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

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***Abstract*—In 2030 the electricity sector in the Faroe Islands should be 100% renewable, according to the local electrical power company SEV. It is therefore necessary to study, how this goal can be reached with the minimum costs. This can be determined through optimisation of the future electricity sector. This paper presents such an optimisation. The optimisation is conducted using the computer simulation tool Balmorel, which has been developed for the purpose. Two of the seven power grids in the Faroe Islands are modelled, and input data such as weather and projected demand are defined. The model is allowed to invest in wind, solar and tidal power, in addition to pumped storage systems. The results show that if the least-cost path to a 100% renewable electricity is followed, SEV should invest in 98 MW of wind power, 125 MW solar power, a battery system of 1.6 MW/6.7 MWh and a pumped storage system with a storage of 7.3 GWh. Additionally a cable between the two investigated grids should be installed, to allow for transmission between the grids. In order to get better and site specific results, the model should be expanded with extra demand profiles and input weather data.**

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 **Su**ðuroy. 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, a significant amount of renewable generation capacity will have to be installed. This is due to two reasons:

1) The production that currently stems from diesel plants has to be covered by renewables.
2) The expected demand increase has to be met.

The demand projection that SEV bases expansion plans on includes 100% electrified heating and transport sectors by 2030, and additionally a historically based 2% annual increase. This results in a total annual demand of 600 GWh in 2030 [1]. The total demand in 2018 was 350 GWh.

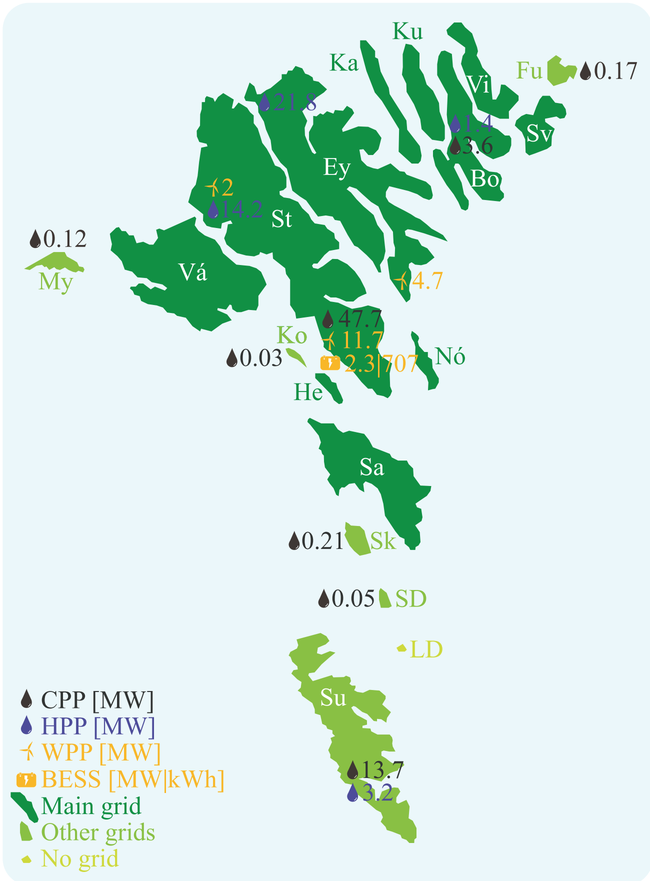

Fig. 1. Overview of the Faroese electrical power grid in 2019. The amounts of installed conventional power plants (CPPs), hydro power plants (HPPs), wind power plants (WPPs), and battery energy storage systems (BESSs) at each site are shown.

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 1300 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 [2]. Tidal has gained a lot of attention in the Faroe Islands, but the technology is still developing and has yet to be proven 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 biogas plant of 1.5 MW will be installed in 2020 by a private company.

