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100% Sustainable Electricity in the Faroe Islands: Expansion Planning Through Economic Optimization

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ABSTRACT SEV, the Faroese Power Company, has a vision to reach a 100% renewable power system by 2030. SEV is committed to achieve this, starting from a 41% share of renewables in 2019. A detailed expansion plan for the generation, storage and transmission is needed to reach this goal. This is the focus of this study. Practical constrains e.g. resource potential and available space must be considered. Balmorel, an optimisation tool, has been used to optimise investments and dispatch. A method to translate optimal results to a realistic RoadMap was developed and applied. The impact of different technologies and costs has been investigated through multiple scenarios. In ratios of average consumption in 2030, installed power will be 224% wind, 105% solar with 8-9 days of pumped hydro storage according to the proposed RoadMap. The plan is economically favorable up to 87% of renewables, but in order to reach a 100% renewable production in an average weather year, the renewable generation capacity has to be increased by 80%. The study also shows that if biofules or tidal technologies become viable, these will be game changers needing a significantly lower total sum of installed renewable power.

INDEX TERMS Expansion planning, sustainable energy, economic optimisation, Balmorel, islanded system.

I. INTRODUCTION

THE Faroe Islands are aiming for a 100% renewable electricity sector by 2030. A vision set by SEV, the local power company. The power system consists of 7 isolated grids: The main grid connects 11/18 islands (90% of the consumption), the most southern island Suðuroy (10%) and 5 small systems (0.2% in total). The generation capacity is 102 MW of thermal power using fuel oil (FO) and gas oil (GO), 41 MW of hydro power (HP) with reservoirs, 18 MW of wind power (WP), 0.25 MW of photovoltaic (PV) power and 1.5 MW of biogas (BG) power. 42 MW of new WP and a pilot project with 0.2 MW of tidal power (TP) are committed. The generation in 2019 was 387 GWh of which 14% was wind energy and 27% hydro. Demand ranges between 22 MW and 60 MW.

The average wind speed north-west of the capital Tórshavn measured at 104 m is 10.1 m/s [1], the average precipitation is 1284 mm [2] and the annual hours of bright sunshine are 840 [2]. On a monthly basis these resources complement each other, as seen on the upper plot on Fig. 1 [3]. The monthly wind speeds are average values based on the years from 2011 to 2015. The precipitation and solar data are monthly averages based on 2007-2015. The complementary is also apparent when analysing a specfic year, i.e. not average values. Although the potential for solar energy is relatively low, it complements the wind and hydro resources which could make it interesting for the Faroese power system. The average monthly tidal streams are close to constant throughout the year. Even though the four resources complement each other very well on an average monthly basis, there are periods with a low renewable energy potential, see lower plot on Fig. 1. Tidal is clearly the most constant resource, but varies by a factor of two over the shown spring–neap cycle.

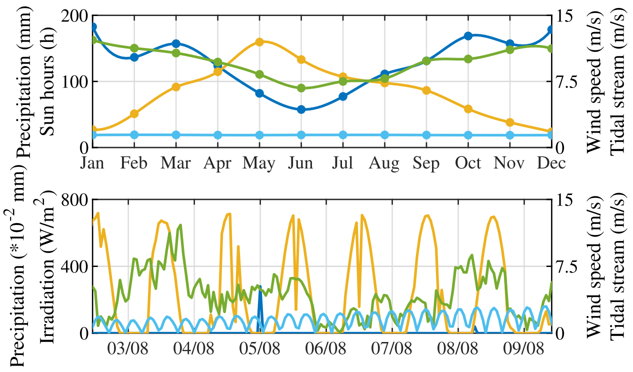

FIGURE 1. The potential for hydro (blue), photovoltaics (yellow), wind (green) and tidal (cyan) energy on a monthly [3] and hourly basis (2017).

The Faroese power system is rarely studied or discussed in peer-reviewed literature. However, the system has been analysed in other studies and technical reports. These are typically initiated or conducted by SEV. The most extensive study, summarised in [4], included a projection of the future energy demand [5], production simulations using different demand and generation technology combinations [6], the role of flexible loads [7], the economically optimal investments towards 2030 [8], expansions required to assure renewable production also during dry years [9], analysis of needed storage capacities with different compositions of renewables [10], the feasibility of tidal energy [11], relevant types of energy storages [12], feasibility of a cable to neighbouring countries [13] and an initial study of the future power system stability [14]. A technical overview of the mentioned studies can be found in reference [15]. The main conclusion is an expansion plan (a RoadMap) that includes 148 MW of wind power, 80 MW of PV power and hydro pumped storage (PS) systems with 146 MW of pumping capacity and 109 MW of generation capacity towards 2030. The need for larger reservoirs should be evaluated later. Another conclusion is that a cable to neighbouring countries is not financially viable [16], nor is it interesting politically as a self sufficient energy system is desired [17]. Finally, that tidal energy technology is currently not mature enough to be considered as a part of the power system in the near future. Other studies have analysed different aspects e.g. economic optimisations of future investments using tools like HOMER [3], [18], Balmorel [19] (also used in ref. [8]) and simpler manual approaches [20]. A few studies have also analysed the system with different scenarios using fixed capacities, i.e. not an optimisation [21]–[23]. Finally some studies have focused on the feasibility of specific components e.g. flow batteries [24] and fuel cells [25]. The presented studies have been conducted using different approaches and focusing on different components of the system. The majority of the studies do conclude that wind power together with PV and pumped storage is the most feasible combination to reach a high penetration of renewables in the Faroe Islands.

One of the remaining challenges towards a 100% renewable power system is the power system stability when increasing the penetration of inverter-based technologies. In order to conduct a realistic investigation of this, it is necessary to have a very detailed RoadMap, which should consider: 1. The exact location of each investment (generation, storage and transmission), 2. Constraints based on available space for new plants, 3. Variation in demand and renewable resources based on location, 4. If the necessary transmission capacity is sufficient or reinforcements are needed and 5. The costs of keeping thermal power plants as back up. The present RoadMap towards a 100% renewable electricity sector in the Faroe Islands [4] is based on studies, which have either simplified or ignored these aspects. Thus, this study aims to present an updated RoadMap considering these details, which then can be used for future power system analyses.

