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# Analysis of Energy Storage Technologies for Island Microgrids

## A Case study of the Ærø Island in Denmark

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***Abstract*—Microgrids can increase the security of supply of electricity systems, and also can support to achieve a carbon-free electricity system in the areas where the security of supply is close to 100%. Besides technical aspects, characteristics such as optimum design, cost consideration factors and different technologies have to be addressed. Meanwhile, there are challenges for cost-effective carbon-free microgrids due to intermittency and fluctuation issues. Therefore, energy storage technologies have been proposed to facilitate the transition to a CO2 emission-free solution. This paper proposes a framework to analyze the feasibility of energy storage technologies for microgrids. The method considers input requirements and issues such as economic feasibility, energy technology selection, renewability assessment, storage capability, etc. The method is applied in a case of a Danish island to achieve the overall goal of having a 100% renewable portfolio. Several storage technologies are evaluated with three defined criteria. The result shows that it is possible to obtain a feasible solution with the application of energy storage technologies in the island with a drawback of increasing the final energy cost.**

***Index Terms*—Microgrid, Island, Energy Storage Technology, Framework.**

### I. Introduction

With the increasing energy demand and the climate change challenge, the European Union (EU) Commission has an ambitious climate action to implement the proposed renewable goals until 2030 [1]. Among other solutions, islands are specifically handled by the EU as architects of their own energy transition and case studies for achieving a 100% renewable energy system [2].

To implement the EU goals, communities including islands need to consider increasing their energy resiliency and reliability while transitioning to a carbon-free energy system, and microgrids stand out as a feasible solution [3]. A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [4]. A microgrid can connect and disconnect the main electricity grids to enable the operation in both grid-connected or island mode. Microgrids can trade electricity with the main grids which can be an advantage when the non-dispatchable distributed energy resources are intermittent.

To improve microgrid reliability and resilience, energy storage technologies become crucial for the full adoption of renewable energy systems that can release network unbalances by storing energy at off-peak hours and supply energy at peak hours [5], [6]. Energy storage technologies can be applied over several applications, such as peak shaving, spinning reserve, voltage support, black start, frequency regulation, power quality, etc. [5].

In recent years, research on energy storage systems for microgrids mainly focuses on control strategy and technical requirements [7]. Meanwhile, most work is based on theoretical simulations, and neglects the real world challenges when analyzing case scenarios [8], [9]. Therefore, there is a need to focus on the real-world aspects such as cost consideration factors, technology limitations, energy storage life quantization, etc. with a systematic methodological approach for the application of technologies, e.g. energy storage, in microgrids.

Microgrids can increase the security of supply of electricity systems, and also can support the achievement of a carbon-free electricity system in the areas where the security of supply is close to 100%. Few researches have addressed the aspect of the carbon-free system via storage technologies applied to microgrids. Therefore, this paper uses a Danish island called Ærø as a case study to investigate the green transition in small communities such as islands. Ærø is characterized as a grid-connected community microgrid and has a goal of being 100% renewable and self-sufficient by 2025 [10].

### II. Methods

The framework for the investigation of energy storage technologies in island microgrids is based on three criteria: renewability, cost of energy and security of supply. These criteria generate conflict objectives. The production side must be entirely renewable. However, renewable sources usually represent some kind of intermittence and, a high investment is required to ensure the possibility to have high security of supply. Furthermore, keeping the energy price close to the grid-connected reference is the main economic challenge since more investment in a renewable microgrid. Legal challenges also are a major concern when increasing the renewable fraction of an energy system, such as preservation areas, public resistance, etc.

The proposed framework is shown as a flowchart in Fig. 1 with five main components: Dimensioning, Technologies, Implementation, Evaluation, and Sensitivity.

