The Least-Cost Path to a 100% Renewable Electricity Sector in the Faroe Islands

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I. Introduction

The Electrical Power Company SEV, the Faroe Islands, is aiming for a 100% renewable electricity sector by 2030. Through optimisation of the future investments and dispatch, it is possible to determine how this goal can be reached following the least-cost path. This paper aims to determine the least-cost path to a 100% renewable electricity sector in the Faroe Islands.

There are seven seperate grids in the Faroe Islands. 99.8% of the total demand is on the main grid (11/18 islands) and the grid on **Suð**uroy. The remaining 5 grids are due to their modest sizes, neglected in this study. The total generation capacity today is 125 MW, of which 53% is diesel power, 33% is hydro power and the remaining 14% are wind power. The renewable generation shares the past years have been roughly 50%. SEV has monopoly on transmission and distribution in the Faroe Islands, and owns >98% of the installed generation capacity. The islands, grids and capacities of the different technologies are shown in Figure 1.

In order to reach the goal of a 100% renewable production, new renewable plants will have to be installed, so that the production that today stems from diesel plants, and the production necessary to meet the expected demand increase can be covered. The demand increase that SEV considers is 100% electrified heating and transport sectors by 2030, in addition to a historically based 2% annual increase. This results in a total annual demand of 600 GWh in 2030 [1], [2]. The total demand in 2018 was 350 GWh.

The technologies considered in a 100% renewable electricity sector on the Faroe Islands are wind, solar, tidal, biogas, hydro and pumped storage. The potential for wind and hydro is high, as the average wind speed is 10 m/s and the average precipitation is 1284 mm/year. The potential for solar power is not as high, but it complements wind and hydro well, which makes it interesting, see Figure 2 [3]. Tidal has gained a lot of attention in the Faroe Islands, but the technology is still developing and has not been proven to be financially viable. SEV does not plan to expand the hydro production due to environmental concerns, but the plan is to modify some of the existing plants into pumped storage. A private company will install a biogas plant of 1.5 MW in 2020.

A few studies have already investigated the future energy mixture of the Faroe Islands, these are briefly discussed in [4]. The studies agree that the most feasible technologies to invest in are wind power and solar, and that existing hydro plants should be modified into pumped storage. SEV's current road map requires 148 MW of wind power, 72 MW of

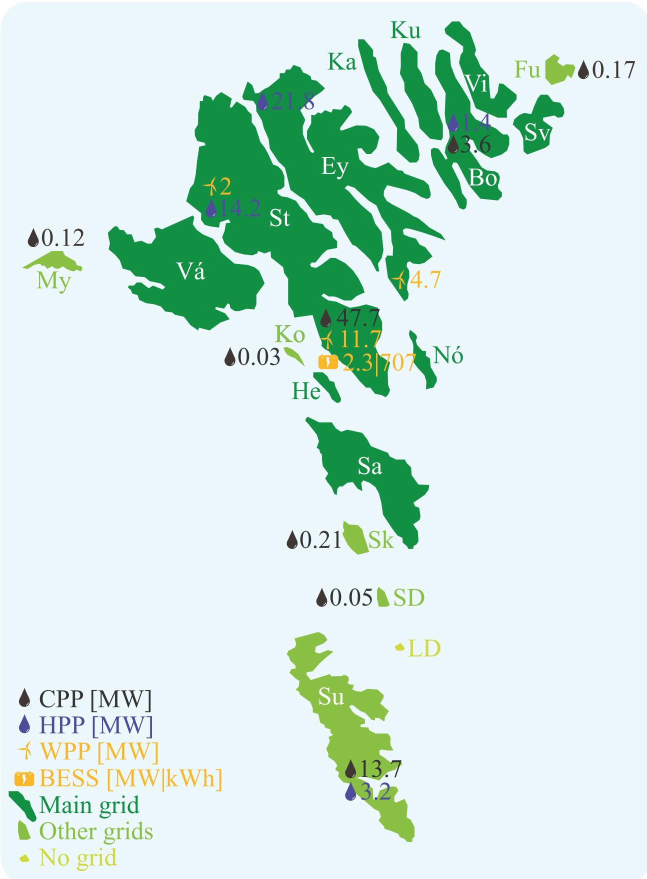

Fig. 1. Overview of the Faroese electrical power grid in 2019. The amounts of installed conventional power plants (CPPs), hydro power plants (HPPs), wind power plants (WPPs), and battery energy storage systems (BESSs) at each site are shown.