Multiple energy system modelling tools have been developed, and can be used for expansion planning. A broad range of energy system models have been discussed, categorised, and compared in [26]–[31]. The focus in the mentioned review studies varies, e.g. reference [27] focuses on categorising the tools in order to guide the reader to choose the best fitted tool, while others focus on comparing the different approaches [30] and identifying state of the art issues with regards to expansion planning [31]. Based on [27], Balmorel has been chosen as the most suitable tool for this investigation as it can optimise the future investments annually and the dispatch hourly. In addition, it is an open source and transparent tool, that is flexible in terms of immature technologies. Balmorel has been applied to multiple energy systems and is under continous development, see [32].

A disadvantage with Balmorel and other optimisation tools is that an economically optimal solution might not be realistic nor practical, as the capacity of a cable, reservoir or generation unit increases annually, where in reality it has to be installed or not. In order to tackle this challenge, a very detailed model in Balmorel addressing the aspects mentioned previously was defined, and then a method to translate the optimal results to a RoadMap with realistic projects, that are close to the optimal solution, was developed. Other related studies, Faroese [3], [8], [9], [15], [18]–[21] or international [33]–[38], do not transform the optimal results into an actual action plan. Reference [34] analyses the feasibility and security level of a highly renewable power system in the Mainland Portugal using the tool EnergyPLAN and a single predefined scenario. A model focusing on the integration of unit commitment problem is developed in [35] and tested on the Greek power system. The annually optimal investments are obtained. The operation challenges in a renewable system are integrated in a model proposed by [33]. An expansion planning study of Santiago, Cabo Verde, defines each suitable location for renewables and the available capacity, but investments are not optimised [36].

The applied and detailed approach used in this study, based on the tacit knowledge from a system provider actively pushing the limit for variable renewable energy penetration in

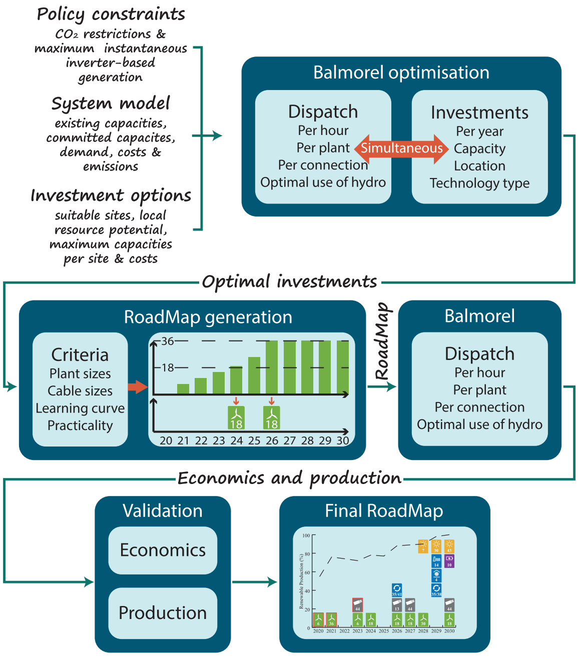

FIGURE 2. **A flowchart illustrating the methodology followed in this study.**

an isolated grid, differs from the other expansion planning studies we have found, as these are typically more academical in motivation and outcome. The approach presented in this study is especially applicable for other small systems, where it is possible to map out every relevant renewable generation and define the local resource potential and maximum capacities. In addition to the developed methodology, the study also presents very interesting results that show the influence the relatively persistent tidal source and dispatchable biofuels can have on the future power composition. The study is based on political decisions in the Faroe Islands, and the actual power system considering the local constrains, which makes this a realistic RoadMap that will be used in the expansion planning of the power system. The structure of the paper is: The topic is introduced in section I, methodology and modelling in section II. The results are presented and discussed in section III. Section IV concludes the study.

II. METHODOLOGY AND MODELLING

The method used to generate a RoadMap, consists of two parts; an economic optimisation in the partial equilibrium model Balmorel, and a translation of the optimal results to a realistic expansion plan. This chapter starts by describing the methodology and then the modelling of the system, technologies, investment options and the different scenarios, which have been run in this study.

Fig. 2 shows the applied methodology. The inputs required to Balmorel are specifications on the system, investment options and policy constraints. The previous Faroese Balmorel models [8], [19] have been developed futher in to a significantly more detailed model, considering the aspects mentioned in the introduction and more scenarios have been simulated analysing the impact of different technologies, constraints and costs. In Balmorel the least-cost investments are optimised annually, while the least-cost dispatch is optimised hourly. Balmorel seeks to minimise the total costs of the electrical power system through a linear optimisation problem. The costs considered are for fixed operation and maintenance (O&M), variable O&M, investments in generation, storage and transmission capacity (1). The optimisation is subject to meeting the power demand in each region (2), the production not exceeding the hourly available resources (3) nor the transmission capacity (4). Additionally, two policy constrains have been set. The first one limits the CO_2 emissions to decrease linearly to zero in 2030 (5). The other limits the maximum instantaneous inverter based generation. The current inverter based operation limit is set to 60%, with the three planned wind farms this limit is increased to 80% in 2021, and then increases linearly to allow 100% instantaneous inverter-based generation in 2030 (6). The years from 2020 to 2030 have been optimised based on different scenarios (Table 2). The results obtained are the optimal hourly dispatch etc. and the annual optimal investments from 2021 and forward. For further details on the optimisation algoritm: [39].

