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Energy supply security in remote areas

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The current geopolitical situation has demonstrated the importance of the islands in the Arctic ocean. For many of these islands secure energy supply is demanding since connecting to the mainland electrical grid is not feasible. From an environmental perspective there are also initiatives to increase the use of renewable energy sources. For some locations the production of electricity has been based on coal and a transition takes places where diesel is the main energy source and initiatives are made to a further transition into wind and or solar energy sources.

A major challenge with solar- and wind-based plants is the need for energy storage for these variable power sources. Both use of hydrogen and batteries have been considered. The paper presents a quantitative energy supply security analysis framework for remote areas. Several simplified case studies are provided, and in particular the paper focuses on the modelling of variable energy sources relying on energy storage systems like hydrogen or batteries where the storage capacity proves to be a major challenge since during the winter there are periods where the wind is hardly blowing

Keywords: Energy supply security, Remote areas, Zero emission energy sources, Wind and solar.

1. Introduction

1.1. *Background*

Greenland, The Faroe Islands, Iceland, Jan Mayen, and Greenland are all islands in the Arctic Ocean and are facing challenges in order to secure energy supply. The challenges are similar to all remote areas where it is not possible to connect to the mainland electricity grid. Many of the Arctic Ocean islands are searching solutions where the aim is two-folded, i.e., increase the energy supply security and introduce more renewable energy sources.

1.2. *Objectives*

The main objective of this paper is to analyse the energy supply security at Svalbard for different configurations combining wind, battery, and diesel solution. Obviously, other configurations could also be considered, e.g., combining wind and solar power and/or replacing the battery solution with hydrogen or ammonia for energy storage. A solution without the use of diesel is considered unrealistic, since variable energy sources cannot guaranty adequate energy over long periods without wind and sun. To achieve the main objective a set of sub objectives have been defined:

(i) Analyse wind data to calculate realistic energy production from the wind farm.
(ii) Develop a discrete event simulation model to simulate the dynamic of wind power generation, battery storage and redraw, and the need for electricity production from the diesel generators.
(iii) Calculate total energy supply security taking rare events into account such as delay in diesel replenishment from the mainland in period with no wind power production.
(iv) Establish a cost model for evaluation of vari-

ous configurations.

1.3. *Limitations*

The analysis is based on rough estimates of failure rates for main components in the energy system. Further wind data from the Longyarbyen airport is used as a baseline, and the extrapolation to higher mean sea level is based on standard models not taking local terrain effects into account. Further replenishment of strategies of diesel from the mainland is classified information so only some sensitivity analyses have been conducted. Battery capacity is very expensive. Cost of battery capacity is based on public information and no extrapolation based on significant expected drop of such cost are not included. Also note that numerical results are "shifted" to avoid revealing the actual vulnerability.

2. Energy production model

Electrical power can be added to the grid from three sources:

(i) Production from the wind farm
(ii) Draw power from the battery
(iii) Production from the diesel generators

2.1. *Wind speed model*

Wind speed data used is based on measured values at Svalbard Airport weather station (station SN99840 Yr.no (2026)) from 01.01.2021 until 01.01.2026 (Seklima (2026)). The weather station measures wind at 28 metres above sea level (MSL). The temporal resolution of the measurements are in hours and is used consistently throughout the modelling process. It is assumed that wind turbines are not placed at ground level or in valleys, but rather at elevated locations where wind conditions are more representative and losses due to local terrain effects are reduced. Since wind speed measurements are only available at a limited height above ground, wind speeds are extrapolated to turbine hub height using the wind gradient model. To estimate wind speeds at hub height, the wind profile power law is applied:

$$v_w(h) = v_0 \cdot \left(\frac{h}{h_0}\right)^a \tag{1}$$

where $v_w(h)$ is the velocity of the wind [m/s], at height h, v_0 is the velocity of the wind [m/s], at height h_0 and a is the Hellman exponent.

The Hellman exponent depends on the terrain shape, the coastal location, and the air stability. A turbulent (neutral) atmospheric flow is assumed, corresponding to a Hellman exponent of $\frac{1}{7}$.

2.2. *Wind energy effect model*

The analysis focuses on how the number of installed wind turbines and the size of battery storage system affect the total system costs. Environmental, social, and ecological impacts, such as as effects on wildlife and landscape aesthetics, are outside the scope of this work. The study is therefore limited to the power generation and techno-economic performance of the system.

To limit model complexity and ensure consistent comparison between different system configurations, a common used land-based wind turbine is selected as the reference. This turbine is selected due to its documented suitability for cold-climate operation. A slightly larger turbine model from the same manufacturer is currently in operation at the Havøygavlen wind farm (Finnmarkkraft, 2026; NVE, 2026a), which is the northernmost wind farm in the world. This provides a relevant reference for operational reliability under Arctic and sub-arctic conditions.

