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Clean energy for EU islands: Samos energy community: developing a holistic strategy

Samos, Greece

Samos

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Summary

Electra Energy Cooperative, the University of the Aegean, and the Municipality of Eastern Samos applied for Technical Assistance from the Clean energy for EU islands secretariat in April 2022. Their application, named *Samos Energy Community: Developing a holistic strategy* was selected among the 20 projects to be supported that year. This report is the final deliverable for the project.

The goal of this study is to identify which energy storage systems (e.g., batteries, pumped hydro, etc.) are feasible from a technical and financial point of view. In addition, this work analyses how they could support the seamless integration of renewable energies into Samos' grid. Two use cases have been studied: the first consists in increasing the renewable energy penetration by making better use of the existing and planned RES, while the second use case relates to alleviating the grid from the current congestion issues.

As part of Task 1, a high-level evaluation of various energy storage systems was performed based on: a) their technical capability to meet the use case requirements, b) their suitability to be installed on the island, c) their financial feasibility, and d) their technological maturity. The analysis showed that Battery Energy Storage Systems (BESS) with a longer discharge duration time are the most suitable solution for Samos. Concretely, the 4 hour Lithium-ion (Li-ion) and the 5.4 hour Sodium Sulfur (NaS) battery systems were chosen to be modelled in Task 2 in order to meet the first use case (increasing the renewable fraction).

Task 2 illustrated that a significant capacity of new renewables should be installed to attain meaningful increases in the renewable fraction and to make the battery energy system installation worthwhile. An optimum solution was found when adding 66.4 MWp of additional solar PV and a 4 hour Li-ion battery storage system of 48 MW/192 MWh. While this might be difficult to reach in terms of space constraints, landscape issues, grid problems, capital requirements, and timing concerns, it shows that Samos still has a lot of potential to install additional renewables and reduce their dependency on expensive and volatile HFO.

In Task 3, the focus was moved to the secondary use case of alleviating grid congestion. A new method is proposed the size of an energy storage system, in terms of power and energy to ensure security of supply by avoiding the interruption cost occurred due to the distribution grid constraints. Due to the lack of grid data, a reduced grid model has been used. From the technical and economic studies, the ESS is justified at 3MW, 12MWh with 10-year Investment Recovery Period reducing the Expected Energy Not Supplied (EENS) from 343 to 229 MWh per year.

The two use cases investigated in Task 2 and Task 3 and complementary and synergetic. Both renewable energy penetration and congestion relief both are predictable and can be valorised whenever their application is most needed. The suggested installed battery capacity is thus not mutually exclusive but can be used for either application depending on what is valued most at each time interval.

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Glossary

BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CETA	Clean energy Transition Agenda
ESS	Energy Storage System
NPC	Net Present Cost
WACC	Weighted Average Cost of Capital

Introduction

Samos is a Greek island located in the eastern Aegean Sea, south of Chios, north of Patmos, and the Dodecanese, and off the coast of western Turkey, from which it is separated by the 1.6-kilometre-wide Mycale Strait (see Figure 1).

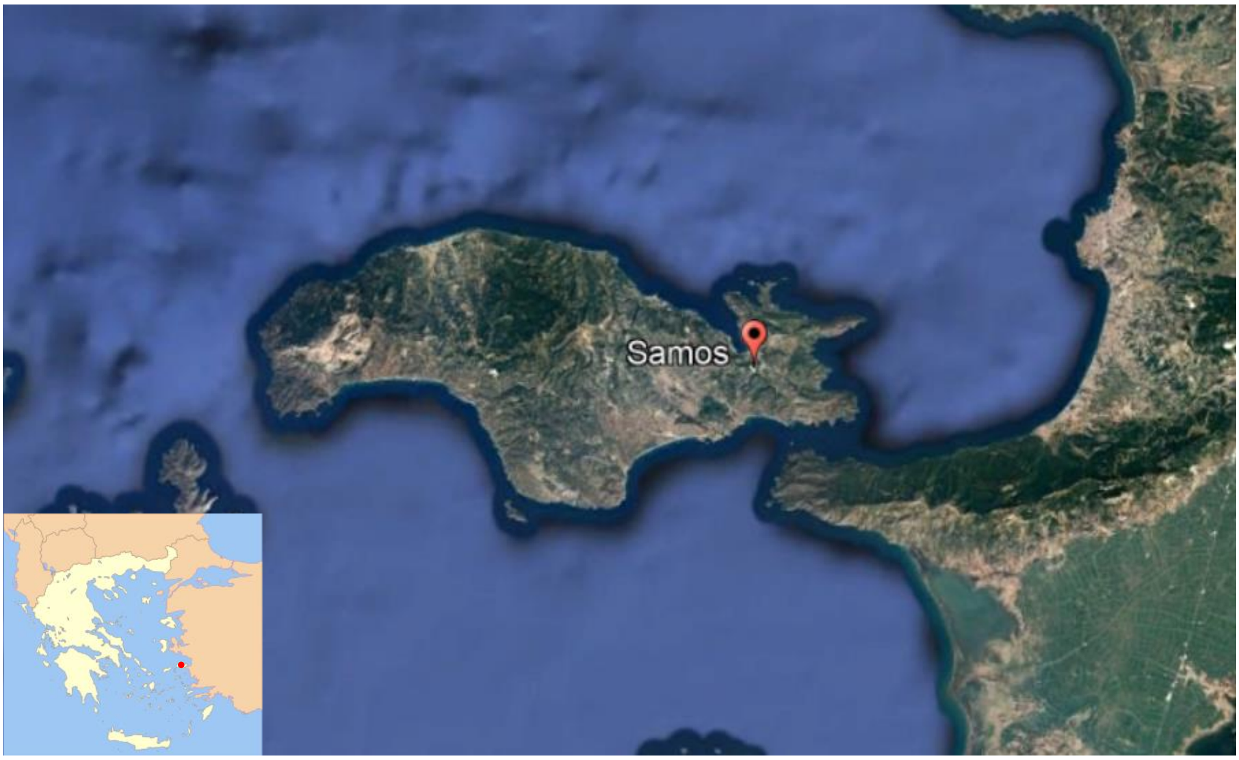

Figure 1: Site location

In 2020, Samos developed its Clean Energy Transition Agenda (CETA), following the guidelines of the Clean energy for EU islands secretariat. The CETA is a strategic roadmap that sets out the paths that the energy transition in Samos will follow, to be jointly implemented by the local community and the stakeholders.

The second stage (2023-2027) of this plan focuses, among others, on storage systems for the Samos grid, which is non-interconnected to the mainland. The goal of this report is to study which storage options (e.g., batteries, pumped hydro) are feasible from a technical and financial point of view and how they can support the seamless integration of renewable energies into the island's grid. This means that the energy storage system should increase the renewable energy penetration by making better use of the existing and planned RES. Furthermore, it can help to alleviate the grid from the current congestion issues.

According to the IRENA storage valuation framework [3], four main steps are designated to assess the applicability of ESSs for the use case on Samos, as below:

- High-level evaluation of various ESS (using the ES-Select Tool of SANDIA)
- Sizing the ESS for the primary use case (using the Homer Pro Tool of NREL)
- Performing a financial evaluation (using the Homer Pro Tool of NREL)
- Stacking applications to enhance the business model

For the present study, the following steps have been followed:

1. High-level evaluation of various energy storage systems
   A first preliminary evaluation of various energy storage systems is performed based on their technical capability to meet the application requirements, on their suitability to be installed on the island, on their financial feasibility, and on their technological maturity. One energy storage system is selected and modelled in detail in the second task.

2. Sizing the ESS for the primary use case based on a financial evaluation
   The most suitable energy storage solution has been modelled as a part of the whole Samos energy system. This includes the current energy system (including the 100 kW solar plant), as well as various scenarios for upcoming developments such as a decreased energy consumption due to increased energy efficiency and sensibilisation and the development of additional renewables such as small wind turbines and solar PV. This has led to the optimal sizing of the energy storage system that takes into account the primary use case of increasing renewable energy penetration, and the financial cost.

3. Rough calculation of the required ESS size for congestion alleviation
   The secondary use case relates to congestion alleviation on the island. This can serve as a form of value stacking, where the ESS could be used for both increasing renewable penetration and solving congestion issues. Since no information was received from the DSO, this section gives a rough first calculation of the required ESS size for congestion alleviation.

Task 1: High-level evaluation of various energy storage systems

In this task, a first preliminary evaluation of various energy storage systems is performed. They are ranked based on:

- their technical capability to meet the specific application requirement
- their suitability to be installed on the island
- their financial feasibility, and
- their technological maturity.

Based on this assessment, one energy storage system will be selected and modelled in detail in the Task 2.

This task first introduces various Energy Storage Systems (ESS) business models. Afterwards, the business model is mapped to a specific ESS technology for the specific case of Samos Island. This is done by first analysing the most important ESS applications on Samos and using the ES-Select software to identify the best ESS for the island.

Energy Storage Systems business models

The energy storage solution suggested for Samos will be chosen based on the business model offering the most beneficial output. A business model is the combination of value propositions, revenue streams, and the investor's role as presented in Figure 2. Quite often, several revenue streams can or must be stacked in order to better hedge the risk of the initial investment. For example, this can be achieved through load shifting and ancillary services provision.