TABLE 1. **Nomenclature for Equations (1)-(6).**

T	Target	g	Technology	F	Fuel consumption
y	Year	G	Generation	K	Existing capacity
a	Area	Z	System costs	W	Emission factor
t	Time	r	Resource	x	Transmission line
c	Costs	I	Investment	X	Transmission capacity
D	Demand	fix	Fixed O&M	i	Inverter based
f	Fuel	w	Emission		

Minimise

$$Z_y = \sum_{g,t} c_{g,t} G_{g,t} + \sum_{g,f,t} c^f_{g,t} F^f_{g,t} + \sum_{g} (a c^I_g + c^{fix}_g) I_g + \sum x a c^I_x I_x \quad (1)$$

subject to

$$\sum_g G_{g,t} + \sum_x (1 - loss) X^{Import}_{x,t} = \sum_x X^{Export}_{x,t} + D_t \quad (2)$$

$$G_{g,t} \leq r^f_t (K_g + I_g) \quad (3)$$

$$X_{x,t} \leq K^x + I^x \quad (4)$$

$$\sum_{g,t} W^f_w F^f_{g,t} \leq T_w \quad (5)$$

$$\frac{\sum_g G^i_{g,t}}{\sum_g G_{g,t}} \leq T_{i,t} \quad (6)$$

The annual optimal investments from Balmorel are used as an input to the *RoadMap generation* (Fig. 2). The left box shows the criterias set to a realistic RoadMap, which are as follows: 1) Each investment in a power plant needs to be a reasonable size, e.g. a full wind farm in one year instead of multiple small investments. 2) It is not possible to increase the capacity of a cable year after year, therefore these investments need to be conducted in one step. Additionally the investments need to reflect the capacity of the onshore cables used in the transmission system, i.e. 44 MW. 3) The learning curve of the system operators has to be considered, as each investment has a big influcence on the power system operation, and the operators should have a chance to adapt to the new investments. This means that the sizes of the first wind farms are smaller and with more time inbetween the investments. 4) The energy authority in the Faroe Islands makes tenders for each new wind farm. Thus, from a practical perspective it is highly unlikely that the authority will make several tenders during the same year. This should therefore be avoided to the extent possible, in order to obtain a realistic RoadMap. The four criterias are considered by manually investigating the optimal investments for each site/connection separately. An example from on of the wind farms is found in the right box in *RoadMap generation* in the flowchart. This site has a maximum capacity of 36 MW, and by 2024 just above half of this is needed (20 MW), by 2026 the wind farm reaches full capacity. As the figure shows, these optimal results have been transformed into a two step investment by installing 18 MW in 2024 and 18 MW in 2026. 36 MW is considered too much in one step from a power system operation point of view, and therefore the commission is in halves. This is also in relatively good correspondence with the optimal results. This example shows how the plant size, the learning curve, i.e. the operational experience of the system operators, and practicality have been considered at this specific site.

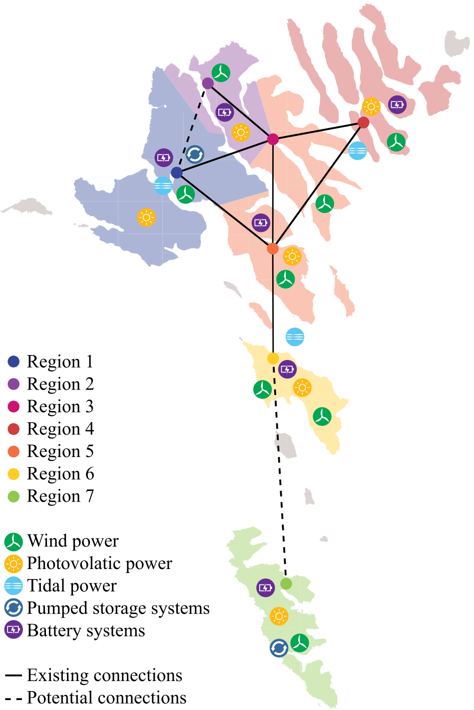

FIGURE 3. **The regions in the modelled power system, existing and potential connections between regions and the generation/storage investment options.**

The next step is to define the proposed RoadMap as committed capacities in Balmorel and rerun the simulation, without any additional investment options. The Balmorel outputs used from the second run are the economic and production data. The RoadMap has then been validated by comparing the economical results to the optimal solution. This is done to ensure that the RoadMap is close to the economically optimal solution. Additionally, the production using the proposed expansion plan has to be 100% renewable in 2030, for the RoadMap to be validated. The final output of the applied methodology is a RoadMap, which is based on an optimisation, but has been translated into a realistic hands-on expansion plan.

A. MODELLING THE POWER SYSTEM

The 5 small isolated (islands) systems are ignored in this study as these are neglectable compared to the rest of the system. The power system has been modelled by dividing the main grid into 6 regions (R1-R6), based on the existing transmission grid, and by defining Suðuroy as region 7 (R7). Any production or consumption has to be related to a specific region. If the region demand is higher than the region production, energy has to be transmitted from another region which results in a 2% loss of the transmitted power. The regions are illustrated in Fig. 3. Region 3 is a connection point (a busbar) without demand and production. The existing transmission capacities are 35 MW, except from the R5-R6 connection which is 10 MW, which will be increased to 44 MW in 2023. The model is allowed to invest in transmission capacity in every connection shown in the figure, except from R1-R3. The investment options are defined based on internal plans for the transmission system [40].

Demand profiles are assigned to the regions. The demand consists of three parts; normal, heating and transport. The normal demand includes everything except for electricity which is needed for heating and transport. The future demand in the Faroe Islands has been investigated and projected previously [3], [5], based on either one or two regions. This model is divided into 7 regions which means new projections are required. The projection assumes that the normal electricity demand, the number of households, and cars in each region continue to increase with the same pace that has been seen from 2009 to 2018. This historic data is obtained from every electricity meter in the Faroe Islands, Statistics Faroe Islands and the Faroese Vehicle Administration. It is assumed that 50% of the heating and transport sectors will be electrified in the year 2025 and 100% in 2030. This is a worst case scenario in terms of investments required to meet the demand. The annual consumption of an electric vehicle is set to 3 MWh [6]. Heat pumps are assumed to consume 5 MWh annually, based on a heat pump coefficient of performance factor of 4 [6] and that for the annual heat demand of a house 20 MWh [41] can be considered a reasonable assumption. The demand in region 7 has an addtional demand increase due to planned new fish

