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Modeling a sustainable energy transition in northern Greenland: Qaanaaq case study

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ABSTRACT

Many remote Indigenous communities in the high Arctic rely on diesel or other fossil fuels for their electricity generation, yet the high cost of the imported fuel limits households' ability to afford food and adequate housing and in turn, undercuts living conditions in the Arctic. While roughly 65% of energy generated by the Greenlandic utility company Nukissiorfiit comes from renewable sources, nearly 70% of public and private energy consumption for electricity and heat is fossil-fuel based Naalakkersuisut (2018) [1] . A transition to renewable energy achieved in partnership with the communities could strengthen local energy self-reliance and build technical capacity in ways that embrace their cultural heritage. This paper examines initial feasibility of the incorporation of solar energy for the hunting/fishing village of Qaanaaq, Greenland, a challenging environment where there is little wind or hydropower potential. Unit commitment optimization models are used to assess the feasibility of possible energy projects that include solar energy and energy storage in Qaanaaq's energy system, in hybrid systems with diesel generators. We also consider future energy system planning via electrified heat. We find that under a variety of economic conditions, solar and battery electric storage contribute to decreased costs to generate electricity in Qaanaaq. Currently, hydrogen storage is found to increase costs of energy in Qaanaaq, even considering future decreases in capital costs. However, green hydrogen may have positive impacts to the energy as a long-term energy planning strategy.

1. Introduction and literature review

Small coastal communities in the Arctic commonly manage energy through diesel-powered micro-grid systems. In northern Greenland, these communities often lack flowing rivers for hydropower and have little wind potential, yet the residents desire affordable, renewable energy to lessen their dependence on imported fuel and to lower their energy costs. The United Nations has identified seventeen global goals for sustainable development. Sustainable Development Goal Seven (SDG 7) is to ensure access to affordable, reliable, sustainable and modern energy for all. SDG 7 has been identified as one of the high priority goals for Arctic communities and has been endorsed by the Arctic Council. This paper is focused on assessing the feasibility of supply side solutions based on hybrid diesel generator, solar photovoltaic (PV) and battery storage energy systems. We will be conducting site assessments for potential solar installations in future field work. Energy efficiency is also an important step for cost reduction and increased energy reliability, and efficiency measures should be implemented if funds are available for retrofitting or new construction. We are addressing energy conservation analysis in research that is beyond the scope of this paper.

The hybridization of remote, diesel-only grids in Arctic communities with renewable resources has become a crucial strategy for abating high diesel costs and future climate change impacts, and increasing energy security of Arctic energy infrastructure. Cold Arctic conditions, winter months without sunlight, and 24 h sunlight in summer months present challenges and opportunities for renewable energy and a potential for a sustainable energy transition in northern Greenland.

Diverse energy generation portfolios that make use of regional renewable resources will enhance resilience in energy systems. Energy diversification of both production and storage technologies enables optimal installation sizes and grid operation. For example, in remote-islanded grids, simple solar–fossil fuel hybridization models tend to

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oversize solar installations, but by including one or more storage technologies, installation costs and solar curtailment can be decreased [1]. Previous studies of diesel-hybridization of energy systems in remote, Arctic communities show that PV or wind can be economically viable because of the high costs of diesel and transportation. Das and Cañizares found the maximum feasible renewable penetration into several of Canada's Arctic, diesel-only communities [2]. Ninad modeled typical solar–diesel hybrid micro-grids in the Canadian Arctic to find maximum renewable penetration without the need for curtailment [3]. They found that for PV prices of less than 5 Canadian Dollars/Watt, it was economical to generate electricity with PV. This is highly dependent on diesel price, which is volatile in the Canadian Arctic and elsewhere. Chade and others have studied the feasibility of wind–hydrogen–diesel energy systems on an islanded grid off the coast of Iceland [4]. A wind–hydrogen–diesel system in this grid was the lowest operational cost option and had a reasonable initial capital cost. The technical feasibility of solar, battery, and hydrogen power for the off-grid energy supply to a Finnish house has also been evaluated [5]. The authors found that both hydrogen and battery storage were necessary to meet the off-grid demand year-round. In mid-latitude locations where direct sunlight is available on a daily basis, hydrogen storage has been used. For example, on Italian island of Favignana, battery and hydrogen in combination were found to be the best method for managing excess energy when hydrogen was channeled into electric vehicles or hydrogen fuel cell busses [6]. Isolated, remote communities have been identified as critical applications of community energy storage systems for economic and sustainability goals [7,8]. In Iran, a novel probabilistic model has been developed for the optimal planning of hydrogen microgrids, addressing the stochasticity of renewable resources and their impact on grid reliability-specifically the impacts of electric and hydrogen vehicles on microgrids [9]. In this work we investigate potential solar feasibility in Greenland using the village of Qaanaaq, Greenland as a case study to demonstrate several optimized energy scenarios.

1.1. Alternative energy in the arctic

Both wind turbines and solar photovoltaic (PV) are mature technologies. Despite being mature, use of solar PV in Greenland on a community scale is limited. Dramatic and ongoing reductions in the cost of solar energy and battery storage combined with copious sunlight for seven months of the year suggest that solar and storage could play an important role in reducing costs and dependence on fossil fuels in Greenland and elsewhere in the far north. Solar and wind resources, along with other renewable resources must be considered in a local and seasonal context. Other alternative energy sources, such as tidal energy or pumped hydro-storage could be considered for a coastal, Arctic community. Tidal energy is energy that is harnessed from the movement of water caused by tides, and is still in relatively early stages of development [10]. Several tidal energy systems have been created including the tidal barrage and tidal turbine. Tidal barrages operate on a similar principal to hydroelectric, but with bi-directional flow. Tidal turbines operate like wind turbines, but on the sea floor where tidal flow is very strong [11]. Concerns for tidal energy infrastructure in a coastal Arctic fishing community include potential impacts to marine life. Building a dam-like barrage may impact tidal flow direction and water quality. Marine energy sources can displace species, affect nutrient production, and risk the introduction of invasive species [12].

Pumped hydroelectric energy storage, where electricity is converted into potential energy by pumping water uphill during off-peak hours for it to eventually flow downhill through a turbine during peak hours (for example in Hawaii), is another alternative energy generation source. Pumped hydro is a highly flexible and commercially mature energy storage mechanism with potential for coupling with other renewable resources in the mid-latitudes [13]. However, in the high Arctic, the benefits of the massive pumping that could be achieved via solar power in the summer may be offset by the energy required to keep water above freezing all winter. In addition, Arctic permafrost and unstable soils create challenges in constructing containment basins or uphill structures. The feasibility of pumped hydroelectric storage is thus very site-dependent. Pumped thermal energy storage is explored for cost-effective, site-independent energy storage via different working fluids [14]. Currently, pumped hydroelectric energy storage has not been widely explored in cold climates or Arctic communities, although it has been explored in isolated energy systems in the mid-latitudes [15].

In this preliminary feasibility study we also consider hydrogen storage, which has been identified as a pathway towards expanding energy access in off-grid areas while promoting decarbonization [16]. Hydrogen storage balances electricity demand, making energy systems more flexible and able to take advantage of overproduction of renewable resources. Hydrogen has potential for increasing renewable penetration into a micro-grid by reducing the uncertainty associated with non-dispatchable resources such as solar. Hydrogen technologies are well suited for long-term (seasonal) storage because of no self-discharge [5,17]. Additionally, unlike batteries, hydrogen systems are not constrained by cycle lifetimes [18]. However, hydrogen has a lower round-trip efficiency than batteries due to energy conversion losses in the fuel cell and electrolyser, making hydrogen less favorable for short cycle times [5,19]. Flow batteries have a high potential for long duration energy storage, but are not currently affordable or industrially established [20]. A diverse remote grid could utilize both battery electric storage for short and mid-term balancing and hydrogen storage for seasonal balancing [21]. There also exists potential to turn hydrogen storage systems into combined heat and power systems that could increase the efficiency of the hydrogen system and simultaneously meet other community needs [17,22]. One analysis suggests that the most pressing need for Greenland is to convert heating demands to electric, after the electric supply systems become renewable-based [23]. Hydrogen could encourage green electrified heating by supporting greater renewable capacity additions. Alternatively, hydrogen could support the existing district heat operation or be used as a fuel for generating heat, eliminating the need for conversion into electricity. Hydrogen has high energy density but very low volumetric density at ambient temperature. The low volumetric density necessitates large storage volumes and thus high capital costs. Therefore, regarding engineering considerations, the biggest barriers to feasible hydrogen energy storage on a community scale are storage density and capital costs.

In 2018, the Greenlandic national utility company, Nukissiorfiit, explored hydrogen feasibility in Ilulissat, Greenland, where there is a significant over-production of hydropower energy [24]. The high cost of the electrolysis process, coupled with the existing energy storage system associated with the hydropower plant, made hydrogen storage economically unfavorable and unnecessary for energy balancing. The analysis concludes that in Ilulissat, it would be more economically advantageous to use the surplus energy generation for the electrification of heat via air–air or water–air heat pumps. Electrolysers are projected to decrease in costs and increase in efficiency [16]. Therefore, exploring hydrogen in a Greenlandic context as a long-term energy resiliency strategy could prove to be economically feasible for communities without existing hydropower or storage/balancing capacity.