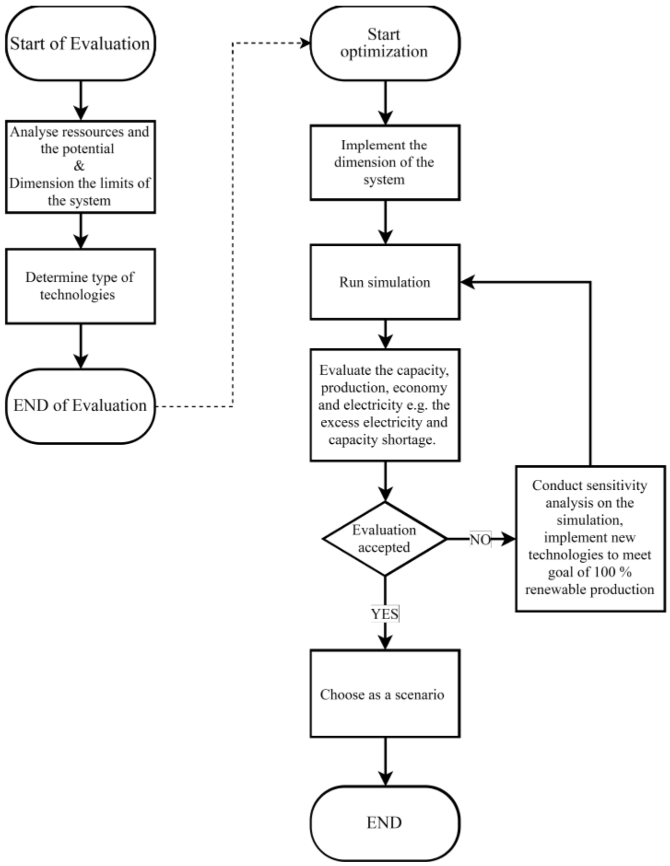


Fig. 1. Energy storage systems framework applied to microgrids.

## A. Dimensioning

Dimensioning is the pre-study before the microgrid structure is proposed. In this phase all characteristics of the island needs to be taken into consideration. One of the most important elements is the load profile that shows how much energy the system consumes and how this can change over the analysed period. Besides that, all efforts to improve energy consumption and energy efficiency needs to be considered. The available resources and the restraints to import energy sources are essential for the next phase.

The economic investment comes in two ways: 1) the investment in storage technologies that give the ability to move excess production to periods where production is too low, 2) the need of over production capacity to ensure hours with excess production.

## B. Technologies

Given the analysis of the island, its potential and restrictions, the technologies selection are conducted based on the available energy resources, such as average solar irradiation, wind speed, hydro availability, etc. Potential candidates can be excluded later, depending on their cost, for example. Although different approaches can be conducted in this phase, the main proposition of this paper is to analyze the viability of storage systems as transition drivers.

The evaluated storage technologies are shown in Fig. 2. The capabilities of each technology is dependent on the discharge time and their optimum power rate, where flywheels provide energy on second basis, li-ion batteries provide energy on minute to hours basis, while fuel cells are able to provide energy as long as hydrogen is available. That means that flywheels are better suited for system stability, batteries for peak shaving, and the hydrogen set-up for long term load shifting.

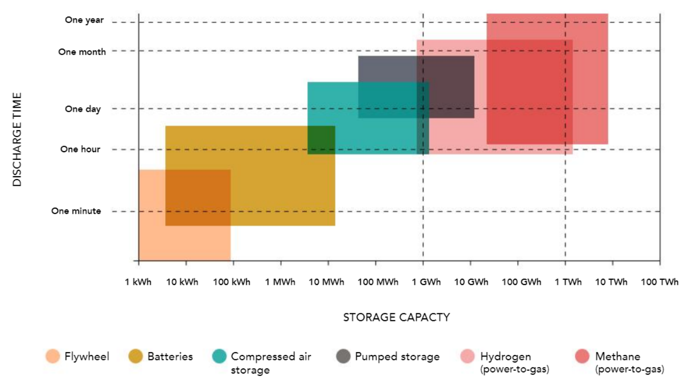


Fig. 2. Storage technologies [11].