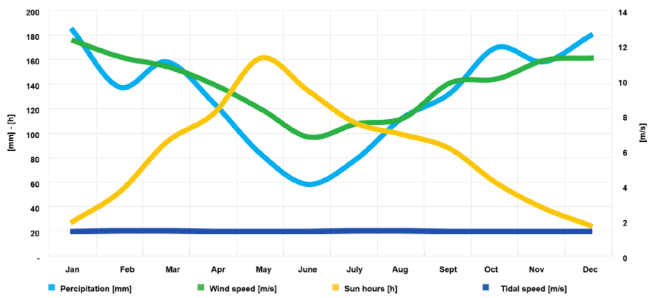

Fig. 2. The monthly average energy resources available in the Faroe Islands. [3]

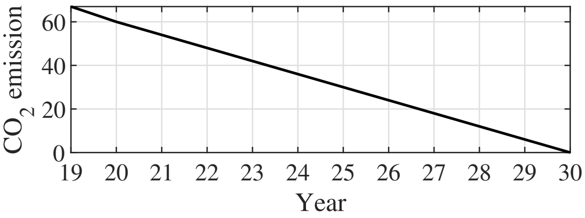

Fig. 3. The limit on CO_2 emissions in ktonne/year.

solar power and pumped storage with a generation/pumping capacity of 84 MW/140 MW. New knowledge is constantly gained, and plans have to be adapted, which is why another study of the future energy mixture, which utilises the newest knowledge is required.

II. Methodology and Material

Several tools have been developed and used to determine current and future optimal energy mixtures from an economic point of view. The majority of these, have been thoroughly reviewed in e.g. [5] and [6]. One of the tools is the transparent model Balmorel. Balmorel can optimise investments and dispatch simultaneously, based on input data such as availability of resources, demand profiles, investment options and costs. The aim of this study is to define the least-cost path to a 100% renewable electricity sector, which is done by optimising both future investments and dispatch. Hence, Balmorel was considered a suitable tool for this particular study. The Faroese power system has previously been modelled in Balmorel [2], but this study contributes with updates on previous assumptions.

A. Model Configuration

Balmorel models are constructed in three geographical layers: *Countries*, *regions* and *areas*. For this study only one *country* is considered, but Balmorel can optimise interconnected systems as well. Since countries in interconnected systems might have different politics on the energy sector, policies are defined for each country seperately in Balmorel. One policy has been set in the Faroese model. This is a policy of having no CO_2 emissions from the electrical power production in 2030. This means that for each simulated year, the CO_2 emissions for the whole country have to stay within a certain limit. The limits are set as a linear decrease from now until 2030, see Figure 3.

This study is, as previously mentioned, limited to investigate the main grid and the grid on Suðuroy, these two grids are considered *regions* in Balmorel. A demand has to be defined for each region, and it is possible to transmit electricity between the regions. Since there is no transmission cable between the main grid and Suðuroy, the model can not initally transmit power between the regions, but the model can invest in a transmission cable between the main grid and Suðuroy, which then allows for power transmission between the regions.

Each power plant, both existing and future, has to be assigned to an *area*. These areas are mainly defined per input weather data. Example: One area is defined per wind profile and in each of these wind areas, the model is allowed to invest in wind turbines. This study's model can invest in 3 wind areas, 2 solar areas, 3 tidal areas and 2 pumped storage areas. Table I shows the model's investment options.

TABLE I
The model's investment options. The number indicates in how many areas per region the specific technology can be invested in.

	Wind	Solar	Pumped storage	Tidal	Battery
Main	2	1	1	3	1
Suðuroy	1	1	1	0	1

B. Formulation of the Optimisation Problem [7]

The objective function which is minimised in Balmorel in the study case of the Faroese electricity sector can be seen in Equation 1. The symbols used in the equations are defined in Table II. The function consists of investment costs, variable and fixed operation and maintenance costs. This function is optimised for every simulated year. In this study simulations were run from 2019 to 2030. If the model e.g. decides to invest in solar energy in year 2022, then the installed capacity is updated accordingly in 2023.

The objective function is subject to two balance equations. These assure that the demand is met at all times (Equation 2), and that the fuel consumption is proportional to the generation from fuel based generation units (Equation 3). Technology constraints restrict the model so that the generation does not exceed the possible generation, i.e. based on the available resources (Equation 4) and the storage level (Equation 5). The power transmitted is also restricted to be below or equal to the transmission capacity (Equation 6). As mentioned previously, a policy has been set to decrease the emissions linearly, this is therefore also set as a constraint (Equation 7). Finally, a dispatch rule has been set to assure that the generation is larger than or equal to the full load hours multiplied by the existing and invested generation capaity (Equation 8). For additional information about the optimisation procedure please see [7].