Hydrogen can be compressed, liquefied, or bound chemically in order to increase storage density. Compressed hydrogen is a commercially mature method but is still requires high storage volumes. Compressed hydrogen is stored in vessels pressurized up to 35–70 MPa, where hydrogen density is around 40 kg/m3. Liquified hydrogen has a higher volumetric density, but requires special insulation systems to prevent boiling at low temperatures [25]. Solid state materials, such as metal hydrides, for hydrogen storage are a promising option, but are neither widely available nor currently cost-effective [26]. A community-scale hydrogen storage system has been demonstrated using metal hydride storage tanks in Nottingham, UK, for mid-to-long term storage [27]. Up to 4 kg of hydrogen can be stored with magnesium powder, pressurized to 12 bar, increasing the storage density of hydrogen. The feasibility of using this hydrogen system, however, is dependent on demand load shifting, which requires taking advantage of periods of valley and peak pricing, which does not occur in Greenland, due to constant, subsidized electricity rates [27]. Hydrogen can also be stored underground for greater volumes. This method, however, was not considered for this initial analysis due to the permafrost and soil instability in Qaanaaq. This preliminary analysis will assume a compressed hydrogen storage system.

1.2. Case study: Qaanaaq, Greenland

Qaanaaq, Greenland is a settlement of approximately 600 people in northwest Greenland. Qaanaaq's electric power consumption is approximately 4800 kilowatt-hour (kWh)/capita, which is similar to other communities in Greenland, which are generally less than in Denmark, with 5500 kWh/capita. This lower electric demand is due in part to 24-hour sunlight during summer months, but also reflects the fact that fossil fuels are more widely used for heating demands. Heating demand exists year-round in the high-Arctic village of Qaanaaq, which has approximately 17,500 Heating Degree Days for a 18 degree Centigrade base temperature; this is more than 25% greater than the more southerly Greenlandic capital, Nuuk. Nukissiorfiit is responsible for producing and supplying electricity (and water) to Qaanaaq, and all other communities in Greenland. While 65% of energy generated by Nukissiorfiit comes from renewable sources,the benefits of renewable energy are not equally distributed across Greenlandic localities [28].Nukissiorfiit provides subsidized electricity rates to all of Greenland to account for the disparity in electricity generation costs between larger settlements with access to inexpensive hydropower, and small settlements like Qaanaaq, that rely on expensive imported fuels for all heat and electricity generation. While this measure is meant to provide equality across Greenland, energy costs are still burdensome for small, remote communities, especially when considering heat demands and comparatively smaller household incomes resulting from a largely subsistence lifestyle. Nukissiorfiit needs cost-saving measures to reduce energy prices in order to shift away from fossil fuel based electricity and heat generation. Our hypothesis is that renewable hybridization of Qaanaaq's energy infrastructure would lessen the community's dependence on imported fuel, saving money for Nukissiorfiit, and in doing so, ease the future inclusion of electrified heat sources.

Qaanaaq has several potential sites for utility-scale solar installations. The town faces an open, South-West facing fjord, with hills to the North-East. There are no trees, and few buildings on the outskirts of town. Therefore excessive shading can be avoided when the sun is above the horizon. Future field work will assess site-specific considerations for solar arrays.

This preliminary study considers solar, battery-electric, and hydrogen power in the analysis. In Qaanaaq, the solar resource is only available during periods of polar daylight (from mid-April to the end of August) and the sun is below the horizon for the rest of the year. However, during these summer months, the solar resource is abundant. While a small amount of wind, measured at the local airport, occurs year-round, the average speeds rarely exceed the cut-in speeds of many commercial turbines. Additional meteorological data is needed to fully assess the potential localized wind resource.

2. Methods

We created several mixed integer linear programming models of Qaanaaq's energy system. Economic minimization is used to determine the new energy sources and their sizes in order to minimize the total cost of electricity generation over a project lifespan by modeling a representative day of demand and solar insolation for each month of the year in Qaanaaq. This minimization is constrained by numerous linear relationships that govern the operation of diesel, solar, batteries, and hydrogen power generation, as well as binary constraints governing the on/off status of generators over time.

By modeling different storage strategies, we created several scenarios for maximizing the benefit of renewable energy resources and reliable grid operation, while prioritizing minimal costs. The model simulates 288 h of electricity generation as one model year. This method was also in the Canadian Arctic [2]. Recurring costs are analyzed in terms of net present costs over the project lifespan of 25 years (inverters, fuel costs, operation and maintenance, etc.). Re-occurring costs and hydrogen storage capacities are converted to annual parameters by multiplying by 30. Commercial software Generic Algebraic Modeling Software (GAMS) was used to solve the optimization problems and MATLAB was used to visualize and pass data. Appendix A contains detailed information on model inputs, sources of information, and justifications for diesel, solar, and storage model constraints.

Table 1 shows important parameters used for modeling the new capacity additions in the energy infrastructure in Qaanaaq.

Table 1
Important parameters of new proposed capacity additions.

Component parameter	Value
Diesel O&M	0.02 USD/kWh
Diesel Lifespan	45,000 hr
Diesel Maintenance Downtime	10%
Electrolyser CapEx	165,000 USD (1,100 USD/kW)
Electrolyser O&M	5%CapEx
Electrolyser Lifespan	40,000 hr
Electrolyser Efficiency	70%
Fuel Cell CapEx	75,000 USD (500 USD/kW)
Fuel Cell O&M	5%CapEx
Fuel Cell Lifespan	20,000 hr
Fuel Cell Efficiency	50%
Compressed Storage CapEx	31 USD/kWh
Compressed Storage O&M	1%CapEx
Compressed Storage energy discount	85%
Storage Tank Lifespan	25 years
Photovoltaic CapEx	2,560-3,760 USD/kW
Photovoltaic O&M	0.012 USD/kWh
Photovoltaic Lifespan	25 years
Li-Ion CapEx	760 USD/kWh
Li-Ion Lifespan	3,000–10,000 cycles

2.1. Mathematical model for optimization:

This optimization is subject to several sets of constraints: those regarding diesel generators (x), new solar (s), battery (b), and/or hydrogen capacity (h2). All sets are a function of time (t), and costs are summed and minimized over the project horizon from year (y) 1 to the project horizon (p).

$$Objective\ Fxn : MINz = \Sigma_{1:p} DieselGenerationCost(x,t) + \Sigma_{1:p} RenewableGenerationCost(s,b,h2,t) \tag{1}$$

Diesel Generator Constraints:

Diesel generators are constrained by a minimum loading capacity, which is 40% of the nameplate capacity. The set 'i' indexes though the number of generators. The binary variables vU and vDown govern the on/off status of each generator per time step.

$$\text{Generator Constraint} : Cap_{GenMin} * vU(i,t) < x(i,t) < Cap_{GenMax}(i) * vU(i,t) \tag{2}$$

$$\text{Start Up Cost} : \Sigma_{1:p} \Sigma_{i,t} vUp_{i,t} * \frac{StartUpCost(i)}{1 + dr^{y(p)-1}} \tag{3}$$

$$\text{Shut Down Cost} : \Sigma_{1:p} \Sigma_{i,t} vDown_{i,t} * \frac{ShutDownCost(i)}{1 + dr^{y(p)-1}} \tag{4}$$

$$\text{Generator On/Off}: vU(i,t-1) + vUp(i,t) - vDown(i,t) \quad (5)$$

$$\text{Maintenance Down Time}: \Sigma(t, vU(i,t)) * 30 < 8760 * (1 - T_{Maintenance}) \quad (6)$$

$$\text{Fixed Costs}: \Sigma_{1:p} \frac{30 * \frac{\Sigma_t vU(i,t)}{GenLife} * C_{Newgen} * Cap_{GenMax}(i)}{(1+dr)^{(y(p)-1)}} \quad (7)$$

$$\text{O\&M Costs}: \Sigma_{1:p}\left(\frac{30 * \Sigma_t, x(i,t) * 0.02}{(1+dr)^{(y(p)-1)}}\right) \quad (8)$$

$$\text{Fuel Costs}: \Sigma_{1:p} \frac{30 * FuelCost_{liter} * FuelConsumption}{(1+dr)^{(y(p)-1)}} \quad (9)$$

$$\text{Diesel Generation Costs}: \Sigma_i O\&M(i) + \text{FuelCost} + \text{StartUpCost} + \text{ShutDownCost} + \Sigma_i \text{FixedCost}(i) \quad (10)$$

$T_{maintenance}$ is the percentage of hours in a year a generator can run before requiring maintenance, C_{Newgen} is the cost of new generation capacity per kilowatt, GenLife refers to the number of hours a generator can run in its useable life, Fuel consumption is the sum of each generator over all hours and is calculated based off linearized fuel consumption curves for diesel generators of the varying capacities already installed in Qaanaaq.