All economic calculations in this study are based on a project lifetime of 20 years, corresponding to typical economic lifetimes used for energy infrastructure in Norway. Cost assumptions and discounting parameters are primarily based on data from the NVE publication NVE (2015).

Location, hub height and wind adjustment

Wind speed data is measured at Svalbard Lufthavn at 28 m MSL and must be extrapolated to the turbine hub height using a wind profile model.

Because the assumed turbine location in the model is around the same location as the wind speed data was gathered at around 28 m MSL, the effective height becomes $h \approx 144.5\,\mathrm{m}$ when the hub height is set as 116.5 m. Using Eq. (1) this gives a wind speed scaling of

Table 1. Datasheet of Vestas V117 - 3.450MW wind turbine (Vestas, 2025)

Technical data	Details
Number of blades	3
Nominal power	3450 kW
Rotor diameter	117 m
Wind class swept area	10751
Rated wind speed	12.5 m/s
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Assumed life time	25 years

approximately $\left(\frac{144,5}{28}\right)^{\frac{1}{7}} \approx 1.26$.

This implies that a wind speed measured at 20 m/s at 28 m becomes $\tilde{2}5$ m/s at 144.5 m, which is at the top of the wind turbine cut-out, and could therefore result in zero production during such events. A key modelling sensitivity is therefore whether the wind farm should be placed at very high elevation or at a more accessible height, as the height adjustment can shift the wind distribution above the cut-out speed as mentioned above. Placing the wind turbines at higher elevation enables the use of lower measured wind speeds to increase power generation on low wind days. This comes at the cost of production on days with higher measured wind speed.

The power curve in Fig. 1 is used to convert wind speed to power. The cut-off wind speed is 25 m/s. Wake effects are not considered in this study.

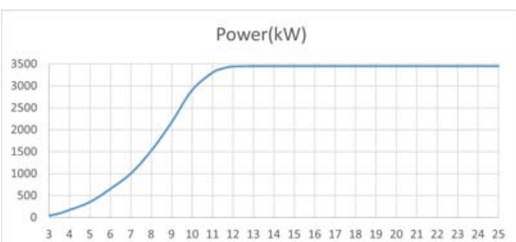

Fig. 1. Power output curve (Vestas, 2025)

2.3. *Wind turbine reliability data*

As a baseline for wind turbine reliability, the Reliawind database gives an overall failure of approximately, Reliawind (2011):

$$\lambda_{WT} \approx 1.9 \text{ failures/turbine/year}$$

with mean downtime (MDT) varying strongly by subsystem failure rates and MDTs, and the total unavailability contribution is reported as 1.90%.

This is a bit optimistic and the ReliaWind summary itself notes that other studies indicate roughly 30% higher total failure rate.

In an Arctic logistics context (Svalbard), the MDT can also be substantially higher than ReliaWind averages due to limited access of maintenance personnel, weather windows, availability of spare parts and specialists, meaning the unavailability U can increase even if the failure rate λ stays similar.

A central finding for energy supply security is that some components behave as single points of failure at system level. While one wind turbine failure reduces production marginally, a failure in the power export path can disconnect many turbines at the same time.

ReliaWind provides transformer figures at assembly level (within the Power Module) with transformer failure rate $\lambda_{\mathrm{Tr}} \approx 0.033$ per year and $\mathrm{MDT} \approx 94$ hours. Even if this is not the highest failure rate component, its system consequence is high if it is shared, e.g., one main step-up transformer for the wind farm. For an island grid like Longyearbyen, that is critical: it increases dependence on diesel backup, reduces renewable share, and can cause shortage if backup is constrained.

ReliaWind vs Chinese wind farm data

From Chinese wind farm data (76 multi-MW turbines, $\tilde{1}.44$ million operating hours) it is reported a higher overall failure rate $\lambda_{\mathrm{WT}} \approx 2.57$ failures/turbine/year. Here it is indicated that the subsystems Cooling & Hydraulics and Electrical Facilities have the highest failure rates and variation compared to the data from ReliaWind.