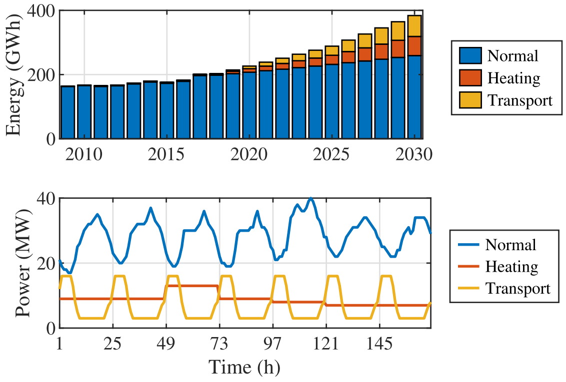

FIGURE 4. **The upper plot shows the historic and projected electricity demand (GWh) in R5. The lower plot shows the projected hourly demand in R5 throughout week 1 in 2030.**

factories. These factories are assumed to add a constant load of 1 MW and 2 MW from 2020 and 2023 respectively. The total demand is projected to 659 GWh in 2030. Additionally, a 4% loss is added to the demand, representing distribution losses. An example of the demand projections and the historic demand (R5) can be found in Fig. 4 as well as the hourly demand profiles. The pattern of the hourly profiles for the normal demand is obtained from the electricity meters. The profile of the heating demand is assummed to be constant throughout a day, but varying from day to day based on the outside temperature, as there is a correlation between these two [42]. The majority of the electric vehicles are assumed to charge during the night, due to financial incentives. These profiles are then scaled to meet the annual demand. Similar assumptions have also been made in references [3], [6].

B. SCENARIOS INVESTIGATED

Multiple scenarios, all emerging from the 2030 vision, have been simulated in this study in order to analyse how different technologies and restrictions can affect the future energy mixture. The scenarios are listed below. The main scenario considers wind power, photovoltaic power, a pumped storage system in R1, batteries and transmission capacity as investment options. Scenario 2-5 are all variations of the main scenario. Scenario 2 additionally considers tidal energy as an investment option. Although previously claimed not sufficiently developed, the technology is considered very interesting in the Faroe Islands, which because of the predictability could provide a type of base load generation. In scenario 3 the model is allowed to burn biofuel (BF) at the thermal plant in R5. In scenario 4 the constraint on the CO_2 emissions has been removed, and thus the feasibility of investing in renewable energy is shown. Scenario 5 includes a PS system in R7, which is a highly discussed topic in the Faroe Islands.

A sensistivity analysis of the results has been conducted. This sensitivity analysis is made by increasing and decreasing the investment costs of WP, PV, the PS system in R1, BS, transmission cables and fuel costs by 20% one at a time.

TABLE 2. **A List of the scenarios investigated.**

#	Scenario description
1	Main
2	Incl. tidal energy as an investment option
3	Incl. permission to burn BF at FO plant in R5
4	Excl. restrictions on CO_2 emissions
5	Incl. PS system in R7

TABLE 3. **Existing and committed generation capacities [MW]. The committed capacities are in parentheses.**

	R1	R2	R4	R5	R6	R7
Fuel oil	-	-	-	77	-	13
Gas oil	-	-	4	5	-	-
Biogas	-	-	-	2	-	-
Hydro	14	22	1	-	-	3
Wind	2	(18)	-	16 (18)	-	(6)

C. MODELLING GENERATION AND STORAGE TECHNOLOGIES

The location of the existing and committed generation capacities, which are considered in this study, are given in Table 3. The modelling of these and the investment options are described in the following subsections. All resource data, i.e. wind speeds, solar irradiation and precipitation, is from 2017 which showed to be the year with the median resources available in the years from 2014 to 2018.

1) THERMAL POWER

The inputs required to model existing thermal power generators are capacity, lifetime (LT), fuel type and efficiency. The efficiency of the FO engines is set to 42%, the GO engines have an efficiency of 45%, while the efficiency of the BG plant is set to 35% [8]. The emissions and energy content depend on the fuel type. No new investments in thermal power are allowed, however one of the thermal plants in R5 is modelled as a combined technology in one of the scenarios, meaning that it is possible to burn BF at this plant, which originally uses FO. The model is not allowed to decommission the thermal power plants, as they will be kept as emergency backup due to the possibility of a lack of renewable resource potential, e.g. a summer with less than average sun hours, wind speeds and precipitation. The fixed O&M costs of these units therefore have to be included in the optimisation.

2) HYDRO POWER

HP with reservoirs is modelled using the turbine and reservoir capacities, the inflow to the reservoirs, the full load hours (FLH) and specification of how much of the reservoir can be regulated. The reservoir capacity used in this study is set lower than the actual reservoir capacity, in order to account for total losses associated with the power plants. The losses are assumed to be 15% [43]. Overflow is rare (a couple of times annually), and thus it is assumed that the weekly inflow can be estimated using logged production data and the water level in the reservoir. The FLHs for each turbine are available from production data. These vary between 1154 and 5295 and depend on the local precipitation and the reservoir sizes. The water level of the reservoirs can not go below 50% of the current storage capacity. The model is not allowed to invest in new hydro capacity, as there is a political and public resistance towards HP.

3) PUMPED STORAGE SYSTEMS

Two of the locations with one or more HP plants are considered suitable for PS systems. PS systems are modelled as long-term storages which can be used to balance the system throughout the year. The first one, located in R1, will utilise two of the existing cascading HP plants. In this PS system, all components are optimised, i.e. pumps, turbines and reservoir sizes. The reservoirs are however limited the highest capacity proposed in a previous study [9]. 100% of the new invested storage capacity can be used to balance the system. The other investment option in a PS system is in R7. This system is however not optimised. The turbine and pumping capacities are fixed to 4 and 6 MW respectively, and the system is assumed to be commissioned in 2023. Due to the system not being optimised, it is only considered in one of the simulation scenarios.