Solar Power:

$$\text{Solar Generation}: Sg(t) = Rad(t) * \eta_{solar} * \frac{Cap_{solar}}{Cap_{panel}} * A_{panel} \quad (11)$$

$$\text{Solar O\&M}: \frac{30 * \Sigma_t Sg(t) * 0.0120}{(1+drr)^{y(p)-1}} \quad (12)$$

$$\text{New Solar Capital}: C_{kW} * Cap_{solar} + inverterNPC \quad (13)$$

$$\text{Total Solar Costs}: \text{NewSolarCapital} + \text{Solar O\&M} \quad (14)$$

Sg(t), Rad(t), are the solar power generated, and incoming solar radiation at time t, respectively, and Cap_{solar}, Cap_{panel} are the total chosen capacity of the new solar installation and the capacity of the individual panel, respectively. Lastly, A_{panel} is the area of the individual panel in square meters.

Battery Energy Storage:

$$\text{State of Charge}: SOC_{bat}(t) = SOC_{bat}(t-1) + \eta_C * Pch_{bat}(t) - \frac{Pdis_{bat}(t)}{\eta_D} ** \quad (15)$$

$$\text{State of Charge Constraints}: SOC_{bat,Max} * DoD_{bat} < SOC_{bat}(t) < SOC_{bat,Max} \quad (16)$$

$$\text{Maximum Rate of Charge/Discharge}: Pch_{bat}(t) \& Pdis_{bat}(t) \leq \frac{1 - DoD_{bat}}{TD} * SOC_{bat,Max} *** \quad (17)$$

$$\text{Minimum Rate of Charge}: Pch_{bat}(t) \geq Ich_{bat}(t) \quad (18)$$

$$\text{Minimum Rate of Discharge}: Pdis_{bat}(t) \geq Idis_{bat}(t) \quad (19)$$

$$\text{Charging/Discharging Status}: Idis_{bat}(t) + Ich_{bat}(t) = 1 \quad (20)$$

$$\text{Additional Capacity Requirements}: CA_{bat} = \Sigma_{1:p} \frac{\Sigma_t(Pch_{bat}(t) + Pdis_{bat}(t))}{MaxCycles} \quad (21)$$

$$\text{Battery Costs}: C_{bat} * SOC_{bat,Max} + \Sigma_{1:p} \frac{CA_{bat} * C_{bat}}{(1+dr)^{y(p)-1}} \quad (22)$$

** [29]
**** [2]

DoD_{bat} is the depth of discharge of the batteries, and TD is the time the battery can continuously discharge (4 h). η_c, η_D are the efficiencies of charging and discharging. Pch_{bat}, $Pdis_{bat}$ are power directed to charge the batteries and power being discharged from the batteries at time t. $Idis_{bat}$, and Ich_{bat}, are the binary operators governing the status of the battery. SOC_{bat}, and $SOC_{bat,Max}$ are the state of charge of the battery and its maximum nominal state of charge.

Table 2
Sensitive parameters.

Sensitive parameter	Values
Diesel Price	0.71, 1.02,1.87 USD/liter
Installed solar panel cost	2560,3760 USD/kW

Hydrogen Energy Storage:

$$\text{Electrolyser Operating Limits}: P_{el,min} * I_{ch} < Pch_{H2} < P_{el,max} * I_{H2,ch} * \eta_{el} \quad (23)$$

$$\text{Fuel Cell Operating Limits}: P_{fc,min} * I_{dis} < Pdis_{H2} < P_{fc,max} * I_{H2,dis} * \eta_{fc} \quad (24)$$

$$\text{On/Off Constraint}: I_{H2,h} + I_{H2,dis} = 1 \quad (25)$$

$$\text{H2 SOC}: SOC_{H2}(t) = (Pdis_{H2}(t-1) + Pch_{H2}(t-1)) * 30 + (Pch_{H2}(t) - Pdis_{H2}(t)) * 30 \quad (26)$$

$$\text{H2 SOC Upper limit}: SOC_{H2}(t) < CAP_{H2,Nominal} \quad (27)$$

$$\text{H2 Supply and Demand Balance}: \Sigma_t Pch_{H2}(t) = d_{compress} \Sigma_t Pdis_{H2}(t) \quad (28)$$

The state of charge is the level of energy stored relative to the nominal capacity, normally expressed as a percentage [18]. To maintain a linear system of equations, here, the state of charge is expressed in kilowatt-hours and is constrained by the maximum nominal capacity in another constraint.

The hydrogen supply and demand balance shows a discount to the energy that charges the system, as some of it is used to compress the hydrogen. This discount depends on the pressure the hydrogen is compressed to. Here, $d_{compress}$ is 85%, meaning a discount of 15% is applied in order to compress the hydrogen. $P_{el,min}$, $P_{el,max}$, I_{ch}, $P_{fc,min}$, $P_{fc,max}$, I_{dis}, η are the electrolyser power constraints and binary operator, and the fuel cell power constraints, binary operator, and efficiencies and, $SOC_{H2}(t)$, is the state of charge of the hydrogen storage system at time 't'.

$$\text{Total Hydrogen Cost}: C_{el} + C_{fc} + C_{H2,store} + OM_{el} + OM_{fc} + OM_{H2,store} + C_{Compressor} \quad (29)$$

$$\text{Fuel Cell O\&M Costs}: \Sigma_{1:p} \frac{0.05 * C_{fc}}{(1+dr)^{y(p)-1}} \quad (30)$$

$$\text{Electrolyser O\&M Costs}: \Sigma_{1:p} \frac{0.05 * C_{el}}{(1+dr)^{y(p)-1}} \quad (31)$$

$$\text{Storage Tank O\&M Costs}: \Sigma_{1:p} \frac{0.01 * C_{H2,store}}{(1+dr)^{y(p)-1}} \quad (32)$$

$$\text{Renewable Generation Costs}: \text{Solar Cost} + \text{Battery Cost} + \text{Hydrogen Costs} \quad (33)$$

$$\text{Total Demand Balance}: Demand(t) = \Sigma_i, x(i,t) + Sg(t) + Pdis_{bat}(t) - Pch_{bat}(t) + Pdis_{H2}(t) - Pch_{H2}(t) \quad (34)$$

2.1.1. Sensitive parameters:

Table 2 shows important sensitive parameters for analysis. Installed solar panel costs refers to the total cost of the installed panel in Qaanaaq, including shipping, and excluding the inverter which is analyzed separately as a net present cost, as it is a re-occurring cost. Appendix A details the ranges of values chosen for analysis. The diesel price of 0.71 USD/liter reflects the actual, subsidized fuel price in Greenland for 2020–2021. Solar prices are estimated from Nukissiorfiit.

3. Scenarios and results

This analysis considers scenarios of renewable energy capacity additions that vary from near-to-long-term implementation, because the price of renewable technology will continue to decrease over time, especially considering the rapid developments currently evolving hydrogen storage. Three types of hybrid energy systems were chosen as models for analysis: solar–diesel, solar–battery energy storage(BES)-diesel, and solar–BES–hydrogen–diesel. These three models represent increasing capital and complexity being brought into the energy system to show how scaling energy projects will impact the system, both economically and in terms of grid operation and reliability. In every case, the diesel part of the energy system represents the current installed capacity in Qaanaaq plus future required capacity to be purchased during the project lifespan. The evaluation of these scenarios is on an Levelized Cost of Energy basis (LCOE). The LCOE of an individual energy generation sources for example diesel, solar, or batteries represents its lifetime net present costs divided by its total lifetime energy production. The combined LCOE is the weighted average LCOE of all energy generation sources included in the scenario. This combined LCOE represents the cost at which electricity could be sold at a break-even point.

3.1. Solar–diesel

The objective of the solar–diesel model is to provide an achievable and scaleable energy project that could be implemented immediately. Additional energy resources, for example batteries, additional solar, or hydrogen storage can be added later for a long-term sustainable energy transition. This model also provides important insights on how the incorporation of a non-dispatchable resource impacts an islanded, dispatchable, single-sourced grid.

Generally, high fuel prices allow for greater solar installations and thus fuel savings under an economic minimization model. The low costs of fuels in Greenland make it challenging for renewables to become cost-competitive in the analysis. However, as seen in Fig. 1, solar installations of 300 kWs can still result in cost savings despite a low fuel price. Solar capacity additions of these sizes would enable 18%–25% of Qaanaaq's electricity generation to come from renewable resources. Fig. 1 considers a reasonable economic case where solar panels are 3160 USD/kW, with a 4% discount rate, with the current, low fuel cost of 0.71 USD/liter. For several sized solar installations, the levelized cost of electricity (LCOE) of the hybrid energy system is presented. It is clear that solar power can lower the LCOE relative to the base-case (diesel-only) for every installation size considered. None of these installations result in LCOEs lower than the subsidized electricity price of 0.24 USD/kWh (1.65 DKK/kWh), but a 300 kW installation minimizes the LCOE. The optimal capacity additions and their resulting LCOE's are presented in Table 3, which shows the capacity additions and LCOE's for the different fuel and installed solar costs.

Additionally, the LCOE of each energy generation source can be analyzed. Table 4 shows that solar does reach parity with diesel and is the lower cost energy generation source compared to diesel, even when diesel is at the lowest, subsidized price.