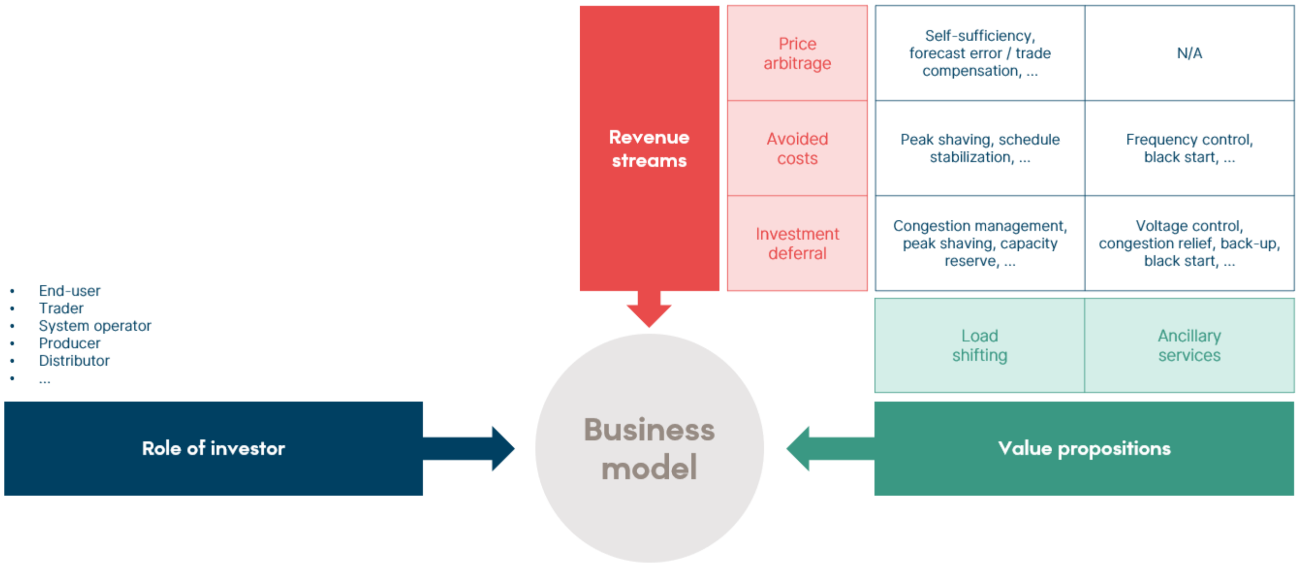

Figure 2: ESS's possible business model realisation[1].

Business models should be carefully matched to the available technologies as each technology has its specific characteristics. When matching the technical capabilities of storage systems, three main operational parameters are of importance:

- ESS' Power capacity (in MW)
- ESS' Response time (in sec)
- ESS' Discharge duration (in h)

The operational requirements for different business models are presented in Figure 3 [1]. Although there are some commercially available technologies that can serve all the identified business models, certain combinations of technologies and applications simply work better from a technical and financial perspective and therefore have preference in comparison to alternative solutions.

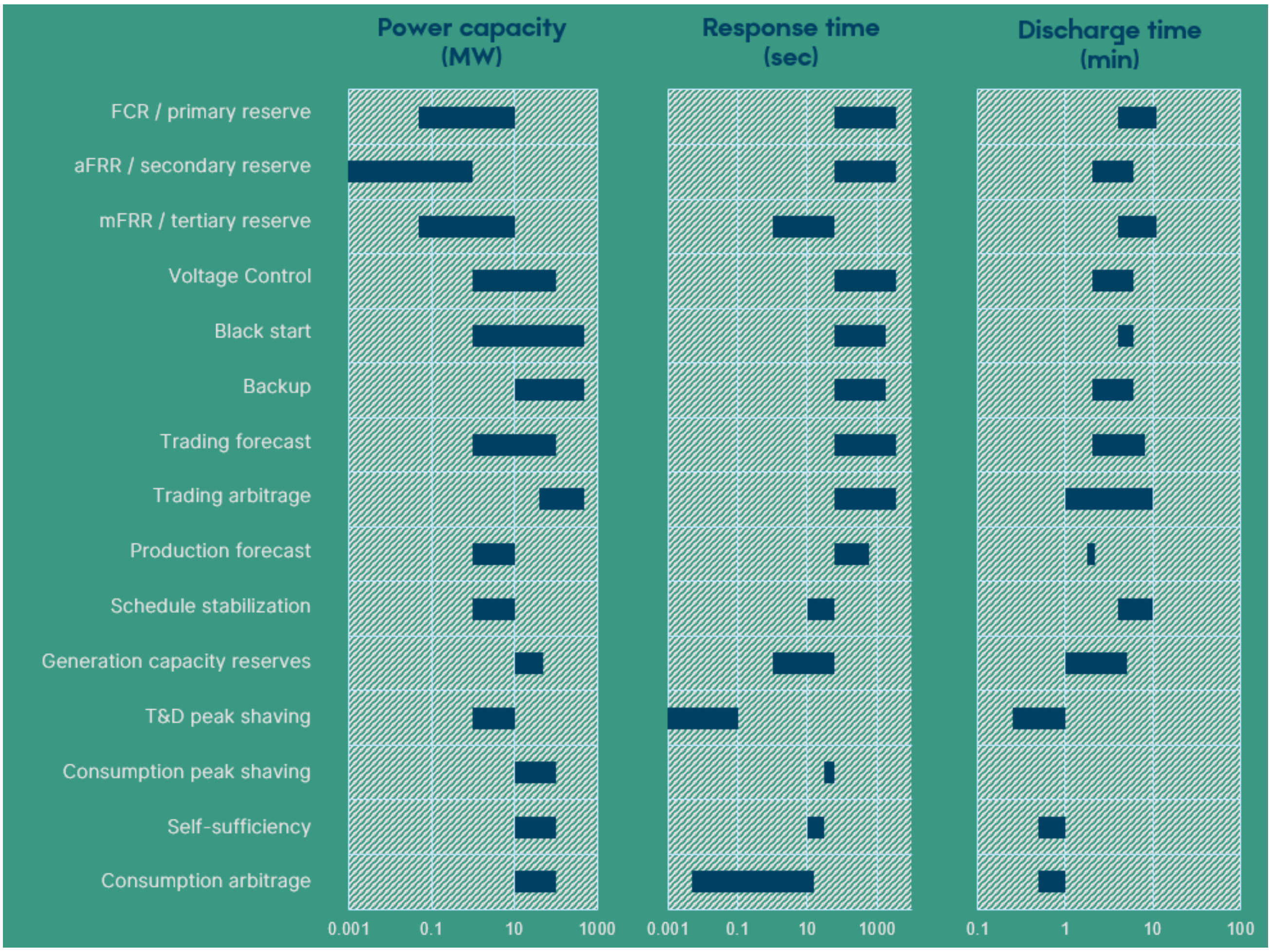

Figure 3: ESS's applications technological requirements review.

Figure 4 presents a comparison of different ESS options when it comes to their potential to operate in different timeframes. While ESS with a short duration timeframe capture the intra-day variability, ESS with a long duration timeframe are fit for extreme events that last for multiple hours and even days. Among all ESS technologies, Compressed Air Energy Storage (CAES) and Pumped Hydro Energy Storage (PHES) are popular technologies in large-scale power systems due to their longer discharge times and large capacity.

Figure 4: Comparative review of common ESS technologies.

Mapping the business model to an ESS Technology

Samos has two primary ESS applications: increasing the renewable energy penetration and alleviating grid congestion. These applications need discharge times of several hours, a response time of several minutes (especially for grid congestion) and a power capacity of at least several MW in order to meet the island's requirements. However, several secondary applications could be useful as well since a successful business model is based on stacked synergetic applications. Therefore, the arbitrage of both solar and wind energy is chosen as well.

The ES-SELECT Tool is used to map the business model (and its corresponding applications) to the best ESS option. This choice is based on four pillars:

1. The technical capability to meet the business model operational requirements (discharge time, response time, power capacity, etc.)
2. The island's suitableness for each technology (mobility, size, weight, scalability, etc.)
3. The financial feasibility (Capex per kW and kWh)
4. The technological maturity (readiness for commercial deployment)

ES-SELECT then calculates a feasibility score for each technology by performing a geometric average of the scores of each of the four pillars. For this purpose, the geometric average is preferred to the arithmetic average as it penalises solutions that provide low scores on specific pillars and also disqualifies a technology if it has a zero score in one of the pillars.

Taking as an input the desired use cases in Samos, the top five ESS options and feasibility scores for the chosen applications are presented in Table 1. Several insights can be derived from these results: first, the top four ESS options are all battery energy storage systems (BESS), while Compressed Air Energy Storage (CAES) is on the fifth place. Furthermore, other non-battery options such as pumped Hydro, flywheels, or capacitors are not included in the top five. **This illustrates that BESS options are most suitable in the case of Samos Island.**

Table 1 ESS options and feasibility scores for single application: Utility back-up

N	Storage Type	Acronym	Feasibility scores
1	Sodium Sulfur	NaS	68%
2	Sodium Nickel Chloride	NaNiCl	60%
3	Lithium ion – High Energy	LIB-e	57%
4	Hybrid LA & DL-CAP	Hybrid	56%
5	Compressed-Air ES, cavern	CAES-c	54%

Secondly, it illustrates that **BESS with a longer discharge duration time tend to be favoured**. This is better visualised in the bubble chart in Figure 5. This bubble chart shows the total installed cost of AC storage in function of the discharge duration. The bubble chart illustrates that CAES offers the best discharge duration and total cost installation. However, CAES is mostly suitable for very large applications, starting from 50 MW. Hence, NaS solutions are the best suited taking into account the desired discharge duration and the lowest cost for the case of Samos.

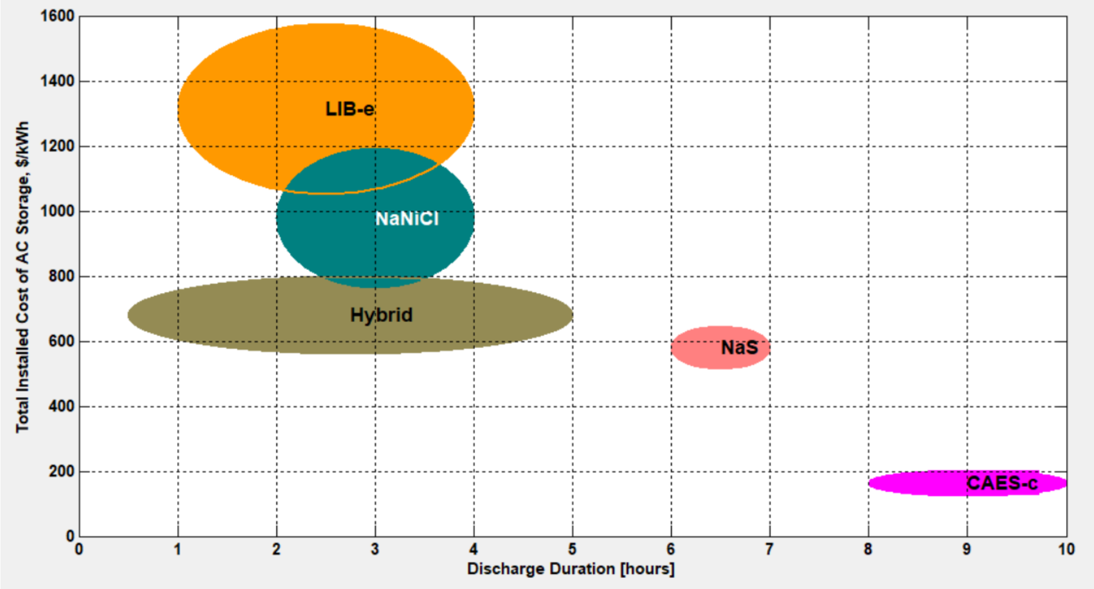

Figure 5: Total installed cost of AC storage in function of the discharge duration for the top five feasible ESS technologies from ES-SELECT.