A few studies have already investigated the future energy

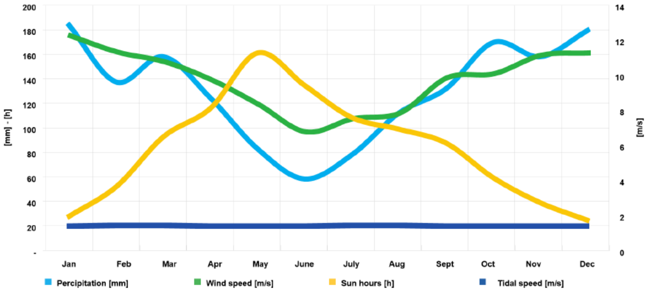

Fig. 2. The monthly average energy resources available in the Faroe Islands. [2]

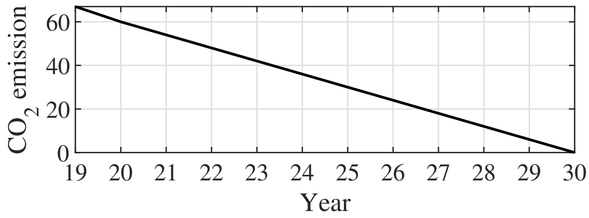

Fig. 3. The limit on CO_2 emissions in ktonne/year.

mixture of the Faroe Islands, these are briefly discussed in [3]. The studies agree that the most feasible technologies to invest in are wind and solar power, 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 solar power and pumped storage with a generation/pumping capacity of 84 MW/146 MW. However, 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 the current and future optimal energy mixtures from an economic point of view. The majority of these, have been thoroughly reviewed in e.g. [4] and [5]. 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 [7], 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. Countries in interconnected systems might have different policies on the energy sector; hence, 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. There is no transmission line or cable between the main grid and Suðuroy; thus, the model can initially not transmit power between the regions, but the model can invest in a transmission cable, which then allows for power transmission between the main grid and Suðuroy.

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 [6]

The objective function which is minimised in Balmorel in the study case of the Faroese electricity sector is represented by Equation 1. The symbols used in all 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 see [6].

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:

$$\sum_g G_{g,t} + \sum_x (1 - loss_x) X^{Im}_{x,t} = \sum_x X^{Ex}_{x,t} + D_t \quad (2)$$

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

Technology constraints:

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

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

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
DESCRIPTION OF SYMBOLS USED IN EQUATIONS.

		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
	-hydro	r^{HY}
	Existing capacity	K
	Invested 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. Therefore three profiles and annual demands are used for each region. An example of the weekly demand profiles on the main grid and on Suðuroy is shown in Figure 4. In the regular demand, which covers everything expect from heating and transport, 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 SEV's encouragement to customers of charging 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].

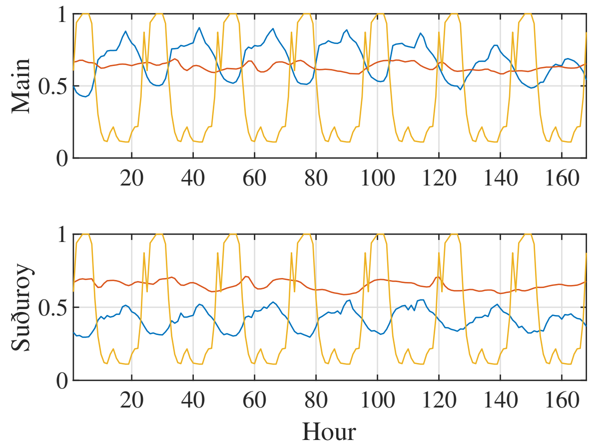

Fig. 4. Example of weekly demand profiles. Regular demand (blue), the heating demand (red) and the electric vehicle demand (yellow).

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

The potential solar, tidal and hydro production are likewise based on a profile and an annual sum, i.e. the full load hours (FLH). Table IV summarizes the FLH for the resources at the different sites. The hydro data is based on actual production, while 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 measurements, and the wind turbine's characteristics. This means that the potential power output from a wind turbines is based on a power curve of a turbine. In this study the power curve for a Enercon E44 wind turbine has been implemented.

TABLE IV
THE FULL LOAD HOURS FOR THE DIFFERENT RESOURCES AT DIFFERENT LOCATIONS.

