestmanna and Skalabotn increased in this scenario (compared to scenario 1 presented in section 3.2.1.1) is because of the 40 MW hydropower installed at Vestmanna that tries to support the high load demand in the north-eastern area.

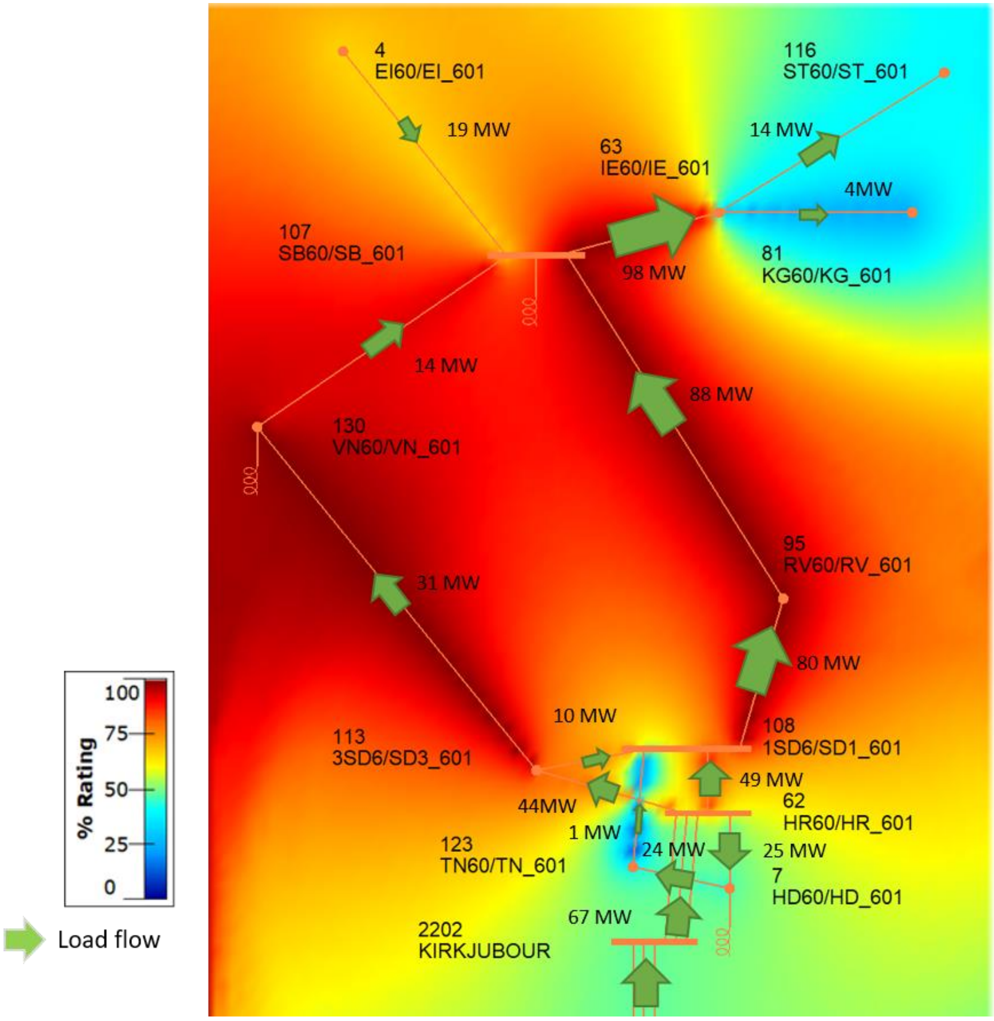
3.2.2.2 Low load, maximum wind

For this case, the grid is simulated during an hour where the load is low (144 MW) and the only generating unit in the grid is wind power (strong winds). The defined scenario leads to a generation surplus of in total 64 MW. Different to scenario 1 low load case, here additional storage (or flexible industrial loads) was considered as a solution to balance the grid (complemented by a moderate curtailment of wind, ca. 20 MW). To meet the demand, the pumped hydro in Vestmanna was partly used with the addition of storage or industrial loads (e.g. batteries, hydrogen) placed in Innan Eid, Runavik and Skalabotn. As it can be seen based on the different chosen solutions to balance the low load case between scenario 1 and scenario 2, there is a high variety and combination of measures possible to address the challenges arising from grid operation in hours with a large generation surplus. The goal of choosing different solutions was to illustrate the impact on load flow directions that can be seen in the simulation results in Figure 14.

Compared to the low load case presented in section 3.2.1.2, the use of pumped hydro in Vestmanna changes the direction of flow between Vestmanna and Sund. Additionally, the added wind in Eidisværket (EI60) changes the direction of flow towards Skalabotn. Also, he loading of power lines between Sund, Vestmanna, Runavik, Skalabotn and Eidisværket are higher, this is a result of the increased installed capacity of wind power at their buses. The power line between Skalabotn and Innan Eid have a higher loading which is to expect because of the higher load level and addition of battery storage placed at Innan Eid.

The largest flow of power is still towards the north-eastern part of the grid. Even though this is the low load case the load level is quite high because of the additionally added storage in the form of pumped hydro and batteries that is being used to store the surplus in the grid generated from the wind power.

Figure 14: Heat map indicating the line loadings in case of low load, maximum wind power in scenario 2



Note: The green arrows represent the direction and amount of active power in the grid. The heat map indicates which lines that are the most loaded.

As seen in the figure the lines that are the highest loaded are between Sund-Runavik (1SD-RV60, 233 % of MVA cable rating), Runavik-Skalabotn (RV60-SB60, 237 % of rating), Skalabotn-Innan Eid (SB60-IE60 ,314 % rating), Sund-Vestmanna (3SD-VN60, 200 % of rating) and Vestmanna-Skalabotn (VN60-SB60, 78 % of rating).

3.2.2.3 Scenario 2 summary

In the second scenario, a more optimistic peak load development with a more extensive wind development was assumed. The defined scenario was unable to reach a balanced system in both the high load, zero wind case and low load, high wind case. This implies that measures are needed to obtain a balanced solution of generation and load presented in Table 7.

Table 7: Overview of generation deficit and surplus in the scenarios as well as mitigation measures chosen for scenario 2

Case	Generation deficit [MW]	Generation surplus [MW]	Measure

High load, zero wind	215	0	Additional (predictable) generation units/storage
Low load, high wind	0	64	Load/Storage/Curtailment

According to the solution presented for scenario 2, additional 215 MW generation units/storage are needed to balance the system in the high load, zero wind case. As for scenario 1, different alternatives of measures are analysed for this scenario in section 4.1. In the low load, high wind case a surplus of 64 MW needs to be considered with either load, storage or curtailment. In this solution storage and curtailment was used to solve the problem, analysed in more detail in section 4.2.

The differences in these cases between load and generation level is referred to system losses which are around 14 MW in the high load, zero wind and even 42 MW in the low load, high wind case of scenario 2. The reason why the losses are that high is due to the high loading of the power lines, especially for the low load, high wind case in scenario 2.