The two data sets shows vastly different failure rate values for the same component subsystems, but there are significant differences between the location and operation of the two. The Chinese turbines are reported as less than three years old and still in their warranty period, meaning that

Table 2. Comparison of subsystems with the most variation between the ReliaWind report and the Chinese Wind Farms

Source	Subsystem	Failure rate
ReliaWind	Cooling system	0.0059
Chinese Wind Farms	Cooling system	0.8085
ReliaWind	Hydraulics	0.0227
Chinese Wind Farms	Hydraulics	0.8431

early life/infant mortality can show bias failure patterns. The Chinese dataset also defines failure broadly, including stoppage events, alarms, harmful states and predetermined periodic replacements. This can inflate the counted failure rate compared to databases that count major stoppages. The last cause is related to location and environmental effects. The Chinese study explicitly observed that wind farms in mountains/deserts show different failure rates than flatland, and highlights external conditions such as sand and temperature differences as contributors to the increased failure rates. When it comes to Svalbard, neither dataset is perfect, but Svalbard is an extreme environment with access constraints, extreme weather and temperature, icing, and storms. A practical approach is therefore to use ReliaWind as a baseline and apply an additional location factor as well as increased MDT times to represent Arctic conditions, then use the Chinese dataset to justify why subsystems like cooling and hydraulics can dominate the failure rate and drive the maintenance planning.

The Chinese dataset explicitly notes that preventive maintenance every six months is suitable based on the observed failure rate behaviour with an 18 month inflexion point. By using the effective failure rate approximation in the Weibull model, i.e., $\lambda_{\mathrm{E}}(\tau) \propto \tau^{\alpha-1}$ where τ is maintenance interval and α is the ageing parameter, we can calculate the effective MTTF as a function of τ.

Downtimes are assumed to be log-normal. We distinguish between preventive maintenance, PM, and corrective maintenance/repair (CM). Also we distinguish between minor and major activities. μ and σ are mean value and standard deviation respectively.

Table 3. Wind turbine reliability data

Quantity	Value
Maintenance interval	Average 3 Times per year
MTTF	3928 Hours
Ageing parameter, α	3
Minor PM (90%)	$\mu = 1.5$, $\sigma = 0.3$: $\approx$ 2-6 hours.
Major PM (90%)	$\mu = 3.8$, $\sigma = 0.4$: $\approx$ 25-70 hours
Minor CM (25%)	$\mu = 1.5$, $\sigma = 0.4$: $\approx$ 3-7 hours
Major CM (70%)	$\mu = 3.8$, $\sigma = 0.4$: $\approx$ 25-70 Hours

2.4. *Diesel Generators*

In this paper, an energy solution consisting of wind turbines, battery and diesel generators are investigated. The diesel generators functions as the base of the energy production. If there is a period of no wind, and the battery state of charge equals zero, the energy production will rely a 100% on power generated from the diesel generators. The simulation model uses a diesel generator setup based on the current configuration in Longyearbyen. This means that the diesel generator setup used in the simulation model, is engineered to fulfil the current energy demand. By adding wind turbines as an additional source of energy production, the energy production capacity exceeds the current energy demand. The margin by which the energy demand exceeds is relative to the number of wind turbines installed. The technical data for the diesel generator setup is given in Table 4. Reliability data is based on data from Longyearbyen Lokalstyret and Svalbard Energi.

The simulation model uses the diesel generator setup in Table 4. The diesel generators are simulated to fail, be maintained, and be repaired. The simulation incorporates a preventive maintenance policy based on the current maintenance policy. Maintenance is scheduled every 500 hours of continuous operation. The diesel generator failure rate is assumed to follow a Weibull distribution. Repair times are assumed to follow a log-normal distribution. The simulation uses the same maintenance policy and assumed failure/repair rate for

Table 4. Diesel generators technical data

Technical Data	Main Diesel Generator	Backup
Quantity	3	3
Power Capacity	2.00 MW	1.75 MW
Speed Type	High Speed	High Speed
Diesel Cost	10 NOK/Liter	10 NOK/Liter
Lifetime	30 Years	30 Years
Discount Rate	5 %	5 %
Relegation Rate	0.5 %	0.5 %

both types of diesel generators (main and backup). Table 5 reliability data used.

Table 5. Diesel generators reliability data

Quantity	Value
Maintenance Interval	Every 500 operating hours
MTTF	5000 hours
Ageing parameter	2
Minor PM (90%)	$\mu = 0.9$, $\sigma = 0.4$: $\approx$ 1-4 hours
Major PM (90%)	$\mu = 3.8$, $\sigma = 0.4$: $\approx$ 25-70 hours
Minor CM (25%)	$\mu = 1.5$, $\sigma = 0.3$: $\approx$ 2-6 hours
Major CM (70%)	$\mu = 3.8$, $\sigma = 0.4$: $\approx$ 25-70 hours

Diesel is stored in a diesel tank with an assumed capacity of 2 million litres. A supply chain model simulates the delivery of diesel from Tromsø port to Longyearbyen port, using M/S Norbjørn as a container ship vessel. The container ship is assumed to have an average lead time of 10 days. The diesel inventory model follows a standard re-order point, quantity model ($r - Q$ model). A conservative re-order point strategy is set to $r = 2/3$ of the diesel storage capacity. With Q set to $Q = 1/3$ of the diesel storage capacity. Sensitivity analysis on r is conducted in this study.