Minimize

$$\sum_{g,t} c_{g,t}^{var} G_{g,t} + \sum_{g} (c_g^{inv} + c_g^{fix}) I_g + \sum_{x} c_x^{inv} I_x \quad (1)$$

subject to

Balance equations:

$$\sum_{g} G_{g,t} + \sum_{x} (1 - loss_x) X_{x,t}^{Im} = \sum_{x} X_{x,t}^{Ex} + D_t \quad (2)$$

$$F_{g,t} = \frac{G_{g,t}}{\eta_g} + k_g \kappa_g O_{g,t} \quad (3)$$

Technology constraints:

$$G_{g,t} \leq r_t (K_g + I_g) \quad (4)$$

$$L_{g,t+1} = L_{g,t} + r_t^{HY} (K_g + I_g) - G_{g,t} \quad (5)$$

Transmission constraints:

$$X_{x,t} \leq K_x + I_x \quad (6)$$

Policy targets:

$$\sum_{g,t} W_g F_{g,t} \leq T \quad (7)$$

Dispatch rules:

$$\sum_{t} G_{g,t} \geq FLH_g(K_g + I_g) \quad (8)$$

TABLE II
PARAMETERS AND SYMBOLS.

		Symbol
Indices	Technology	g
	Electricity	e
	Fuel	f
	Time	t
	Transmission line	x
	Areas	a
Factors	Costs	c
	-variable	c^{var}
	-fixed O&M	c^{fix}
	-investment	c^{inv}
	Marginal efficiency	η
	Fuel consumption	F
	Idle fuel consumption	k
	Nominal unit size	κ
	Variable resource	r
	Existing capacity	K
	Investmented capacity	I
	Loss factor	$loss$
	Target	T
	Emission factor	W
Variables	Generation	G
	Demand	D
	Transmission	X
	-import	X^{Im}
	-export	X^{Ex}
	Units online	O
	Storage level	L

C. Input data

The input data presented in this section consists of demand and resource data. The demand input in Balmorel is in two parts; the total annual demand and a unit less demand profile. The demand profile then scaled according to the annual demand. As mentioned previously, SEV considers the demand to increase due to electrification of the heating and transport sectors and a traditional load increase, due to this three profiles and annual demands are used for each region. An example of the weekly demand profiles in the main grid and on Suðuroy is shown in Figure 4. In the regular demand, the profile clearly shows a variation throughout the day, but this is not valid for the heating profile, which is close to constant throughout the day. The transport demand is predominantly during the night, this assumption is based on that SEV encourages customers to charge the electric vehicles during the night. The annual demands for each region are tabulated in Table III. The projections are based on the demand in 2015 [1].

The potential solar, tidal and hydro production are likewise based on a profile and an annual sum, i.e. the full load hours

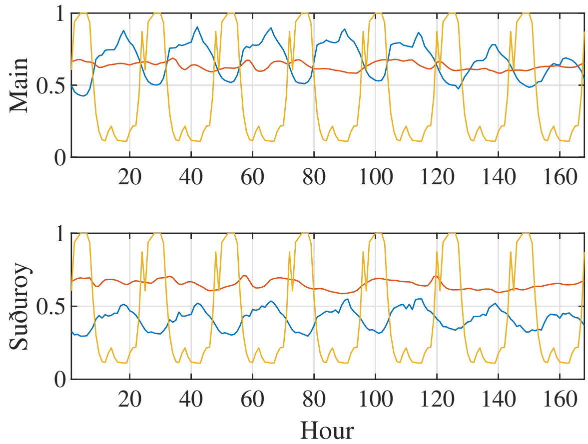

Fig. 4. Example of weekly demand profiles. Regular demand (blue), the heating demand (red) and the electric vehicle demand (yellow).

TABLE III
THE ASSUMED ANNUAL DEMAND [GWH].

	Regular	Heating	Electric Vehicles
Main 2015	279	0.24	0.03
Main 2030	379	83	70
Suðuroy 2015	36	0.03	0.004
Suðuroy 2030	48	11	9

(FLH). Table IV summarizes the FLH for the resources at the different sites. The hydro data is based on actual production, the tidal data is based on an analysis of insitu measurements, and the solar data is based on satellite data.

