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Investigating alternative power supply solutions under long term uncertainty for offgrid-offshore fish farm: The case of Hinnøya island, Norway

Dejene Assefa Hagos, Yongping Liu, Lizhen Huang *

Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology (NTNU), Beryll-bygget, Teknologivn. 22, 2815 Gjøvik, Norway

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ABSTRACT

The aim of this paper is to explore potential least-cost decarbonisation solutions for an off-grid and offshore fish farm power supply system under long term uncertainty. The Hinnøya island in Norway is used as a use case. Three distinctive off-grid and grid-based alternative power supply solutions were proposed and studied as a replacement to the existing diesel power solution in a three-stage stochastic model and under two critical long-term uncertainties: (1) access to strong grid and (2) storage battery cost. The TIMES modelling framework is applied. The stochastic model results reveal that grid integrated storage is an optimal near-term investment for a storage battery cost of 295 €/kWh and less by 2025. In scenarios with no access to strong grid, grid integrated storage continues to be a least-cost solution in the long-term as well, whereas in those scenarios with strong grid access, new investment in storage is not required after 2030. Contrary to the stochastic model runs, the equivalent deterministic model runs showed that a hybrid wind and diesel solution is an optimal near-term investment. From 2030, however, a similar technology pattern in both stochastic and deterministic model runs are observed. Nevertheless, the results are very sensitive to the assumed storage battery costs. Higher storage costs (as high as 704 €/kWh by 2025) would make the hybrid wind and diesel solution an optimal solution instead of the grid integrated storage solution in near-term investment in both stochastic and deterministic model runs.

1. Introduction

The contribution of aquaculture production to global CO_2 emissions has significantly increased in between 2000 and 2020. The global salmon production reached more than 2.45 million metric tons in 2020 [1]. It has contributed for a 7.70 million tons of CO_2 emissions[1] in 2020 [2]. Norway is the leading producer of Atlantic salmon and accounts for more than 50% of the global salmon production in 2020 [1]. In Norway, currently almost all fish farms are operating offshore and approximately 50% of them are using grid power (95% is originating from hydropower) [3,4]. The remaining off-grid fish farms are operating on expensive diesel generators and are a source of CO_2- and air pollutant emissions. On average an offgrid and offshore fish farm in Norway consumes 60,000 L[2] of diesel fuel per annum (mainly for feeding) and emit 160 tons of CO_2.[3] The carbon footprint of salmon fish in grid connected fish farms in Norway is estimated to be in between 2.89 [5] and 3.39 kg/kg fish [6] at the producer's gate, while in the US the corresponding number is 7.01 kg/kg fish mainly due to the fossil fuel dominated electricity mix [6]. This implies that the carbon footprint of the salmon in diesel operated off-grid fish farms in Norway would be much more significant. In line with the enhanced climate goal of the Norwegian government to reduce GHG emissions by 50–55% in 2030 and 80–95% in 2050 compared to 1990 level [7], there is a growing political interest for deep decarbonisation of onshore- and offshore industries in Norway such as aquaculture, either using grid connection or standalone hybrid and full renewable power supply solutions.

* Corresponding author.
E-mail address: lizhen.huang@ntnu.no (L. Huang).

[1] Calculated based on the average carbon footprint of salmon production in Norway (3.14 kg CO2 equivalent/kg of fish).

[2] Diesel fuel is used to generate power that drives the feeding system (mainly compressor), cage monitoring equipment (video cameras, sensors, computers), cage lamp, indoor and outdoor lighting on the feed barge, appliances on the feed barge (ovens, fridge, freezers, boiler, coffee machine etc.). The diesel consumption data is based on personal communication with fish farm owners in Norway.

[3] The CO_2 emission factor of diesel assumed to be 2.66 kg/lit under complete combustion.

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Hybrid and fully renewable standalone power systems are widely used in island micro-grids and offshore industries. It helps to reduce energy costs, reduce/avoid GHG emissions, improve quality of energy service, and open a new market opportunity for power utility companies. Hybridisation of off grid standalone diesel power systems could reduce the average generation costs by 0.3–8% in private-sector financing terms and 12–16% if public sector funds the project [8]. In Ref. [9] a 25–30% reduced electricity selling price is achieved when the share of renewables in standalone hybrid power system reached 90% and higher. Nevertheless, at a high penetration level, variable renewable energy sources (VREs) could potentially impose grid stability and reliability issues particularly in a weak grid [10,11] and need to be complemented with relocation technologies such as storage battery. In Refs. [12,13], renewable energy integration and energy self-sufficiency in a geographical island vis-a-vis a weak mainland grid were investigated. The studies indicated that stationery storage as a relocation technology and hydrogen as an energy carrier play a key role towards the integration of solar energy. In Ref. [14], based on local renewable resources, alternative power, heating, and cooling energy supply to off grid mine is compared with conventional fuels. The results indicated that albeit it is technically feasible, cost wise it is not competitive with the existing standalone conventional energy supply system.

This study is part of the GIFT (Geographical island flexibility) project that aims to explore least-cost decarbonisation strategies and flexible alternative energy systems in European Islands [15]. Integration of high share of VREs and innovative energy technologies (such as storage technologies) in the existing energy system (power, heating and cooling, and transport) is at the core of the project. Hinnøya (including a small neighboring island called Grytøya) is a use case island in Norway within the GIFT project. The focus of this study is on off-grid fish farms located around the coast of Grytøya which could potentially be connected with the main grid of Hinnøya via Grytøya.

Hinnøya is located in the Northern part of Norway and is the largest island in Norway. The total number of inhabitants as of 2018 is estimated to be 25,141, and more than 80% live in Harstad city alone (the main city in Hinnøya). Electricity is the main energy commodity in the island covering more than 61% of the total energy supply while transport fossil fuel makes up 30%, non-transport fossil fuel 4%, and wood-based resources 5% [1]. Run-of-river hydro plants are the only local power sources with 18.35 MW installed capacity and 47–53% annual capacity factor. The island's power production and consumption were 77.63 GWh and 660 GWh in 2018, respectively. More than 88% of the electricity demand was imported from the mainland through the 700 MW grid connection with the Nordpool electricity market region NO4. Regarding Grytøya, there is no official data on the number of settlements in the Grytøya island but are estimated in hundreds. The total electricity demand was 7.5 GWh in 2018 and is entirely imported from the mainland through a 3–4 MW power transmission connection between Grytøya island and Harstad. Nevertheless, since the grid is too weak for new loads and the demand is too low to upgrade the grid, the distribution service operator (DSO) has a binding requirement that new grid users, such as fish farms, must install storage battery at their premises that could be used during peak demand periods.

In this study, potential alternative power supply solutions for three off-grid fish farms are investigated in the light of the long-term whole energy system development of Hinnøya and under long term uncertainty of key variables. These alternative solutions are: (1) off-grid hybrid onshore/offshore wind and diesel power, (2) off-grid hybrid onshore/offshore wind and storage battery, and (3) grid integrated night charging storage battery. The distinction between onshore and offshore wind turbine systems is merely on the assumed radial distance between the wind turbine and the fish farm feeding barge. It is assumed to be 200 m for the onshore- and 100 m for the offshore wind turbines. The storage battery is assumed to be installed on the feeding barge in all cases.

To the authors knowledge no study has attempted to investigate the deep decarbonisation of off grid fish farms, and aquaculture industry at large, under the long-term uncertainty of access to strong grid. The contribution of the paper is twofold: (1) it investigates potential least-cost decarbonisation pathways based on local resources, and (2) demonstrate the impact of short hedging to avoid short-term wrong investments.

The rest of the paper is structured into five sections: Section 2 presents the general methodology, the TIMES-Hinnøya model development and application, and discusses long term uncertainty modelling in the TIMES modelling framework. Section 3 presents scenarios design and formulations. Section 4 presents the results and discussion, followed by conclusions in section 5.

2. Methodology

The aim is to investigate least-cost alternative power supply solutions to fish farms while capturing the whole energy system dynamics and its long-term development. Thus, the application of a long-term optimisation model is essential and deemed appropriate. In this section the modeling framework, data and assumptions, and model development are presented.