Task 2: Energy Storage System Sizing

The previous task has indicated that battery energy storage is the most optimal solution for Samos. This task aims at dimensioning this potential battery energy storage system, taking into account several future scenarios. This analysis has been carried out using HOMER Pro, a software that allows finding the optimal power system configuration based on user input and requirements.

In this section first the future scenarios are described. Secondly, the model of the Samos power system is explained, including the present components as well as potential additions such as extra wind turbines. Finally, the results for each of the scenarios are discussed.

The scenarios

Three different scenarios are modelled in order to understand how the energy system would look like and what would be the optimal battery size. These three scenarios are:

1. The current energy system or the status quo
   The current energy system includes the current electrical load and the existing fuel power stations, solar PV and wind turbines as described in the next section. This scenario aims at setting the baseline (identifying the current renewable fraction, current load curve, etc.), and to identify what the potential of battery energy storage could be if nothing else changes.

2. Decreased energy consumption due to increased energy efficiency
   Samos has progressed in its energy transition, including the development of their CETA and the creation the first energy community on the island. One of the benefits this energy community could bring is the increased sensibilisation when it comes to energy. This, in turn, could lead to a reduced electricity consumption, with positive effects on the fuel consumption and renewable fraction. This scenario looks at increasingly larger reductions in the electricity consumption to evaluate its impact on several criteria, among others, the battery energy storage size.

3. Inclusion of additional solar PV and small wind turbines
   Samos already has some renewable energy installed, as described in the next section, but the power system is still largely dominated by the fuel power stations. This scenario explores the addition of new solar PV and small-scale wind turbines on the island. It gives a first look at how many renewables could be added while still reaching a financially optimum solution. However, it must be noted that this is a pre-feasibility exercise, not considering space constraints, landscape issues, grid problems, capital requirements, timing concerns, and so forth. The result should be understood as preliminary: for more precise results, feasibility studies would be required.

Samos already has some renewable energy installed, as described in the next section, but the power system is still largely dominated by the fuel power stations. This scenario explores the option of adding new solar PV and small-scale wind turbines on the island. It gives a first look at how many renewables could be added while still reaching a financially optimum solution. However, it must be noted that this is a pre-feasibility exercise, not taking into account space constraints, landscape issues, grid problems, capital requirements, timing concerns, and so forth. The result can thus not be used without first taking these prior considerations into account.

Description of the Samos Island power model

This section first displays the electricity demand on the island. Thereafter, the various renewable technology components included in the Homer model are identified. Finally, the general assumptions of the model are explained.

Electricity demand

The electricity consumption profile for the year 2021 was collected from the local DSO. This amounted to a total electricity consumption of 105 500 MWh. However, according to the Clean Energy Transition Agenda developed in 2020 [4], the electricity consumption is supposed to be closer 150 000 MWh. It is assumed that the 2021 electricity profile has been adversely impacted by the Covid-19 pandemic, and therefore represents a lower total electricity consumption. Therefore, the 2021 electricity profile has been scaled up linearly[2] so that the total electricity consumption amounts to 150 000 MWh.

Figure 6 depicts the net load duration curve for Samos Island. The peak load is 39.3 MW and is achieved during the summer, whereas the minimum load is 5.9 WM and takes place in October. As a result, the minimum to maximum load ratio is equal to 0.15.

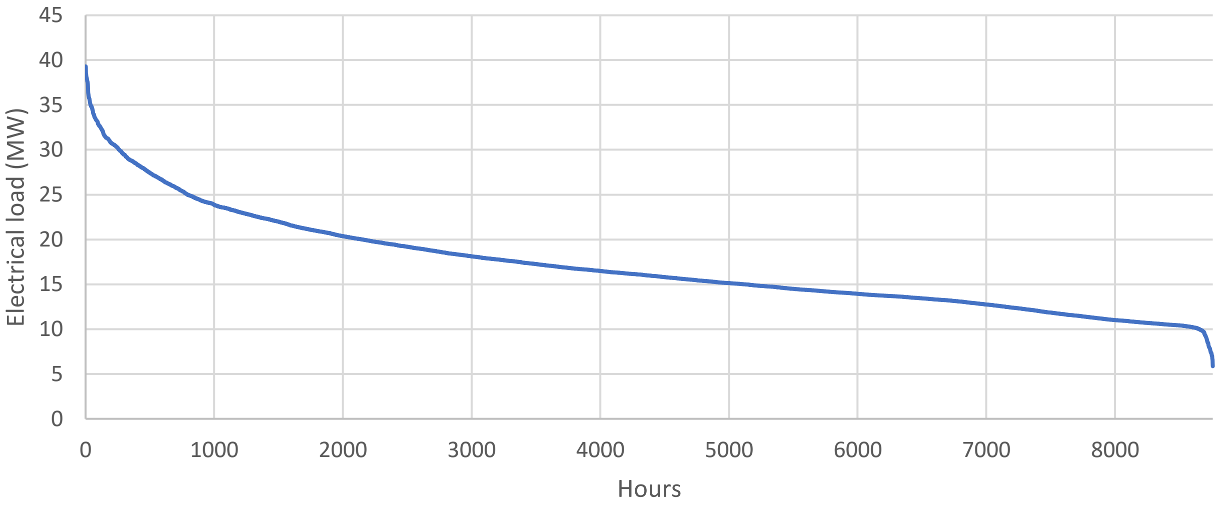

Figure 6: Load duration curve for Samos Island (year 2021 scaled up to 150,000 MWh)

Figure 7 shows the electricity load per month throughout the year, illustrating that July and August are the most load demanding months. This seasonal effect is explained by the tourist sector which

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[2] An argument could be made that Covid-19 has impacted the summer tourist season more adversely, and thus that not all time stamps should be scaled up equally. However, due to a lack of additional data, a linear scale-up has been retained

remains inactive during the winter period. However, winter months (December, January, and February) still demand quite some electricity due to lower temperatures. Samos relied for decades on the use of heating oil for heating; however, its use has been reduced due to increased taxes since 2010. Heating oil has slowly been substituted by electricity, mainly through the use of heat pumps, and biomass.

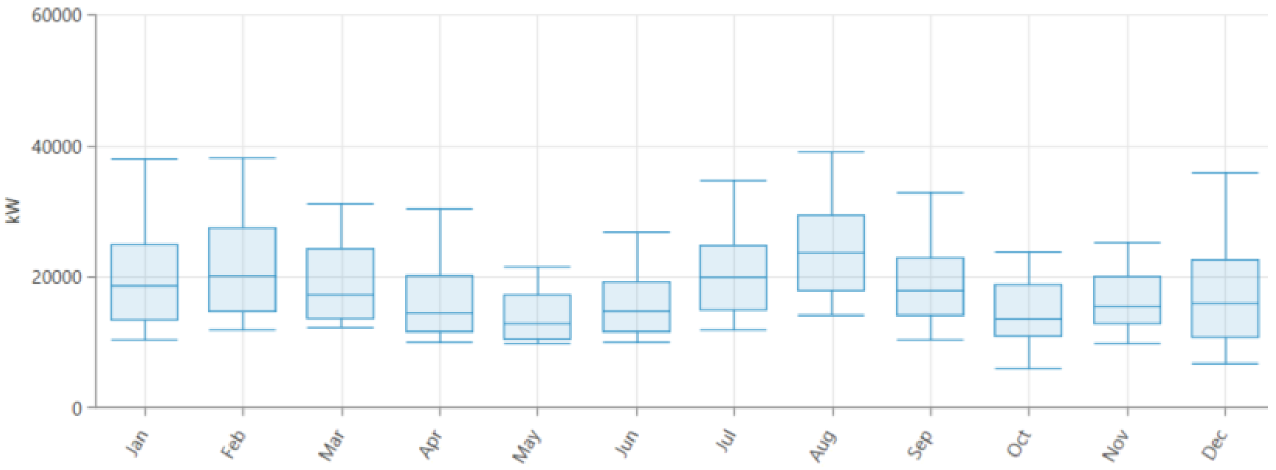

Figure 7: Samos Electricity load throughout the year

Components

The electrical components that are included in the model are:

Generator: The isolated power system of Samos is mostly fed by an autonomous power station with a total installed capacity of 47.75 MW. The station consists of six generators that consume heavy fuel oil (mazut). Their technical characteristics are given in Table 2. The investment cost of these components is set to zero as they are already built. However, their operation requires O&M and fuel costs that could be reduced by shifting to storage and increased renewables. The O&M cost is set at €0.01 /operational hour and the fuel cost is set at €0.75 /l [3] [5] . At the time of writing, fuel prices (gas, oil, etc.) in Europe have increased significantly as a result of the Russian-Ukrainian war. This disruption is not expected to last although the new price equilibrium will most likely be higher than before, yet still unclear as to how high. Therefore, a sensitivity analysis will be carried out to study whether changing these prices upwards or downwards has a significant impact on the results.

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[3] Average cost of Very Low Sulfur Fuel Oil (VLSFO) in Piraeus from January 2020 till October 2021 (time of writing)

Table 2: Technical characteristics of Samos Island diesel power units (source: [6])

N	UNIT TYPE	P_{MAX} (MW)	P_{MIN} (MW)	FUEL
1	Cegielski 9RTA-F58	11.00	6.140	Heavy Fuel Oil
2	Cegielski 6RTA-F58	6.00	3.125	Heavy Fuel Oil
3	Cegielski 9RTA-F58	6.00	3.125	Heavy Fuel Oil
4	Wartsila W32-18V	8.25	4.125	Heavy Fuel Oil
5	Wartsila W32-18V	8.25	4.125	Heavy Fuel Oil
6	Wartsila W32-18V	8.25	4.125	Heavy Fuel Oil

Solar PV: Samos has a total of 4.47 MWp of solar PV installed, including the 100 kWp plant whose energy will be shared among the newly developed energy community [4]. The systems are assumed to be oriented towards the south with a tilt of 37.75°. The PV panels are of the crystalline silicon type and the total losses equate 18.16%, including aging, wiring, connection losses, dust, shading, and so forth in order to reach the same capacity factor of 17.7%, as described by Bouzounierakis et al. [6]. The investment cost and O&M of this component are set to zero as it is already built and will thus continue to be used (unlike the generators which due to their running fuel cost and emissions might be partially phased out).