## C. Implementation

To evaluate the feasibility and capacity of each component, an optimization is performed followed by the selection criteria to find the best candidate. An optimization calculation is performed to define the best microgrid configuration. There are several conflict objectives regarding microgrids. The cost for each generation unity should be fully addressed with the consideration of the initial capital investment, replacement costs, operation, maintenance cost, fuel prices, expected variation, etc.

To validate the proposed framework, the Hybrid Renewable and Distributed Generation System Design Software (HOMER) was used [12]. HOMER is used to simulate microgrids systems including energy storage technologies analysis. For every component type, there is a built-in catalog with different brands and capacities with all necessary technical and financial information. The microgrid can have the option to connect to the main grid or not. When simulating a microgrid system, HOMER performs three different processes: simulation, optimization, and sensitivity analysis.

## D. Evaluation

The evaluation of the system depends on the restriction of the electricity characteristics, e.g. which type of storage unit is suited for implementation, the excess electricity, capacity shortage, etc. As the information is gathered, the simulations can be run and are evaluated on the following performance aspect:

- Cost of Energy (COE)
- Net Present Cost (NPC)
- Annualized costs
- Unmet electrical load
- Capacity shortage
- Excess electricity
- Renewable fraction
- Emissions

The simulation estimates the life-cycle cost of the system, that can be calculated as one value, the Net Present Cost (NPC), which allows the comparison of different systems, as shown in Equation 1. Where $C_{ann}^{total}$ is the total annualized cost, $i$ is the discount rate, and $N$ is the project life span.

$$NPC = \frac{C_{ann}^{total}}{\frac{i(1+i)^N}{(1+i)^N - 1}} \tag{1}$$

Concurrently, the Cost Of Energy (COE) is calculated, as shown in Equation 2. Where $E_{pim}$ is the total primary load, $E_{def}$ is the total deferrable load, and the $E_{grid\ sales}$ is the total amount of energy sold to the grid.

$$COE = \frac{C_{ann}^{total}}{E_{pim} + E_{def} + E_{grid\ sales}} \tag{2}$$

After the current system is defined and simulated, a pre-study is made, where simulations are made for different storage technologies and different scenarios with energy production, e.g. increased wind production. The evaluated storage technologies have different characteristics such as range of capacity and supply time from flywheels, li-ion batteries, and fuel cells. Depending on the outcome of the pre-study, different scenarios can be combined to form the best off-grid solution.

### *E. Sensitivity*

An important aspect of this phase is to consider the uncertainty of the input variables. Values such as the fuel price, wind speed, solar irradiation, inflation rate, etc. can suffer significant variation during the project lifetime. Therefore, a sensitivity analysis needs to be considered for the most important inputs.

## III. Case Study

This study uses the island of Ærø as a case study to validate the methodology. Ærø lies in the Baltic sea and it is located in the southern archipelago of Denmark. The island is largely rural and covers an area of 90 km$^2$ with 5,335 measure points and around 6,200 inhabitants that consume around 26 GWh/year of electricity [10]. The island's population density is about 13% that of the average national value, however, the same pattern is found in 75 of Denmark's 98 municipalities [13].

Table I presents all the primary energy sources for Ærø, including onshore wind turbines, biomass district heating plants, and solar plants. Ærø has worked actively over more than 30 years to encourage the use of renewable sources. Today, over 60% of the island's total energy is produced by six large wind turbines supplemented by more than 250 solar panels and three district heating plants based on solar heat and biomass, ensuring a high share of carbon-neutral electricity and heat. Nowadays, a large portion of the energy production in Ærø comes from the installed solar and wind energy, is comprised of six 2 MW wind turbines and residential PVs of 1.35 MW. The energy vision is to become carbon neutral and self-sufficient with renewable energy by 2025 [10].