Unlike other technologies, the wind production is based on the actual wind speeds measured at the areas, and the characteristics of the wind turbine. The characteristics used are based the Enercon E44 wind turbine.

D. Committed Capacities

Balmorel allows for exogenous input to capacities. This means that already planned plants, i.e. committed capacities, can be set as inputs, so that the model includes them in the defined area. In this study case 3 upcomming wind farms and a conventional power plant have been set as committed capacities, see Table V. All of these will be commissioned in 2020 according to current plans. The model can however decommission the units again, if that is a part of the optimal solution.

TABLE IV
THE FULL LOAD HOURS FOR THE DIFFERENT RESOURCES.

Location	Resource	FLH
Suðuroy	Hydro	1403
Main, **Eys**turoy	Hydro	2909
Main, **Borð**oy	Hydro	1913
Main, **Str**eymoy	Hydro	3389
Main	Solar	830
Suðuroy	Solar	830
Main, **Vág**oy/**Str**eymoy	Tidal	2349
Main, **Eys**turoy/**Kal**soy	Tidal	2873
Main, **Str**eymoy/**San**doy	Tidal	3695

TABLE V
COMMITTED CAPACITIES.

Type	Location	Capacity [MW]
Heavy oil	Main	36
Biogas	Main	1.5
Wind	Main	36
Wind	Suðuroy	6.3

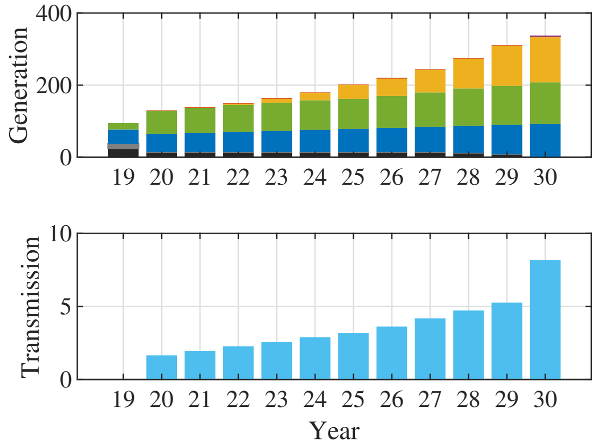

Fig. 5. The optimal generation and transmission capacities [MW]. Fuel oil (black), gas oil (grey), hydro (dark blue), wind (green), solar (yellow), biogas (red), battery (purple) and transmission (light blue).

III. RESULTS

This section presents the results of the optimisation. On Figure 5 the accumulated generation and transmission capacities are shown. The results show that for the first years the investments should be in wind power, while during the later years it should be invested in . As the figure show, the capacities based on fuel and gas oil decrease to zero. This is due to the requirement of a 100% renewable electricity sector by 2030. The model starts investing in transmission capacity already in 2020, and the optimal capacity increases each year. From 2029 to 2030 the capacity jumps from just above 5 MW to around 8 MW, in order to meet the requirements set.

The model did decide to invest in a pumped storage system on the main grid in the existing hydro plant on **St**reymoy, but not on Suðuroy. Figure 6 shows the capacities of the pumped storage system. As the figure shows, the storage capacity does not have to be increased until 2028. The main expansion of the storage occurs from 2029 to 2030, when the production has to become 100% renewable. The necessary turbine capacity in the plant increases evenly throughout the simulated period, while the pumping capacity increases all years, but especially from 2028 to 2030.

The different capacities that were shown in Figure 5 and Figure 6, are summarised for 2030 in Table VI. The optimal capacities according to this study are that the main grid should have a wind capacity of 97 MW, solar of 119 MW, biogas of 1.5, hydro turbines of 89 MW (total of all hydro plants), with a pumping capacity in the pumped storage system of 56 MW and a storage capacity of 7.3 GWh. The capacities on Suðuroy should be 19 MW of wind, 6 MW of solar, a battery of 1.6 MW and the existing hydro power