On top of this, in the last scenario, additional solar PV was modelled using the same technical characteristics as the existing PV. The investment cost was set to €800 /kWp and the O&M cost to €15.5 /kWp/year, based on recent costs for utility scale PV installation according to IRENA [7] with an additional premium of 10% due to the more remote location. The expected lifetime is 25 years.

Wind turbines: Samos has a total 7.975 MW of wind turbines installed, spread over several parks [4]. However, no information was provided to the authors regarding the number of turbines, the type of turbines, or their location. According to Bouzounierakis et al. [6], the capacity factor for the wind turbine installations equals 29.38%. In the HOMER model, 10 Enercon E-53[4] of 800 W were introduced, leading to a capacity factor of 28.4%, reasonably close to the reference.

On top of this, in the last scenario, two types of small-scale wind turbines were modelled. Small-scale wind turbines were chosen upon request of the island representatives, since they have limited environmental impact and pose less visual obstruction.

- The Eocycle EOX M-21[5] with a nominal power of 100 kW and a hub height of 32 m. The capital cost was given by an Eocycle sales representative and equals €305 000 for the turbine itself, the installation, and the additional civil and electrical works, while the O&M cost are about €4000 per year. The expected lifetime of the wind turbine is 20 years.
- The Wind Energy Solutions WES2506 with a nominal power of 250 kW and a hub height of 48 m. The capital cost was given by a WES sales representative and equals €520 000 for the turbine itself, the installation, and the additional civil and electrical works, while the O&M cost are about €3800 per year. The expected lifetime of the wind turbine is 30 years.

The battery: Task 1 indicated that battery energy storage offered the best solution for Samos. Specifically, Sodium Sulfur, Sodium Nickel Chloride and Lithium-ion (high energy) batteries were

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[4] Gearless, variable speed and single blade adjustment. Rotor diameter of 52.9m and hub height of 73m.

[5] https://eocycle.com/m-series/

[6] https://windenergysolutions.nl/wes/windturbine-wes-250/

found to be most suitable. Sodium Sulfur and Sodium Nickel Chloride are both high-temperature batteries, which means that they utilise liquid active materials and a solid ceramic electrolyte. As they possess similar characteristics, only Sodium Sulfur is modelled since it offered the highest feasibility score. Lithium-ion (high energy) batteries have been modelled as well since they also had a high feasibility score and have become the most used battery type nowadays, making up about 90% of the battery market and also rapidly decreasing in cost due to its widespread use and industrial fabrication. Below we present an overview of the type of batteries that have been modelled.

- A 5.4 hour Sodium Sulfur (NaS) battery of 270 kW and 1.45 MWh. NaS batteries have the advantage of relatively high energy density, still at the low end of Li-ion batteries but significantly higher than the redox-flow and lead-acid technologies. They also offer the potential for high cycle lifetimes at comparably low costs. The main disadvantage of the NaS battery is the relatively high annual operating cost as a result of heating the active materials to make them liquid. The capital cost was based on the IRENA's Electricity storage and renewables report and equals €380 000 for a 270 kW/1.45 MWh battery while the O&M cost are about €5 000 per year [8]. The battery module has a roundtrip efficiency of 85%, a lifetime throughput of 10 500 MWh, and an expected lifetime of 20 years.
- A 4 hour Lithium-ion (Li-ion) battery in modules of 1 MW and 4 MWh. Li-ion batteries have the advantage of high round-trip efficiency, relatively long lifetime, and a low self-discharge rate. The capital cost was based on the IRENA "Electricity storage and renewables report [8]." and equals €1 000 000 for a 1 MW/4 MWh battery while the O&M cost are about €7 500 per year The battery module has a roundtrip efficiency of 90%, a lifetime throughput of 21 000 MWh, and an expected lifetime of 15 years.
- A 1 hour Li-ion battery in modules of 100 kW and 100 kWh. This is a high-power battery with a 1-hour discharge duration that is included for the scenarios where renewable energy is not yet that abundant. The capital cost equals €25 000 for a 100-kWh battery while the O&M cost are about €1 000 per year [8]. The battery module has a roundtrip efficiency of 90%, a lifetime throughput of 300 MWh, and an expected lifetime of 15 years.

General assumptions

Several assumptions were made in order to run the simulations. These assumptions are drawn from the author's experience in similar projects as well as international best practices. The input parameters for the HOMER model have been estimated as:

- Project lifespan: The lifespan has been set to 15 years.
- Discount rate: The nominal discount rate is 12%, based on the average weighted average cost of capital (WACC) for solar PV projects in Greece between 2009 and 2017 [9]
- Inflation: The average expected inflation rate in Greece is 1.36%, based on the projections of 2022 to 2026 [10]
- Cost reflectivity: There often are no recoverable costs at the end of the lifespan of such a system. However, as the project lifespan is set to 15 years and the lifespan of the solar PV and wind turbines components is larger, the software does assume a salvage value directly proportional and linear to its remaining life.

Results and discussion

Base case

First, the base case of the island's electricity system (without battery energy storage) is modelled to serve as a baseline. It is clear that the electricity system is dominated by the generators, as illustrated in Figure 8. The renewable fraction—the percentage of load covered by renewable energy—reaches 17.3% over the entire year. The annual fuel consumption of all conventional power units is 32.5 million litres.

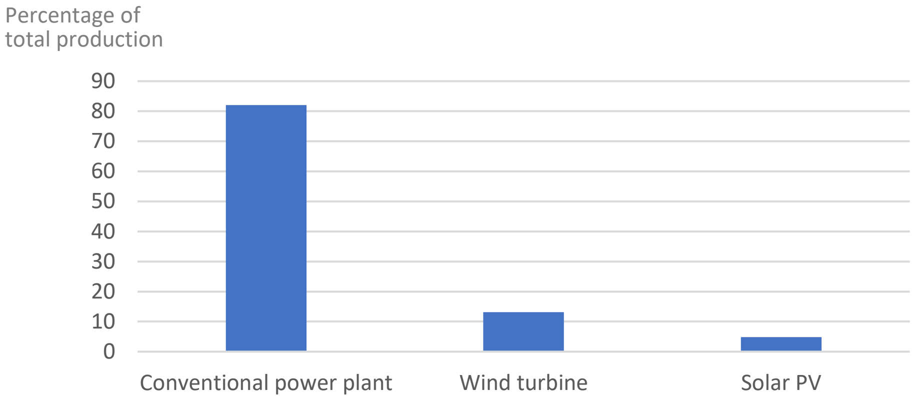

Figure 8: Share of annual electricity production on Samos per source

Adding battery energy storage

When including battery energy storage systems in the base case, the 1 hour Li-ion battery comes out as a suitable option that brings additional financial gains. However, the optimal size remains quite small compared to the other power components in the system. Figure 9 shows the optimal size of battery energy storage depending on the fuel oil price. An increasing cost makes the generators more costly, although the effect on the battery size is quite minimal. A cost of 0.75 €/l leads to a battery size of 1.3 MWh while a cost of 2 €/l leads to 3.2 MWh. The battery size does increase somewhat linearly but reaches a plateau at 1.75 €/l and, more importantly, stays quite low compared to the total installed power capacity. This is due to the fact that the current renewable energy capacity is not sufficiently high to make good use of a battery. In other words, the battery will only at very limited times store surplus renewable electricity with a €0 marginal cost, while most of the time it will store electricity from the generators at a marginal cost of 183 €/MWh[7]. Even though there is some use in storing electricity from the generators – surplus electricity when the generator minimum load ratio exceeds the required load or increased efficiency when they work closer to nominal capacity – this effect is quite minimal. **The current scenario is thus not a particularly interesting business model for the battery energy storage system.** The effect on the renewable fraction is then also minimal, increasing from 17.3% in the status quo scenario to 17.5% in the battery scenario and only going slightly up to 17.7% when HFO becomes more expensive.

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[7] Considering that the heavy fuel oil costs 0.75 €/l

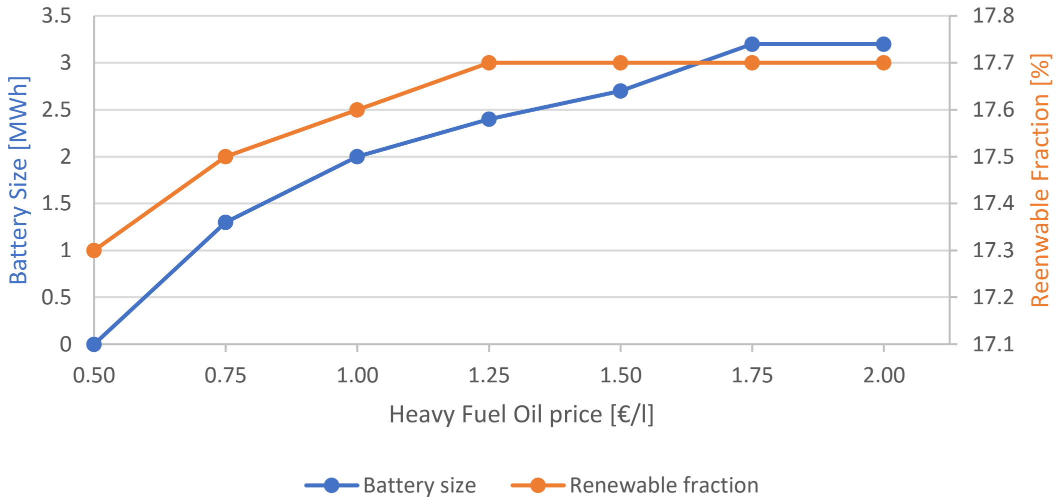

Figure 9: Optimal battery size and renewable fraction in function of heavy fuel oil price

Decrease in electricity consumption

Samos is progressing in its clean energy transition: developing a CETA and having created its first energy community. One of the benefits this energy community could bring is increased sensibilisation when it comes to energy. This, in turn, could lead to a reduced electricity consumption, with positive effects on the fuel consumption and renewable fraction.