TABLE I
THE ENERGY SUPPLY ON ÆRØ.

| Supply | Capacity/quantity |
|---|---|
| Wind Turbine | 6 x 12 MW (V90-2.0) |
| Residential PV | 1.35 MV |
| Main Grid 1 | 21.3 MW (12.1 km) |
| Main Grid 2 | 23.4 (6.75 km) |

Although Ærø's electricity and heating systems have integrated renewables, the transport currently relies almost entirely on fossil fuels. Like most of the islands in Denmark, Ærø is grid-connected with two cables with capacities of 21.3 MW(12.1 km) and 23.4 MW(6.5 km).

There are small protected areas on Ærø by Natura 2000 [14], and there is still available area to increase the number of wind turbines. In the zone plan, a total of 14 positions for wind turbines are suggested where currently only three were placed [15]. Ærø's annual electricity consumption is shown in Fig. 3. It drops from January to July and rises afterward until December. Therefore, more power is needed during winter for heating appliances. There are small peaks around Easter and summer holidays that are the high tourism seasons. On a daily basis, the average peak of the island is around 5 MW.

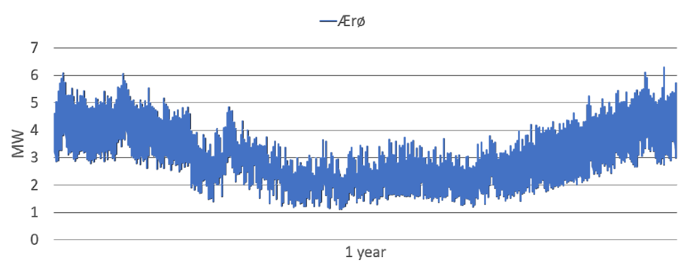


Fig. 3. Yearly load profile of Ærø (2017) [10].

In the year of 2018, Ærø had five months when the production was higher than their own local consumption and in the remaining period, the average monthly wind production was 70% [16]. The duration curve in Fig. 4 shows that around 2000 hours of the year have zero, or close to zero production from the wind. This shows the opportunity to use the excess electricity in these hours. To accomplish this, the framework of Fig. 1 will be applied in this case study to help the island to achieve its self-sustainable goals.

The data of the electricity consumption is captured from the Energinet's market data web service [17]. The component price is obtained from the technology catalog [10]. Futhermore, the connection data is from the grid company supplying electricity in Southern Jutland and parts of Northern Jutland [18]. The considered inflation rate is 2% since it is the average

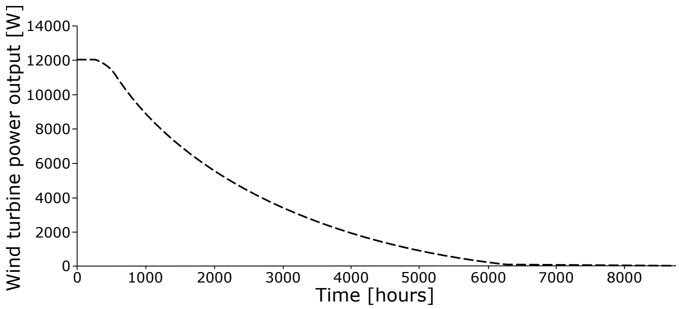


Fig. 4. Duration curve for the power output of the wind turbines over the year [10].

inflation rate in Europe [19]. Average wind speeds regarding Ærø's geographic location were obtained from NASA database over a 10 year period from 1983 to 1993. With this data, the yearly production from the current turbines is found and compared with the ones in the simulation. The project lifetime is set to be 25 years.

## IV. Results

Six scenarios were selected as potential candidates by the optimization using HOMER software [12]. Their production and storage capacities are listed in Table II. As shown in Fig. 2, different storage technologies are capable of supplying energy for different time horizons. The flywheel could supply energy for the shortest amount of time, since it has the highest capacity shortage. The fuel cell and electrolyzer combination, which has the longest supply time, fits better into the system as it has the best ability to fill out the time when the wind turbines don't run. This storage solution is the most expensive candidate and results in the highest COE for the pre-study scenarios (Fig. 5). As it is the most expensive scenario, it could be better to use other cheaper storage technologies for the last peak hours, instead of upscaling the size of the fuel cell, electrolyzer, and storage tank.