2.1. The TIMES-HINNØYA model

The Integrated MARKAL-EFOM (Market Allocation Energy Flow Optimisation Model) System, abbreviated as TIMES, is a generic energy system model generator and optimisation tool developed and maintained by the Energy Technology System Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency (IEA) [16]. The schematic representation of the modeling framework is shown in Fig. 1. In TIMES all the main sectors of an energy system can be modelled including electricity, heat, and transport sectors. It is a perfect foresight, partial equilibrium linear programming, bottom-up, technology rich and demand driven optimisation model. The objective function minimises the total discounted system cost for the whole modelling period and maximises the social surplus of the system at different temporal time resolution. Therefore, TIMES is suitable for long-term energy planning, from primary energy extraction to final energy consumption, and to analyse the impact of energy and climate policies on technology mix, fuel mix, GHG emissions, and cost to energy systems. It has been applied to investigating, for example, the role of technology development to achieve global climate goals [17], modelling household and transport energy use behaviour and heterogeneity [18], and comparing decarbonising strategies in transportation system of many regions or countries such as China and USA [19].

The TIMES-HINNØYA model is developed in the framework of the GIFT project to explore use case specific problems. In the TIMES-HINNØYA model, the yearly timeslices are divided into seasonal (12 timeslices), weekly (2 timeslices), and daylight levels (24 timeslices); 576 timeslices in total. In the model the whole Hinnøya island is divided into three regions: (1) Harstad (the main city in the island), Grytøya, and Rest Hinnøya (all settlements other than Harstad and Grytøya). The higher time resolution aims to explore storage technologies and to avoid possible underestimation of the cost to storage in long-term planning model. The internal electricity trade between each region and across the market region (NO4) of Nordpool is also tracked at high time resolution (daynite level). The reference energy system (RES) is calibrated for the year 2015. The model horizon is in between 2015 and 2050. The model assumes a 6% general discount rate in all cases irrespective of technologies.

The RES comprises of power-, residential-, economic (primary, secondary, tertiary)-, and transportation sector. In the RES a total of 18.35 MW run-of-river (ROR) hydro plant installed capacity (3.95 MW in Harstad and 14.4 MW in remaining Hinnøya) is modelled with annual capacity factor of 53% and 47%, respectively. Based on [4] maximum cumulative new investments capacity in small-scale ROR hydropower plants is assumed to be 2.41 MW in Harstad and 16.34 MW in rest

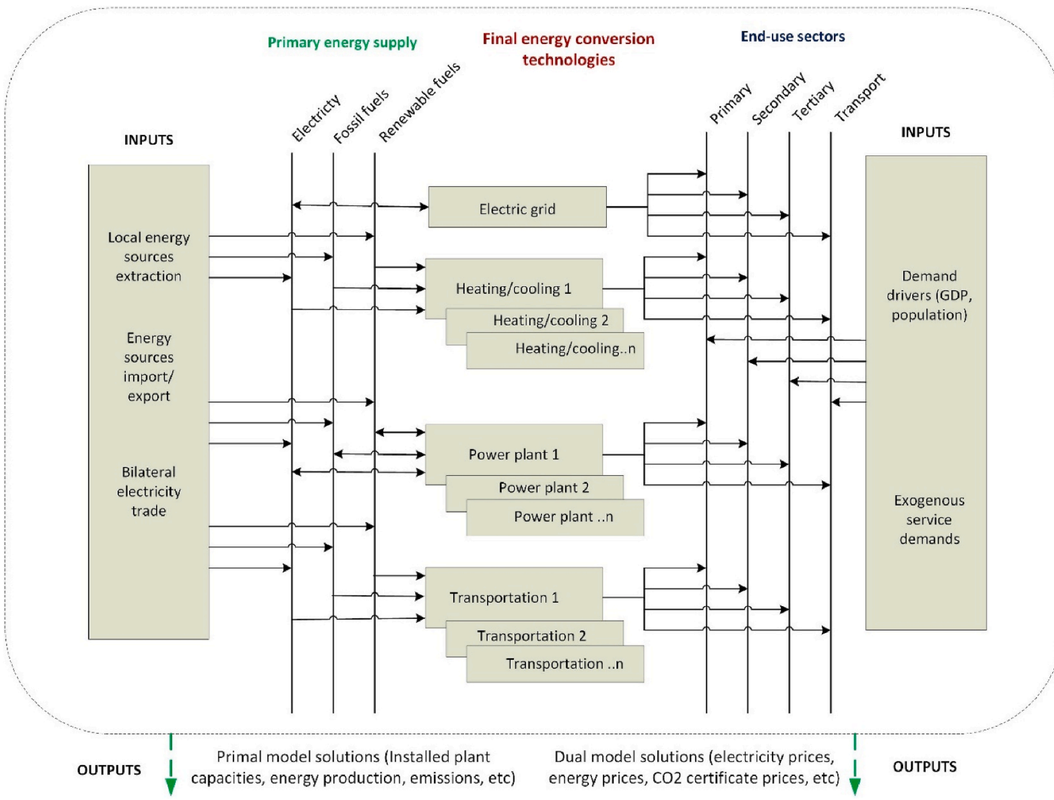

Fig. 1. Schematic representation of the TIMES modelling framework. The output arrows indicate the model run primal and dual solutions while the input arrows show the resource supply and the exogenous energy demand and/or demand driving input parameters used for demand projection within the model.

Hinnøya. It is assumed that the capacity credit of ROR plants is 30%.

In the current version of the model, end-use technologies in residential and industry sectors are not modelled but the electricity demand and its diurnal demand pattern are modelled as exogenous input parameters. Based on measured data in southern part of Norway [20] and assuming that the consumption pattern would be similar in the Northern part as well, the normalized aggregate diurnal electricity consumption profile of residential, primary (agriculture and forestry, fishing, and fish farming), secondary (industry and mining), and tertiary (service) economic sectors are used as exogenous input in TIMES-Hinnøya model.

The electricity trade between Hinnøya and Nordpool electricity market regions NO4 (Norway) and SE1 (Sweden) is modelled at high temporal resolution. Since market region NO4 is connected with neighboring market region SE1 (Sweden), Hinnøya will export when the electricity market price in SE1 is higher than NO4 and vice versa, if any. The import-export prices are calibrated based on the 2015 hourly prices data. The future electricity prices (electricity market region NO4) are based on [21]; 39 €/MWh in 2025, 36 €/MWh in 2030, and 42 €/MWh after 2040.

Assumed investment costs, operation and maintenance costs, service demands, and fuel prices are provided in the Appendix. Active policy instruments in Norway such as basic fuel tax and CO_2 tax are assumed to exist within the model horizon.

2.2. *Modelling alternative power solutions*

The schematic representation of the existing power solution (standalone diesel power) and alternative power solutions and their detailed descriptions are shown in Fig. 2 and Table 1. Three distinct alternative power supply solutions are considered for new investments: (1) off-grid hybrid onshore/offshore wind and diesel (ALT1), (2) off-grid hybrid onshore/offshore wind and storage battery (ALT2), (3) grid integrated night charging storage battery (ALT3). The distinction between onshore and offshore wind turbine systems is merely on the assumed radial distance between the wind turbine and the fish farm feeding barge. The storage battery pack is assumed to be modular and installed on the feed barge in all cases. Owing to the size of the fish farms' power demand, wind turbines are available for investments in discrete capacity as 50 kW, 100 kW, and 150 kW. Thus, it is a mixed integer model.

2.3. *Modelling long term uncertainties*

One of the limitations of deterministic optimisation models is that the assumption of full knowledge of future events. The analysis is usually based on a set of consistent distinct stories called scenarios, which provide a range of different outcomes. Future uncertainties of particular events are addressed using distinct sensitivity analysis [22]. Nevertheless, such an approach does not provide the likelihood of occurrence of the assumed events and the associated uncertainty costs. Also, it does not capture the interaction between the uncertain variables as it is tailored to a specific sensitivity case. To fill this gap, a multi-stage stochastic optimisation variant that enables to address a range of possibilities in a single model run was implemented in the standard TIMES modelling framework [23]. Few studies apply stochastic MARKAL (Predecessor of TIMES) to explore investments under uncertainty in carbon taxes [24], GHG emission reduction policies [25,26], future fuel prices and biomass availability [27], and air pollutant policies in the power sector in the USA [28]. In Ref. [29] comparison between stochastic and equivalent deterministic scenarios were made in stochastic MARKAL. It showed that a set of technologies were more competitive in the stochastic (hedging strategies) scenarios than the corresponding deterministic scenarios.