4) WIND POWER

There are two methods to model WP in Balmorel. The first method is to use production data, i.e. FLH and an hourly generation profile, or wind speeds and a power curve (7) can be used. The second method requires information about the height of the wind turbines and measured/modelled wind speeds, and finally the shear factor per wind site.

$$P = \frac{\gamma}{1 + \exp(-g \cdot K \cdot (u - M - \epsilon)} \tag{7}$$

The symbols in the power curve (7) are P: power output (p.u.), $\gamma = 1.01\,\text{p.u.}$ is the maximum power output, $g = 0.58\,\text{p.u./ms}^{-1}$ is the maximum slope of the logistic curve, $K = 0.76$ is a wind farm smoothening parameter, u is the hourly wind speed (m/s), $M = 9.86\,\text{m/s}$ is the speed at which g is reached and finally $\epsilon = 0.89\,\text{m/s}$ is an offset in the wind speed. The power curve of Enercon's E44 wind turbine was curve fitted to find γ, g and M. K and ϵ were found by optimising the correlation between actual production data and calculations using wind speeds and the equation given. WP is also modelled with storm control, meaning that it is assumed that wind turbines are producing rated power up to 28 m/s, and then decrease linearly to 0 MW at 34 m/s.

Existing wind farms where no wind speed measurements are available have been modelled using FLH and generation profiles from logged production data, while all the other wind sites are modelled using measured wind speeds or modelled wind speeds [1]. The model is allowed to invest in WP in 8 different locations as shown in Fig. 3. Each site has been chosen based on a previous study [44] and internal estimations at SEV. A maximum capacity is defined for every location.

TABLE 4. **O&M Costs of existing and comitted power plants.**

	FO	GO	BG	HP	WP
Fix. O&M (EUR/kW)	50	151	50	50	37
Var. O&M (EUR/MWh)	8	8	8	0	3

5) PHOTOVOLTAIC POWER

The hourly solar irradiation in each region has been extracted from the Faroese WRF model [1], and validated against the only long-term measurements available. The performance ratio of PV systems in the Faore Islands has been calculated based on three pilot projects, and is found to be 81%. The expected FLH and generation profiles, which are the inputs necessary to model PV power in Balmorel, can be obtained by multiplying irradiance with the performance ratio [45]. The FLH in the regions based on the calculations computed vary between 584 and 620. PV power is not as site specific as e.g. WP. This technology is therefore assumed to be installed all over the region, and no maximum capacity has been defined.

6) TIDAL POWER

Similary to PV power, the necessary inputs to model TP are a generation profile and the FLH. A model of the tidal streams around the Faroe Islands has been developed by Simonsen and Niclasen [46]. Using these tidal streams and a power curve supplied by Minesto, the generation profiles and FLH hours can be calculated. The FLH vary between 3793 and 4656. A limit has been set on the maximum installed capacity in each location based on space requirements and that no more than 15% of the power can be extracted [47]. In total, it is possible to install 115 MW in the chosen three locations shown on Fig. 3, assuming each installation is 100 kW.

7) BATTERY STORAGE SYSTEMS

The battery systems (BS) in this study are modelled as short-term storage, i.e. the energy can be stored for a week. The C rating is 0.25C, meaning that the batteries have a discharge time of 4 hours. The round trip efficiency of a BS is set to 80%. As shown on Fig. 3 the model can invest in BS in every region except for R3.

8) COSTS

Table 4 contains the costs of existing power plants. The costs for FO, GO, HP and WP are based on experience at SEV [8], while the cost of BG and BF are set to be equal to FO.

The capital costs of WP are based on the costs of the committed wind farm in R2 with a learning rate and LT based on [8], [48]. The capital costs of WP in R4 are assumed to be 70% higher than the other wind farms, due to difficult accessibility [49]. Investing in PV in the Faroe Islands has proven to be relatively expensive. The capital costs in this study are based on the existing 250 kW PV plant with a learning rate, O&M costs and LT based on [8], [48]. All costs for tidal energy are based on input from the manufracturer of the committed tidal generators in R1. The costs

TABLE 5. Costs Associated with the different investment options. The components of the PS system are: Pump (P), Turbine (T), Reservoir (R), Upper (U) and Lower (L). *EUR/kWh.

Tech.	Years	Capital (EUR/kW)	Fix. O&M (EUR/kW)	Var. O&M (EUR/MWh)	LT
WP	'20-'24	1045	26	7	20
	'25-'29	1004	26	7	20
	'30	963	26	6	25
PV	'20-'24	1400	8	0	25
	'25-'29	1210	7	0	25
	'30	1110	7	0	30
TP	'20-'24	2063	28	26	20
	'25-'30	1192	18	11	20
PS - P	'20-'30	220	50	0	60
PS - U.T.	'20-'30	266	50	0	60
PS - L.T.	'20-'30	591	50	0	60
PS - U.R.	'20-'30	14*	0	0	60
PS - L.R.	'20-'30	5*	0	0	60
BS	'20-'30	296*	2	0	15

TABLE 6. Estimated investment costs of transmission cables.

Connection	Cost/capacity [EUR/MW]	Connection	Cost/capacity [EUR/MW]
R1-R2	145 455	R1-R5	87 273
R2-R3	65 455	R3-R4	61 818
R3-R5	127 273	R4-R5	189 091
R5-R6	105 455	R6-R7	1 867 000

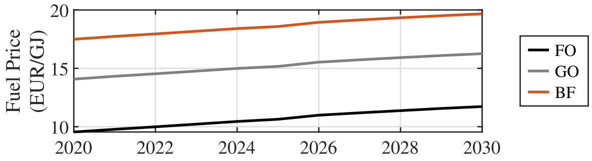

FIGURE 5. The assumed fuel price for FO, GO and BF.

of pumped storage systems are based on previous studies [8], [9]. The battery capital costs for a 0.25C battery are based on input from Tesla, which refers to Bloomberg New Energy Finance, and using a LT from the Danish Technology Catalogue [48]. The mentioned costs can be found in Table 5. The cost of onshore transmission cables has been estimated internally to 160 EUR/m, and the capacity of the cables used is 44 MW which leads to costs between 61.818 EUR/MW and 145.455 EUR/MW depending on the connection. The potential subsea cable between R6 and R7 is estimated to 1.867.000 EUR/MW. Cable costs are found in Table 6.