The solar–diesel hybrid energy system does not assume any storage or balancing mechanisms. Therefore, overproduced solar could not be stored or used. The solar–diesel optimal solar capacity additions might be considered oversized for this reason. Summer-time demand in Qaanaaq rarely exceeds 275–300 kWs. Any solar installation larger than the peak summer demand is sized to generate the most solar power possible during transitional seasons where solar radiation is not strong and the sun is at a very low angle. While solar power from transitional seasons for several weeks each spring and fall would be beneficial, it would still need to be supplemented with diesel power. Considering diesel engines that are on and serving load should not be run less than 40% of their rated capacity, there is a limit to how beneficial transitional season solar power can be. If solar radiation is

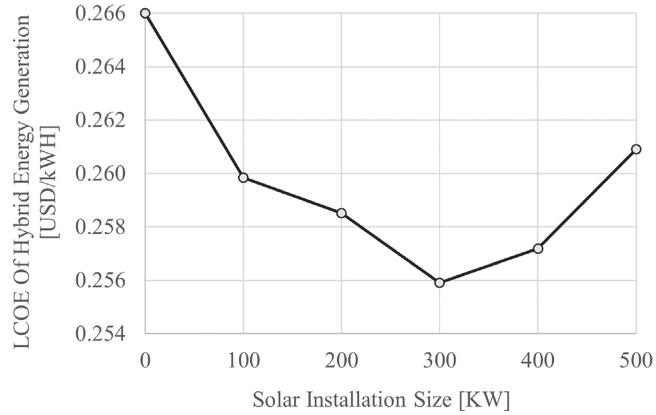

Fig. 1. Levelized cost of electricity for the hybrid combinations of various solar installations with diesel for a constant installed solar cost of 3160 USD/kW and fuel cost of 0.71 USD/kW with a 4% discount rate.

strong, but cannot cover the entire demand, then diesel generation of at least 75 kW is required (assuming only 1 300 kW generator is on). For example, if demand is 300 kW, and solar power could generate 275 of those kilowatts, 50 kW of solar power would still need to be curtailed. Curtailment on days when a generator is needed could be minimized by replacing the smallest generator with one or more smaller generators (of 60–100 kW in capacity) at the end of its useful life. This would allow these 'peaker' generators to operate very efficiently and for the maximization of renewable penetration during transitional periods or during periods of solar unavailability in low-demand summer hours. This solar only scenario does not include any dispatchable baseload. This could be an issue for reliability if reserve capacity is not already included in the dispatch order. A backup generator should be ready to connect to the grid in case of periods of solar unavailability. This model assumes two generators are always off and in reserve. The next generator in the dispatch order should be turned on when the current generator's capacity utilization is near its maximum.

3.2. Solar–diesel–BES

The addition of battery energy storage (BES) to solar installations enables the grid to be more resilient by providing short-term balancing of the non-dispatchable energy resource. The objective of battery storage in Qaanaaq's energy system would be to supplement solar power for a 'diesel-off' mode in the summer by providing back-up power for when the solar resource decreases on a short (hourly) timescale, for example for hours when there is heavy cloud cover. For hours when solar power is slightly too low to meet the full demand, battery storage can make up the difference with previously stored energy from periods of solar overproduction without requiring diesel support. Accurate diurnal load information is necessary for predicting battery dispatch. The present analysis does not contain historical hourly demand data for Qaanaaq because the data has been unavailable to us; in this analysis, hourly demand data is predicted using a smaller data set from Nukissiorfiit, which is discussed further in Appendix A. This analysis aims to predict how large a BES system should be in order to minimize energy costs, based on battery prices, lifetimes, and availability of excess solar generation. Table 5 presents the cost to generate electricity in Qaanaaq with the proposed capacity additions, as well as the levelized cost of electricity for the renewable combination. The cost to generate electricity is not predicted to increase due to renewable installations, and in many cases, the cost to generate electricity can be lowered relative to a diesel-only base case. Additionally, Table 4 shows that the levelized cost of solar and batteries is very similar to solar by itself. Both the solar LCOE and the solar + BES LCOE are lower than the diesel LCOE for each fuel price.

Table 3
Solar–Diesel Hybrid Solar Installations and Combined LCOE (C-LCOE) for all fuel prices considered at a 4% discount rate, LCOE is in USD/kWh, and capacity additions are in kW.

Diesel price parameter	0.71		1.02		1.87	
	C-LCOE	Capacity addition	C-LCOE	Capacity addition	C-LCOE	Capacity addition
2560 USD/kW	0.251	335	0.337	381	0.535	747
3760 USD/kW	0.253	265	0.344	335	0.569	516
Base Case	0.27	0	0.37	0	0.64	0

Table 4
Solar LCOE vs. Diesel LCOE for an installed panel price of 3160 USD/kW for each diesel price, where LCOE is presented in [USD/kWh].

Diesel price	Solar LCOE	Solar+BES LCOE	Diesel LCOE
0.71 USD/liter	0.11	0.11	0.17
1.02 USD/liter	0.11	0.11	0.24
1.87 USD/liter	0.14	0.15	0.45

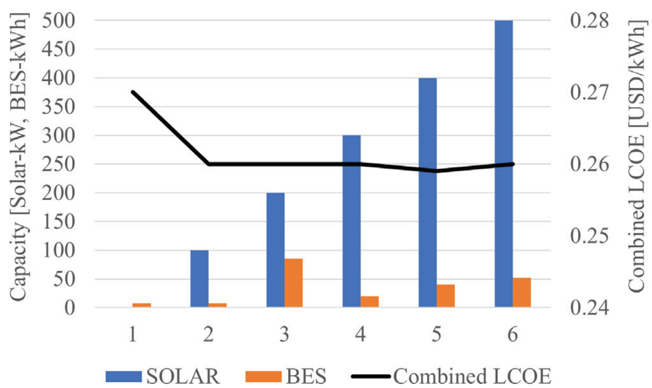

Fig. 2. Levelized cost of electricity for the hybrid combinations of various solar installations with diesel, each considering a variable BES capacity addition, shown in the orange bars.

Fig. 2 shows the relationship between solar and BES capacity for the economic scenario in which fuel cost is 0.71 USD/liter, solar is 3160 USD/kW, and the discount rate is 4%. For 6 scenarios with increasing solar capacity, the optimal BES size is determined. The combined LCOE for each scenario is presented on the right-hand y-axis. Minimum combined-LCOE's can be achieved with approximately 400 kW of solar with a small battery capacity (scenario 5). At solar capacities lower than peak summer demand (300–350 kW), high BES is chosen to pick up the slack to enable a 'diesel-off' or low diesel mode. As solar installations increase, smaller BES capacities become optimal, as the larger solar installation can comfortably cover the summer demand, leaving batteries for balancing smaller, intermittent changes in demand. Table 5 shows the optimized solar and battery capacity additions for both ranges of solar prices considered for each fuel cost. In agreement with Fig. 2, the optimized solar capacity additions are near 400 kW. Although the optimal capacity of solar–BES–diesel hybrid systems are larger than solar–diesel, the solar installation sizes chosen under solar–BES–diesel hybrid scenarios can be considered more reasonably sized than under solar–diesel hybrid scenarios. Batteries can recover some over-generated energy to reduce curtailment. Curtailment reduction is limited to the capacity of the batteries and cycle times. More batteries would allow for more charging and less curtailment, but lack of supply and demand variations on an hourly timescale could make this extra stored energy unnecessary, especially considering the lack of variability in lightness and darkness during periods of 24-hour sunlight and darkness in the high Arctic. However, battery installations at or exceeding average hourly consumption are important for reliability. If energy sources were to suddenly stop operating, batteries could meet the load for 1 h or more while repairs or maintenance occurred. Long-term (days-months) storage would allow this energy to be used when the solar resource and demands in Qaanaaq change dramatically. Battery lifespans are expected to drastically increase. A sensitivity analysis on battery cycling is presented in Appendix B to analyze the impacts of increased lifespans on possible capacity additions in Qaanaaq.

3.3. Solar–diesel–BES–hydrogen

The objective of incorporating hydrogen storage in combination with solar and battery energy storage is to balance out the large seasonal variation in demand and solar resource. Hydrogen storage enables opportunities for future coupling with other community needs, for example district heating or desalination. The model forces the inclusion hydrogen storage by the enforcing at least 500 kWh per year of hydrogen dispatch.

For this preliminary analysis, the hydrogen is assumed to be compressed to 35–70 MPa, which takes approximately 15% of the total energy from the stored hydrogen, with expected hydrogen densities of 23–38 kg/m3. Table 6 shows the combined LCOE's and capacity additions chosen for each fuel price scenario. High fuel savings are offset by high capital costs, of storage space specifically, resulting in higher combined LCOE's than solar–diesel and solar–BES–diesel scenarios. Additionally, solar capacities are larger in order to over-produce energy to store.

Only high fuel costs results in a hydrogen hybrid energy system being almost cost-competitive with the base case. Storage tank costs are the primary bottleneck, and storage tank costs are not expected to drastically decrease. Fig. 3 and the corresponding Table 7, show seven different capital cost scenarios for hydrogen components with constant solar, BES, and fuel prices of 3160 USD/kW, 760 USD/kW, and 0.71 USD/liter respectively. The right axis shows the combined LCOE. The two lines overlapping the bar chart show, for each scenario, the combined LCOE of the scenario in comparison with the base case cost of energy. Decreasing capital costs do not result in an LCOE that meets the base case cost of energy. Reaching parity with the diesel-only base case would require unrealistic cost reductions in storage, electrolyser, and fuel cells components.