The power lines between Sund-Runavik (1SD-RV60), Runavik-Skalabotn (RV60-SB60), Skalabotn-Innan Eid (SB6060-IE60), Vestmanna-Skalbotn (VN60-SB60) are significantly overloaded in both cases, high load, zero wind as well as in low load, high wind. Additionally, Sund-Vestmanna (3SD-VN60) is clearly overloaded in the low load case as described in section 3.2.2.2. These power lines represent bottlenecks in the simulation with the location of the measures included to cope with generation deficit and surplus. As already described for scenario 1 in 3.2.1.3 it is expected that other measures would also result in bottlenecks for the similar power lines, due to the fact that the highest loads remain in the same location. However, in this scenario it can be especially seen that the placing of additional storage sites can have an impact o the resulting power flows as it can be seen from the overloads of the power lines from and towards Vestmanna which are highly affected by the additional pumped hydro which is assumed to be installed in this simulation. The impact of placing batteries or other storage at different locations in the grid is discussed more in chapter 4 and 5.

3.2.3 Scenario 3

In scenario 3, a similar case setup is used as in scenario 2, a more optimistic peak load development with a more extensive wind build out until 2030. But the difference is the possibility of load flexibility and the addition of pumped hydro and batteries installed in the grid, see Table 8.

Table 8 Demand and wind power assumptions for Scenario 3 (ref. Status quo)

Electricity demand [GWh]	Peak load [MW]	Flexibility [%]	Wind power[41] [MW]	Hydro power [MW]	Thermal power [MW]	Add. battery storage [MW]
Status quo[42]						
371	70	-	18	36	97	-
Scenario 3: Increased demand with more wind, flexibility and storage						
960	240	25	250	36 + 40[43]	0	30

Below, the scenario simulations are presented in more detail for the two considered cases.

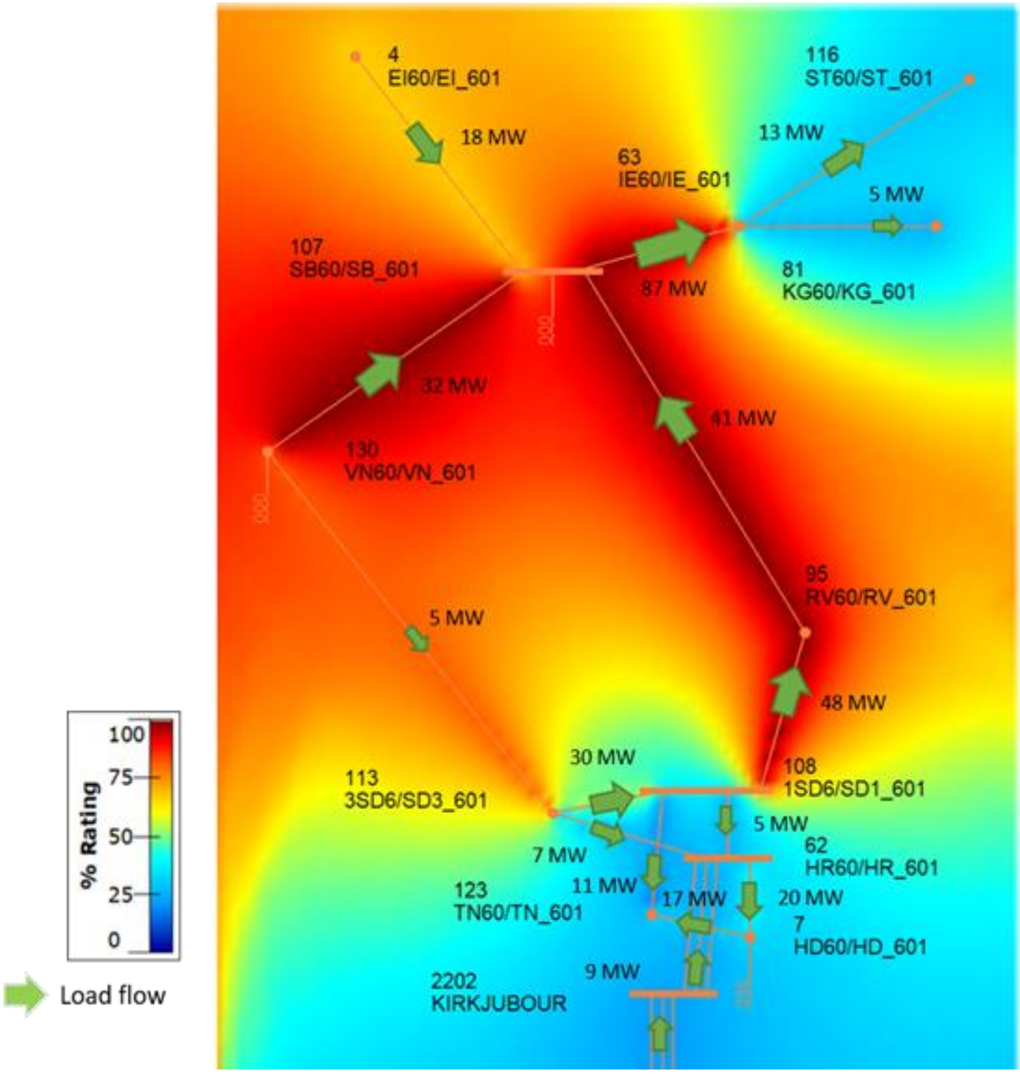
3.2.3.1 High load, zero wind

In this case a peak load hour is simulated with a total load of 240 MW with a share of flexibility of the load. To reach a balance in the grid it is necessary to use the flexibility of loads. As it is assumed in this case that there is no generation from wind available (wind not blowing). The below presented results are based on the assumption that additional predictable generation units like batteries, hydro (or thermal) power plants of a total of 202 MW is implemented. The locations where the generation units are chosen are in Sund, Strond, Torshavn and Suderoy. Additionally, the 40 MW reservoir at Vestmanna is considered as well as generation units in Innan Eid, Runavik and Skalabotn. As mentioned before, the location is chosen due to existing grid preconditions.

The result for the balanced case is seen in Figure 15. Once again, the flow is towards the north-eastern parts of the grid. The reason for the high flows towards this area, is the increasing demand. The battery at Innan Eid is placed to support the grid close to the demand and therefore also limits the need of transporting active power from other buses. This reduces the flow in the grid and lower the stress on the power line between Skalabotn-Innan Eid, but it is not enough, which is why this power line is still overloaded.

[41] All wind power assumed to be onshore
[42] US, SEV. Figures for 2020
[43] Additional 40 MW generation capacity and 70 MW pump capacity

Figure 15: Heat map indicating the line loadings in case of high load, zero wind power in scenario 3



Note: The green arrows represent the direction and amount of active power in the grid. The heat map indicates which lines that are the most loaded.

As presented in Figure 15 above, the lines that are the highest loaded are between Sund-Runavik (1SD-RV60, 132 % of MVA cable rating), Runavik-Skalabotn (RV60-SB60, 120 % of rating), Skalabotn-Innan Eid (SB6060-IE60, 278 % rating) and Vestmanna-Skalbotn (VN60-SB60, 120 % of rating).