The fuel prices for FO and GO are based on Danish prices [50] with add-on costs for transport and taxes [8]. BF costs are assumptions due to lack of better data. Fig. 5 contains the fuel prices.

III. RESULTS AND DISCUSSION

The following sections will present the results of the economic optimisation described in the previous chapter. First the results of the scenarios (Table 2) are presented with focus on the main scenario. There are significant differences between the scenarios, except from scenario 5, which is close to identical to the main scenario and thus, not included in the figures and tables. The results from the sensitivity analysis are also presented, followed by the proposed RoadMap based on the optimal results. The execution time of running all scenarios simultaneously through the Balmorel algorithm was 2 hours and 5 minutes using a Hewlett Packard Enterprise x64 equipped with Intel Xeon CPU E5-2667 v4 @ 3.20GHz 3.20GHz (2 processors) and 192 GB RAM.

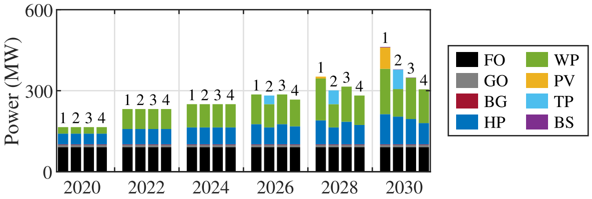

FIGURE 6. Optimal generation capacities (MW) every other year from 2020 to 2030 in four scenarios. The scenario number is shown above the bars.

TABLE 7. The optimal generation capacities in 2030.

	FO	GO	BG	HP	WP	PV	TP	BS	Total
1	91	8	2	112	168	79	-	2	462
2	91	8	2	103	102	-	72	1	379
3	91	8	2	94	153	-	-	1	349
4	91	8	2	79	125	-	-	-	305

A. GENERATION CAPACITIES

The economically optimal generation capacities every other year from 2020 to 2030, based on four of the scenarios (Table 2) are shown in Fig. 6, and the final capacities are tabulated in Tabel 7. As previous studies have suggested, the optimal solution in the main scenario includes significant amounts of WP complemented with PV and PS. The generation capacity of the PS system is included in HP. A small battery capacity is also a part of the optimal solution. This BS is placed in R7, and is used to balance this remote region. It is expected that a significantly higher BS capacity is needed for grid stability, but this will be addressed in another publication. Although they are initially similar, the scenarios give rise to significant differences in power composition by 2030. If TP will reflect the assumptions, it could reduce the total generation capacity by 84 MW. PV is no longer a part of the optimal solution, there is a significant decrease of WP, while HP and the BS capacities are also slightly decreased. This shows that the feasibility of TP could have a significant impact on the future energy mixture. The 3rd scenario, where it is possible to burn BF at a FO plant, shows that burning BF with the assumed fuel costs is a better solution financially than installing PV plants. There is also a significant decrease in WP compared to scenario 1. The total capacity is also reduced by 113 MW. The large reduction is due to BF being a dispatchable technology. Finally, the unrestricted CO_2 scenario shows that investing in WP and PS systems

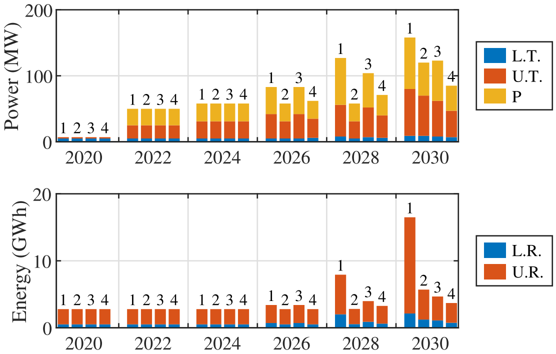

FIGURE 7. **Optimal capacities of the lower turbine (L.T.), upper turbine (U.T.), pumping capacity (P), lower reservoir (L.R.) and upper reservoir (U.R.) in the PS system in R1 every other year from 2020 to 2030.**

is more profitable than thermal generation up to a certain point. From 2026 and forward the capacities in scenario 4 start to differ from scenario 1. This shows that the final renewable percentages do not earn back the investment, given the assumed development in oil prices. What this scenario also shows is that PV power is not economically feasible in the Faroe Islands under the given assumptions. The fact that PV complements WP and HP seasonally is however important in order to reach 100% renewables, as the alternative is increased storages, which are expensive. Based on these results, the best strategy is to aim for 100% (main scenario) while being open to significant adaptations in the later half of the RoadMap time span, especially with regards to the development of TP and the cost of BF.

B. PUMPED STORAGE SYSTEM

Storage is vital in order to reach 100% renewables. The optimal pumping, generation and storage capacities of the proposed pumped storage system in R1 are shown in Fig. 7. These results show that it is feasible to invest in both pumping and more generation capacity in 2022, but that there is no need to increase the storage capacity until 2026. A 100% renewable production, where neither TP nor BF are an option, does require a significant increase in reservoir capacity. Investing in storage capacity is part of the optimal solution in all scenarios, but the variations are large, especially between the main scenario and other scenarios. These results, similarly to the previously presented results, show the importance of ongoing evaluations of expansion plans, as the feasibility of technologies can change over time and this can have a major impact on the optimal expansions. The demand increase should also be monitored, as the large investments in scenario 1 do not occur until 2028 and these increases might not be necessary if the demand does not increase as assumed. Increasing the storages to the level of scenario 1 in 2030 would require significant increase in dam sizes above populated areas, which could lead to public resistance due to the environmental impact, but these investments are necessary in order to reach 100% renewables with the presented assumptions and currently available technologies.