Although this preliminary analysis of hydrogen energy storage in Qaanaaq presents currently unfavorable economic parameters, it should still be considered as a long-term energy planning tool if the idea of hydrogen storage is favorable within the community, because the technology for hydrogen storage is rapidly improving. Hydrogen storage makes the best use of the solar power generated in the summer by reducing fall, winter, and spring diesel use. Future hydrogen feasibility studies for Arctic communities should also consider using hydrogen as a fuel for producing heat in a boiler or oil-space heater. This would negate some capital costs, such as the fuel cell required to convert the hydrogen into electricity. Furthermore, this may reduce the need of large storage capacities. Due to the year round heat demand, the

Table 5
Solar–Diesel–BES Hybrid Solar Installations and Combined LCOE (C-LCOE) for all fuel prices considered at a 4% discount rate, LCOE is in USD/kWh, and capacity additions are in kW for solar and kWh for BES.

Diesel price parameter	0.71			1.02			1.87		
	C-LCOE	Solar capacity	BES capacity	C-LCOE	Solar capacity	BES capacity	C-LCOE	Solar capacity	BES Capacity
2560USD/kW	0.26	380	455	0.34	383	73	0.56	688	112
3760USD/kW	0.26	370	36	0.35	377	80	0.62	473	111
Base Case	0.27	0	0	0.37	0	0	0.64	0	0

Table 6
Solar–BES–H2–Diesel Hybrid Solar Installations and combined LCOE (C-LCOE) for all fuel prices considered at a 4% discount rate, LCOE is in USD/kWh, solar capacity additions are in kW, and BES and H2 capacities are in kWh.

Diesel price parameter	0.71				1.02				1.87			
	C-LCOE	Solar capacity	BES capacity	H2 capacity	C- LCOE	Solar capacity	BES capacity	H2 capacity	C- LCOE	Solar capacity	BES capacity	H2 capacity
2560USD/kW	0.38	472	45	5095	0.46	520	16	5910	0.68	941	240	5593
3760USD/kW	0.39	404	81	3650	0.48	488	238	5480	0.70	622	190	6090
Base Case	0.27	0	0	0	0.37	0	0	0	0.64	0	0	0

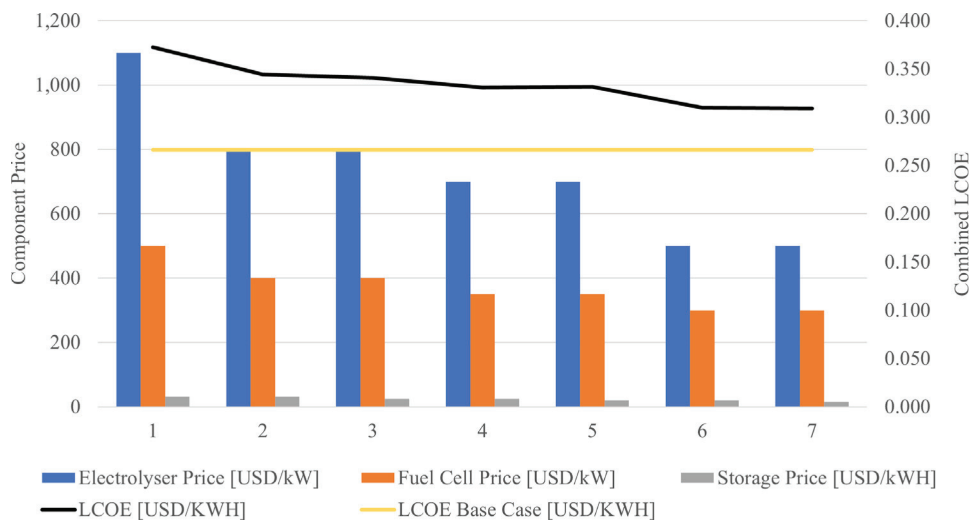

Fig. 3. LCOE vs. capital costs of hydrogen storage components, considering a constant solar price of 3160 USD/kW, and fuel price of 0.71 USD/liter.

Table 7
Capital costs for hydrogen storage components corresponding to Fig. 3, for a constant solar price of 3160 USD/kW, and fuel price of 0.71 USD/liter.

Scenario	Storage price	Electrolyser price	Fuel cell price
1	31 USD/kWh	1100 USD/kW	700 USD/kW
2	31 USD/kWh	800 USD/kW	500 USD/kW
3	25 USD/kWh	800 USD/kW	400 USD/kW
4	25 USD/kWh	700 USD/kW	400 USD/kW
5	20 USD/kWh	700 USD/kW	350 USD/kW
6	20 USD/kWh	500 USD/kW	300 USD/kW
7	15 USD/kWh	500 USD/kW	300 USD/kW

hydrogen can displace in-home fossil fuel burning during the summer and transitional months, rather than provide electricity in the mid-winter, decreasing the excessive storage costs. Economic scenarios in which externalities of fossil fuel are included and the true cost to supply diesel fuel to the community are used may see hydrogen storage as a more favorable option. The dispatch of hydrogen and impact of storage size are discussed in Appendix C.

4. Conclusions and potential policy benefits

Our calculations in this initial feasibility study show that inclusion of solar energy and battery energy storage may increase resilience and save money associated with electricity generation small communities in remote areas of northwest Greenland. Solar installations of 300–400 kW with optional battery storage capacities of 80–100 kWhs decrease the cost to generate electricity with payback periods of less than 12 years, in almost every economic scenario chosen for analysis. A summary of the annual cost savings in USD per year projected for the solar–BES–diesel scenarios is shown in Table 8.

These potential cost savings can be achieved by Nukissiorfiit, as the cost to generate electricity for Qaanaaq decreases with new solar and battery energy storage installations. Although these cost savings per kilowatt-hour [summarized in Table 5] are not large enough to overcome the subsidized price of electricity that consumers pay (1.65 DKK, or 0.24 USD per kWh), investing in solar power would contribute to lower operating costs for Nukissiorfiit. Therefore, consumers would not see decreases in electricity rates unless there is reform to the one-price model, enacted in 2018. Since 2018, Nukissiorfiit has published large cost deficits (153 million DKK in 2020), citing the cause as the ongoing, loss-making investments that must be made to supply the whole country with water and energy (largely via fossil fuels). Even without a change in the one-price model, government investment in solar energy for communities around Greenland will lower Nukissiorfiit's dependence on fossil fuel which would help to reduce the associated large ongoing deficits incurred by Nukissiorfiit [30].

Looking ahead, energy independence initiatives can help safeguard communities against future energy price increases or decreases in utility-supplied energy due to lack of secure supply. Investment in

Table 8
Annual cost savings in USD/ Year for Solar–BES–diesel hybrid scenarios.

Installed panel price	0.71 USD/liter 4% Discount rate	1.02 USD/liter 4% Discount rate	1.87 USD/liter 4% Discount rate
3760 USD/kW	10,600	52,300	83,200
2560 USD/kW	38,500	81,700	205,800

renewables in small, islanded communities in Greenland is an important strategy to consider in decreasing energy system operating costs and reducing deficits in Nukissiorfiit; Greenland government's investment in renewable energy that is appropriate to local conditions for communities around Greenland is an important long-term strategy for Nukissiorfiit.

In ongoing research, we will examine energy issues in a whole-systems approach by assessing energy demand as well as the potential impact of investments for improving energy conservation in homes. Heating demand in Qaanaaq will be investigated in order to estimate additional capacity required for electrified heating. This feasibility of electrified heat will be assessed in conjunction with investigations into building energy-efficiency and the indoor air quality of homes using oil heaters. Additional capacity requirements to convert homes to electrified heating will be minimized when homes are properly insulated and well-sealed.

Because of the large spatial extent of Greenland and the varying conditions of solar, wind, and hydropower across the nation, consideration of specific energy targets and approaches would help guide place-based decision-making between local and national government, and could serve both to sustain local communities and to foster a sustainable national energy system. This is true for not only the local source of renewable energy, but also for possibilities for energy storage. For example, the cost of hydrogen storage is declining globally, and in the long term if members of remote communities see safety and value in that new technology, the future addition of hydrogen storage in the energy system might be useful for remote villages. In addition to technical considerations, energy policy focused on promoting local expertise in decentralized/renewable energy production, along with the training that will be needed, could make renewable energy more accessible to remote communities [31]. This preliminary assessment investigated the technical aspects of implementing renewables in the village of Qaanaaq. In ongoing research, we will continue to conduct research with the citizens of Qaanaaq and other nearby settlements and with Nukissiorfiit to assess preferences and possibilities for a refined plan that will enable these communities to reach their short-term and long-term energy and sustainability goals, which includes the preservation of aspects of their cultural heritage via decreased energy burdens and greater self-reliance as a community. Meeting these community energy goals will also benefit the nation of Greenland as a whole.