In this scenario, the most suitable battery is also the 1 hour Li-ion battery. Table 3 shows the optimal battery size when changing both the heavy fuel oil price and reducing the yearly electricity consumption. The first row represents the same situation as in the previous section, with current electricity consumption levels: the battery size is shown in function of the heavy fuel oil price. The table illustrates that higher heavy fuel oil prices and lower electricity consumption lead to increased battery sizes to achieve a financial optimum situation. The reason why a higher heavy fuel oil price increases the optimal battery size has been explained in the previous section. A lower electricity consumption also increases the optimal battery size since the battery can actually perform its primary use, storing surplus renewable energy at zero marginal cost. This occurs since renewable electricity production will now more often be higher than the (decreased) electricity demand.

Table 3: Optimal battery size (in WWh) in function of heavy fuel oil price and electricity consumption reduction

	Heavy Fuel Oil price [€/L]						
Electricity consumption	0.5	0.75	1.0	1.25	1.5	1.75	2.0
100%	0	1.3	2	2.4	2.7	3.2	3.2
95%	0.7	1.3	2	2.7	4	4	4
90%	1.2	1.6	3.2	3.2	4	4.8	4.8
85%	1.6	2.7	3.2	4	4	5.4	5.4
80%	2.4	3.2	4	4.8	4.8	5.4	8
75%	2.7	4	4	4.4	8.8	8.8	9.6

Decreasing the electricity consumption also has a beneficial effect on the renewable fraction, as displayed in Table 4. As with the previous table, the first row represents current electricity consumption levels, with renewable fraction shown in function of the heavy fuel oil price. The increase in renewable fraction is mostly independent from the heavy fuel oil price but depends more on the electricity consumption. Approximately, for every 5% decrease in electricity consumption, the renewable fraction increases by 1%. While this effect is larger than the change in the heavy fuel oil price, it still is relatively small. **In order to attain meaningful increases in the renewable fraction and in order to make the battery energy system installation worthwhile, a significant capacity of new renewables should be installed.** The next section discusses what this could look like.

Table 4: Renewable fraction (in %) in function of heavy fuel oil price and electricity consumption reduction (incl. the optimal battery size)

	Heavy fuel oil price [€/L]						
Electricity consumption	0.5	0.75	1	1.25	1.5	1.75	2
100%	17.3	17.5	17.6	17.7	17.7	17.7	17.7
95%	18.3	18.4	18.5	18.5	18.6	18.6	18.6
90%	19.2	19.3	19.5	19.5	19.6	19.6	19.6
85%	20.3	20.5	20.5	20.6	20.6	20.7	20.7
80%	21.5	21.6	21.8	21.8	21.8	21.9	22.1
75%	22.8	23	23	23	23.5	23.5	23.6

Addition of small-scale wind turbines and PV

This scenario explores the option of adding new solar PV and wind turbines in order to ideate what a possible future could look like. However, it must be noted that this is still a pre-feasibility exercise, not taking into account space constraints, landscape issues, grid problems, capital requirements, timing concerns, and so forth.

The optimal solution—adding solar PV, wind turbines, and battery—looks drastically different to the base case scenario, as shown in Table 5. In the base case, only 17.3% of the load was covered by renewables; whereas in the optimal solution renewables amount to 74.7% of the total electricity consumption, leading to a reduction in fuel consumption of 22 516 555 litres. To reach this number, 60.6 MWp of additional solar PV and a 41 MW/164 MWh 4 hour Li-ion battery storage system have been installed. The 4 hour Li-ion battery is favoured over the 1 hour Li-ion battery since adding more PV requires a battery that can store energy over multiple hours. Furthermore, the 4 hour Li-ion battery is also favoured over the NaS battery since it offers long-duration storage at a price which is lower per MWh and has a better roundtrip efficiency. Even if NaS offers a higher lifetime throughput per MWh, this maximum is not yet reached within the 15-year project lifetime and thus has no impact. No small-scale wind turbines are part of the electricity mix In the optimal solution provided by HOMER Pro because they are significantly more expensive than solar PV[8].

While the optimum solution requires a significant large initial investment of €89.1 million, the operating costs do decrease by €17.83 million per year because less fuel is being consumed. This leads to a discounted payback time of 8.26 years. Important to note is that a renewable fraction above 60% can have practical implications on grid stability and space constraints, and thus requires

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[8] The WES250 has a LCOE of €0.153 /kWh and the EOX M-21 one of €0.254 /kWh, while solar PV boasts a LCOE of€ 0.06 /kWh.

more detailed studying. In any case, the results show that Samos has a large potential to install additional renewables and reduce their dependency on expensive and volatile heavy fuel oil. Constructing only a part of the proposed system already has positive implications as the combination of solar PV and battery storage have been shown to be cost-competitive with the existing conventional power plants.

Table 5: Comparison of Base case and optimum case

Description	**Base case**	**Optimum case**[9]
Power system		
PV capacity	4.4 MWp	4.4 MWp + 60.6 MWp
Wind turbine capacity	7.975 MW	7.975 MW
Generator capacity	47.75 MW	47.75 MW
Battery capacity	—	41 MW/164 MWh
Annual Energy balance		
Total electricity production [MWh]	151 216	174 296
PV energy production [MWh]	7 345	116 397
Wind turbine production [MWh]	19 874	19 874
Generator production [MWh]	123 997	38 025
Total electricity consumption [MWh]	151 216	177 294
Electricity demand [MWh]	150 000	150 000
Excess electricity [MWh]	884	14 330
Electricity lost in conversion (converter/storage) [MWh]	332	9 966
Environment		
Renewable fraction [%]	17.3%	74.7%
HFO consumption [L]	32 528 364	10 011 809
Finances[10]		
Net present cost	€214 million	€154 million
Initial investment	—	€89.5 million
Operating cost	€26 million	€8.69 million
Discounted payback time		8.26
Net present worth		€38.6 million

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[9] Assuming a heavy fuel oil price of €0.75 /L

[10] Calculated using the parameters described in General assumptions

Figure 10 shows the impact of the volatile heavy fuel oil price on the optimal PV and battery size, and on the renewable fraction. In comparison to the previous scenarios, the impact of the heavy fuel oil price on the system has been significantly reduced, since only 22% of produced electricity comes from conventional power plants while this was 82% in the base case.

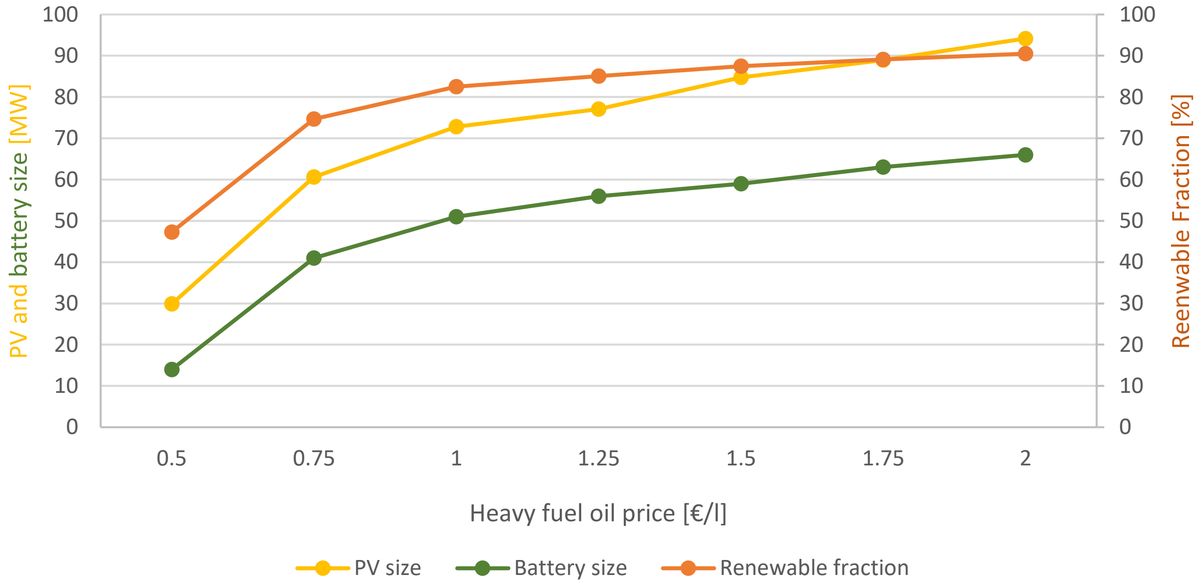

Figure 10: Optimal PV and battery size and renewable fraction in function of HFO price

Task 3: Energy Storage System sizing for virtual distribution capacity (reliability/congestion)

The previous task looked into the primary use case of increasing the renewable energy penetration on the island. This task however analyses the secondary use case aimed at congestion relief. Congestion refers to a situation when generation or demand at a certain point in the grid exceeds the transfer capabilities. Integrating renewables into the island distribution system represents a capacity challenge due to intermittent generation profiles, location, and rare to zero flexibility and dispatchability.

Mitigating congestion by the grid operator is conventionally managed by load curtailment and generation rescheduling, while the reactive power and voltage control are exhausted prior to them. A smart congestion management is required to ensure the maximum utilisation of the existing grid transfer capability and to maintain the system reliability at an acceptable level. When the current infrastructure cannot handle the peak demand, either shaving the peak load or upgrading the distribution grid would be necessary. To adequately counterbalance the peak demand, a storage system is sized in this study to meet both the power and energy requirements.

Due to the lack of data on the Samos Island's grid configuration and parameters, a detailed analysis of the possible grid congestions is not feasible. It is presumed that more loads exist on the distribution feeders than the feeders can handle during peak times. A conventional solution is upgrading the overloaded asset e.g., line or transformer, while installing a storage downstream the feeder could postpone the grid upgrade for a few more years. It will also help to reduce the need for expensive and polluting peaker plants, which are only used to meet peaks in electricity demand. In this study, a probabilistic method is proposed for calculating the size of an electrical energy storage system for a network reinforcement deferral use case to improve reliability for customers without having to build conventional network assets. In conjunction with the reliability of the energy storage and the current overhead wires, the effects of power and energy capacity are taken into account.