TABLE 8. **The optimal transmission capacities (MW) between the regions were reinforcements and new connections are required.**

Year	’21	’22	’23	’24	’25	’26	’27	’28	’29	’30
R1-R5	35	35	35	35	35	35	35	35	35	38
R5-R6	10	12	46	46	46	46	51	63	63	63
R6-R7	2	2	3	4	4	6	6	7	8	13

C. TRANSMISSION CAPACITIES

New transmission cables and reinforcements are required in order to transmit the power from production to consumption. A new connection is needed between R6 and R7, while reinforcements are required between R1-R5 and R5-R6. Table 8 shows the investments required based on the main scenario. This shows that the committed R5-R6 connection of 44 MW will not meet the future requirements. R1-R5 connection needs to be reinforced in 2030, and that is likely due to the PS system being located in R1, while the majority of the consumption is in R5. The R6-R7 capacity increases slowly from 2021 and forward, but in 2030 the capacity increases from 8 MW to 13 MW, in order to reach 100% renewables in R7. All scenarios showed similar results in terms of transmission capacity.

D. PRODUCTION

The main focus of this study is expansion planning, but Balmorel also optimises the hourly production. Fig. 8 shows the optimal annual production in the four presented scenarios, which are almost identical until 2026. In scenario 1, 3 and 4 WP is dominating the production, while in scenario 2 TP is a large part of the generation. This is caused by the restriction that TP can not be curtailed while WP can; thus, the curtailment of WP in scenario 2 is high. BF produces a small part of the energy in scenario 3, which means that the energy composition is not changed significantly even though the power composition is, and this is due to the technology being dispatchable. It is noteworthy how tidal takes on a role similar to base production and how BF seems like an obvious candidate for backup power in less energetic years. The production in scenario 4 is up to 87% renewable in certain years, but in 2030, when the demand has increased more, the financially optimal renewables shares have decreased to 86%. There are small variations between the total production of the scenarios. This is due to the transmission losses which differ, depending on the location and capacity of the different generation and storage units. It should be noted that HP shows the netto production, i.e. pumping, has been subtracted and therefore the shares of hydro power are low.

E. ECONOMICS

The annual optimised capital costs, O&M costs and fuel costs for every other year are shown in Fig. 9 together with the

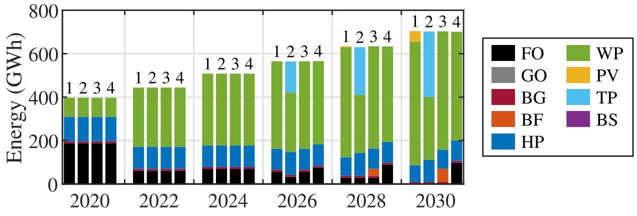

FIGURE 8. **Production in the four scenarios every other year from 2020 to 2030.**

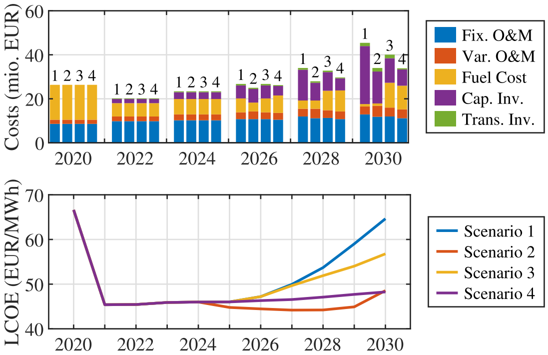

FIGURE 9. **Annualised costs of the optimal solutions every other year from 2020 to 2030 in the four scenarios.**

levelised cost of energy (LCOE), i.e. annual costs from the optimisation (upper plot) divided by annual energy production (Fig. 8). The figure does not include the annual capital costs of committed or existing capacity. This figure shows that out of all the scenarios, the most expensive scenario is the main scenario where a 100% renewable production is required and it is not possible to invest in TP, nor is it possible to burn BF at existing FO plants. The difference between scenarios 1/2 and 3/4 are the increased capital costs and decreased fuel costs. This shows that even with higher fuel costs for biofuel, it would still be more feasible than the main scenario. Scenario 2 is shown to be cheaper than scenario 4 until 2030, when it is slightly more expensive. However, the sum of the annual costs from 2020 to 2030 in the four scenarios are 311, 278, 301 and 285 mio. EUR respectively. This means that over the range of 10 years, a 100% sustainable power system with the assumed costs of TP is more feasible than a power system without restrictions on the CO_2 emissions, where it is not possible to invest in TP. The LCOE decreases from 2020 to 2021, and this is due to the increased renewable production, i.e. decreased fuel costs. Although the LCOE of the main scenario is significantly higher than the other scenarios, it is still lower in 2030 with a 100% renewable power system than in 2020.

F. SENSITIVITY ANALYSIS OF GENERATION CAPACITIES

The sensitivity analysis did not show any significant differences in the generation capacities. The generation capacities of hydro, wind, PV and battery in 2030 for every sensitivity scenario and the main scenario are shown in Table 9. The capacites of batteries and the pumped storage system are close to constant for all the scenarios. The wind power capacity is also quite constant but varies between 149 MW and 189 MW, so although wind is by far the cheapest renewable source, by 2030 it has obtained close to a saturation level where added production is out of sync with local consumption. This finding is interesting as it to some degree opposes recent political dogma. It states, that introducing a free local electrical market will not only generate new business opportunities, due to lower energy prices, but also help solve the nations transition to a 100% renewable electrical grid. If there is a clear saturation limit for the only existing economically viable renewable energy source (WP), any additional investments will not help the transition to a purely renewable electrical grid. The solar capacity is the only capacity that deviates significantly. The differences are especially visible if the PV or PS costs are decreased or increased, reflecting that the main challenge is power supply in the summer months with reduced wind power.