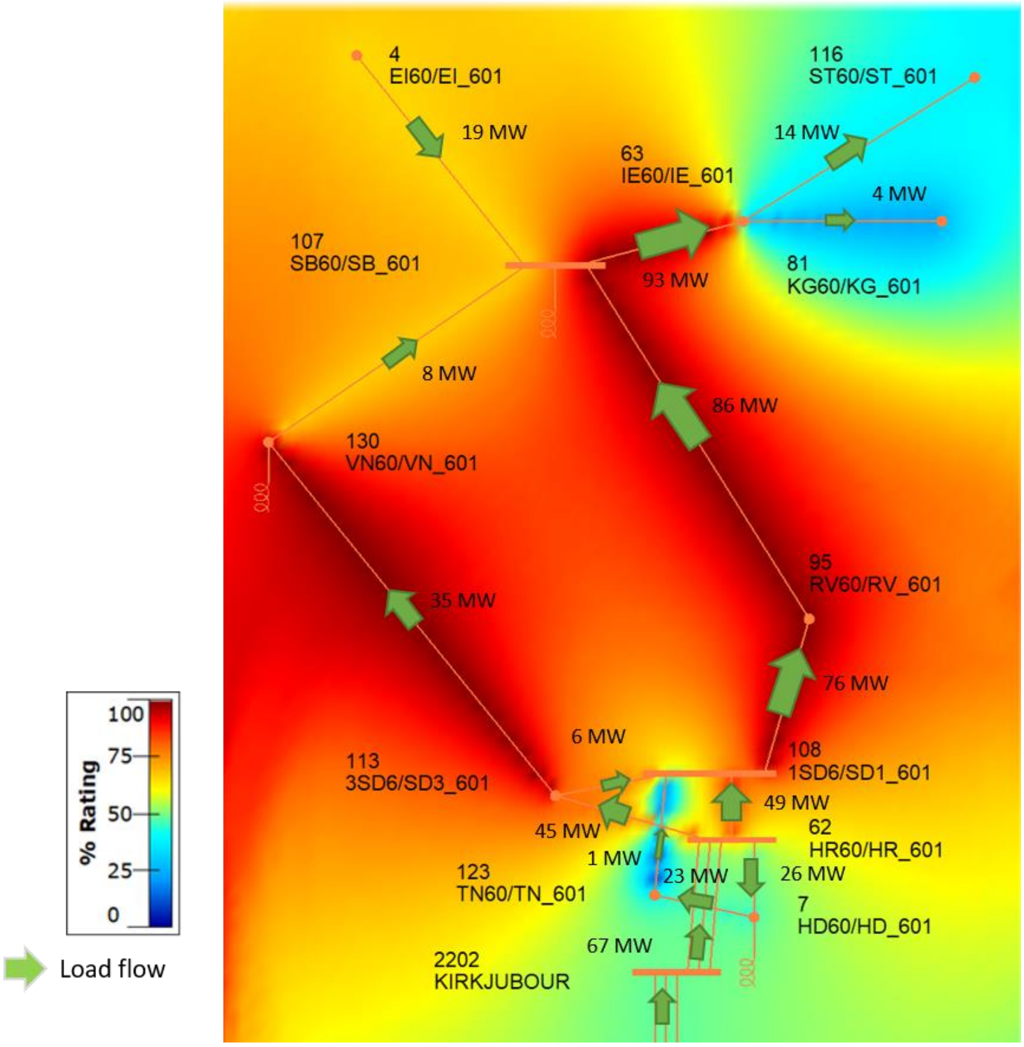
In comparison with the results in section 3.2.2.1, the battery placed at Innan Eid is smaller and instead the hydropower is now generating more to meet grid balance. However, this will increase the power flow and increase the stress over the power line between Skalabotn-Innan Eid. But this does also create higher stress on the power lines between Sund-Runavik-Skalabotn since more generation from Sund is needed to make up for the smaller battery in Innan Eid.

3.2.3.2 Low load, maximum wind

For this case, the grid is simulated during an hour where the load is low and the only generating unit in the grid is wind power. For this case, energy storages are needed to reach balance in the grid because of the large surplus of energy generated from wind, but still within the original defined levels of scenario 3. To meet the peak load the pumped hydro in Vestmanna is used with the addition of batteries placed in Innan Eid, Runavik and Skalabotn.

The simulation results of this balanced case are illustrated in Figure 16. The highest flow of power is still towards the north-eastern part of the grid. Even though this is the low load case the load level is quite high because of the additionally added storage in the form of pumped hydro and batteries that is being used to store the surplus in the grid generated from the wind power.

Figure 16: Heat map indicating the line loadings in case of low load, maximum wind power in scenario 3



Note: The green arrows represent the direction and amount of active power in the grid. The heat map indicates which lines that are the most loaded.

As seen in Figure 16, the lines that are the highest loaded are between Sund-Runavik (1SD-RV60, 222 % of MVA cable rating), Runavik-Skalabotn (RV60-SB60, 232 % of rating), Skalabotn-Innan Eid (SB60-IE60, 296 % rating), Sund-Vestmanna (3SD-VN60, 214 % of rating) and Vestmanna-Skalabotn (VN60-SB60, 55 % of rating).

3.2.3.3 Scenario 3 summary

In scenario 3 a more optimistic peak load development and an extensive wind development were assumed. Additionally, in this scenario, flexibility was utilised and both additional pumped storage and batteries were added. To be able to solve the simulation case the levels of generation and load are needed to be adjusted with the levels as presented in Table 9.

Table 9: Overview of generation deficit and surplus in the scenarios as well as mitigation measures chosen for scenario 3

Case	Generation deficit [MW]	Generation surplus [MW]	Measure
High load, zero wind	93	0	Additional (predictable) generation units/storage
Low load, high wind	0	0	

As can be seen in Table 9, additional 93 MW generation units/storage are needed to reach a balanced system in the simulation for the high load, zero wind case. As mentioned before, different alternatives to measures are analysed in section 4.1. For the low load, high wind case, there were no generation surplus indicating the considered pumped hydro and battery sites specified in the scenario are sufficient to balance the system.

The system losses are around 8 MW in the high load, zero wind case and 41 MW in the low load, high wind case of scenario 3.

The power lines with high loading are Sund-Runavik (1SD-RV60), Runavik-Skalabotn (RV60-SB60), Skalabotn-Innan Eid (SB6060-IE60), Vestmanna-Skalabotn (VN60-SB60) in the two cases and as for scenario 3 Sund-Vestmanna (3SD-VN60) in the low load case. These represent bottlenecks in the simulation with the chosen location of the considered measures. Similar conclusions can be drawn for scenario 3 as for scenario 2 regarding the power flows and loading of the power lines and their dependency from the installed pumped hydro and battery storage.

4 Analysis

In this chapter, each scenario is analysed on the basis of the simulation results presented in section 3.2, in which, the simulation results and assumptions were presented and introduced on a high level. The focus of the chapter is to go one step deeper into the analysis and to discuss the size of generation surplus and deficit in the scenarios, and which alternative measures should be considered when tackling upcoming changes related to peak load (power deficit) and low load situations (power surplus) in the grid.

As described section 3.2, generation capacity deficit or capacity surplus means that there is an imbalance in the system. Consequently, measures need to be in place to balance it out. This is especially relevant in this case since the Faroese power system is an isolated system. This means that there are no surrounding systems which can absorb or provide additional power as it has been introduced in section 3.1.1.

For every scenario, and every case (high load, zero wind and low load, high wind) the required investment level to manage the increased load and generation on the grid is estimated. Grid investments can vary significantly depending of the chosen technology, for instance between overhead line (OHL) or underground cables. Since there are ongoing plans from SEV to replace OHL with underground cables for the 60 kV grid [44], investments levels for underground cables[45] as well as overhead lines[46] are considered within this study. As introduced before, usually power systems are dimensioned in a way so that even in (N-1) events security of supply is guaranteed. Thus, the analysis in the following indicate the overload of the power lines in case of an outage of a line (N-1).