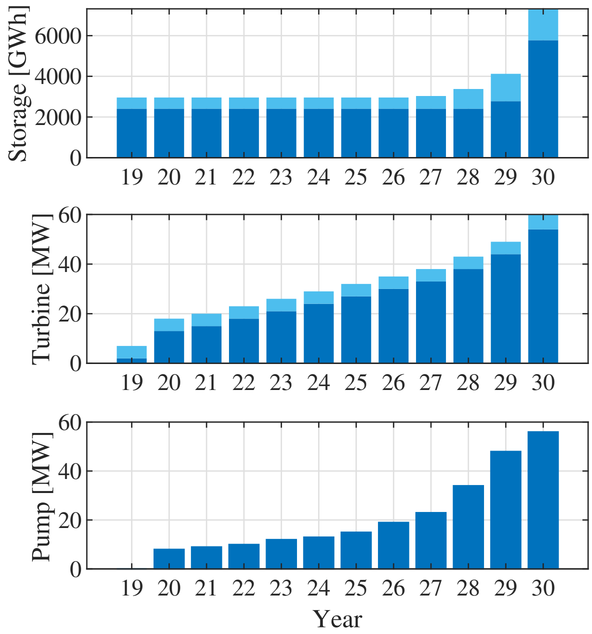

Fig. 6. The storage [MWh], turbine [MW] and pump [MW] capacities for the pumped storage system in the main grid. Upper plant (dark blue) and lower plant (light blue).

TABLE VI
GENERATION, TRANSMISSION AND STORAGE CAPACITIES IN 2030

	Main	Suðuroy
Wind [MW]	97	19
Solar [MW]	119	6
Biogas [MW]	1.5	-
Battery [MW]	-	1.6
Hydro turbines [MW]	89	3.3
Pump [MW]	56	-
Storage [GWh]	7.3	-
Transmission [MW]	8.2	

plant should be kept at 3.3 MW. Additionally a transmission cable between themain grid and Suðuroy of 8.3 MW should be deployed.

The annual productions is shown for each region on Figure 7. According to the results, the renewable shares on the main grid will be high already in 2020, but then slowly reach 100% by 2030. On Suðuroy the production will not be as green as soon as on the main grid, but will also reach 100% renewability by 2030.

IV. DISCUSSION

As mentioned previously the Faroese model has been simulated in Balmorel before, but this study presents an updated and improved version. The main difference is in the committed capacities. Prior simulations e.g. considered a pumped storage system on Suðuroy as committed capacity, and 18 MW of wind on the main grid were considered as committed capacity for 2020, instead of 36 MW as shown here. These updated committed capacities, are due to actual plans which have been changed.

As shown on Figure 5, the transmission capacity increases

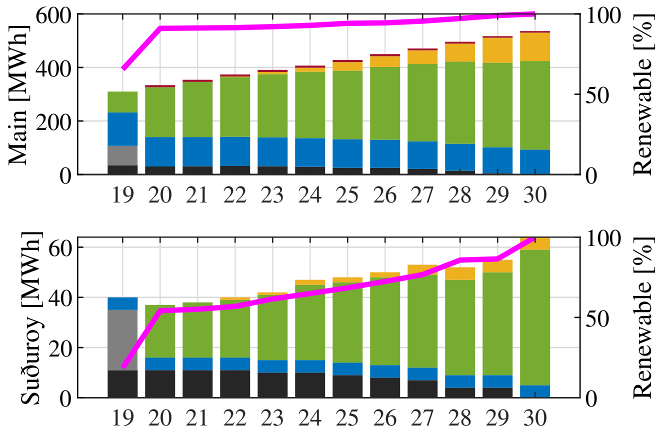

Fig. 7. The optimal production [MWh]. Fuel oil (black), gas oil (grey), hydro (dark blue), wind (green), solar (yellow), biogas (red) and battery (purple).

quite significantly from 2029 to 2030. The reason behind this can be found in Figure 7. The total generation on Suðuroy is 68 GWh, which 4 GWh higher than the demand shown in Table III, whilst the generation on the main grid is 532 GWh, which is 4 GWh lower than the demand. Therefore extra transmission capacity is needed to reach 100% renewability in both regions by 2030.

The generation shown on Figure 7 shows that the the generation in 2020 and 2021 is lower than in 2019, this is not caused by a lower demand, but is due to the imported power from the main grid.

As the production figures show, the production, especially on Suðuroy, is mainly covered by wind. If a this high share of wind power is realistic can be discussed, since SEV today only allows 60% of the instantanous production to origin from wind power, but Balmorel suggests this, due to the low costs and no restrictions on the shares of variable renewable energy sources.

If a 100% renewable electricity sector is reached by 2030, the production probably continue being 100% years afterwards. This due to the fact, that in 2030, all heating and transport should already be electrified, which leaves only the traditional load increase. This load increase will not require as massive investments, and will be more normal investments.

V. Conclusion

A. Future Works

References

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