CRediT authorship contribution statement

Alyssa Pantaleo: Conceptualization, Methodology, Writing – original draft, Software, Investigation. **Mary R. Albert:** Supervision, Project administration, Funding acquisition, Conceptualization. **Hunter T. Snyder:** Data curation, Writing – original draft, Investigation. **Stephen Doig:** Conceptualization, Writing – review & editing. **Toku Oshima:** Conceptualization, Validation. **Niels Erik Hagelqvist:** Writing – review & editing, Validation.

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.

Data availability

Data will be made available on request.

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Appendix A. Model inputs and sources of data

The following sections describe the sources of data, assumptions, and various constraints used to model diesel, solar, battery, and hydrogen energy generation and storage.

A.1. Diesel generator constraints

The community currently has five diesel generators of capacities ranging from 300–616 kilowatts(kW). For the models, three of these generators are designated as available capacity, and two are reserved for ancillary services. Each generator is constrained to run between 40%–100% of its rated capacity. Additionally, generators have fixed costs relating to their run-hours in order to pay for new capacity when generators reach their lifespan (45,000 run hours).

A.2. Load data

Qaanaaq's demand information was provided by Nukissiorfiit. For this preliminary study, load profiles for a representative day for each month were created based on available trend curves from Nukissiorfiit's SCADA system with added randomly generated fluctuations; the total fabricated demand falls within 0.5% of the known total generation for the 2019–2020 year. Hourly demand data over the course of a year are currently inaccessible by Nukissiorfiit. Nukissiorfiit requires special and expensive servers to access data logged by the metering system. The implications of the unknown diurnal cycling are discussed in Section 3.2, but the level of diurnal load variation is not expected to significantly change the estimate of the chosen battery capacity.

A.3. Fuel cost calculations

Fuel costs in Greenland are determined by an agreement between a fuel wholesaler, PolarOil, and the Government. Fuel is bought in bulk on a yearly basis and stored in local deposits to ensure price stability. The fuel price is fixed for all localities to ensure equity. Therefore the consumer diesel price in Qaanaaq is the same as in the much farther south Nuuk. The only tax imposed on fuel is a small environmental tax, unlike Denmark and other European countries that apply energy, CO2, NOx, and value added taxes. The consumer price of fuel in Greenland is therefore very low compared to Europe. However, this consumer price likely does not reflect the full embedded costs of transportation, port fees, or taxes that would be applicable if Greenland were more independent economically from Denmark. Several methods were used to calculate fuel costs based on a build-up method (calculating the cost of diesel per liter based on barrel price, freight (bunker, fixed hire, insurance), and port costs). A sensitivity analysis of fuel price on models

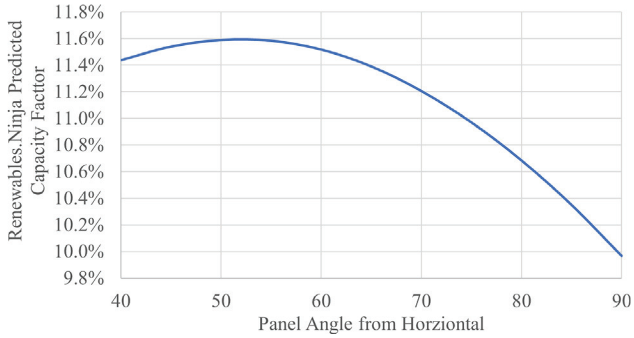

Fig. 4. Predicted Capacity Factor for Solar Installations vs. solar panel tilt from horizontal.

is included using 2021 prices from 0.71 US-Dollar (USD)/liter - 1.87 USD/liter, where the lower end represents a realistic cost of fuel coming from Amsterdam, Rotterdam, or Anterwerp (ARA) to Nuuk using projected futures for ultra-low sulfur diesel fuel contracts, translating to spot prices around 2.50 USD/Gallon. This final price per liter is very close to the consumer price for diesel in Greenland of roughly 0.68 USD/liter(4.55 DKK) depending on exchange rate for the 2020–2021 oil prices. A mid-range price, 1.02 USD/liter assumes more costs are incurred by PolarOil (owned by the Government of Greenland) in order to ship the oil more North. The highest fuel price represents the price of diesel fuel in Denmark at the time of analysis (Fall 2021), which embodies the taxes Greenland would pay for diesel fuel with greater economic independence from Denmark. Nukissiorfiit purchases diesel fuel for community power plants at the subsidized price directly from PolarOil. However, being a government-run entity, an analysis of community energy systems with higher prices and potential long-term savings from increased use of renewables would be of interest to the Greenlandic Government as global fossil fuel prices increase.

A.4. Solar resource and cost prediction

Solar resource data was collected from NASA's Prediction of Worldwide Energy Resources GIS data and RenewablesNinja, which uses the Surface Solar Radiation Data Set - Heliosat (SARAH) [32]. Solar power was then calculated by converting GIS data to power generated on a tilted panel suited for Qaanaaq's latitude. A brief analysis, shown in Fig. 4 using RenewablesNinja shows that a tilt of 50–55 degrees optimizes the capacity factor for fixed-axis panels facing South (azimuth 180) [32,33]. Fig. 5 shows the insolation Qaanaaq receives over the course of one year according to GIS data. Qaanaaq experiences 24-hour, low-angle sunlight from about April until November, but from November until mid-February, the sun does not rise above the horizon for any portion of the day. For a 1000 kilowatt-peak installation, the yearly average specific yield in kWh/kWp is 567 (or 1.57 per day), which can be compared to Suldal, Rogaland, Norway, (the location closest in latitude to Qaanaaq that global solar data is analyzed) which has 970 kWh/kWp per year at 59 North latitude, according to the Global Solar Atlas. Since site-assessments for solar arrays in Qaanaaq are forth-coming, and there are no trees or buildings near potential solar sites, any minimal losses due to shading are included in the estimation of total losses. The total losses are assumed to be 17%, including losses from inverter efficiency, age, wiring, light-induced degradation, soiling, snow and shading. Losses due to snow and soiling from dust are likely to be the main sources of solar power loss in Qaanaaq due to windbourne dust from the glacial till and small bouts of precipitation.

Solar power is not widely used in the far north of Greenland. Therefore, there is little comparison for costs of panels, transportation, and installation. In Sarfannguit, Greenland, PV prices were estimated at 2800 USD/kW in 2014 [34]. In the Canadian Arctic, panel price estimates have exceeded 5000 USD/kW in 2019 and 2020 [2,3]. A range of installed panel prices (excluding inverters and cabling) were suggested by Nukissiorfiit based on two potential categories: fixed PV installed on solid bedrock and fixed PV installed on terrain that requires additional foundations both of which are considering WINAICO monofacial 375 kWp/panel panels. The range of prices considered is 2560 USD/kW–3760 USD/kW, with additional costs of inverters and accessories. Bifacial panels have the potential to increase the output significantly in Greenland, considering the highly reflective surfaces of the nearby water and land, however, it is estimated that bifacial panels could cost up to 33% more in Greenland than monofacial, according to Nukissiorfiit. Qaanaaq sits on permafrost and glacial till, which will require additional foundation materials. The price range of for PV installed on this terrain is likely 3160 USD/kW–3760 USD/kW. Therefore, 2560 USD/kW is used as a low, optimistic value, and 3760 USD/kW is used as a conservative high.

A.5. Energy storage constraints

The battery capacity is chosen by the model optimization. The state of charge is constrained by this capacity, and by the depth of discharge, which is assumed to be 80%. The round-trip efficiency of the battery is fixed and assumed to be 80%. New battery capital costs are added when the chosen capacity exceeds 3000 charging cycles, although longer battery lifespans are explored [2].

The hydrogen storage system assumes an 150 kW fuel cell and electrolyser, and a variable storage tank size (kWh). To be efficient for long-term storage, a large tank is needed at the expense of higher capital. The fuel cell and electrolyser operate at fixed efficiencies of 50% and 80% respectively. Because this model assumes compressed hydrogen, $100,000 is added into hydrogen capital costs for the compressor [4]. Operations and maintenance costs for the electrolyser, fuel cell, and storage are expressed as percentages of the capital costs of each component.

Appendix B. BES cycling sensitivity analysis

It is projected that future battery lifespans will increase dramatically, due to ongoing innovations in battery technology. Therefore, a short sensitivity analysis on battery cycle has been pursued, using the 0.71 USD/liter fuel price. In the above analysis, a lifespan of 3000 cycles was used. The following analysis assumes the commercially available batteries for these energy projects can survive 10,000 cycles, or that the price of batteries that can be achieved in Greenland decreases by half. Table 9 shows that optimal capacities for batteries will be sensitive to cycle lifetimes and price. However, the impact on LCOE is small. Waiting for lower prices or increased capacities, however, will not greatly improve the economic feasibility of incorporating BES into Qaanaaq's energy system. Including battery energy storage at the time of solar array installation will increase system resilience and provide the greatest benefit.