In this work, given the size of the fish farms' electric energy demand and possible future access to strong grid around Grytøya, the current binding storage battery requirement to connect with the weak grid might not remain enforced in future. Thus, to avoid wrong near-term

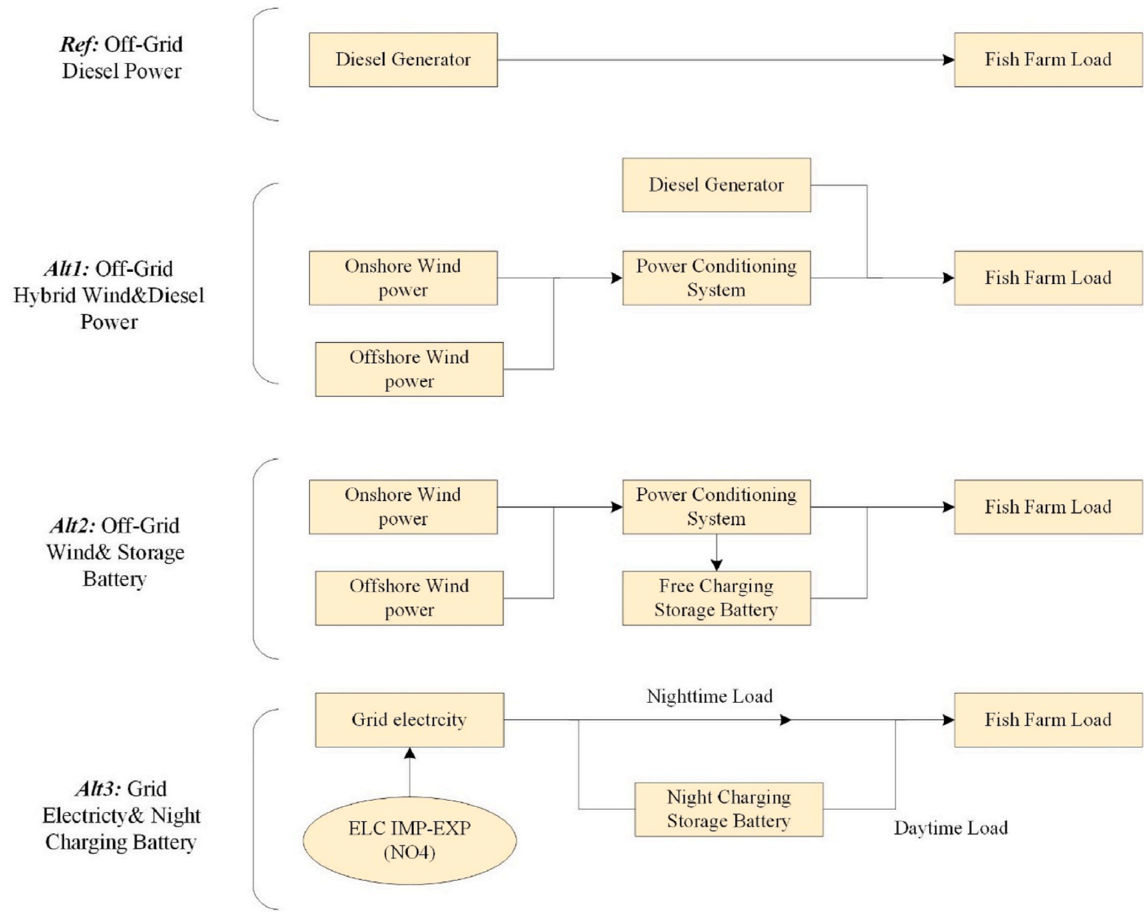

Fig. 2. Schematic representation of the existing diesel power (REF) system and alternative power supply systems' pathways.

investment decisions, the probable future events should be considered in our model. Also, the other key uncertain variable is the future storage battery cost development that might alter near term investments. The aim is thus to incorporate the long-term uncertainty of access to strong grid and storage battery cost development in a three-stage stochastic optimisation model and generate useful insights as to which alternative power supply solution is the least cost solution for fish farms. The stochastic TIMES variant has been applied to explore the robustness of near-term investments decisions for the aforementioned uncertainties. The model minimises the expected cost of the system (eq (1)) subjected to eqs (2) and (3)

$$COST_{STOCH} = MIN \sum_{t \in T} \sum_{s \in S(t)} C_{t,s} * X_{t,s} * p_{t,s} \tag{1}$$

$$\text{Subjected to: } A_{t,s} * X_{t,s} \geq b_{t,s}, \ \forall t \in T, \ \forall s \in S(t) \tag{2}$$

$$\sum_{t \in T} D_{t,s} * X_{t,s} \geq e_s \ \forall t \in T, \ \forall s \in S(t) \tag{3}$$

Where t is the time period, T is the set of all time period, s is state of world (SOW), S is the set of state of words at period t, $C_{t,s}$ is the cost row vector in period t, under state s, $X_{t,s}$ is the column vector of decision variables in period t, under state s, $p_{t,s}$ is the probability of s in period t, $A_{t,s}$ is the coefficient matrix of single period constraints in period t, under state s, $b_{t,s}$ is the right hand side column vector of single period constraints in period t, under state s, $D_{t,s}$ is the coefficient matrix of multi period constraints in period t, under state s, and e_s is the right hand side column vector of multi period constraints under state s.

The event tree is shown in Fig. 3. The chosen starting period of stage 2 is 2025. In the event tree, a scenario is represented by a pathway from the root node (2025) to a last leaf node (2050) and comprises of the probability of occurrence of the uncertain parameters revealed at stage 2 and stage 3. In stage 1 all the uncertainties are not revealed, and hence, the investment decisions are not affected by the uncertain parameters. In stage 2, when access to strong grid uncertainties are revealed, owing to the decisions in stage 1, the model will choose the least-cost strategies in each event tree. And, it will have a learning effect in the subsequent stage (stage3). In stage 3, owing to stage 1 and stage 2 investments, the model will then determine the investment level that corresponds to the least-cost strategy based on the total expected cost.

To keep the intractability of the model within the computational capability of a standard computer, the number of discrete values that the random variable assigned is limited to three. The probability of the random variable to occur is assigned equal weight. The assumption is based on the Laplace criterion of insufficient information.

It is worth valuing the cost of uncertainties in stochastic model. The expected value of perfect information (EVPI) is one of the useful metrics. It is calculated as the expected cost of stochastic model ($COST_{STOCH}$) minus the probability weighted expected cost of the equivalent deterministic model for the relevant scenario ($COST_{DETER}$).

$$EVPI = COST_{STOCH} - \ COST_{DETER} \tag{4}$$

$$\text{Where } COST_{DETER} = \sum_{k=1}^{n} p_k * COST_{PI}(k) \tag{5}$$

$COST_{PI}$ can easily be estimated by solving eq (1) with $p_{t,s} = 1$ for the relevant scenario k.

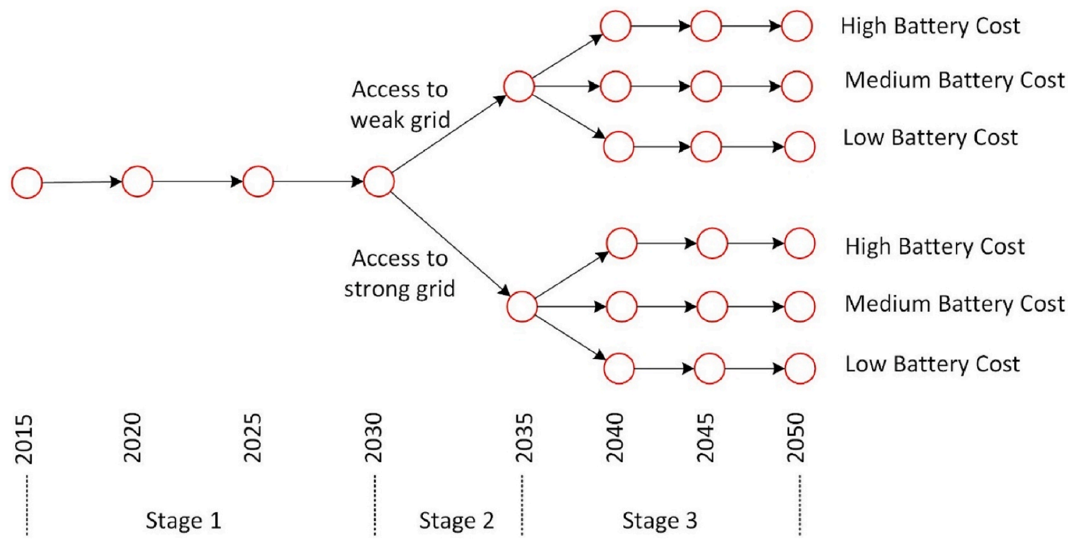

Fig. 3. Schematic representation of the event tree in stochastic TIMES. The node (red circle) indicates a state of the world or resolved uncertainty and the arrow indicate the long-term time step between uncertainty realization. The combination of nodes and arrows indicate a scenario; we have six distinct scenarios in total. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Scenario design and formulation

The aim is to explore a least-cost alternative power solution under access to strong grid- and storage battery cost uncertainty. The access to strong grid parameter is a proxy to non-binding use of storage battery. The notion is that if the future electricity demand in Grytøya is big enough to upgrade the current weak grid, fish farms would most likely be connected to the grid without a binding storage battery requirement like other grid connected fish farms in Norway. Also, future storage battery specific investment cost development is the other identified key variable as shown in Table 2. Technology learning rate, cumulative installed capacity growth, and on-going research and development activities are expected to reduce the cost of storage battery, but the rate of reduction would remain uncertain. In this study we have assumed low-, medium-, and high storage battery costs as shown in Table 2.