TABLE 9. **Generation capacities [MW] in 2030 in the main scenario and all the sensitivity analysis scenarios. c - 20% Cheaper, e - 20% more expensive, FU - Fuel, CA - Cable.**

	1	cBS	cCA	cFU	cPV	cPS	cWP	eBS	eCA	eFU	ePV	ePS	eWP
HP	112	112	112	112	112	112	112	112	112	112	112	111	113
WP	168	168	168	168	149	173	184	168	168	168	189	169	157
PV	79	80	79	79	149	31	53	79	79	79	20	119	101
BS	2	3	2	2	3	2	2	2	3	2	2	3	2

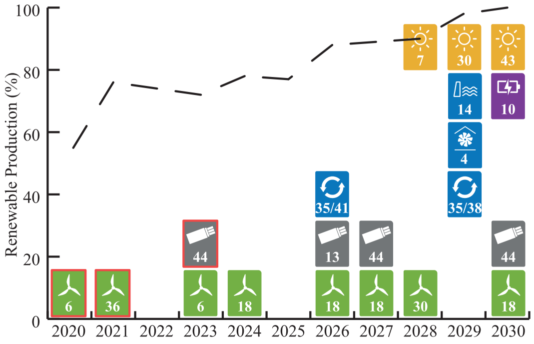

FIGURE 10. **The proposed RoadMap towards 2030, which has been made based on the optimisation results from Balmorel. All the values are given in MW, except for the reservoirs (GWh) and BS (MWh) in row 5 from the bottom.**

G. ROADMAP

Fig. 10 shows the proposed RoadMap, which is based on the main scenario. The RoadMap includes committed WP and cables (red border). The locations of the optimised investments are tabulated in Table 10. The location number indicates the region. In the case where multiple WP investment sites are in one region, the region number is followed by the site number, which has been numerated from the top and down (Fig. 3).

Most of the investments are conducted as 2030 comes closer. This is when the CO_2 restrictions will be hardened, and more investments will be needed in order to meet the

TABLE 10. **The location of the optimised investments presented in Fig. 10. *MWh **GWh.**

Year	Tech.	Power (MW)	Location
2023	WP	6	7
2024	WP	18	6.2
2026	WP	18	6.2
	CA	13	6-7
	PS - U.T./P	35/41	1
2027	WP	18	1
	CA	44	5-6
	BS	10*	
2028	WP	30	6.1
	PV	7	7
2029	PS - U.T./P	35/38	1
	PS - L.T.	4	1
	PS - U.R./L.R.	12/2**	1
	PV	22/8	4/7
2030	WP	18	5.2
	CA	44	1-5
	PV	39/3/1	4/6/7

requirements. All investments in onshore cables have been set to 44 MW, even though the needed capacity in some cases is significantly lower, but the onshore cables used in the Faroe Islands can transmit 44 MW. Comparing the proposed RoadMap to the previous simpler one [4], we see that the overall results are quite similar, even though several factors have been modified. The underlying reasons seem to be that the cheapest energy source (WP) reaches a saturation level of installed power over two times the average consumption in 2030 (75 MW), while the expensive but seasonally out of sync energy source (PV), must be able cover the average load on calm summer-days. There are some differences related to the pumped-storage configuration, but these seem to be driven by a trade-off between small storage with rapid response vs. larger storage with relative slower response. One important difference is also that this study aims at a renewable solution for an average year and not any year.

There is a need to validate the optimality the RoadMap, by rerunning Balmorel using the RoadMap as committed capacities. Fig. 10 includes the renewable shares of the production based on the RoadMap. According to simulation results it is possible to reach above 80% renewables already in 2021. Using the proposed RoadMap, it should be possible to reach 100% renewables by 2030. The second validation parameter was the cost of the system. The sum of the annual capital costs, fuel costs and fixed and variable O&M costs from 2020 to 2030 in the main scenario are 305 mio. EUR, while the RoadMap is 4% more expensive at 316 mio. EUR. The difference is caused by a higher fuel consumption, due to the investments in the RoadMap occuring slightly later than the optimal results. Based on the presented results, the proposed RoadMap is considered valid and applicable.

IV. CONCLUSION

This study has analysed the energy balance of the future Faroese power system using Balmorel. The study shows that the feasiblility of technologies has to be carefully considered, as development of e.g. TP and BF can impact the RoadMap significantly. Therefore constant revising and partial investments along the way could be the best approach when aiming for 100% renewables. This has been shown through different scenarios. The study has also shown that the presented results are not very sensitive to variations in the investment and fuel costs. A RoadMap towards reaching the goal of 100% renewable production in 2030 has been generated, based on a method developed for the purpose of achieving a realistic RoadMap from an economical optimisation. A method which is applicable to other, especially small and isolated, power systems. This RoadMap shows the exact location and capacity of added generation, storage, and transmission. The locations of new generation and storage plants have been carefully considered and constraints like available space and local renewable resources have been considered. These assure the realisability of the proposed investments. It is assured that the needed transmission system is capable of transmitting the power between the regions. Overall it can be said that investing in renewables is financially the best option up to 86%-87% renewable production shares depending on year, demand and power composition. The WP capacity should be 224% of the average demand, while PV should be 105% and a storage capacity of 8-9 days is needed in the pumped storage system. The development of the realistic RoadMap and the unveiling of the impact tidal energy has on the energy mix and the economics are the key findings in this study.

FUTURE WORKS

Balmorel has perfect foresight throughout a year, but no across years. This means that Balmorel knows which resource is available every hour throughout the year and can optimise the dispatch to a degree which is not possible in reality. The optimisation is unfamiliar with cost reductions or increases across the years, which means that the model can e.g. do a large investment in wind power in 2024, without knowing that the cost reduced significantly in 2025. In order to address this in Balmorel the algorithm has to be enhanced. Otherwise the power system must be analysed using other tools with different approaches, but with the same inputs, so that it is possible to see the influence this has on the expansion plan.

The presented RoadMap will be used in the expansion planning of the Faroese power system towards 100% renewables, and thus long term follow up studies will be conducted and the RoadMap will be reevaluated in case new technologies becomming feasible. Following this RoadMap, analyses of the dynamic behavoir of the power system in order to ensure a stable and reliable power supply are necessary. The following studies will focus on the system frequency- and voltage stability, and will be presented in other publications.

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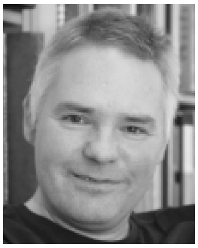

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