In line with the objectives of the study introduced in section 1.2, considerations and analysis regarding the cases with generation capacity deficit (high load, zero wind section 4.1) are presented as well as regarding the cases with generation capacity surplus (low load, high wind section 4.2). For both cases the deficit or surplus resulting from the defined scenarios is quantified and measures discussed how these situations could be addressed to ensure coping with these challenging worst-case operational situations. Subsequently, in section 4.3, grid capacity deficits, bottlenecks and investment need are discussed.

4.1 Generation capacity deficit in high load case

As can be seen in *Figure 17*, generation capacity deficit occurs for all scenarios in the high load, zero wind case. To cope with this, measures are needed.

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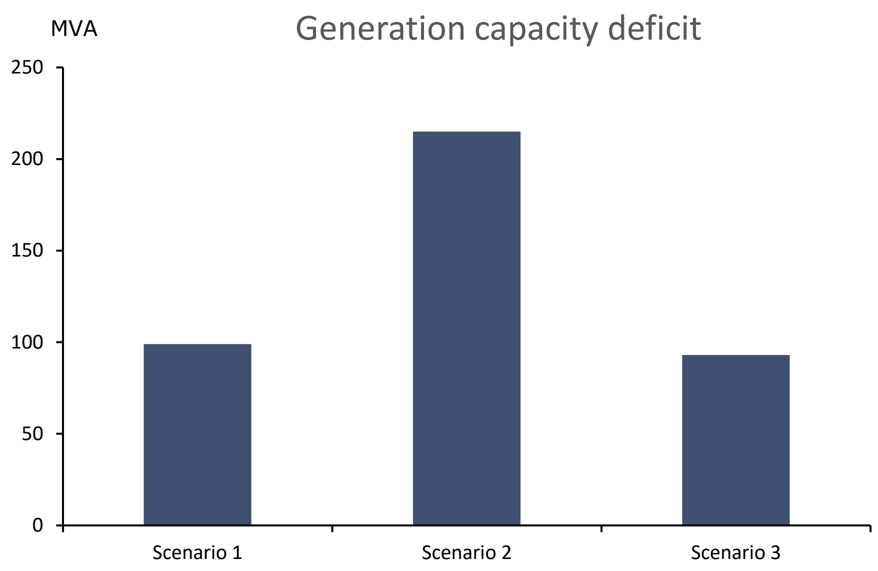
[44] SEV: https://www.sev.fo/english/news/the-majority-of-the-power-grid-is-now-underground/

[45] The Swedish Energy Markets Inspectorate (https://www.ei.se/bransch/rapportera-in-uppgifter-till-ei/forhandsreglering-natavgifter/dokument---forhandsreglering-av-intaktsramar-elnat-for-tillsynsperiod-2020-2023, Normvärdeslista elnät 2020-2023 (Cable type: Jordkabel Landsbygd normal - Al 3x1x630 mm² PEX and Jordkabel tätort - Al 3x1x630 mm² PEX with an rated current of 1150 A)

[46] The Swedish Energy Markets Inspectorate (https://www.ei.se/bransch/rapportera-in-uppgifter-till-ei/forhandsreglering-natavgifter/dokument---forhandsreglering-av-intaktsramar-elnat-for-tillsynsperiod-2020-2023, Normvärdeslista elnät 2020-2023 (Line type: FeAl 593 mm² - ledningsgata 42 m and rated current 3000 A)

Figure 17: Generation capacity deficit [MVA]



When the fossil free electricity generation cannot meet the demand, there are essentially two fossil-free alternatives that can be used. The first option is demand flexibility. If demand is flexible it is possible to reduce the peak load in specific situations and thus lower the power that is needed during that time. Another option is storage, where, for example, a battery or pumped hydro could serve as a backup when the load is high, and the fossil free electricity generation is low.

In scenario 1 and 3 the generation capacity deficit is similar, ~100 MW. This implies that even with more electricity demand (scenario 3), the available storage (30 MW batteries + 40 MW pumped hydro) can lower the amount of deficit to similar level as in scenario 1, where the demand is lower, but there is no storage option.

Measures to cope with the generation capacity deficit needs to sum up but can consist of several of the above mention alternatives. However, 25% demand flexibility is already assumed for both scenario 1 and 3 and if this is the limit to the demand flexibility, increasing storage would be one of the primary options to investigate.

The generation capacity deficit for scenario 2 is higher than for other scenarios as no demand flexibility was considered. Especially in this extreme case the considered storage levels are not sufficient and a great amount of additional storage (>200 MW batteries and/or pumped hydro) would be required to guarantee security of supply without utilising thermal power as reserve. This clearly shows that demand flexibility can have a significant impact.

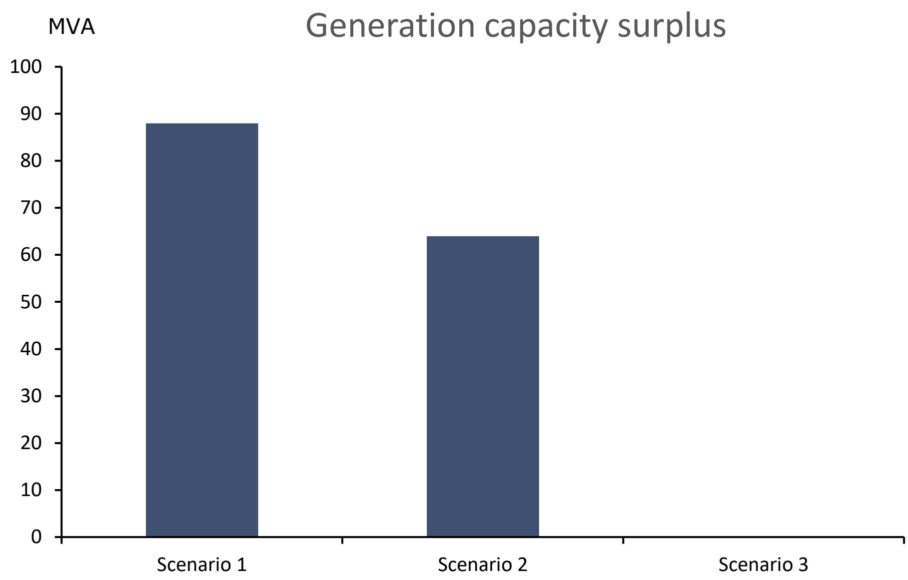
As mentioned before in 1.3 , the amount of electric heat pumps is expected to increase as well as the district heating network and the number of electric vehicles. Depending on the level of the increase, it could affect the flexibility potential. If a higher potential will be reached, less electricity will be needed during some hours throughout the year. Additionally, industries are likely to be able to offer flexibility to a certain degree, either by reducing production and consequently their load or by ensure their supply by their own in specific hours with own reserves.

In conclusion, with the development plans as of today and the predicted demand development in the three Scenarios, Faroe Islands will in worst-cases, when no electricity generation come from wind, not be able to meet demand. This can be solved by either increasing flexibility or storage options.

4.2 Generation capacity surplus in low load case

In *Figure 18* the generation capacity surplus for each scenario is illustrated.

Figure 18: Generation capacity surplus [MVA]



When generation capacity surplus occurs, several measures can be considered. Curtailment, storage activation, and increased flexible demand such as hydrogen production are a few and are outlined below.

In scenario 1, where there was no storage available, the generation capacity surplus of almost 90 MW had to be solved by curtailment. However, from a strategic perspective it can be reasonable to avoid curtailing wind. On a market level, wind curtailment can be seen as a service to ensure system security. However, for the grid owner it is not desirable as the grid owner might need to compensate the wind farm owner since wind curtailments often imply a loss of income for the wind owner. The compensation should be related to the foregone revenue to limit the market risk and ensure technology financing costs are not disproportionate[47].