The electricity demand growth is highly dependent on the fish demand growth, population growth, and economic growth. Preliminary model runs showed that high-, medium-, and low demand growth rate have similar technology mix profile and development. Thus, for demonstration purpose, we have chosen the medium demand growth rate based on [30,31] as shown in Table 3.tbl4[4] The total demand represents the sum of three similar fish farms' demand around the coast of Grytøya and each with a 60,000 L annual diesel consumption.

The stochastic scenarios are a replica of their corresponding deterministic scenarios except the fact that the access to grid and storage battery costs are stochastic variables. Thus, in total we have six deterministic scenarios and six corresponding stochastic scenarios as shown in Table 4.

In addition to the global uncertainty regarding the future market development of stationer storage battery in general there exist a great deal of disparity between various sources in the literature and local supplier's data. Thus, as a sensitivity case, it is of interest to consider a higher storage battery cost than the base assumptions (see Table 3) as shown in Table 5.

Table 1
Existing and alternative power supply systems with their corresponding description.

Power supply system	Abbreviation	Description
Existing	REF	It represents a standalone off-grid diesel power supply system.
Alternative system	ALT1	It represents a standalone hybrid onshore/offshore wind and diesel power supply system. The average distance between the fish farms and the onshore wind turbines is assumed to be 200 m while for offshore wind turbines a closer distance of 100 m is assumed.
	ALT2	It represents a standalone hybrid onshore/offshore wind turbine and storage battery power supply system. The storage battery could be charged and discharged at any instant following the load imbalance. The assumed onshore/offshore wind turbine distances are similar with ALT1.
	ALT3	It represents a grid integrated storage battery (sealed lithium-ion battery) power supply system. The storage is assumed to be charged during low electricity demand periods (or more specifically during nighttime) and discharges when the demand is high (during daytime). The average distance between the fish farms and the grid is assumed to be 200 m.

Table 2
Storage battery system specific investment cost scenarios (€2018/kWh) [32].

Investment cost	2020	2025	2030	2035	2040	2045	2050
Low	272	182	128	116	103	91	78
Medium	329	243	185	174	162	150	139
High	341	295	261	244	228	212	195

Table 3
Fish farm electric energy demand scenarios (TJ) [33,34].

Service demand	2020	2025	2030	2035	2040	2045	2050
Electric energy	2.28	2.53	2.81	3.11	3.46	3.83	4.25

[4] Owing to the global market share of China and its five-year socio-economic development action plan in fisheries and aquaculture sector, FAO has developed three scenarios (2%, 2.1% and 2.2% annual growth rate) for the global fish production and trade in between 2018 and 2027. We have assumed the 2.1% growth to reflect a medium electric energy demand growth by further stretching the time duration to 2050 with the same annual growth rate.

Table 4
Assumed scenarios and associated description.

Model	Scenario name	Scenario description
Deterministic	D_WG_HBAT	This scenario assumes binding storage requirement (access to weak grid) and high storage battery cost in a perfect foresight strategy.
	D_WG_MBAT	This scenario assumes binding storage requirement (access to weak grid) and medium storage battery cost in a perfect foresight strategy.
	D_WG_LBAT	This scenario assumes binding storage requirement (access to weak grid) and low storage battery cost in a perfect foresight strategy.
	D_SG_HBAT	This scenario assumes no binding storage requirement (access to strong grid) and high storage battery cost in a perfect foresight strategy.
	D_SG_MBAT	This scenario assumes no binding storage requirement (access to strong grid) and medium storage battery cost in a perfect foresight strategy.
	D_SG_LBAT	This scenario assumes no binding storage requirement (access to strong grid) and low storage battery cost in a perfect foresight strategy.
Stochastic	S_WG_HBAT	This scenario assumes no binding storage requirement (access to weak grid) and high storage battery cost in a hedging strategy.
	S_WG_MBAT	This scenario assumes no binding storage requirement (access to weak grid) and medium storage battery cost in a hedging strategy.
	S_WG_LBAT	This scenario assumes no binding storage requirement (access to weak grid) and low storage battery cost in a hedging strategy.
	S_SG_HBAT	This scenario assumes no binding storage requirement (access to strong grid) and high storage battery cost in a hedging strategy.
	S_SG_MBAT	This scenario assumes no binding storage requirement (access to strong grid) and medium storage battery cost in a hedging strategy.
	S_SG_LBAT	This scenario assumes no binding storage requirement (access to strong grid) and low storage battery cost in a hedging strategy.

Note: In all scenarios, the grid's maximum contribution to supply demand during peak demand hours is assumed to be 25% (75% from storage battery).

Table 5
Sensitivity case assumptions of storage battery system specific investment cost (€2018/kWh) [33,34].

Investment cost	2020	2025	2030	2035	2040	2045	2050
Low	880	704	528	430.5	333	275	217
Medium	1120	896	672	548	424	352	280
High	1829	1463	1097	894	691	570	449

4. Results and discussion

In this section, the results are presented and discussed in the light of the applied assumptions. Sensitivity case results are also presented. Emphasis is given to the electricity mix development and new investments prior to uncertainty resolution periods. As introduced in section 2.3, the alternative power solutions will be referred to as ALT1, ALT2, and ALT3 and the existing power solution as REF.

4.1. Electricity supply mix development

Fig. 4 and Fig. 5 present the electricity supply mix by energy commodity (left axis) and installed power capacity (right axis) in between 2015 and 2050 in S_WG_HBAT and S_SG_HBAT scenarios and their corresponding equivalent deterministic scenarios D_WG_HBAT and D_SG_HBAT, respectively. The importance of addressing long-term uncertainty is to minimises the adverse consequence of short-term investment decisions in the future energy system development; due to their long-term lock-in effect that arise from path dependences and longer lifetime of energy technologies. This has been captured in the results. The stochastic model run is able to make an optimal short-term investment that anticipates the future opportunities (access to strong grid by 2030). The deterministic model runs lack such flexibility due to the perfect foresight assumption. This results in short-term investment difference between the two model runs as seen in Figs. 4, Figure 5, and Fig. 6.

In terms of power solution, ALT3 (Grid integrated storage solution) is a least-cost solution invested as early as 2025 in the stochastic scenarios while ALT1 (hybrid wind and diesel solution) is invested in the corresponding deterministic scenarios. Furthermore, the ALT3 solution completely substitutes the existing REF solution throughout the model horizon in all stochastic scenarios. This is mainly due to the high competitiveness of ALT3 solution over ALT1 and ALT2 solutions already by 2025 under low-, medium-, and high storage battery cost cases.

It is worth mentioning that, in ALT3 solution, the assumed maximum contribution of the grid to load at any time is limited to 25%. Due to this assumption, in all scenarios where ALT3 is invested, storage accounts for 56% of the total annual energy supply of ALT3 while the grid covers the remaining 44%. This is due to the matching of storage discharging periods and peak demand periods of the fish farms, specifically in between 07:00 a.m. and 17:00 p.m. (see Figure A1 in Appendix section). The required storage capacity would thus be largely determined by its assumed role on the grid stabilization or peak load shaving during peak demand periods. The higher the grid contribution during peak demand periods, the lower would be the required storage size and hence cost to storage.