Location	Resource	FLH
Suðuroy	Hydro	1403
Main, **Ey**sturoy	Hydro	2909
Main, **Bo**rðoy	Hydro	1913
Main, **St**reymoy	Hydro	3389
Main	Solar	830
Suðuroy	Solar	830
Main, **Vá**goy/**St**reymoy	Tidal	2349
Main, **Ey**sturoy/**Ka**lsoy	Tidal	2873
Main, **St**reymoy/**Sa**ndoy	Tidal	3695

All assumptions on investment costs and other economic aspects are explained in reference [7].

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, a biogas plant and a conventional power plant have been set as committed capacities, see Table V. All of these will according to current plans be commissioned in 2020. The model can however decommission the units again, if that is a part of the optimal solution.

TABLE V
COMMITTED CAPACITIES.

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

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 main investments are wind power, while during the later years most investments are solar power. As the figure shows, 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 between the main grid and Suðuroy 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 Streymoy, 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 we reach 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. The model invests in a pumping capacity

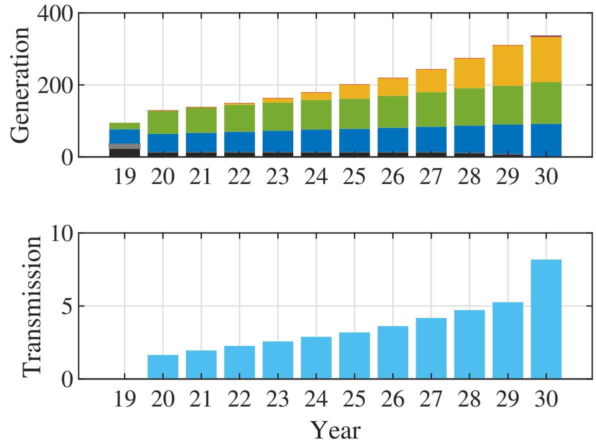

Fig. 5. The optimal generation and transmission capacities [MW]. Fuel oil (black), gas oil (grey), hydro (dark blue), wind (green), solar (yellow), biogas (red), battery (purple) and transmission (light blue).

already in 2020, and the capacity increases slowly to 2027, but from 2027 to 2030 the capacity almost triples.

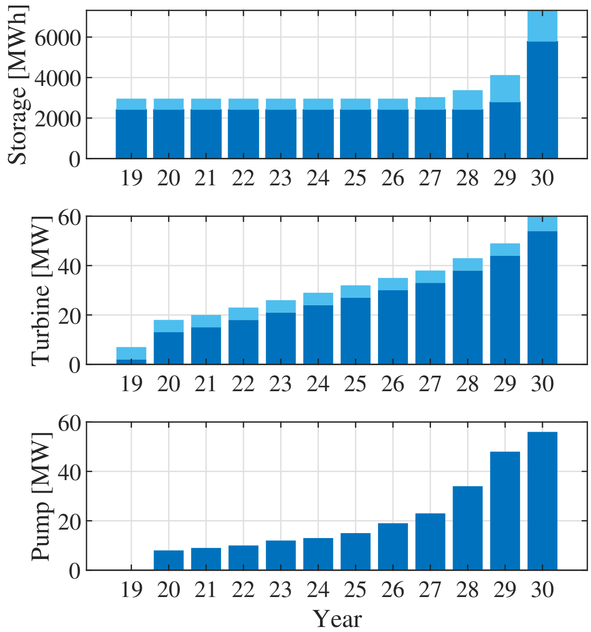

Fig. 6. The storage, turbine and pump capacities for the pumped storage system in the main grid. Upper plant (dark blue) and lower plant (light blue).

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, 119 MW solar, a biogas plant of 1.5 MW, 89 MW of hydro turbines (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 power, 6 MW solar, a battery of 1.6 MW/6.7 MWh and the existing hydro power plant should be kept at 3.3 MW. Additionally a transmission cable between the main grid and Suðuroy of 8.2 MW should be deployed.

TABLE VI
GENERATION, TRANSMISSION AND STORAGE CAPACITIES IN 2030

	Main	Suðuroy
Wind [MW]	97	19
Solar [MW]	119	6
Biogas [MW]	1.5	-
Battery Power [MW]	-	1.6
Battery Energy [MWh]	-	6.7
Hydro turbines [MW]	89	3.3
Pump [MW]	56	-
Storage [GWh]	7.3	-
Transmission [MW]	8.2	

The annual productions for each region is shown 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.