In scenario 2, where a generation capacity surplus of 64 MW occurs, storage or curtailment could both be used to solve the problem. The disadvantages with curtailment imply that a storage option is favourable. It also means that the energy is preserved and can be utilised also to balance a low wind scenario.

In scenario 3, the pre-defined storage is able to solve the simulation without any additionally measures. 40 MW pumped hydro, 30 MW batteries is enough to cope with the surplus in scenario 3.

[47] https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-Priority-Dispatch-and-Curtailment.pdf

The more storage available, the more surplus can be handled. However, it is worth noting that this study is static and does therefore assume that full activation is possible in both directions at the extreme points. Realistically, full activation when needed is not always possible and thus make the measure storage more complex. Additionally, the best suitable location of storage units depends on if there is a surplus or deficit of generation capacity and needs to be further investigated.

Furthermore, flexible demand like hydrogen production, can be a part of the solution. Hydrogen production with electrolysis require a lot of electricity and it is possible to use excess demand to run an electrolyser to produce hydrogen. However, the process is more complex and need more consideration to fully evaluate the potential of hydrogen production as a measure to cope with generation surplus.

In summary, assuming the development of 40 MW Pumped Hydro and 30 MW batteries the Faroese system can handle 250 MW wind power without curtailment also at an extreme point with very high wind and low demand.

4.3 Grid capacity deficits, bottlenecks, and investment need

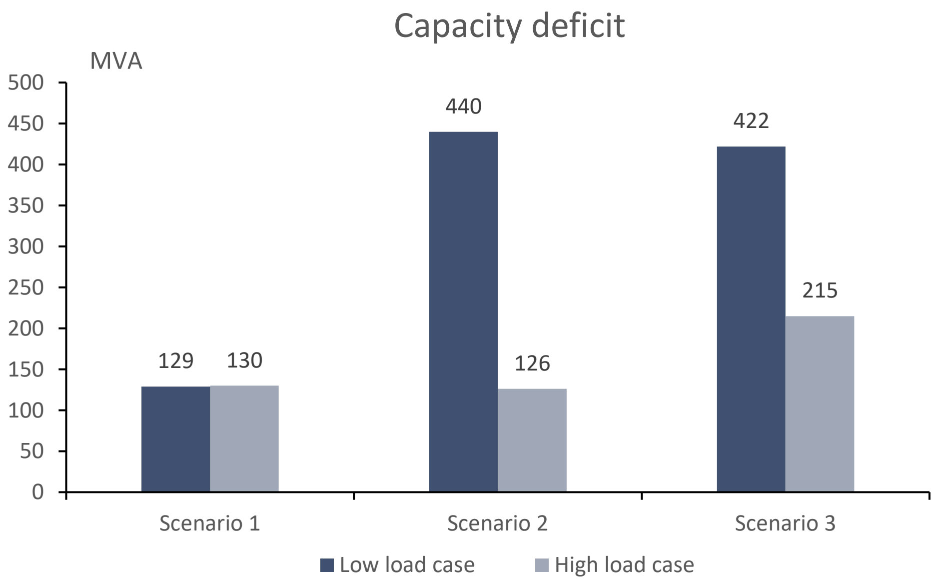
As described in previous chapters, capacity deficit occurs in all cases. This will cause bottlenecks in the electricity grid and limit the security of supply. To prevent power outages and to be able to delivery electricity the grid needs to be reinforced and thus requires investment.

4.3.1 Grid capacity deficit

In both cases for all scenarios there are several power lines with a loading over 100%, indicating that capacity constraints occur and causes problem in the electricity grid. In scenario 2 low load, high wind case, the number of power liens with capacity constraints are twice as many compared to the high load, zero wind case.

The total capacity deficit varies between the scenarios and can be seen in Figure 19. The low load, high wind case for scenario 2 and 3 have compared to the other cases, significantly higher capacity deficit.

Figure 19: Total capacity deficit

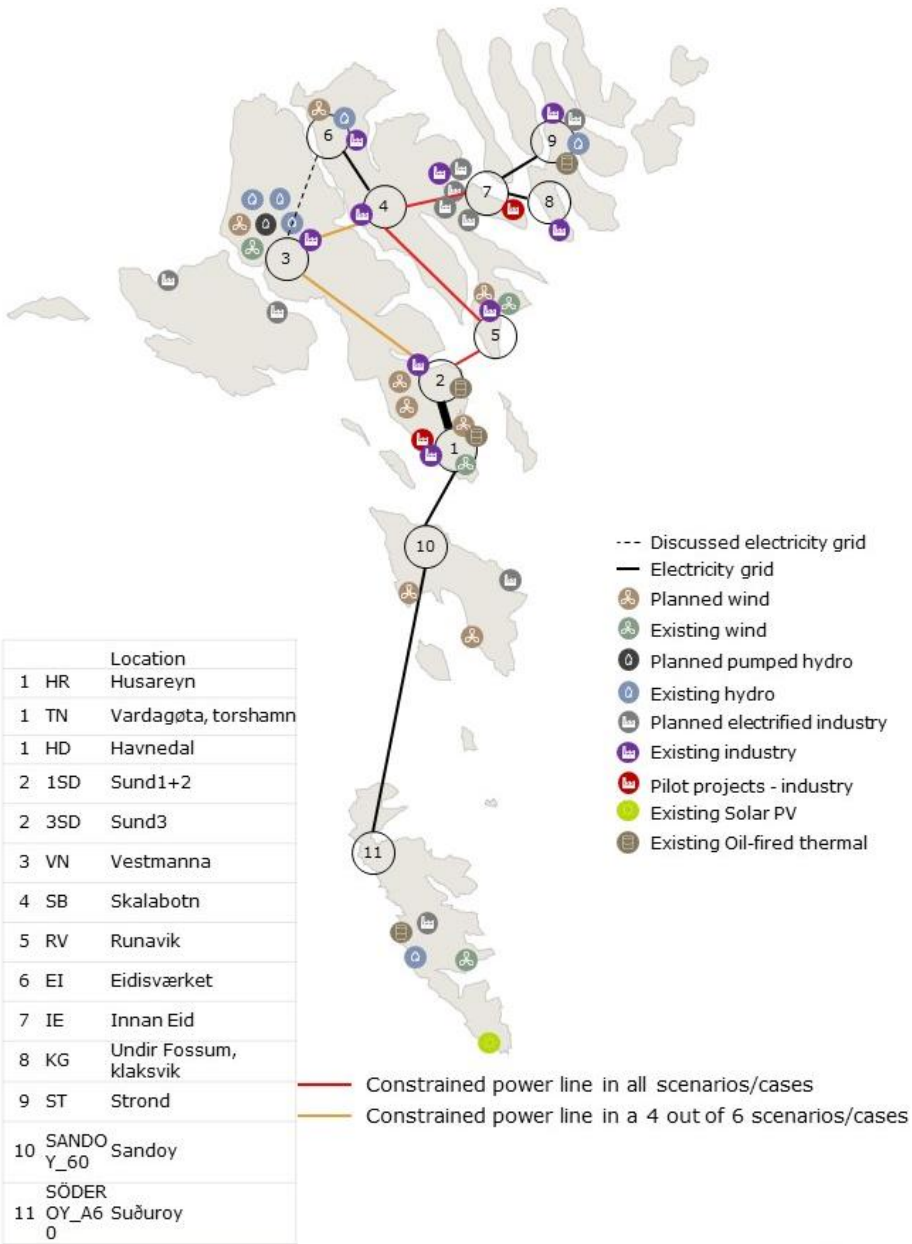


An example of one power line with high loading is the one between Innan Eid-Skalabotn, which, in scenario 3 register a loading of 418% in the high load, zero wind case and 444% in the low load, high wind case. These results indicate high capacity deficit and thus will affect the ability to supply electricity.