In the deterministic scenarios (D_WG_HBAT, D_WG_MBAT, and D_WG_LBAT) as opposed to the stochastic scenarios, ALT1 solution is the optimal short-term investment. The fact that ALT1 starts to replace the REF solution as early as 2025 and grid electricity replaces the role of the diesel in integrating wind energy after 2030 indicates that the cost savings and CO_2 emissions reductions are substantial. For example, the share of renewable energy (wind energy) is 78% in 2025 and more than 83% CO_2 emissions reduction is achieved by 2025 compared to the 2015 level. Nevertheless, the actual capacity factor of the wind turbines is lower than the assumed maximum capacity factor (32%). It is in between 14 and 21%. Owing to the assumed 32% capacity factor in the coast of Grytøya, the remaining 11–18% is curtailed to avoid system disturbance; it shows that it is not economical to invest in storage to utilise the curtailed energy. Wind energy curtailment in off grid power solutions could potentially be avoided using load shifting or demand response mechanisms [35–37]. In this study, the total demand represents the aggregate hourly demand of three similar fish farms. If more offgrid fish farms are connected in cluster, it could potentially levelise the aggregate load profile and reduce energy curtailment.

Fig. 5 present the electricity supply mix by energy commodity (left axis) and installed power capacity (right axis) in between 2015 and 2050 in S_SG_HBAT scenario and its equivalent deterministic D_SG_HBAT scenario. The remaining scenarios (S_SG_MBAT, D_SG_MBAT, S_SG_LBAT, and D_SG_LBAT) show similar technology mix development as the S_SG_HBAT and D_SG_HBAT scenarios and hence only thereof are presented and discussed here.

In S_SG_HBAT (see Fig. 5) scenario, ALT3 solution is serving as a transition technology as ALT1 does in all deterministic scenarios. Given the perfect information regarding the availability of access to strong grid in the recourse stage (after 2030), no new investment is made in storage after the residual storage capacity is null in 2040.

Comparing all the stochastic scenarios in Figs. 4 and 5, the technology choice merit order is found to be direct grid electricity, integrated grid and storage battery (ALT3), hybrid wind and diesel (ALT1), and standalone diesel power (REF). As such ALT3 is a robust solution that have similar technology mix in both deterministic and stochastic scenarios in the hedging stage (before 2030).

The results are in par with prior studies that have looked into off grid and offshore fish farm decarbonisation solutions such as in Ref. [38]

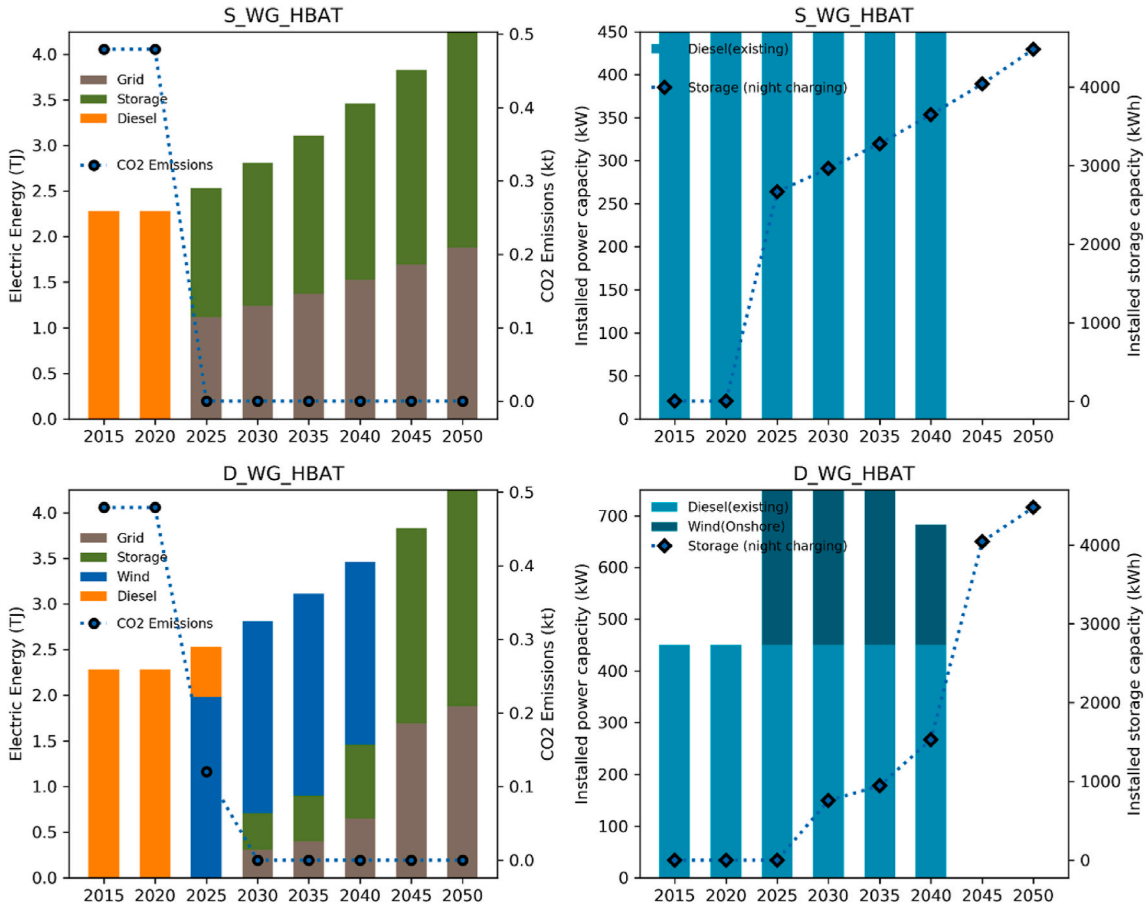

Fig. 4. Electricity mix development (left side) and installed electric capacity development (right side) in S_WG_HBAT and S_SG_HBAT scenarios. CO_2 emissions (kt) and storage capacity (kWh) are shown by broken lines (right axis).

where wind, diesel, and solar PV hybrid solution is a least cost solution. Nevertheless, the authors did not consider the possibility to connect with the grid. In Ref. [39], without considering grid connection possibilities, the study showed that a diesel-solar hybrid offgrid solution reduces the energy costs by 70% compared to a standalone diesel power solution. In our case solar PV is not included due to the low solar irradiation potential in Northern Norway as well as the extended winter period. Not only the capacity factor would be lower but also the maintenance costs would be significant due to accumulated snow and ice. In Ref. [40] the levelised cost of energy of a grid connected diesel-solar-biomass gasifier hybrid system is found to be lower than that of an off grid standalone hybrid system. This is due to the market opportunity that allow the system to interact with the gird and optimise its system cost through import-export. Nevertheless, its economic advantage is case specific and dependent on the size of the demand and the grid extension distance. On the other hand, in off grid areas with both electricity and thermal loads, hybrid wind-solar-combined heating and power (CHP) offgrid solution is more appealing [41]. Few studies [42] have underestimated the integration cost of wind and solar in a hybrid system claiming that exclusive hybrid solar-wind system is feasible. They have followed a static life cycle cost evaluation approach that overlook the dynamics of the hybrid system, and hence, excludes the reserve electric capacity requirement such as diesel power. This could be substantiated by the results in Ref. [43] where a 40% share of renewable energy reduced the cost to energy by only 8% compared to diesel power. This is attributed to the lower system capacity utilization of the wind-solar-wave hybrid system because of the supply and demand dynamics of the energy system.

4.2. System cost

The system cost reflects the cost of providing energy services to fish farms. It is worth mentioning that the relative system cost across alternative scenarios and the REF scenario is of high relevance than the absolute system cost. Accordingly, the system cost saving of the stochastic scenarios is estimated to be 2.38 M€, whereas in deterministic scenarios it is estimated to be in between 2.47 and 2,69 M€. The lower system cost saving of the stochastic scenarios is due to the uncertainty cost.

Table 6 shows the system cost and EVPI for the relevant scenarios. The system cost remains the same across D_SG_HBAT, D_SG_MBAT, and D_SG_LBAT scenarios due to the technology mix similarity while it shows small variations across D_WG_HBAT, D_WG_MBAT, and D_WG_LBAT scenarios mainly due the assumed storage battery cost differences.

The value of perfect information (EVPI) in relation to access to strong grid and storage battery cost uncertainties is estimated to be 0.22 M€. The relatively lower value is due to the alternative power solutions' flexibility. In all strong grid stochastic scenarios, the system avoids new investments in storage in the recourse stage and shift to grid electricity instead, whereas in all deterministic scenarios the installed wind power is fully utilised in the recourse stage until its residual capacity is null.