TABLE II
Technology Scenarios

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| PV [MW] | 1.34 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 |
| Wind Turbine [MW] | 12 | 24 | 12 | 24 | 12 | 24 |
| Battery [MWh] | 50 | 5 | – | – | – | – |
| Flywheel [MW] | – | – | 6.5 | 6.5 | – | – |
| Electrolyzer [MW] | – | – | – | – | 10 | 10 |
| $H_2$ storage [ton] | – | – | – | – | 7 | 10 |
| Fuel cell [MW] | – | – | – | – | 3 | 3 |

Fig. 5 shows that scenario six (Electrolyzer) has the lowest capacity shortage which can provide energy during the whole year. The worst technology in regards to the capacity shortage is the flywheel (scenarios 3 and 4). The fuel cell is the best solution based on analysis result of the duration curve for the wind turbine production in Fig. 4.

### A. Combination of energy storage technologies

It is expected that the capacity shortage and unmet electrical load diminishes if a hydrogen storage tank for the fuel cell and battery for storing the electricity in the system are combined. The combined scenario is a composition of scenarios 2 and 6.

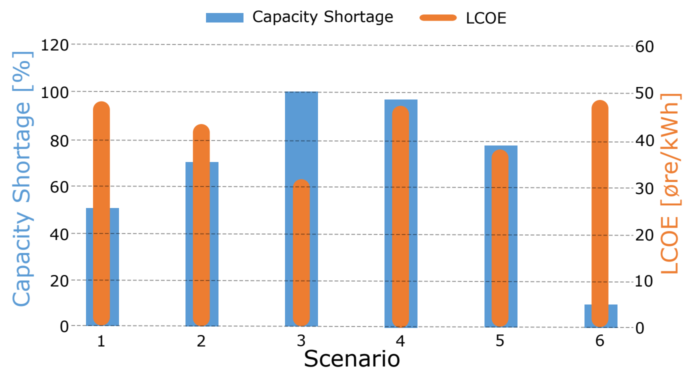


Fig. 5. Capacity shortage and Levelized cost of energy (LCOE) for each scenario.

TABLE III
Off-grid vs. grid-connected system

| | Off-grid | Grid-Connected |
|---|---|---|
| Annualized cost [mDKK] | 25.3 | 4.5 |
| COE [øre/kWh] | 99.6 | 9.1 |
| Excess electricity [%] | 25.4 | 0 |
| Unmet electrical load [%] | 2.31 | 0 |
| Capacity shortage [%] | 3.04 | 0 |
| Renewable fraction [%] | 100 | 86.9 |

The results are shown in Table III. The capacity shortage goes from 5% (in scenario 6) to 3% in this combined scenario. In this case, the electricity price has a slight increase of 2.6%. It goes from 0.970 DKK/kWh to 0.996 DKK/kWh.

The installed battery is approximately the same size as the average daily peak. The battery provides 431 MWh/yr with a COE difference between the two scenarios of 26 DKK/MWh. Therefore, there is only 431 MWh/yr $\cdot$ 26 DKK/MWh = 11, 206 DKK/yr for demand response. With 5,335 measure points on the island of Ærø, there are $\frac{11{,}206\ DKK/yr}{5{,}335 measure\ points} = 2.1\ DKK/yr/measure\ point$. Therefore, the adoption of household batteries is economically feasible.