Background

To satisfy the reliability criteria in both normal operation and contingencies, a reliability-oriented parallel 15 kV overhead line expansion project is considered as a conventional solution. Reliability projects like this go usually forward with little or no opposition — like upgrades, power plant interconnection projects — because of having clear drivers or mandates. However, economic projects (including projects that address specific policy objectives such as utility-scale storage installation for higher renewables penetration and removing bottlenecks) often get obstructed due to different perspectives on need, benefits, and cost responsibility.

Reliability distribution expansion projects are justified based on the historical energy not supplied due to the transmission constraints. The energy not supplied (valued at €6 350/ MWh by ENTSOE) is used to estimate the annual avoided cost. The economic indicators of Internal Rate of Return (IRR) for the Investment Recovery Period (RP) are calculated using the Net Present Value (NPV) formula equalling it to zero.

$$0 = \mathrm{NPV} = \sum_{t=1}^{\mathrm{RP}} \frac{C_t(1+IR)^t}{(1+IRR)^t} - C_0$$

where:

C_t = Avoided cost during the period t
C_0=Total initial investment costs
NPV=Net Present Value
IR : Inflation Rate

A more consistent and realistic criterion would be based on probabilistic methods in which a risk index enables a comparison to be made between various reinforcement alternatives. A value-based probabilistic reliability transmission planning is required in which the investment costs, load shedding costs and generation costs are minimised, associated with integrating Energy Storage System (ESS) and building new overhead lines [11]. In this way, the incremental cost of providing reliability would be compared with the incremental benefit of providing such reliability; by using the customer interruption cost information. Additionally, the System Operator should consider that:

- This transmission redundancy planned to be constructed, would be barely used due to typical high availability and low failure rate of the overhead lines which means this capacity is not needed for most of the times according to the capacity of the existing line and the maximum power needed to be transferred to demand.
- Integration of more energy resources into the downstream grid according to the high renewable generation policy of the island, planned transmission lines will not be any more beneficial.
- There are also several applications for energy storage when they are not used for the main application.
- ESS-based solutions are modular and can be scaled and relocated in the future to fit the needs.
- Reliability projects are Business values of grid development lies in seven different aspects as: safety, supply insurance, fiscal, reputation, customers, ecosystem, and compliance that all should be compromised in an optimal development plan [12].
- The avoided cost of interruption is used widely for mitigating short duration outages, reaching as high average benefit value as €665/kW-year. As a comparison, average benefit values for specific use cases of ESS range from under €11/kW-year for voltage support to roughly €92/kW-year for capacity and frequency regulation services. However, there is no agreement when it comes to making money from increasing the grid resilience [13].

A reduced grid model

The distribution network on the island consists of several 15 kV medium voltage (MV) overhead lines. It is assumed that sources (generation buses) and sinks (load buses) are connected via two parallel 15 kV distribution lines. Assuming an N-1 criteria-based grid planning and development. Each 15 kV is assumed to carry 12 MW (0.55 kA rating current and 0.85 power factor) in total 24 MW.

Maximum demand of 27.62 MW in 2021 would be violating the total transfer capability (TTC) for 57 hours and 1 446.71 MWh in the normal operation. Remedial actions must be imposed to meet the congestion in both normal and N-1 contingencies. Any contingency in the grid may increase the interruption costs due to the transmission constraints drastically. Some reinforcement is required – either conventional or an emerging technology such as ESS. A diagram of the estimated network and grid reinforcement alternatives are shown in Figure 11.

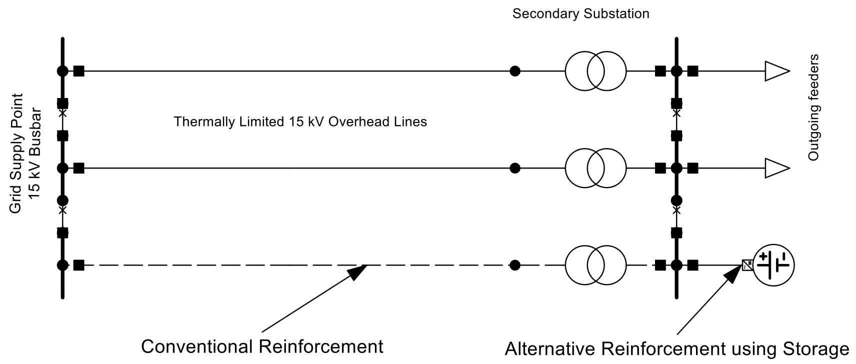

Figure 11: A diagram of the estimated network showing where the ESS is to be installed. The 15kV OHLs are at capacity with the existing demand, meaning some reinforcement is required – either conventional or an emerging technology.

Methodology

Two fundamental approaches, state enumeration and Monte Carlo simulation, are commonly used in composite system reliability evaluation. An analytical approach is utilised in this study. Based on the two-state Markov model of each component, a Markov state of the system is defined by a particular condition where every component is in each operating state of its own. All the possible states of a system make up the state space [14].

Using state enumeration method, the state space of the system i.e., overhead lines and ESS is determined. If there is a double circuit outage, the energy not supplied is equivalent to the entire year's energy consumption which is very rare. If not a double circuit outage, the energy not supplied is assessed using the algorithm presented in Figure 12.

The ESS is modelled as having a finite capacity, and a power rating to constrain the rate of energy exchange. Stored energy at each time step, known as State of Charge, SoC_i, is equal to the stored energy in the previous time step, SoC_{i-1}, minus the power transferred to the grid in that time step. At each time step, the difference between the demand and the network capacity is calculated. If the demand is greater than the capacity, then the required energy is removed from the ESS. If there is not sufficient power or energy available, then the energy not supplied for that day increases. It is assumed that the battery is fully recharged at the beginning of each day. Additional reasoning addresses situations in which the power rating is a limitation or in which the power or energy from the ESS can only partially address the issue.

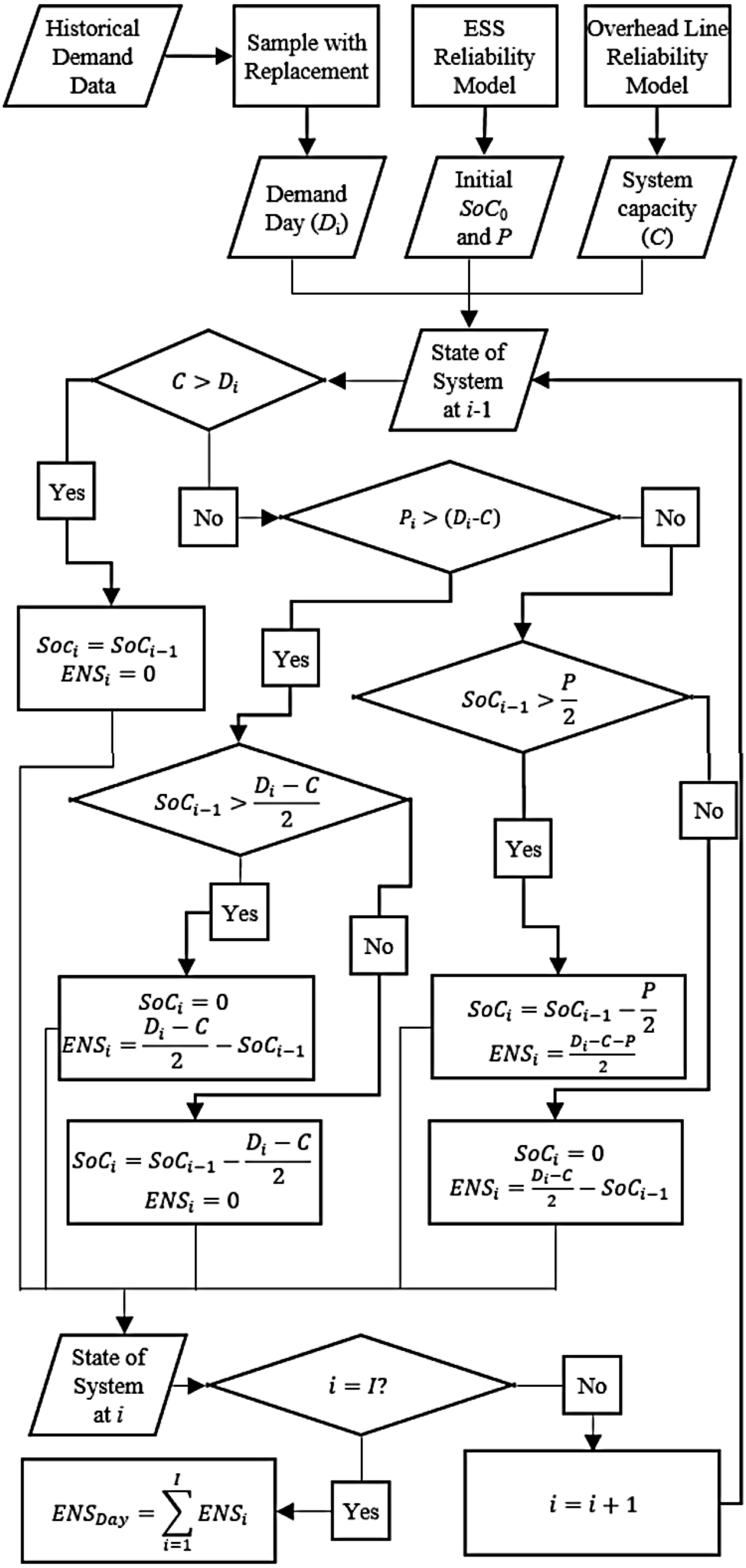

Figure 12: The algorithm used to assess the EENS [15]

Expected Energy Not Supplied (EENS) is calculated from:

$$EENS = \sum_{i=1}^{N} SP_i \times ENS_i$$

Where:

N: Total number of system states in the state space
SP_i: i^{th} State probability
ENS_i: Energy Not Supplied in state i
$EENS$: Expected Energy Not Supplied

Results and discussions

The method was used to evaluate ESS devices with energy capacities ranging from 1-20 MWh and power ratings ranging from 1-10 MW. The overhead lines and ESS are assigned availabilities of 99% and 95% respectively. The result of the simulation is presented in **Error! Reference source not found.** (which spans down to the following page). P and C are the power rating and Energy capacity of the battery energy storage, respectively. The total energy consumption of 2021 is 105 410 MWh.