Appendix C. Hydrogen dispatch discussion

Figs. 6 and 7 show how the hydrogen storage system would optimally be dispatched in Qaanaaq's energy system to minimize energy generation costs considering two different storage capacities. These plots illustrate how the combination of solar and diesel generators contribute to hydrogen generation, and when hydrogen is used for electricity. Ideally, solar over-generation in the summer would contribute to hydrogen dispatch during the fall and beginning of winter to reduce diesel generator use. Fig. 7, which includes 6000 kWh of hydrogen storage capacity shows greater hydrogen dispatch during the spring and winter (hours 50–100), however, there is still a dependence on the largest generator (Gen2) for overproduction for hydrogen. Given that

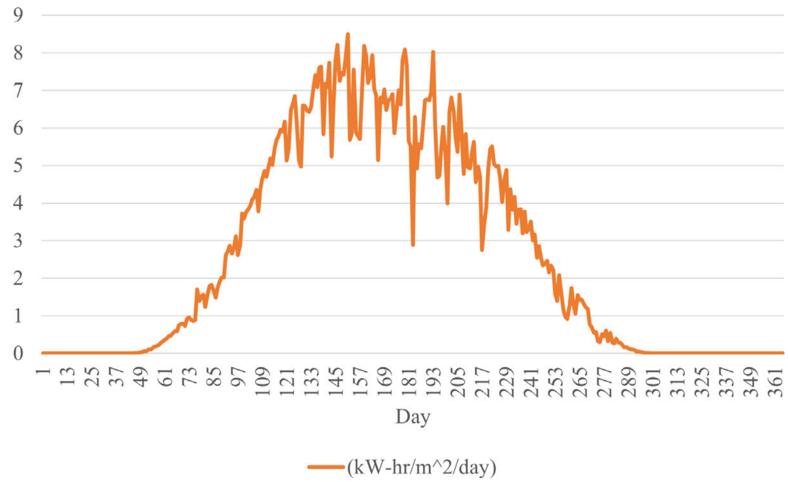

Fig. 5. Solar insolation over the course of a year in Qaanaaq, Greenland.

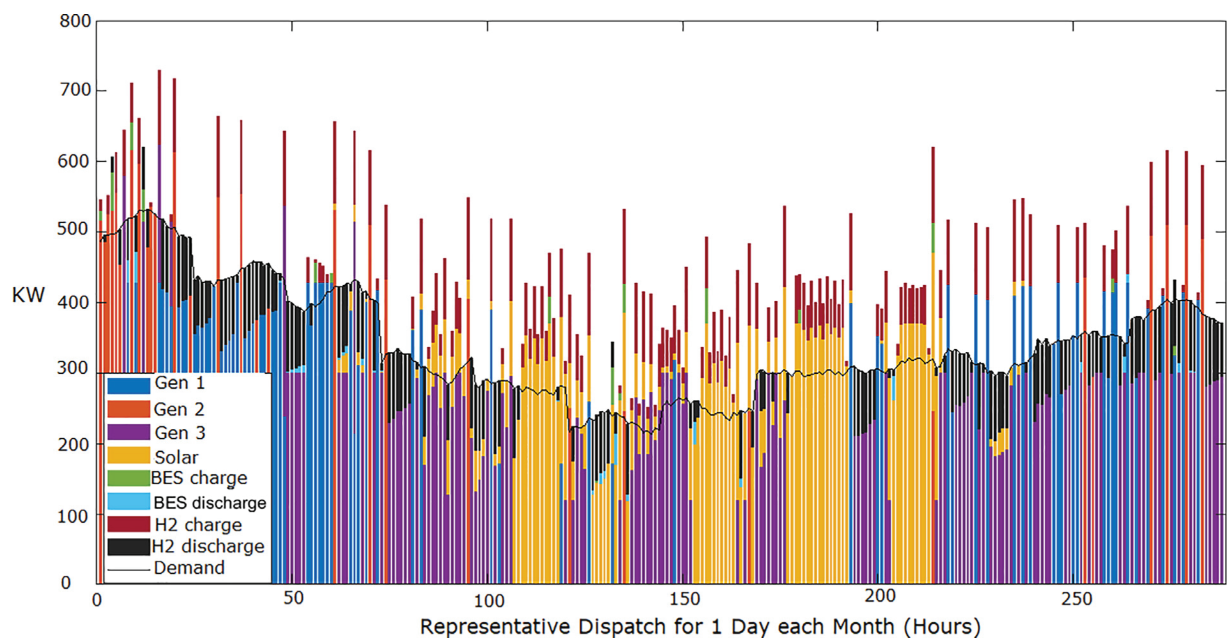

Fig. 6. Dispatch of generating sources under solar–diesel–bes–hydrogen hybridization with 3500 kWh of hydrogen storage available.

Table 9
Solar and BES capacities, and LCOE for BES lifetimes of 3000 cycles and 10,000 cycles.

Parameters	3000 Cycles,760 USD/kWh	10,000 Cycles,760 USD/kWh	3000 Cycles, 380 USD/kWh	10,000 Cycles,380 USD/kWh
Solar Capacity [kW]	380	370	376	362
BES Capacity [kWh]	45	84	78	98
LCOE [USD/kWh]	0.25	0.25	0.256	0.25

fall and winter hydrogen dispatch can still be achieved with smaller storage capacities (Fig. 6), albeit not entirely via renewables, smaller storage capacities may still contribute positively to Qaanaaq's energy system. Stored solar is used during periods of low solar availability and

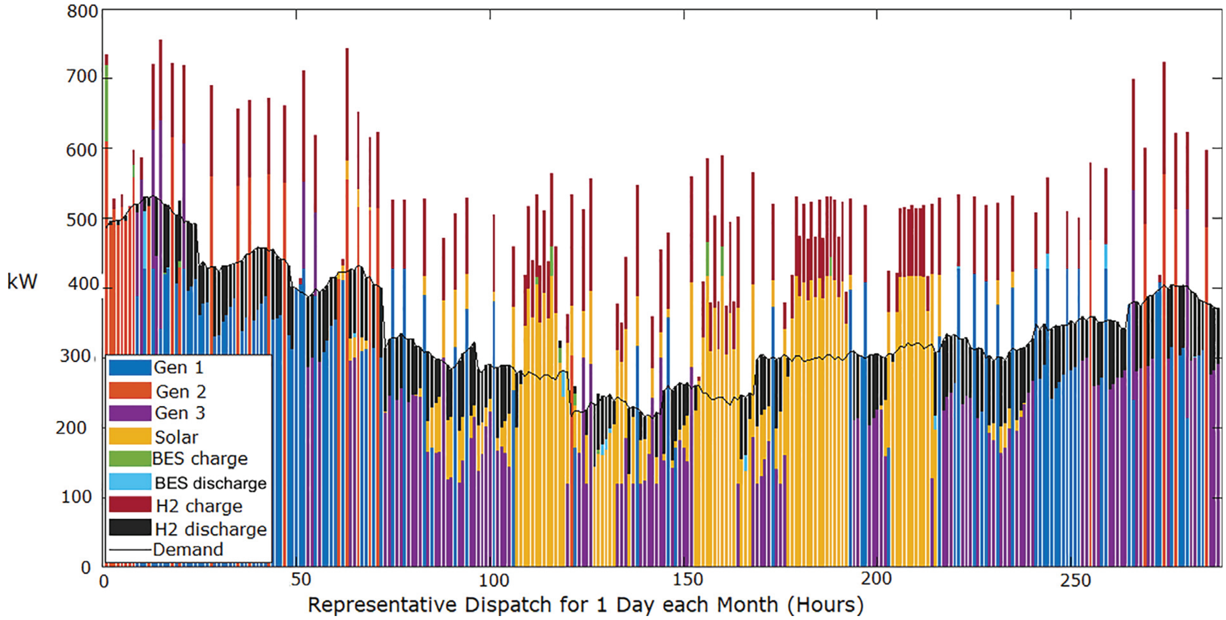

Fig. 7. Dispatch of generating sources under solar–diesel–bes–hydrogen hybridization with 6000 kWh of hydrogen storage available.

as solar resource decreases seasonally. Generators that would typically have to run at a low load due to low demand can run more efficiently at higher load to create hydrogen.

References

[1] Cauz Marine, Bloch Lionel, Rod Christian, Perret Lionel, Ballif Christophe, Wyrsch Nicolas. Benefits of a diversified energy mix for islanded systems. Front Energy Res 2020;8:147. http://dx.doi.org/10.3389/fenrg.2020.00147.

[2] Das Indrajit, Cañizares Claudio A. Renewable energy integration in diesel-based microgrids at the Canadian arctic. Proc IEEE 2019;107(9):1838–56. http://dx.doi.org/10.1109/JPROC.2019.2932743, Conference Name: Proceedings of the IEEE.

[3] Ninad Nayeem, Turcotte Dave, Poissant Yves. Analysis of PV-diesel hybrid microgrids for small Canadian arctic communities. Can J Electr Comput Eng 2020;43(4):315–25. http://dx.doi.org/10.1109/CJECE.2020.2995750, Conference Name: Canadian Journal of Electrical and Computer Engineering.

[4] Chade Daniel, Miklis Tomasz, Dvorak David. Feasibility study of wind-to-hydrogen system for arctic remote locations – grimsey island case study. Renew Energy 2015;76:204–11. http://dx.doi.org/10.1016/j.renene.2014.11.023, URL https://www.sciencedirect.com/science/article/pii/S0960148114007381.