4.3. Sensitivity analysis

Fig. 6 presents the electricity supply mix by energy commodity (left axis) and installed power capacity (right axis) in between 2015 and 2050 for the sensitivity case S_WG_HBAT and S_SG_HBAT scenarios. The sensitivity case results show no difference between the stochastic and

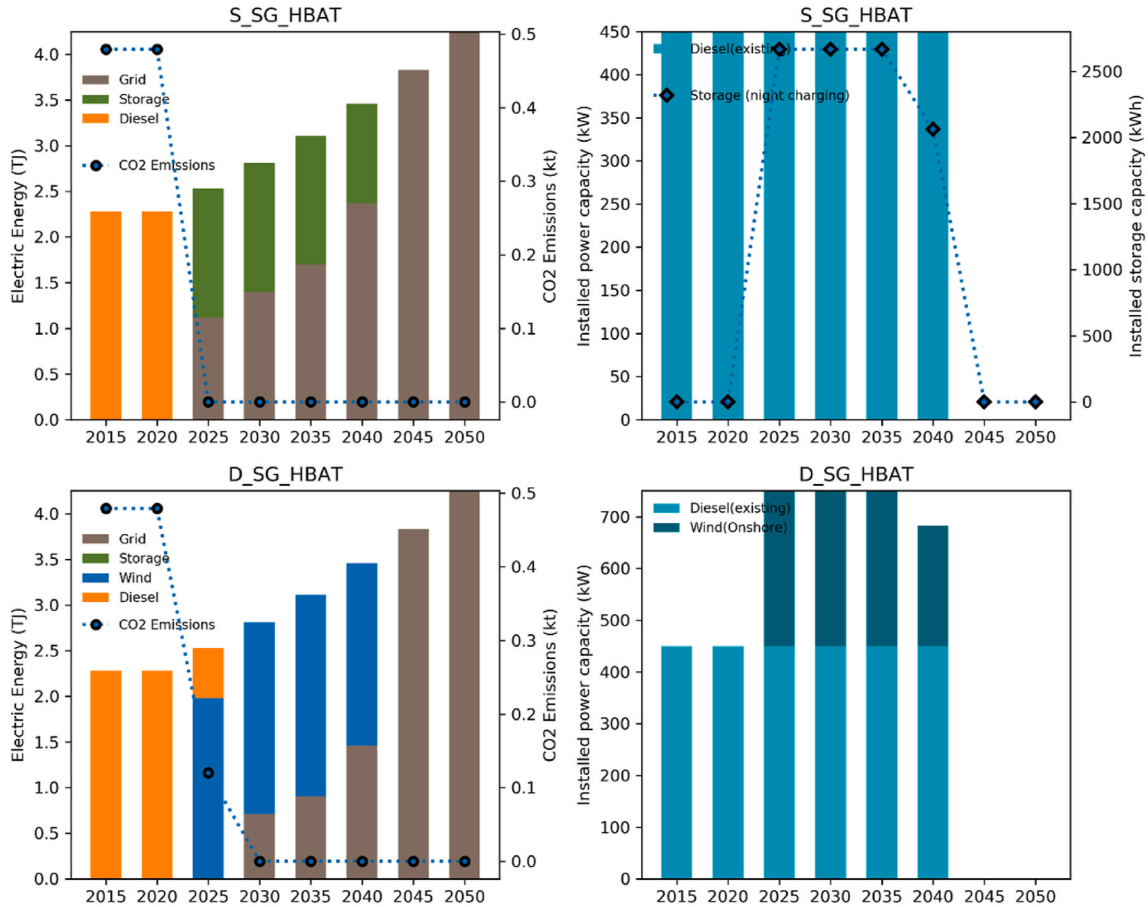

Fig. 5. Electricity mix development (left side) and Installed electric capacity development (right side) in S_SG_HBAT and D_SG_HBAT scenarios. CO_2 emissions (kt) and storage capacity (kWh) is shown by broken lines (right axis).

deterministic model runs. Thus, only the stochastic scenarios are presented here.

As seen in Fig. 6, the assumed higher storage costs make the ALT3 solution uncompetitive and fully replaced by ALT1 solution. This is contrary to the base case assumptions results (see Fig. 4) where ALT3 solution is invested instead. The existing installed standalone diesel power solution is effectively used by ALT1 until after 2040 where new investment is needed afterwards. The share of renewable energy share (wind energy) increases from 78% to 91% in between 2025 and 2050. The rest is covered by diesel. Nevertheless, the actual capacity factor of the wind turbines is lower than the assumed maximum capacity factor (32%). It is in between 14 and 21%. Owing to the assumed 32% capacity factor in the coast of Grytøya, the remaining 11–18% is curtailed to avoid system disturbance; it shows that it is not economical to invest in storage to utilise the curtailed energy.

In S_SG_HBAT (see Fig. 6) scenario, as opposed to the base case results (where ALT3 solution is invested), hybrid wind and diesel solution (ALT1) is the optimal short-term investment. From 2030, however, the grid electricity replaced the role of the diesel until the residual wind capacity is null in 2040 and fully replaced the ALT1 solution afterwards. This is due to the assumed high storage battery cost and the availability of access to strong (without a binding storage requirement). ALT3 is not competitive in any of the scenarios with access to strong grid.

In S_WG_MBAT (see Fig. 7) scenario, however, the storage battery cost reduction by 2045 is adequate for ALT3 to partly replace ALT1. Storage accounts for 26–30% of the total annual energy supply in between 2045 and 2050, while in the low storage cost scenarios (S_WG_LBAT), the share increases to 43–47% in the same period. This is due to the assumed lower storage cost. Also, as opposed to S_WG_MBAT scenario, no new investment in wind power is made after 2040 in S_SG_HBAT and S_SG_MBAT scenarios. This effectively put the off-grid wind power as a “transition technology” in this specific case.

In [44] the author showed that for off grid fish farms far from the coastline, the alternative renewable energy systems are costly than the hybrid diesel and storage battery system. In Ref. [45] the hybrid diesel and storage battery system has shown a better overall system efficiency than a standalone diesel generator system. The author suggested that connecting to the grid is the least-cost solution, but it should be located very close to the coastline. However, both studies [44,45] could have benefited from whole system perspective analysis instead of technology specific analysis. Also, it does not include short- and long-term uncertainties of key techno-economic parameters.

In this study only lithium-ion storage battery were considered to balance the demand and reduce the peak load burden on the grid. It is of interest to consider different types of storage technologies such as hydrogen storage and examine their role for offgrid-offshore fish farms and deep decarbonisation of the offshore industry at large [46]. In a small and distribute energy system, battery storage showed lower system cost than hydrogen storage [47]. Nevertheless, exploring economies of scale and potential synergies in whole energy system perspective is key for a realistic investigation of its competitiveness. This is because hydrogen storage has a great potential to buffer variable renewable energy peaks and levelise the high upfront costs in general [47]. The role of renewable-based hydrogen fuel cell in a hybrid energy system explored extensively [48]. Relocation technologies such as storage are key for the integration of variable renewable energy sources into the whole energy system via smart grid and/or smart energy system concepts [49,50].