Table 6: Results of EENS for ESS with power ratings from 0-10 MW, energy capacities from 0-20 MWh

P MW	C MWh	EENS MWh
0	0	343.18
0	1	343.18
0	2	343.18
0	3	343.18
0	4	343.18
0	5	343.18
0	6	343.18
0	7	343.18
0	8	343.18
0	9	343.18
0	10	343.18
0	11	343.18
0	12	343.18
0	13	343.18
0	14	343.18
0	15	343.18
0	16	343.18
0	17	343.18
0	18	343.18
0	19	343.18
0	20	343.18
1	0	343.18
2	16	219.08
2	17	215.62
2	18	212.26
2	19	209.39
2	20	207.09
3	0	343.18
3	1	327.23
3	2	313.26
3	3	300.90
3	4	290.31
3	5	279.95
3	6	270.19
3	7	261.15
3	8	252.48
3	9	246.40
3	10	240.49
3	11	234.73
3	12	229.06
3	13	223.53
3	14	218.13
3	15	213.25
3	16	209.20
5	11	234.47
5	12	228.70
5	13	222.98
5	14	217.36
5	15	211.97
5	16	206.89
5	17	202.75
5	18	198.76
5	19	194.86
5	20	191.06
6	0	343.18
6	1	327.23
6	2	313.26
6	3	300.90
6	4	290.29
6	5	279.91
6	6	270.13
6	7	261.06
6	8	252.32
6	9	246.17
6	10	240.22
6	11	234.39
8	6	270.13
8	7	261.04
8	8	252.29
8	9	246.13
8	10	240.15
8	11	234.29
8	12	228.52
8	13	222.80
8	14	217.16
8	15	211.74
8	16	206.61
8	17	202.43
8	18	198.41
8	19	194.50
8	20	190.70
9	0	343.18
9	1	327.23
9	2	313.26
9	3	300.90
9	4	290.29
9	5	279.91
9	6	270.13

1	1	327.23
1	2	313.30
1	3	301.83
1	4	291.81
1	5	284.53
1	6	278.83
1	7	273.59
1	8	269.47
1	9	265.63
1	10	261.93
1	11	258.84
1	12	256.47
1	13	254.29
1	14	252.28
1	15	250.50
1	16	248.95
1	17	247.63
1	18	246.53
1	19	245.62
1	20	244.85
2	0	343.18
2	1	327.23
2	2	313.26
2	3	300.92
2	4	290.35
2	5	280.04
2	6	270.68
2	7	262.45
2	8	256.41
2	9	250.59
2	10	244.95
2	11	239.50
2	12	234.47
2	13	230.39
2	14	226.49
2	15	222.71
3	17	205.27
3	18	201.48
3	19	197.76
3	20	194.16
4	0	343.18
4	1	327.23
4	2	313.26
4	3	300.90
4	4	290.29
4	5	279.93
4	6	270.17
4	7	261.09
4	8	252.39
4	9	246.29
4	10	240.37
4	11	234.54
4	12	228.78
4	13	223.09
4	14	217.51
4	15	212.14
4	16	207.11
4	17	203.03
4	18	199.06
4	19	195.20
4	20	191.44
5	0	343.18
5	1	327.23
5	2	313.26
5	3	300.90
5	4	290.29
5	5	279.91
5	6	270.15
5	7	261.07
5	8	252.34
5	9	246.22
5	10	240.29
6	12	228.63
6	13	222.90
6	14	217.26
6	15	211.86
6	16	206.77
6	17	202.62
6	18	198.62
6	19	194.72
6	20	190.92
7	0	343.18
7	1	327.23
7	2	313.26
7	3	300.90
7	4	290.29
7	5	279.91
7	6	270.13
7	7	261.04
7	8	252.31
7	9	246.15
7	10	240.17
7	11	234.33
7	12	228.57
7	13	222.84
7	14	217.20
7	15	211.78
7	16	206.67
7	17	202.51
7	18	198.50
7	19	194.60
7	20	190.80
8	0	343.18
8	1	327.23
8	2	313.26
8	3	300.90
8	4	290.29
8	5	279.91
9	7	261.04
9	8	252.29
9	9	246.11
9	10	240.13
9	11	234.27
9	12	228.50
9	13	222.78
9	14	217.13
9	15	211.71
9	16	206.58
9	17	202.39
9	18	198.36
9	19	194.45
9	20	190.65
10	0	343.18
10	1	327.23
10	2	313.26
10	3	300.90
10	4	290.29
10	5	279.91
10	6	270.13
10	7	261.04
10	8	252.29
10	9	246.11
10	10	240.11
10	11	234.25
10	12	228.48
10	13	222.76
10	14	217.11
10	15	211.69
10	16	206.56
10	17	202.37
10	18	198.35
10	19	194.43
10	20	190.63

In Figure 13, the 3D area plot displays the EENS for ESS with power ratings from 0-10 MW, energy capacities from 0-20 MWh. The energy capacity improves the expected energy not supplied, but the benefits begin to tail off once the capacity reaches 12 MWh. Figure 14 shows that for larger power capacity of ESS than 3 MW, the level of expected energy not supplied is not changing significantly. Increasing the power rating of the ESS initially reduces the expected energy not supplied, but once the power rating reaches 3 MW the EENS levels out. These results can be used to establish a lower bound for the ESS power and energy ratings, with the decision on what constitutes acceptable expected energy not supplied left to the operator's preference. Next, a simple value-based distribution system reliability planning must be performed.

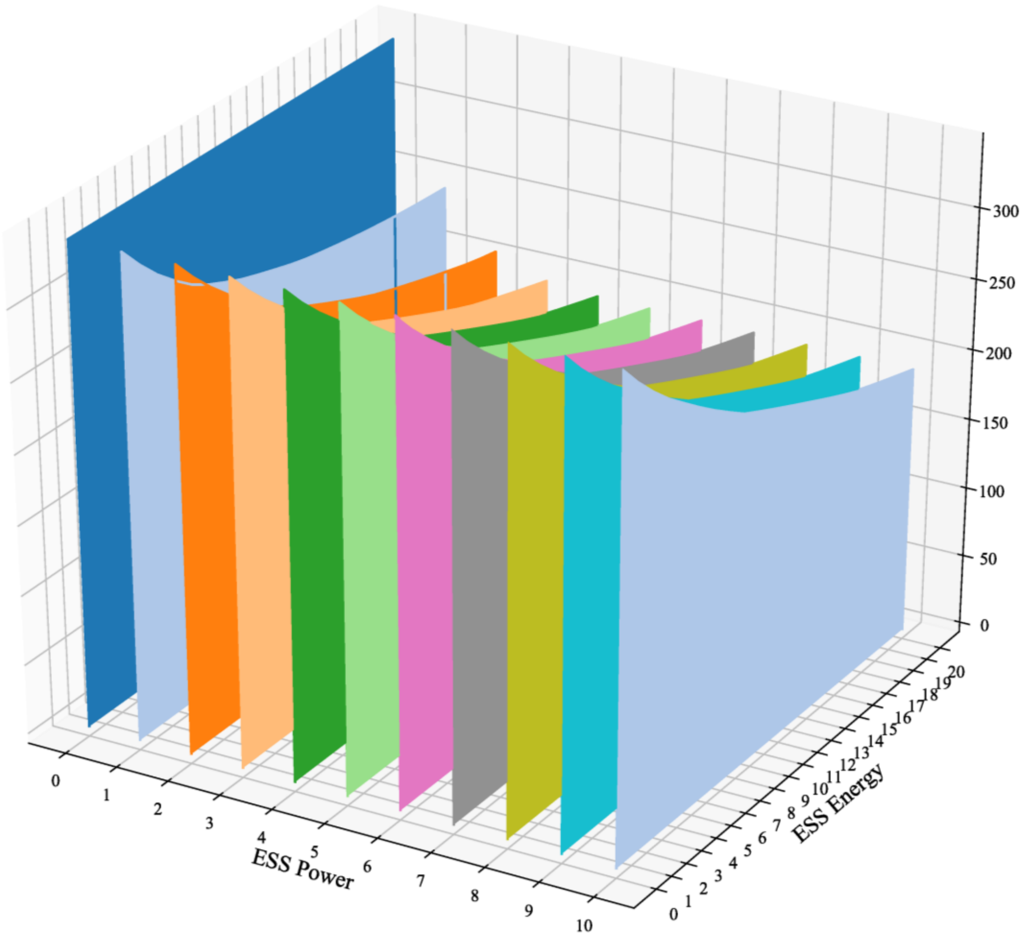

Figure 13: 3D area plot of EENS for ESS with power ratings from 0-10 MW, energy capacities from 0-20 MWh

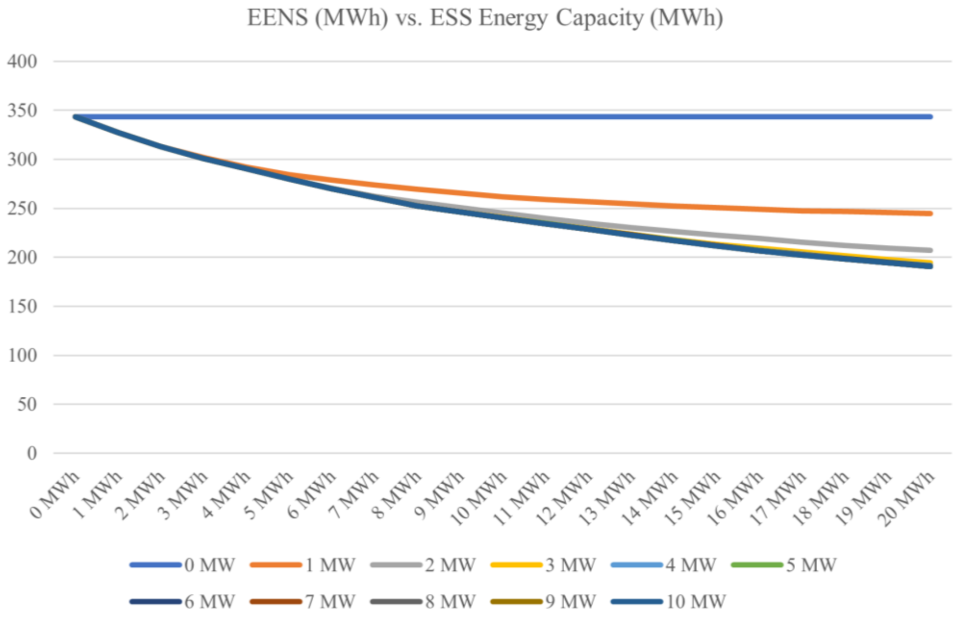

Figure 14: Line graphs of EENS against energy capacity for different power ratings

The peak shaving revenue, R_{PS} is calculated using the expected energy not supplied results:

$$R_{PS} = \Delta EENS \times VOLL$$

where EENS is the loss of energy expectation for the year, and VOLL is the value of lost load – in the EU, VOLL is approximately €6 350 / MWh by ENTSOE. An ESS scheme will be expected to operate for around 10 years which is assumed as the PR (a lithium-ion battery has a lifetime of approximately 3 000 complete cycles). IR and IRR are assumed 0.03 and 0.1, respectively.