4.3.2 Bottlenecks

The level of capacity deficit differs between the scenarios and cases, but the location where the problem occurs is similar. For all cases, the power lines with capacity deficit are Innan Eid-Skalabotn, Runavik-Skalabotn and Runavik-Sund1+2. In some cases, the power line Skalabotn-Vestmanna and Sund3-Vestmanna also suffer from capacity deficit. All the power lines at risk of capacity deficit are illustrated in red in Figure 20 below and face the challenge of creating bottlenecks in the electricity grid.

Figure 20: Faroe Islands map including the overhead lines with capacity deficit.



Note: Exact location, length and type of the new connections is not known in detail. Existing industry refers to load included in the model by SEV, what type of load on each location is not known but assumes to be industrial load.

How well a power line can handle high load depends how they have been dimensioned, e.g. to what conductor temperature it has been dimensioned for. If the capacity deficit is ignored, it will have a negative impact on the overhead lines quality and thus decrease the lifetime. Additionally, a high overload of power lines increases the loss level in the grid significantly and will in worst-case not be able to distribute electricity at all, as an example in scenario 2 there was a power loss of 42 MW in the low load, high wind case due to high loaded power lines. Therefore, the capacity deficit needs to be acknowledged early, even if it's associated with an investment, the cost of not refurbish the grid can be even higher.

4.3.3 Investment need

To cope with the high loading result for both cases, investment is necessary to refurbish the grid. How the refurbishment is performed can vary, either additional power lines are added, or the diameter of the current ones are increased. Below the investment of additional power lines are outlined.

Withdrawn from the result of the capacity deficit and the length of the power line, an estimation of needed investment was calculated for each power line that suffer from capacity deficit. As can be seen in *Table 10* the investment is significantly more expensive for cables than OHL, which is reasonable since the construction is more extensive when cables are implemented. However, OPEX are higher for OHL and number of power faults generally higher.

To be able to handle worst-case situations, the electricity grid needs to be dimensioned for the most critical one and thereby will be able to handle all other situations. As both worst-case situations were simulated (high load, zero wind and low load, high wind) it is possible to identify for each power line which of the cases for the scenarios is the dimensioning case (with the highest overload on the power line). Studying one power line at the time, there is a difference between them in the two cases and thus the dimensioning needs to be adapted to each power line. E.g. for scenario 1, two of the power lines have the highest capacity deficit in the high load, zero wind case and three in the low load, high wind case. The total investment for scenario 1 then is based on the investment of three power lines for one of the cases and two from the other case, indicating the total investment increases compared only looking at the two cases individually.

In *Table 10* the required investment to handle worst-case situations, calculated for each power line are presented.

Table 10: Investment need (dimension for worst-case)

Scenario	Average investment [m€]	
	OHL	Cable
1	0.8	2.0
2	1.9	4.9
3	1.9	5.0

The reason for the high investment in scenario 2 and 3, is a result of high loading in several power lines. The power line with the highest loading is the one between Innan Eid-Skalabotn, where the loading in scenario 2 is 471% and therefore the capacity deficit for that power line is also high, 129.5 MVA. This imply to refurbish this power line will require an investment of 1 m€ for OHL or 2.9 m€ for cables.

5 Discussion

In this chapter, a deeper discussion regarding flexibility, battery location, time horizon for investment and reactive power flows and Non-synchronous generation are outlined.

5.1 Flexibility

To what degree flexibility can contribute as a measure to cope with high load cases on Faroe Islands is not known. Since an increase of flexible loads with a flexibility potential are assumed, one can believe the overall flexibility potential on a system level also will increase. However, the exact potential for Faroe Islands cannot be evaluated thoroughly without investigating each industry and each segment estimated to enable flexibility. Nevertheless, flexibility has a potential to become an attractive alternative to lower the peak load without any major investments needed. However, there is a limit how much flexibility can support the system and for some industries, investment might be needed to be able to be flexible. One perspective to give a specific thought is how flexibility not only can be used to reduce peak load but rather to increase load in low load situations with, for example, a high generation capacity from wind power plants in hours with strong winds. An example for such a load could be a hydrogen site, absorbing electricity from the grid to generate hydrogen in these hours.

5.2 Batteries

As presented in section 3.2 the batteries considered for the simulations within this study are placed in Innan Eid, Skalabotn and Runavik. Optimal location of batteries depends whether there is a surplus or deficit of electricity in the grid and optimising load flows for one of these situations often has a reverse effect to the other. Storage can work as both, load and generation, depending on situation. This means that the best location for batteries also varies. In cases with high load and deficit of power generation, the best location for batteries would be close to large loads to reduce the flows through the grid and consequently reduce system losses. In contrast, in situations with low load and high generation (surplus), the best location would be close to the generation units to avoid unnecessary transmission through the grid and optimise load flows in low load situations.

In general the optimal placing of battery is a very complex issue with many influencing factors such as the above mentioned differences between deficit and surplus situations but also the choice of voltage levels, dimensions, owner structures and potential income streams. Thus, it is recommended to start detailed investigations to identify the potential and appropriate location for additional battery storage.

5.3 Investment planning

Proper investment planning, including investment decision needs to be done soon to be able to have the needed electricity infrastructure in place by 2030. Additionally, collaboration with SEV is necessary. The time horizon for grid investment project, from investment decision until commissioning take years.

5.4 Reactive power flows and Non-synchronous generation

Reactive power flows are not considered in this study, however, reactive power is relevant for maintaining correct voltage level in the grid and should also be optimised to limit the losses. In non-synchronous generation, the reactive power capability is very good but needs to be modelled in appropriate way and thus extensions in the model are required.

In power systems all over the world, renewable power generation based on power-electronic converters is increasing and thus replacing conventional generation based on synchronous machines. In small synchronous areas, this development already affects system operation on a day-to-day basis. A high penetration of power-electronic converters and a low short circuit power has a significant impact on the system stability.

At high levels of non-synchronous generation, the dynamic behaviour of converters dominates many aspects of power system stability. At high levels of non-synchronous generation, short circuit power levels drop. The resulting “weak” grids present a stability challenge for converters. The concern is most acute, when the short circuit level of the system at the point where converters are connected is low relative to the rating of all the converter-based resources in electrical proximity. At high levels of non-synchronous generation, the power system will increasingly depend on converter-based resources to provide essential services such as inertia, short circuit power and reactive power that have traditionally been obtained from synchronous generation.

In general, the problem with increasing amount of non-synchronous generation is that the short circuit levels decrease, which is followed by a number of problems, e.g. regarding dimensioning and planning of protection system and schemes in power systems. The protection system of a power system is usually designed and parametrised based on today’s short circuit levels. If redesign of the schemes is not performed, there is a risk of faults can’t be detected and leading to an increased number of failures in the electricity grid and thus increased stress of the assets.