### B. Criteria analysis

The results shown in Table III needs to be evaluated against the three criteria presented in section II: renewability, cost of energy and security of supply. Regarding the renewable fraction, the off-grid system achieves a 100% renewable production portfolio. An element not reflected in the renewable fraction of the grid-connected system is the amount of renewable energy that is inherent in the main grid. If including this, the renewable fraction of 86.9% would be higher. Regard the cost of energy, the grid-connected system is ten times cheaper. This indicates that storage technologies, such as Electrolyzer/Fuel Cell, still have a costly price when compared with traditional alternatives. For the third criteria, the off-grid solution presentes a relatively high unmet electrical load level when compared with the Danish electricity system.

### C. Sensitivity analysis

Wind speed determines the energy production of wind turbines. This may result in different levels of the capacity shortage and amount of excess electricity. Fig. 6, shows the capacity shortage and the unmet electrical load results in a drop from 10% to nearly 1% to 2% that when the average wind speed increases from 5 to 5.75 m/s. When the average wind speed increases further, the occurrence of capacity shortage and unmet electrical are unlikely to be found. Meanwhile, the excess electricity increases steadily with the average wind speed from 10% to over 50%.

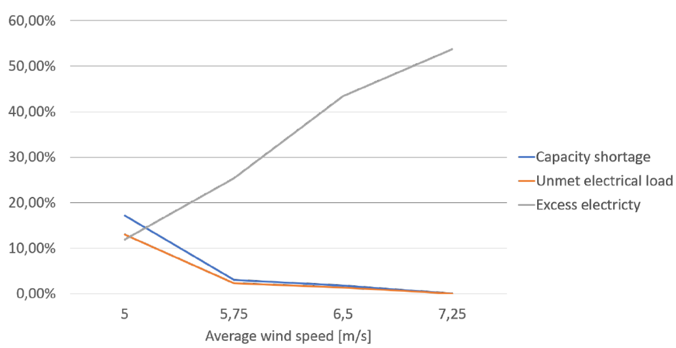


Fig. 6. Comparison of capacity shortage and excess electricity as a function of yearly average wind speed.

The excess electricity can be sold to the main grid to reduce the energy cost. In Fig. 7, the grid sales increase with the wind speed from 50% to 70% which lowers the excess electricity. The excess electricity after sold to the main grid increases instead from 0% to 30% which is averagely reduced 20% compared to not sold to the main grid.

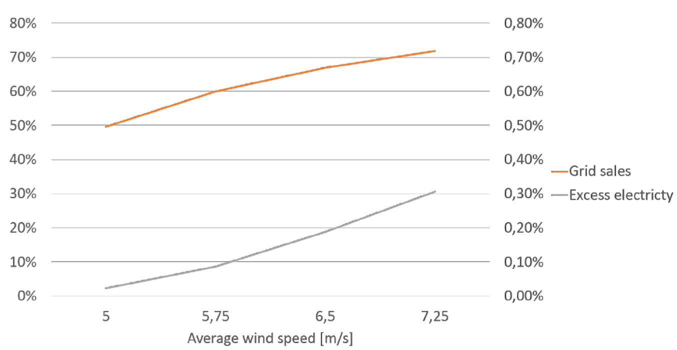


Fig. 7. Comparison of excess electricity and grid sales as a function of yearly average wind speeds. The Grid sales use the left axis while the excess electricity uses the right axis.

## V. Conclusion

The results of the case study show that the island Ærø can be greener. The best proposed hybrid solution is the combination of using both li-ion batteries and hydrogen as storage, and photovoltaics and wind turbines as production units. The sensitivity analysis result shows that the cost of the system can differ as the constraints and assumptions vary, e.g. a lower capacity shortage will change the simulation results. Therefore, the system and its analysis depend on the constraints of the electrical characteristics which would affect the total capacity of the system and the economical evaluation.

There are no significant technical barriers in this case study because there are two main grid connections on the island. Therefore, the stability, security and economic benefits from the main grid is obtained. Although, the hybrid system project is more expensive with a COE of 99.6 øre/kWh than the existing system with a COE of 9.1 øre/kWh, this is feasible due to the political goals regarding renewability.

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