For a reliability cost-worth analysis, the cost and worth are calculated as per the investment cost of the storage system and total ENS avoided cost (as an exemplary CAES system data from [16]).

$$C_t = (343.18 - 229.06)\ MWh \times 6350 \frac{€}{\mathrm{MWh}} = 724655.4\ €$$

$$Reliability\ worth\ NPV = \sum_{t=1}^{\mathrm{PR}} \frac{C_t(1+IR)^t}{(1+IRR)^t} = \sum_{t=1}^{10} \frac{0.725\times(1+0.03)^t}{(1+0.1)^t} = 5.14\ \mathrm{M€}$$

$$Reliability\ cost = A \times P_{ESS}^{max} + B \times E_{ESS}^{max} = 12\ \mathrm{MWh} \times 120 \frac{k€}{\mathrm{MWh}} + 3\ \mathrm{MW} \times 1200 \frac{k€}{\mathrm{MW}} = 5.04\mathrm{M€}$$

that explicates:

$$Reliability\ worth > Reliability\ cost$$

Accordingly, the reliability target is determined as 229.06 MWh. If the optimal reliability target was not achieved in the first step, calculations would be repeated for a new reliability target till convergence. The new reliability target is supposed to be a less than A_1 in case of over investment and more than A_1 in case of under investment (Figure 15).

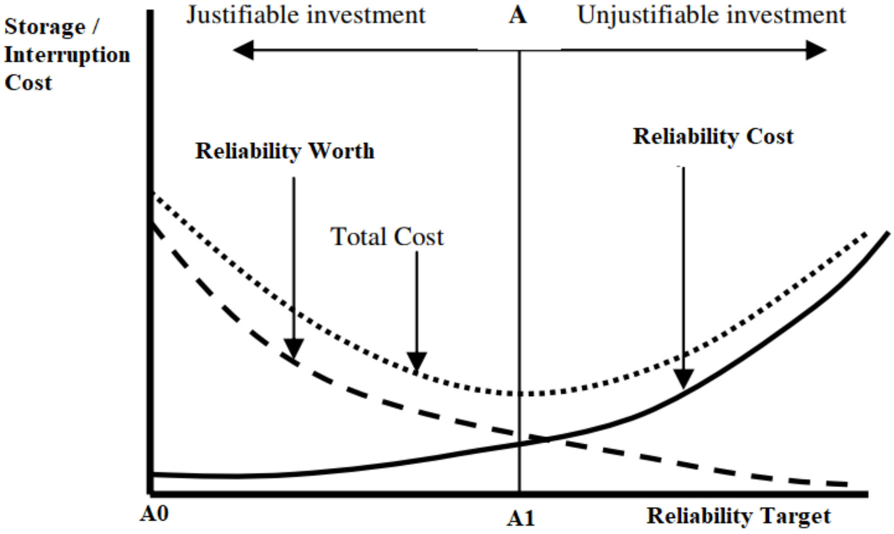

Figure 15: Reliability cost-worth analysis and convergence.

Conclusions and recommendations

The goal of this report was to study which storage options (e.g., batteries, pumped hydro) are feasible from a technical and financial point of view and how they can support the seamless integration of renewable energies into the island's grid. This means that the energy storage system should increase the renewable energy penetration by making better use of the existing and planned renewable energy system. Furthermore, it could help alleviating the grid from the current congestion issues.

Three main tasks have been performed. The first was a high-level evaluation of various energy storage systems in order to determine the most suitable one. The second task consisted of sizing the chosen Energy Storage System (ESS) for the primary use case of increasing the renewable energy penetration, while the third task looked at sizing the ESS for the secondary use case of congestion alleviation.

Task 1 showed that that Battery Energy Storage Systems (BESS) are the most suitable in the case of Samos Island. Furthermore, it illustrated that BESS with a longer discharge duration time tend to be favoured. Considering the aforementioned trends, BESS such as NaS, NaNiCl or high-energy Li-ion solutions are considered to be the most suitable on Samos.

In Task 2, the model of the Samos power system in HOMER Pro has been presented to determine the viability and optimal size of battery energy storage for different scenarios on the island. The base-case scenario is defined as the currently existing power stations, solar PV and wind turbines.

The model shows that adding battery energy storage in the base-case scenario is not particularly interesting as there is barely any surplus renewable electricity that the battery can use. When reducing the electricity consumption, the optimum battery storage size increases because there is more surplus renewable electricity. However, the total battery size is still quite low compared to the total installed power production capacity, and hence the impact on the renewable fraction or fuel reduction is minimal. In order to attain meaningful increases in the renewable fraction and in order to make the battery energy system installation worthwhile, a significant capacity of new renewables should be installed.

When exploring the option of adding additional renewable energy capacity (solar PV and small-scale wind turbines), it is clear that Samos has not yet reached its full potential. 66.4 MWp of additional solar PV and a battery storage system of 48 MW/192 MWh could be installed. Small-scale wind turbines have not been found favourable since they tend to be significantly more expensive than solar PV. Important to note is that this is still a pre-feasibility exercise, not taking into account space constraints, landscape issues, grid problems, capital requirements, timing concerns, and so forth.

As part of Task 3, the use of energy storage systems as a virtual distribution capacity is investigated. A new method is proposed to evaluate how large an energy storage system is justified, in terms of power and energy to ensure security of supply by avoiding the interruption cost occurred due to the distribution grid constraints. Due to the lack of grid data, a reduced grid model has been used. From the technical and economic studies, the ESS is justified at 3MW, 12MWh with 10-year Investment Recovery Period reducing the Expected Energy Not Supplied (EENS) from 343 to 229 MWh per year.

The ESS project will need to access multiple revenue streams in order to increase profitability and compete with conventional reinforcements. This study looked into the synergetic application of increasing RE penetration and congestion relief, as both are quite predictable and can be valorised whenever their application is most needed. The installed battery capacity is thus not mutually exclusive but can be used for either application depending on what is valued most at each time interval.

Investments in power systems need to be taken with long-term consequences in mind. As a result, it is crucial to monitor how the energy storage system's effects will alter as demand increases/decreases. To improve reliability, postpone conventional reinforcement, and increase the availability of energy storage to participate in commercial service markets, the combination of energy storage systems and real-time thermal rating could be seen as taking advantage of the inherent variability in power line rating- because of changing weather conditions.

References

[1] F. Baumgarte, G. Glenk, and A. Rieger, ‘Business Models and Profitability of Energy Storage’, *iScience*, vol. 23, no. 10, p. 101554, 2020, doi: 10.1016/j.isci.2020.101554.

[2] H. Basser and M. B. Cohen, ‘Energy Storage Handbook: Chapter 25’, *Dep. Energy*, pp. 639–651, 2021.

[3] IRENA, *Electricity Storage Valuation Framework: Assessing System Value and Ensuring Project Viability*. 2020.

[4] ‘Transition Plan to the Net Forms of Energy’, Clean Energy for EU Islands, Samos, Oct. 2020.

[5] ‘Piraeus Bunker Prices’, *Ship&Bunker*. https://shipandbunker.com/prices/emea/medabs/gr-pir-piraeus

[6] Nikolaos M. Bouzounierakis, Yiannis A. Katsigiannis, and Emmanuel S. Karapidakis, ‘Operation of a Hybrid Power Station in an Isolated Power System; The Case of Samos Island’, in *4th International Hybrid Power Systems Workshop*, Crete, Greece, May 2019.

[7] IRENA, ‘Renewable Power Generation Costs in 2021’, International Renewable Energy Agency, Abu Dhabi, 2022.

[8] IRENA, ‘Electricity storage and renewables: Costs and markets to 2030’, International Renewable Energy Agency, 2017.

[9] Carlsson, J. et al., ‘ETRI 2014 Energy Technology Reference Indicator projections for 2010-2050’, *Energy Transp.*, 2014.

[10] ‘National Bank of Greece WACC % Historical Data’, *GuruFocus.com*, 2022. https://www.gurufocus.com/term/wacc/OTCPK:NBGIF/WACC-/National-Bank-of-Greece#:~:text=As%20of%20today%2C%20National%20Bank%20of%20Greece's%20weighted,cost%20of%20capital%20is%2011.11%25

[11] M. Eliassi, H. Seifi, and M.-R. Haghifam, “Multi-objective value-based reliability transmission planning using expected interruption cost due to transmission constraint,” in *2009 International Conference on Electric Power and Energy Conversion Systems, EPECS 2009*, 2009.

[12] J. Sun, *Reliability of Transmission Networks: Impact of EHV Underground Cables & Interaction of Offshore-Onshore Networks*. 2019.

[13] P. Balducci, K. Mongird, and M. Weimar, “Understanding the Value of Energy Storage for Power System Reliability and Resilience Applications,” *Curr. Sustain. Energy Reports*, vol. 8, no. 3, pp. 131–137, 2021, doi: 10.1007/s40518-021-00183-7.

[14] J. Endrenyi, Reliability Modeling in Power Systems, John Wiley & Sons, 1978.

[15] D. M. Greenwood, N. S. Wade, P. C. Taylor, P. Papadopoulos and N. Heyward, "A Probabilistic Method Combining Electrical Energy Storage and Real-Time Thermal Ratings to Defer Network Reinforcement," in IEEE Transactions on Sustainable Energy, vol. 8, no. 1, pp. 374-384, Jan. 2017, doi: 10.1109/TSTE.2016.2600320.

[16] H. Basser and M. B. Cohen, “Energy Storage Handbook: Chapter 25,” *Dep. Energy*, pp. 639–651, 2021.