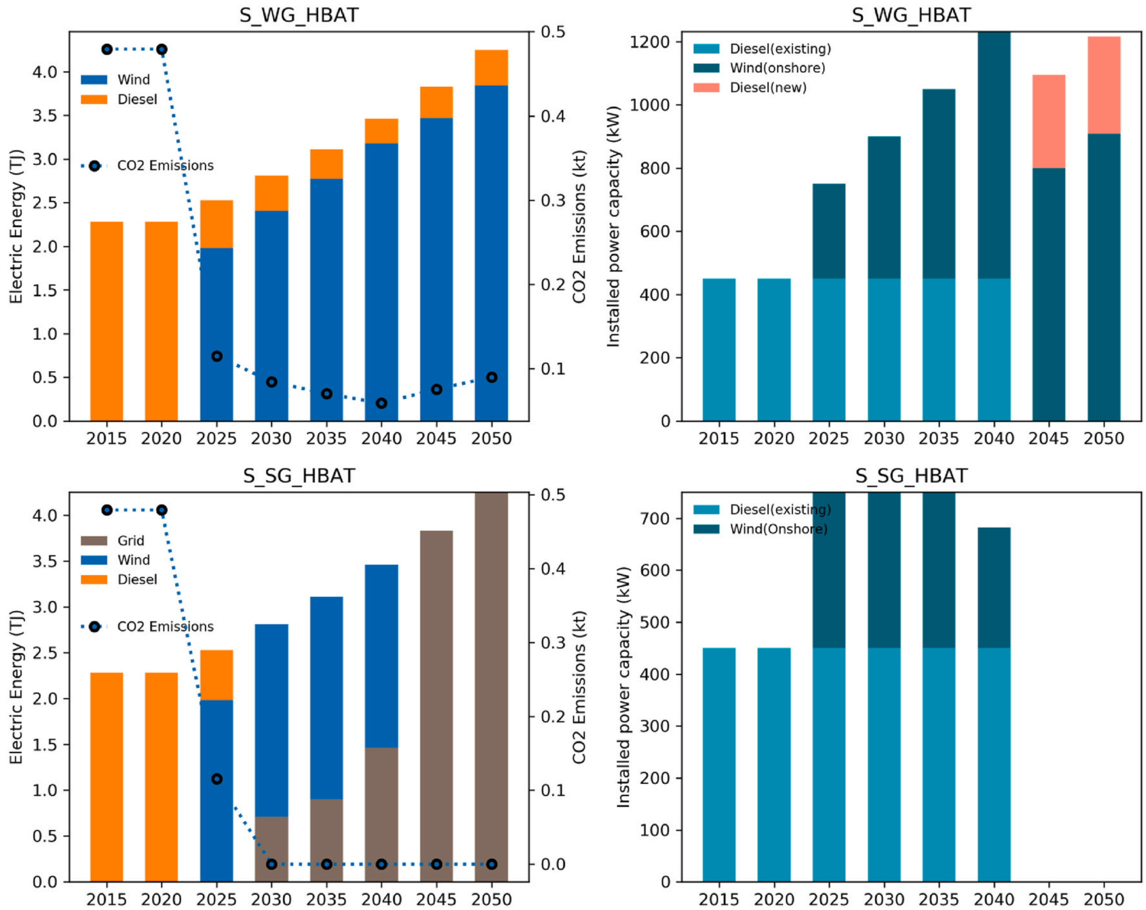

Fig. 6. Sensitivity case results. Electricity mix development (left side) and Installed electric capacity development (right side) in S_WG_HBAT and S_SG_HBAT scenarios of the sensitivity case. CO_2 emissions (kt) and storage capacity (kWh) is shown by broken lines (right axis).

Table 6
System cost and EVPI of the assumed scenarios.

Scenario	Reference scenario (M€2018)					
System cost	1439.72					
Scenario	Deterministic scenario (M€2018)					
	D_WG_HBAT	D_WG_MBAT	D_WG_LBAT	D_SG_HBAT	D_SG_MBAT	D_SG_LBAT
System cost	1437.25	1437.23	1437.20	1437.03	1437.03	1437.03
Scenario	Stochastic scenario (M€2018)					
	S_WG_HBAT	S_WG_MBAT	S_WG_LBAT	S_SG_HBAT	S_SG_MBAT	S_SG_LBAT
System cost	1437.34					
EVPI	0.22					

Prior studies that focused on the decarbonisation of off grid mine showed that hydrogen is an important energy commodity for both decarbonisation and integration of variable renewable energy sources such as solar and wind [12,14]. The fish farm could be benefited from similar studies that incorporate hydrogen technologies. The studies indicated that at the current market prices alternative renewable energy solutions in off grid fish farms are not competitive with conventional diesel generator. Thus, policy instruments that promote energy efficiency and adoption of unmatured renewable energy technologies (such as fuel cell) is key for the long-term decarbonisation of off grid fish farms and the aquaculture industry in general. Owing to the high variability of the fish farm diurnal electricity demand and matching in peak demand periods with the main land grid, off grid solutions are more attractive solutions to avoid grid congestions.

5. Conclusions

Decarbonisation of offgrid and offshore fish farms, or aquaculture at large, in weak grid areas in Norway requires a deployment of either standalone offgrid alternative power solutions or grid integrated storage battery. Nevertheless, short term investments under access to weak grid might have bad consequence (due to path dependencies) if access to strong grid is realized in the mid future. Also, the future storage battery cost development is highly uncertain. Implying that, in the short-term, fish farm owners should make investment decisions under future access to strong grid and storage battery cost uncertainties. In this study the long-term implications of alternative power solutions are explored under the aforementioned uncertainties in three stage stochastic model.

The study revealed that grid integrated storage is an optimal near-term investment for a storage battery cost of 295 €/kWh and less by 2025. In scenarios with no access to strong grid, grid integrated storage continues to be a least-cost solution in the long-term as well, whereas in

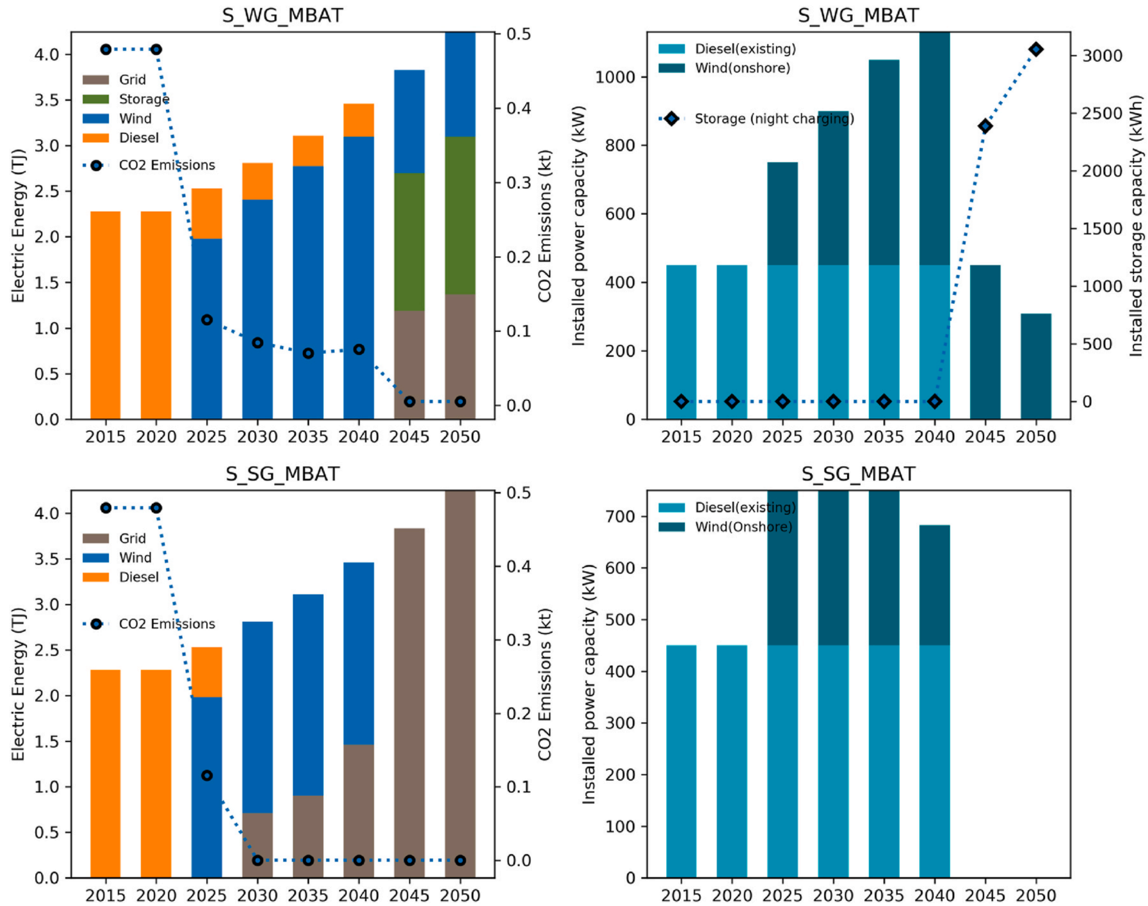

Fig. 7. Sensitivity case results. Electricity mix development (left side) and installed electric capacity development (right side) in S_WG_MBAT and S_SG_MBAT scenarios of the sensitivity case. CO_2 emissions (kt) and storage capacity (kWh) is shown by broken lines (right axis). S_WG_LBAT and S_SG_LBAT scenarios show identical results as S_WG_MBAT and S_SG_MBAT scenarios, and hence, no need to present them separately.

those scenarios with strong grid access, new investment in storage is not required after 2030. Nevertheless, as opposed to the stochastic model runs, the equivalent deterministic model runs showed that a hybrid wind and diesel solution is an optimal near-term investment. In the recourse stage (after 2030), a similar technology pattern in both stochastic and deterministic model runs are observed.

Also, the storage battery cost sensitivity case results showed that a higher storage cost (as high as 704 €/kWh by 2025) would make the hybrid wind and diesel solution an optimal solution instead of the grid integrated storage solution in near-term investment in both stochastic and deterministic model runs. It is worth mentioning that there exists a high disparity both in the current market price and future development of industrial scale stationery storage battery as indicated in Ref. [51] and the results should be interpreted with this in mind.