The modelling and analysis of reactive power flows and impact on the voltage in the grid as well as short circuit levels relevant for system stability and protection scheme coordination can be realised within the developed PSS/E model if appropriate extensions to the model are realised.

6 Conclusion

For the Faroese power system, generation capacity deficit and surplus occur for the high load, zero wind case resp. low load, high wind case. This deficit/surplus needs to be taken care of by additional measures to reach a balanced system.

Estimated level of renewable energy and storage will not be sufficient during occasions with high load and zero wind. This imply more measures are needed, e.g. more storage or inclusion of additional generation units. Furthermore, if other renewable sources such as solar will be included the deficit have the possibility to be lower, however, since solar also is an intermittent source the worst-case situations when no solar occur need to be analysed as well.

In the high load, zero wind case, when generation capacity deficit occurs, the Faroe Islands need up to 215 MW of additional generation units/storage to balance the system. With the planned flexibility of 25% and storage of 70 MW (40 MW pumped hydro and 30MW batteries there is still a need to find a solution for the additional ~100 MW that is needed in times of zero wind and high load.

During occasions with electricity surplus (low load, high wind case) measures need to be considered for security of supply. Storage, flexibility, additional load or wind curtailment are a few that have been analysed. In the worst case 88 MW of generation surplus is generated. Storage could be a solution that can counteract the imbalance in both directions. In the best case when both pumped hydro and batteries are available, the Faroese system can handle 250 MW wind power without curtailment.

In conclusion, if additional storage units are added to support the high load zero wind imbalance (around 100 MW in scenario 1+3, above 200 MW in scenario 2, see above), it will likely also balance the low load, high wind case as well and thus ensure security of supply.

In every scenario and every case, capacity deficit occurs and thus the electricity grid of today will not be sufficient by 2030. As a result of that, investment to refurbish the grid is necessary and the total needed amount differ between the scenarios, from 0.8 to 5 m€, due to different load and generation capacity.

The power lines with capacity deficit are Innan Eid-Skalabotn, Runavik-Skalabotn and Runavik-Sund1+2. In some cases the line Skalabotn-Vestmanna and Sund3-Vestmanna also suffer from capacity deficit. This imply that these are the locations where bottlenecks will occur in the future, if no considerations to the capacity deficit is done, i.e. refurbishment of the power lines.

Based on the findings of this study and the discussions in chapter 5 AFRY recommends to perform the following additional analysis and studies to ensure that all potential challenges and issues of a fossil-free power system operation can be addressed appropriately:

- Continuation of static analysis with focus on reactive power and voltage stability;
- Dynamic analysis focusing on grid stability in weak power system and island systems;

- Quantification of the potential for flexibility from households and industries on the Faroese islands, including a detailed assessment of a potential role of hydrogen production;
  Identification of potential and sites for additional battery storage and pumped hydro.

7 References

Table 11: A summary of the assumptions, origin for the scenarios

	2020	1	2	2
Electricity demand [GWh] /Assumptions based on	371	715	960	960
	US	US, national direction for electrification	US, national direction for electrification	US, national direction for electrification
Peak load [MW] / Assumptions based on	70	180	240	240
	PSS/E model from SEV	AFRY calculations	AFRY calculations	AFRY calculations
Wind power [MW] / Assumptions based on	18	206	250	250
	SEV	US, Vestas, Helma, Norconcult, Dansk Energi	US, Vestas, Helma, Norconcult, Dansk Energi	US, Vestas, Helma, Norconcult, Dansk Energi
Hydro power [MW]/ Assumptions based on	36	36	36	36+40
	SEV	-	-	US, EA, Dansk Energi
Add battery [MW] / Assumptions based on	-	0	0	30
	-	-	-	US, AFRY
Oil-fired Thermal [MW] / Assumptions based on	83	0	0	0
	SEV	National targets	National targets	National targets
Flexibility [%]/ Assumptions based on	-	25	0	25
	-	AFRY	-	AFRY

Table 12: Explanation of footnotes

Footnote nr	Source	Type of information	Origin
1		Notation/remark	
2		Notation/remark	
3	The official gateway to the Faroe Island	General information about Faroe Island	https://www.faroeislands.fo/
4	The official gateway to the Faroe Island/Economy	General information about Faroe Island's economy	https://www.faroeislands.fo/economy-business/economy/

5	Hagstova Föroya / Statistics Faroe Island	General information about Faroe Island's economy	https://hagstova.fo/en
6	The official gateway to the Faroe Island/Energy	General information about Faroe Island's energy	https://www.faroeislands.fo/economy-business/energy/
7	SEV	Information about the power system	https://www.sev.fo/english/the-power-supply-system/
8	SEV	Information about the power system	https://www.sev.fo/english/the-power-supply-system/
9		Notation/remark	
10	US	Information about the power system	During discussions
11	Local.fo	Wind farm	https://local.fo/seven-turbine-porkeri-wind-farm-inaugurated/
12	Nordic council of ministers - Energy in the west Nordics and the Artic (2018)	Information about the power system	
13			
14	Niras	Biogas plant	https://www.niras.com/projects/biogas-from-bakkafrost/
15	SEV	Tidal energy project	https://www.sev.fo/english/projects/minesto-tidal-energy-project/
16	The official gateway to the Faroe Island/Economy	Solar panel park	https://www.faroeislands.fo/the-big-picture/news/first-solar-panel-park-in-faroe-islands-activated/
17		Notation/remark	
18		Notation/remark	
19	US and SEV	Figures for the status quo (2020)	
20		Notation/remark	
21		Notation/remark	
22	Reve	Wind farm	https://www.evwind.es/2021/04/15/vestas-to-expand-wind-power-capacity-in-the-faroe-islands/80373

23	Norconsult - *100% fornybar kraft Pumpekraft, vind og sol* (2018)	Wind farm	Recieved from US
24	Helma - *100% Sustainable Electricity in the Faroe Islands - Expansion Planning Through Economic Optimization (2021*	Wind farm	Recieved from US
25	Dansk Energi - Teknisk notat (2017)	Wind farm	Recieved from US
26	EA - Energy analysis (2018)	Hydro	Recieved from US
27	Dansk Energi - Energilagring på Færøerne - Teknisk opsamlingsrapport (2018)	Hydro	Recieved from US
28	AFRY - Market-based flexibility procurement for Nordic DSOs (2021)	Flexibility	
29		Notation/remark	
30	US and SEV	Figures for the status quo (2020)	
31		Notation/remark	
32		Notation/remark	
33		Notation/remark	
34		Notation/remark	
35		Notation/remark	
36	US and SEV	Figures for the status quo (2020)	
37		Notation/remark	
38	US and SEV	Figures for the status quo (2020)	
39		Notation/remark	
40	US and SEV	Figures for the status quo (2020)	
41		Notation/remark	
42	US and SEV	Figures for the status quo (2020)	
43		Notation/remark	

44	SEV	Information about the power system	https://www.sev.fo/english/news/the-majority-of-the-power-grid-is-now-underground/
45	The Swedish Energy Markets Inspectorate	Price list	(https://www.ei.se/bransch/rapportera-in-uppgifter-till-ei/forhandsreglering-natavgifter/dokument---forhandsreglering-av-intaktsramar-elnat-for-tillsynsperiod-2020-2023, Normvärdeslista elnät 2020-2023 (Line type: FeAl 593 mm² - ledningsgata 42 m and rated current 3000 MVA)
46	The Swedish Energy Markets Inspectorate	Price list	(https://www.ei.se/bransch/rapportera-in-uppgifter-till-ei/forhandsreglering-natavgifter/dokument---forhandsreglering-av-intaktsramar-elnat-for-tillsynsperiod-2020-2023, Normvärdeslista elnät 2020-2023 (Line type: FeAl 593 mm² - ledningsgata 42 m and rated current 3000 MVA)
47	Wind Europé	General information about Faroe Island's economy	https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-Priority-Dispatch-and-Curtailment.pdf