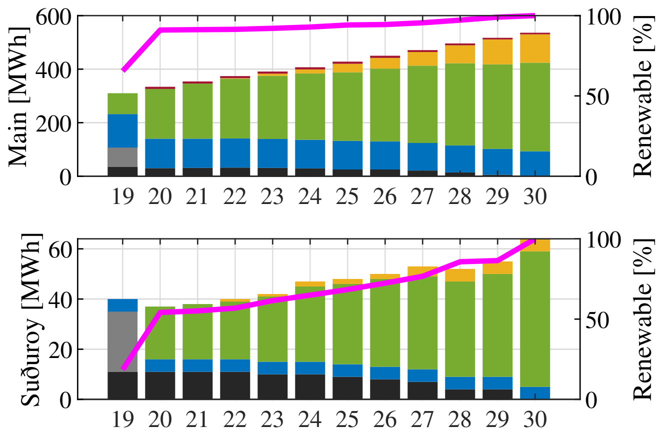

Fig. 7. The optimal production [MWh]. Fuel oil (black), gas oil (grey), hydro (dark blue), wind (green), solar (yellow), biogas (red) and battery (purple).

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 change of plans.

As shown on Figure 5, the transmission capacity increases 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 is 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. It can be discussed if a this high share of wind power is realistic, since SEV today only allows 60% of the instantaneous production to origin from wind power, due to stability challenges and short circuit power. Balmorel suggests this high share due to the low costs and no restrictions on the shares of variable renewable energy sources. In the future this limit will however increase as batteries and synchronous condensers are installed, which will support the stability of the grid, and therefore allow for a higher instantaneous wind penetration.

If a 100% renewable electricity sector is reached by 2030, the production will probably continue being 100% renewable 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 massive investments, and will be considered normal expansion investments.

This study suggests a higher amount of solar power than the road map, this could be due to the fact that the pumped storage system in Suðuroy no longer is a committed capacity. Solar power is cheaper, and the production can directly be utilised, while wind power also produces during the night, and must therefore be stored, which requires a storage capacity. The solar capacity in this study therefore increases, while the optimal wind power capacity decreases. It is debatable if installing 125 MW of solar power in the Faroe Islands is realistic, due to the land it requires.

Balmorel's results are the optimal capacities, and are updated every year. In reality investments are done per plant or cable. E.g. SEV would not invest in a transmission cable between the regions in 2020 and then increase the capacity every year. The cable would be intalled one year with a fixed size. If results from Balmorel are used in expansion planning, it is therefore necessary analyse the results in order to determine how big each plant to be installed should be.

With the input weather and demand data, Balmorel has full foresight of each simulated year. This means that the model from day one knows what resources are available throughout the whole year, and can optimise the dispatch based on this. All results should therefore be considered with caution.

V. CONCLUSION

The optimal energy mixture in a 100% renewable electricity sector in the Faroe Islands in 2030 consists of 116 MW wind power, 125 MW of solar power, a biogas plant of 1.5 MW, a total of 92.3 MW of hydro turbines and a battery system with a capacity of 1.6 MW/6.7 MWh according to this study. Additionally a pumping capacity of 56 MW should be installed in an existing hydro plant, so that this can be used as a pumped storage system. This also requires a storage capacity of 7.3 GWh at the pumped storage site. SEV should also invest in a transmission cable of 8.2 MW between the two investigated grids.

As discussed, there are some weak points of this study. A solar capacity of 125 MW might not be realistic due to the land requires, and all results should be considered with caution, as Balmorel has full foresight of the demand and resources throughout a year, which is not possible in actual power system operation.

A. Future Works

This study has presented an updated model of previous studies, and this model could be even further developed. This could be done by separating the main grid into regions, so that the transmission capacity is accounted for. This would require more demand profiles, as each region has to have a demand profile, and more areas should be defined based on available wind measurements and solar data. Additional restrictions should be added, e.g. a realistic maximum capacity of solar power and the maximum instantaneous wind penetration.

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