The alternative power solutions demonstrated up to a 100% CO_2 emissions reduction and system cost savings compared to the current standalone diesel power solution. The system cost savings are estimated to be 2.38 M€ in the stochastic scenarios and in between 2.47 and 2,69 M€ in the deterministic scenarios.

In this study the major assumptions regarding future developments of investment costs of alternative power solutions and fuel prices are highly uncertain. It should thus be noted that significant change in these costs as well as the assumed load profiles will have a considerable impact on the results. In future work it is of interest to consider solar PV in addition to wind power, albeit low solar radiation availability and extended winter period in most part of the country. Also, electro fuels and non-electric based renewable fuels such as second-generation bio-fuels were not part of the study. It is worth including them in future work.

The recurring uncertainty of hourly electric energy demand[5] might compromise the security of energy supply to fish farms and underestimate the cost of decarbonisation if not satisfactorily captured in long term planning model. Also, uncertain diurnal demand means uncertain peak capacity requirement that in turn determines the role of the storage in supplying peak load. This has not been considered in this study due to the absence historic data. Thus, it is of relevance to incorporate the recurring uncertainty of demand in two stage stochastic optimisation model and generate useful insights as to which alternative power solution is the least cost solution for fish farms in future work. The same argument is valid for studying the variability of wind energy production as in Ref. [52].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[5] Hourly electricity demand is driven by several uncertain factors related to fish feeding such as fish appetite, fish size, and weather condition.

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Appendix

Table A1
Techno-economic data of power plants in 2015 price level

Technology	Efficiency/Capacity factor (%)	Investment cost (M€/MW)			Fixed OM cost (1000€/MW/year)	Variable cost (€/MWh)	Technical life time (year)	Reference
	2020/2030/2050	2020	2030	2050	2020/2030/2050	2020/2030/2050		
Diesel generator	33	0.71	0.71	0.71	161,356	15	25	[53]
Onshore wind turbine	32	1.46/1.17/1.03	1.38/1.11/0.97	1.3/1.04/0.92	14/12.6/11.34	1.5/1.35/1.22	20	[54]
Offshore wind turbine (near-shore)	43	2.01/1.61/1.42	1.95/1.57/1.37	1.91/1.53/1.35	36/34.25/32.54	2.67/2.67/2.3	20	
Run of river hydro	47–53	1.25	1.25	1.25	–	6.84	40	[53]

Note: Specific investment costs of onshore and offshore wind turbines are given for each discrete capacity in the order of 50 kW, 100 kW, 150 kW capacity.

Table A2
Techno-economic data of storage battery system in 2019 price level [33,34].

Technology	Efficiency (%)	Investment cost (€/kWh)	Variable cost (€/MWh)	Technical life time (year)	Reference
	2020/2030/2050	2020/2030/2050	2020/2030/2050	2020/2030/2050	
Li-ion storage battery system	95	1120/672/280	2/1.8/1.6	20/25/30	[33,55]
Battery installtion cost in existing barge	20,000€ per barge				Personal communication with AKVAGROUP
Grid connection cost	59,000 € per barge				

Table A3
Electricity and diesel fuel costs.

Parameter	Attribute	Value (2018 price level)
Electricity	Electricity price	39 €/MWh (2025), 36 €/MWh (2030), 42 €/MWh (2040) [21]
	Transmission &Distribution	18 €/MWh [56]
	Tax	15.4 €/MWh
Diesel costs & taxes	Diesel (port price)	0.43€/L (2020), 0.51€/L(2030), 0.57€/L(2040),0.67€/L(2050) [57,58]
	Diesel distribution	7 €/100 L
	Basic tax	16 €/100 L [59]
	CO_2 tax	4 €/100 L [59]

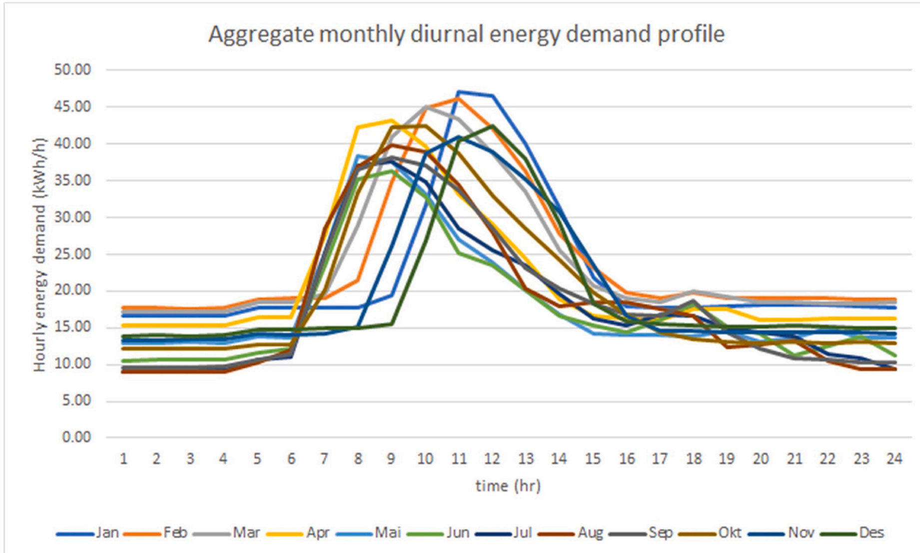

Fig. A1. Monthly hourly average electric energy demand of fish farms.

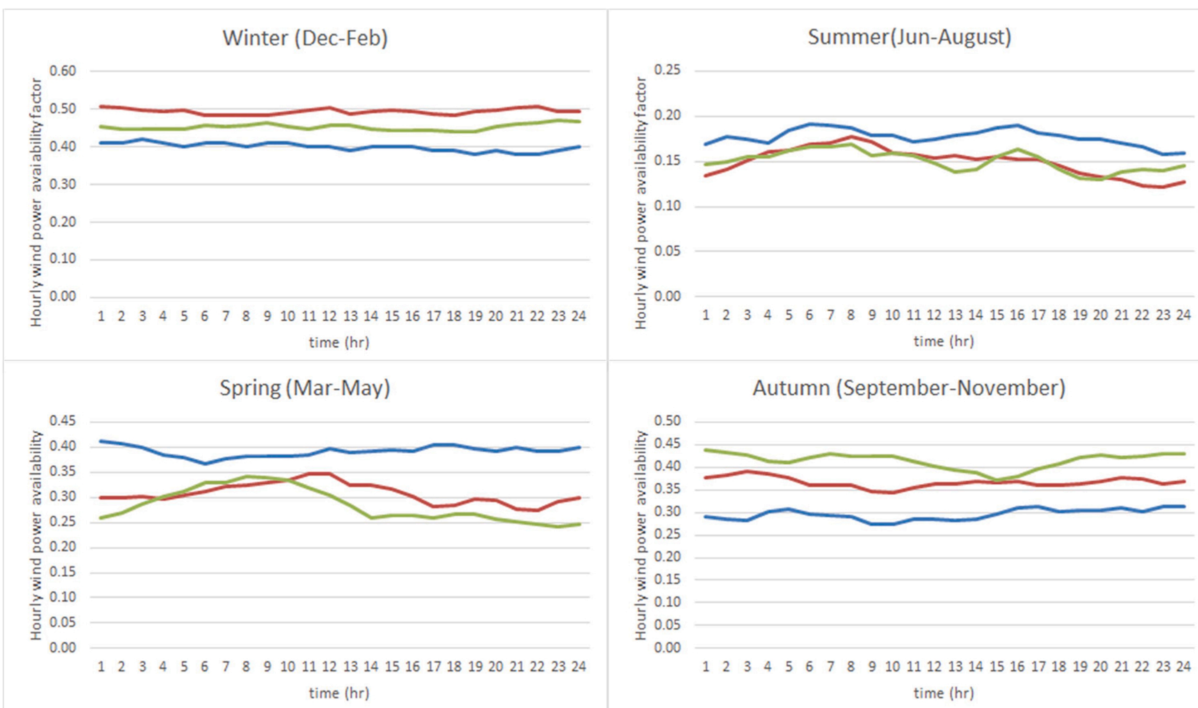

Fig. A2. Monthly hourly average wind power availability (2007–2018) of the closest wind farm to Hinnøya (Nygårdsfjellet Wind Farm) [60].

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