ANNEX A - GLOSSARY AND ABBREVIATIONS

Table 13: Glossary over commonly used words

Word	Definition/explanation
Reactive power	Reactive power, measured in MegaVolt-ampere reactive (MVAR), exists in an AC circuit when the current and voltage are not in phase. Reactive power is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors and directly influences electric system voltage.
Active Power	Active Power is the power which is actually consumed or utilised in an AC circuit. It is measured in Megawatts (MW).
Swing bus	Swing bus is used to balance the active and reactive power in a system while performing load flow studies. It is used to provide for system losses by emitting or absorbing active/reactive power to and from the system.
Load	Connected electricity demand such as households and industries
Grid congestion	When the grid are unable to accommodate all required load
PSS/E	Transmission planning and analysis software
Electricity demand	Electricity demand refers to how much electricity that is used over a period of time, measured in kilowatts-hours (kWh)
Installed capacity	Installed capacity refers to the maximum capacity of generation and demand connected to the grid, measured in megawatts (MW)
Peak load	Peak load is the highest electrical power demand that occur over a specified time period, measured in megawatt (MW)

Table 14: Abbreviation explanation

Abbreviation	Definition
WPP	Wind power plants
OHL	Overhead lines
SLD	Single line diagram
Solar PV	Solar Photovoltaics
PSS/E	Power System Simulator for Engineering

Table 15: Power grid stations that are included in the grid model, its abbreviations and bus number in PSS/E.

Bus number in PSS/E	Bus name in PSS/E	Location
4	EI	Eidisværket
107	SB	Skalabotn
81	KG	Undir Fossum (Klaksvik)
95	RV	Runavik

116	ST	Strond
63	IE	Innan Eid
130	VN	Vestmanna
62	HR	Husareyn
123	TN	Vardagøta (Tornhavn)
7	HD	Havnedal
113	1SD	Sund 1 + 2
108	3SD	Sund 3
2202	KIRKJUBOUR	Kirkjubour
203	SANDOY_60	Sandoy
2301	SÖDEROY_A60	Söderoy

Table 16: Rated power for each 60kV power line

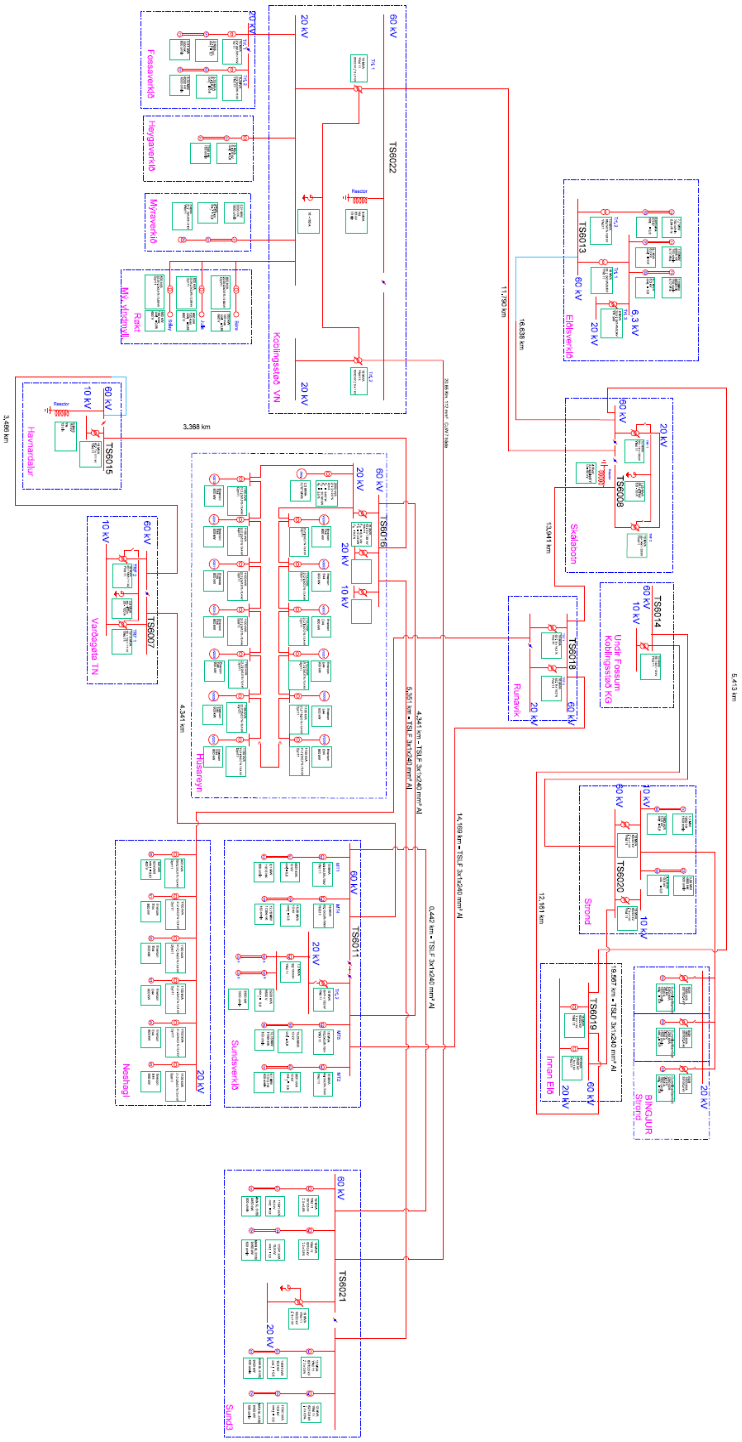
From Location	To Location	Rated power (MVA)
Eidisværket	Skalabotn	36.4
Havnedal	Husareyn	55.5
Havnedal	Vardagøta (Tornhavn)	55.5
Husareyn	Sund 3	55.5
Husareyn	Sund 1 + 2	55.5
Husareyn	Kirkjubour	48.5
Husareyn	Kirkjubour	48.5
Husareyn	Kirkjubour	48.5
Innan Eid	Undir Fossum (Klaksvik)	27.6
Innan Eid	Skalabotn	34.9
Innan Eid	Strond	55.5
Runavik	Skalabotn	42.0
Runavik	Sund 3	42.0
Skalabotn	Vestmanna	29.1
Sund 3	Sund 1 + 2	55.5
Sund 3	Vardagøta (Tornhavn)	74.8
Sund 1 + 2	Vestmanna	27.6
Sandoy	Kirkjubour	48.5
Sandoy	Kirkjubour	48.5
Sandoy	Kirkjubour	48.5
Sandoy	Söderoy	48.5
Sandoy	Söderoy	48.5
Sandoy	Söderoy	48.5

ANNEX B – MODEL MANUAL

Presented in attached PowerPoint file, name: *Power system model - workshop*

ANNEX C – SLD OF TOTAL FAROESE POWER SYSTEM

Figure 21: SLD of Faroese power system including voltage levels below 60 kV



Source: Provided by SEV in “DATA_MEGIN_704_S.pdf”.