Extreme weather are being simulated to test the limits of the model. As the current setup of diesel generators are simulated, the grid demand will be met by diesel generators, even in the case if no wind power is produced and empty batteries. Extreme weathers is simulated to investigate the risk of a complete blackout. Especially if a critical component of the supply chain is out of order, therefore, the main container ship M/S Norbjørn is not available during extreme weathers. During extreme weather, constant high wind speeds may lead to Svalbard become unreachable by sea. In such cases, the inhabitants must rely on local power sources. In this simulation, this includes any potential wind power, charged battery power, or power that may be generated by the diesel in storage. Consistent low winds are also of interest, as this significantly impacts the wind turbine's capacity to produce power. A longer period of low winds in combination with extreme cold temperatures, may freeze the port so that delivery of supplies are halted. The simulation model simulates extreme weathers by the setup given in Table 6. It is twice more likely that an extreme weather occurs during winter. The wind speed is given a stochastic nature by incorporating a Weibull distribution, with unstable, semi-stable and stable shape parameters. The container ship being out-of-order for an extended period of time, is unlikely but not impossible. M/S Norbjørn was out of commission for a total of 6 weeks until 28th of January 2026 (Díaz and Mikalsen, 2026).

Table 6. Simulated extreme weather setup

Quantity	Value
$P_{\mathrm{EW,Summer}}$	1/365
$P_{\mathrm{EW,Winter}}$	2/365
Low mean wind speed	0.8 - 4.0 m/s
High mean wind speed	18.0 - 22.0 m/s
Summer max duration	21 days
Winter max duration	42 days
Weibull Distributed Stability	
Unstable	1.75
Semi-stable	2.5
Stable	3.25

2.5. *Battery*

The current energy production setup includes a battery-park. The current battery has an effect of 6 MW and capable of delivering 7 MWh (Elektro (2022)). The simulation model expands on this battery setup by investigating larger capacities.

Table 7 presents the tehcnical data used. η is the measure of energy efficiency, what percentage of the energy charged may be discharged. The simulation model charges the battery only after the grid demand is met with excess energy from wind turbines.

Table 7. Technical data for the battery park

Quantity	Value
Life time	10 years
Operational state of charge %	70 %
η	0.90
Discount rate	5 %
Relegation rate	2 %

3. Energy Demand

The basic function of a supply chain is to fulfil demand. In Longyearbyen, the demand to fulfil is the energy consumption. In this model, it is assumed that this demand can be expressed through a single variable, the grid-demand. The grid-demand is based upon numbers provided by Lokalstyret and Svalbard Energi during an excursion to Svalbard from 26.05.2025 - 30.05.2025. Modelling the grid-demand is difficult due to the multiple factors. Up until 30$^{\text{th}}$ of June 2025, the last coal mine (Gruve 7) was operational. Every time the coal mine was active, it would draw a substantial amount of power from the power grid, multiple megawatts. This is no longer the case, and so the yearly power demand should be lower than the previous years. The upper scale for the power demand used to be around 10 MW. It may still be advantageous to size the model with an upper scale for power demand of 10 MW. The reason for this is that this is the power profile for Longyearbyen with the most data collected. Oversizing the electrical grid and subsequently the connected supply chain, does increase the security of energy supply. It acts as a contingency in case a the power grid needs to provide more power as well. It is assumed that the power demand is higher during winter/colder months in comparison with summer months. Using historical data from *Yr.no*, the months from October until April are considered winter months. Fig. 2 shows historical temperature data used for parameter estimation.

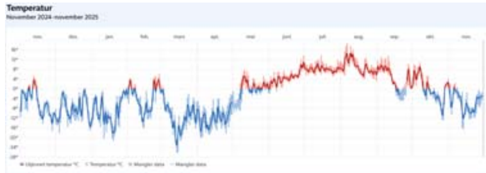

Fig. 2. Historical temperature data. November 2024 - November 2025. Longyearbyen. (NRK, 2026)

The power demand is assumed to follow a beta distribution with a bias towards 6-9 MW for winter months, and a bias towards 3-5 MW for summer months. Table 8 presents α and β estimates. μ and σ are mean values and standard deviations respectively.