[5] Puranen Pietari, Kosonen Antti, Ahola Jero. Technical feasibility evaluation of a solar PV based off-grid domestic energy system with battery and hydrogen energy storage in northern climates. Sol Energy 2021;213:246–59. http://dx.doi.org/10.1016/j.solener.2020.10.089, URL https://www.sciencedirect.com/science/article/pii/S0038092X20311592.

[6] Groppi Daniele, Astiaso Garcia Davide, Lo Basso Gianluigi, Cumo Fabrizio, De Santoli Livio. Analysing economic and environmental sustainability related to the use of battery and hydrogen energy storages for increasing the energy independence of small islands. Energy Convers Manage 2018;177:64–76. http://dx.doi.org/10.1016/j.enconman.2018.09.063, URL https://www.sciencedirect.com/science/article/pii/S0196890418310665.

[7] Parra David, Swierczynski Maciej, Stroe Daniel I, Norman Stuart A, Abdon Andreas, Worlitschek Jörg, O'Doherty Travis, Rodrigues Lucelia, Gillott Mark, Zhang Xiaojin, Bauer Christian, Patel Martin K. An interdisciplinary review of energy storage for communities: Challenges and perspectives. Renew Sustain Energy Rev 2017;79:730–49. http://dx.doi.org/10.1016/j.rser.2017.05.003, URL https://www.sciencedirect.com/science/article/pii/S1364032117306263.

[8] IRENA. The transformative power of storage: Developing IRENA's electricity storage roadmap, URL https://www.irena.org/events/2014/Mar/The-Transformative-Power-of-Storage-Developing-IRENAs-Electricity-Storage-Roadmap.

[9] Aslani Mehrdad, Imanloozadeh Amir, Hashemi-Dezaki Hamed, Hejazi Maryam A, Nazififard Mohammad, Ketabi Abbas. Optimal probabilistic reliability-oriented planning of islanded microgrids considering hydrogen-based storage systems, hydrogen vehicles, and electric vehicles under various climatic conditions. J Power Sources 2022;525:231100. http://dx.doi.org/10.1016/j.jpowsour.2022.231100, URL https://www.sciencedirect.com/science/article/pii/S0378775322001240.

[10] Chowdhury MS, Rahman Kazi Sajedur, Selvanathan Vidhya, Nuthammachot Narissara, Suklueng Montri, Mostafaeipour Ali, Habib Asiful, Akhtaruzzaman Md, Amin Nowshad, Techato Kuaanan. Current trends and prospects of tidal energy technology. Environ Dev Sustain 2021;23(6):8179–94. http://dx.doi.org/10.1007/s10668-020-01013-4.

[11] Etemadi Ahmad, Emami Yunus, AsefAfshar Orang, Emdadi Arash. Electricity generation by the tidal barrages. Energy Procedia 2011;12:928–35. http://dx.doi.org/10.1016/j.egypro.2011.10.122, URL https://www.sciencedirect.com/science/article/pii/S1876610211019485.

[12] Greaves Deborah, Iglesias Gregorio. Wave and tidal energy. John Wiley & Sons: OKtTDwAAQBAJ; 2018, Google-Books-ID.

[13] Rehman Shafiqur, Al-Hadhrami Luai M, Alam Md Mahbub. Pumped hydro energy storage system: A technological review. Renew Sustain Energy Rev 2015;44:586–98. http://dx.doi.org/10.1016/j.rser.2014.12.040, URL https://www.sciencedirect.com/science/article/pii/S1364032115000106.

[14] Koen Antoine, Farres Antunez Pau, White Alexander. A study of working fluids for transcritical pumped thermal energy storage cycles. In: 2019 Offshore energy and storage summit (OSES). 2019, p. 1–7. http://dx.doi.org/10.1109/OSES.2019.8867217.

[15] Kuo Ming-Tse, Lu Shiue-Der, Tsou Ming-Chang. Economic dispatch planning based on considerations of wind power generation and pumped storage hydroelectric plants for isolated power systems. In: 2015 IEEE/IAS 51st industrial commercial power systems technical conference (I CPS). 2015, p. 1–10. http://dx.doi.org/10.1109/ICPS.2015.7266405, ISSN: 2158-4907.

[16] IEA. Technology roadmap on hydrogen and fuel cells. Technical report, IEA; 2015.

[17] Kharel Subodh, Shabani Bahman. Hydrogen as a long-term large-scale energy storage solution to support renewables. Energies 2018;11(10):2825. http://dx.doi.org/10.3390/en11102825, URL https://www.mdpi.com/1996-1073/11/10/2825, Number: 10 Publisher: Multidisciplinary Digital Publishing Institute.

[18] Nastasi B, Mazzoni S, Groppi D, Romagnoli A, Astiaso Garcia D. Optimized integration of hydrogen technologies in island energy systems. Renew Energy 2021;174:850–64. http://dx.doi.org/10.1016/j.renene.2021.04.137.

[19] Steilen Mike, Jörissen Ludwig. Chapter 10 - hydrogen conversion into electricity and thermal energy by fuel cells: Use of H2-systems and batteries. In: Moseley Patrick T, Garche Jürgen, editors. Electrochemical energy storage for renewable sources and grid balancing. Amsterdam: Elsevier; 2015, p. 143–58. http://dx.doi.org/10.1016/B978-0-444-62616-5.00010-3, URL https://www.sciencedirect.com/science/article/pii/B9780444626165000103.

[20] Goldstein Anna. Federal policy to accelerate innovation in long-duration energy storage: The case for flow batteries. Technical report, Information Technology and Innovation Foundation; 2021, URL https://itif.org/publications/2021/04/07/federal-policy-accelerate-innovation-long-duration-energy-storage-case-flow.

[21] Marchenko OV, Solomin SV. Modeling of hydrogen and electrical energy storages in wind/PV energy system on the lake baikal coast. Int J Hydrogen Energy 2017;42(15):9361–70. http://dx.doi.org/10.1016/j.ijhydene.2017.02.076, URL https://www.sciencedirect.com/science/article/pii/S0360319917305517.

[22] Peláez-Peláez Sofía, Colmenar-Santos Antonio, Pérez-Molina Clara, Rosales Ana-Esther, Rosales-Asensio Enrique. Techno-economic analysis of a heat and power

combination system based on hybrid photovoltaic-fuel cell systems using hydrogen as an energy vector. Energy 2021;224:120110. http://dx.doi.org/10.1016/j.energy.2021.120110, URL https://www.sciencedirect.com/science/article/pii/S0360544221003595.

[23] Rud Jakob Nymann, Hørmann Morten, Hammervold Vibeke, Ásmundsson Ragnar, Georgiev Ivo, Dyer Gillian, Andersen Simon Brøndum, Jessen Jes Erik, Kvorning Pia, Brødsted Meta Reimer. Energy in the west nordics and the arctic : Case studies. Nordisk Ministerråd; 2018, URL http://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-5350.

[24] Energianalyse Ea. Udnyttelse af overskudsel i ilulissat til produktion af brint: Analyse af mulighederne for brintproduktion og andre afsætingsmuligheder. 2018.

[25] Tarhan Cevahir, Çil Mehmet Ali. A study on hydrogen, the clean energy of the future: Hydrogen storage methods. J Energy Storage 2021;40:102676. http://dx.doi.org/10.1016/j.est.2021.102676, URL https://www.sciencedirect.com/science/article/pii/S2352152X21004151.

[26] Boateng Emmanuel, Chen Aicheng. Recent advances in nanomaterial-based solid-state hydrogen storage. Mater Today Adv 2020;6:100022. http://dx.doi.org/10.1016/j.mtadv.2019.100022, URL https://www.sciencedirect.com/science/article/pii/S2590049819300967.

[27] Parra David, Gillott Mark, Walker Gavin S. Design, testing and evaluation of a community hydrogen storage system for end user applications. Int J Hydrogen Energy 2016;41(10):5215–29. http://dx.doi.org/10.1016/j.ijhydene.2016.01.098, URL https://www.sciencedirect.com/science/article/pii/S036031991531154X.

[28] Naalakkersuisut. Sector plan for energy and water supply - naalakkersuisut. 2018.

[29] Soroudi Alireza. Power system optimization modelling in GAMS, model DEDESS (Gcode7.1) in chapter energy storage systems. 2017.

[30] Nukissiorfiit. Annual report 2020- nukissiorfiit. 2020.

[31] SDWG Sustainable Development Working Group. Arctic community energy planning and implementation toolkit. 2019, URL https://oaarchive.arctic-council.org/handle/11374/2374, Accepted: 2019-05-08T07:44:49Z Publisher: Arctic Council Secretariat.

[32] Pfenninger Stefan, Staffell Iain. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 2016;114:1251–65. http://dx.doi.org/10.1016/j.energy.2016.08.060, URL https://www.sciencedirect.com/science/article/pii/S0360544216311744.

[33] Staffell Iain, Pfenninger Stefan. Using bias-corrected reanalysis to simulate current and future wind power output. Energy 2016;114:1224–39. http://dx.doi.org/10.1016/j.energy.2016.08.068, URL https://www.sciencedirect.com/science/article/pii/S0360544216311811.

[34] Jakobsen Kasper Rønnow. Renewable energy potential of greenland with emphasis on wind resource assessment. DTU wind energy PhD, DTU Wind Energy; 2016.