Table 8. Demand parameters

Season	α	β	μ	σ
Summer	2	6	4.73 MW	1.00 MW
Winter	4	2	7.66 MW	1.24 MW

4. Levelized Cost of Energy

To assess the economic cost-benefit of a wind turbine in combination with battery storage solution, levelized cost of energy (LCOE) is used. LCOE is essentially discounted total cost during the calculation period divided by the discounted energy production of the same period (NVE, 2026b).

The formulas for LCOE for wind turbines, diesel generators and battery are given by Eqs. (2-4) respectively.

$$\text{LCOE}_{\text{WT}} = \frac{I_0 + \sum_{t=1}^{T} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t(1-d)^t}{(1+r)^t}} \tag{2}$$

$$\text{LCOE}_{\text{DG}} = \frac{I_0 + \sum_{t=1}^{T} \frac{M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t(1-d)^t}{(1+r)^t}} \tag{3}$$

$$\mathrm{LCOE_B} = \frac{I_0 + \sum_{t=1}^{T} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t(1-d)^t}{(1+r)^t}} \qquad (4)$$

where I_0: Investment cost in year 0, M_t: Maintenance cost in year t, F_t: Fuel costs in year t, E_t: Produced energy in year t (for battery; discharged energy in year t), r: Discount rate, d: Relegation rate and T: Unit lifetime.

Each form of energy production/management has different expected lifetimes. The simulation model accounts for this by resting the investment cost if the simulation time exceeds the expected lifetime. The same logic is used for the discount rate and the relegation rate. Table 9 presents cost figures used.

Table 9. Assumed costs used in LCOE calculation

Quantity	Value
Wind turbine infrastructure cost	50 MNOK
Cost per wind turbine	20 MNOK
Maintenance cost/yr/turbine	1.4 MNOK
Diesel generator cost	60 MNOK
Maintenance cost/yr/diesel gen.	1.5 MNOK
Diesel cost per liter	10 NOK/Liter
Cost per kWh battery capacity	13 000 NOK/kWh
Batery maintenance cost/yr	2 × battery capacity

5. Results

A discrete event simulation model has been developed for the simulation. Figure 3 presents the main result. The main decision variables to consider are the *number of turbines* to install and the *battery capacity* in terms of days covering normal demand when it is not blowing. The diesel coverage column highlights the main source of green gas emission. We see that more turbines and more battery capacity reduces such emission but it is not realistic to approach zero emission. A realistic target could be to have 90% renewable energy. This could be achieved by having 25 turbines and battery capacity for two days. One should observe that the LCOE value of 62 NOKs for this (optimal) combination is hundred times higher than cost wind power on the main land. The big cost contributor is the battery.

The rightmost column shows the number of total blackouts per hundred year. Since simulation is run for hundred years these numbers are rather fragile. Table 10 shows the expected number of blackout for various re-order points, r. As expected a low re-order point for diesel replenishment increases the risk of a full blackout for Longyearbyen.

# of turb.	Days battery	Wind coverage without battery	Wind cov. with battery	Wasted power	Diesel coverage	Service Level	Wind LCOE	Battery LCOE	Diesel LCOE	Total LCOE	# of Blackouts
5	1	44%	55%	6%	45%	99.91%	0.5	62	3.6	66	2
10	1	56%	70%	17%	30%	99.99%	0.5	46	4	51	1
15	1	62%	76%	24%	23%	99.90%	0.4	44	4.3	48	3
20	1	65%	80%	30%	20%	99.85%	0.4	43	4.6	48	3
25	1	67%	82%	34%	18%	100.00%	0.4	44	4.8	49	0
5	2	44%	60%	3%	40%	99.98%	0.5	76	3.7	80	2
10	2	56%	78%	14%	22%	99.92%	0.5	57	4.4	62	0
15	2	62%	85%	21%	15%	99.94%	0.4	54	5.1	59	3
20	2	65%	88%	27%	12%	99.94%	0.4	54	5.8	60	1
25	2	68%	91%	33%	9%	99.96%	0.4	55	6.8	62	0

Fig. 3. Main results. Cost given in NOKs

Table 10. Number of blackouts as function of re-order point

r	# of turbines	# of Blackouts
2/3 of capacity	25	1.7
2/3 of capacity	30	1.0
1/2 of capacity	25	2.1
1/2 of capacity	30	3.0
1/3 of capacity	25	3.6
1/3 of capacity	30	3.8

6. Discussion

The main findings from this study is that the combination of wind and battery as a means to reduce greenhouse gas emission is a very costly solution mainly due to battery cost. It is expected that battery capacity cost will decrease in coming years, but for an investment in the near future this solution is consider too costly. A large number of assumptions are made but the overall results indicate that it is the battery cost that is the main cost driver.

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