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Clean energy for EU islands: Virtual Transmission Line for N-1 Security Compliance with Storage

La Palma, Spain

Clean energy for EU islands

Virtual Transmission Line for N-1 Security Compliance with Storage: La Palma, Spain

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Author: Mojtaba Eliassi (3E)
Reviewers: Marina Montero Carrero (3E), Jan Cornillie (3E)

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www.euislands.eu | info@euislands.eu

Preface: the paradigm shift required for power system planning in La Palma

Islands are especially vulnerable to global warming and climate change. La Palma, in its Manifest of Electron (2017) for a new energy model, advocates for a stable, 100% renewable island system with a combination of state-of-the-art technologies and practices including:

- Adapted infrastructures, both planned and demanded by the insular system to the energy transition as per the planned transmission line targeted in this study
- Grid Code reinforcements
- Manageable clean technologies, large storage technologies, self-consumption with net balance and domestic storages.

To trace the route to a 100% renewable island, solutions require a paradigm shift in technology, operational practices, and market design. Accordingly, power system planning methods should change from deterministic approaches like N-1 security to probabilistic approaches while integrating storage as a competitive asset with traditional solutions[1].

N-1 security transmission expansion planning dilemma

Reliability metrics such as ENS (Energy-Not-Served) are widely used for economic viability assessment of reliability-oriented transmission projects. However, these metrics do not measure intrinsic grid properties by considering events that happen to be what occurred. This means that they are non-normalised and may or may not repeat. An overview of the main blackouts of La Palma[2] shows that security of supply depends largely on the central power supply of the power plant while the transmission outage appears only once due to lightning strike which could be a common cause failure similar with an additional transmission line.

If the redundant transmission line is shown to be underutilised and does not provide as much value as originally expected, end customers will end up paying more, and the TSO will come under more pressure to spend capital responsibly. This risk could be perfectly challenged with an extremely flexible Storage-as-Transmission solution.

Planning criteria should be revised with the resilience concept, as the standard “n-1” criteria guides security against the largest single contingency neglecting multiple contingencies that could happen at once. As per solutions, storage can improve reliability, security, and resiliency at the same time in contrary with the traditional wire solutions are mainly for reliability enhancements[3].

Storage-as-Transmission

Storages provides numerous potential operational uses throughout the electricity value chain in a broad and heterogenous space by:

- T&D curtailment
- Time-shifting
- Forecast hedging
- Frequency support
- Voltage control
- Ancillary services

[1] https://energystorage.org/wp/wp-content/uploads/2019/12/2019-Policy-Position-Storage-as-Transmission.pdf

[2]] https://second.wiki/wiki/stromversorgung_von_la_palma#Versorgungssicherheit

[3]https://www.energy.gov/sites/prod/files/2018/06/f53/EAC_Role%20of%20Storage%20in%20Providing%20Resilience%20Reliability%20Security%20Services%20%28June%202018%29_0.pdf

With a fast-tracked cost-competitivity over the past decade, Storage as Transmission (SaT) can offer superfluous value propositions to asset owners and operators, end users, and the grid compared to traditional transmission solutions in different ways such as: flexible reliability services, smart congestion relief, quick deployment, smaller physical footprint, less environmental impact, fewer permitting challenges, option value[4], and higher risk management value[5]. SaT can contextualize the transmission infrastructure planning, so that they favour the energy transition by adding flexibility to: underutilised infrastructure, congested grids, and constrained renewables.

The avoided cost of interruption provides a niche market with a high average benefit value for deployment of Storage for mitigating short duration outages. Furthermore, multifunctional storage can also offer higher asset utilisation when used for both market and reliability services.

SaT Projects Worldwide

Looking to projects currently under construction or consideration proves that SaT is gaining traction in many TSOs in planning studies:

- The German 1 300 MW *GridBooster* energy storage project in 2019 to provide backup transmission capacity as opposed to the grid operators maintaining an entire additional transmission line on standby under N-1 criteria;
- Developed by American Transmission Company (ATC), a 2.5MW/5 MWh storage was planned to take the place of upgrading a 115kV double circuit, and would be deployed post-contingency to prevent voltage collapse in case of transmission line outages (30% cheaper than the cost of the traditional line rebuild option);
- A 2 MW, 4-hour duration storage by Arizona Public Service (APS) contracted with Fluence due to a lower cost than upgrading 20 miles of transmission and distribution lines;
- As an innovative solution for grid reliability, compared to traditional transmission wires solutions, PG&E agreed with third-party owned energy storage projects (totalling 43.25 MW and 173 MWh) to replace fossil generation with clean energy;
- RTE will install its first 40 MW virtual transmission project called RINGO, to increase grid integration of renewable energy and manage power flows.

[4] To meet reliability needs as they occur and change over time while

[5] Traditional transmission solutions are usually not relocatable and should be paid by the customer, even if system dynamics change and operational challenges move or not utilized as expected

Summary of the technical report

La Palma requested technical assistance from the Islands secretariat to investigate a battery energy storage system (a virtual transmission line) as an alternative to the 66 kV transmission overhead line that the system operator and the Spanish Government plan to construct on the island.

To carry out the comparison between the virtual transmission line and the overhead line, the cost of interruption has been used. This cost gives value to the reduction of electricity outages for the island's electricity consumers.

Several technology options have been considered as the energy storage system, including a variety of battery technologies and a Compressed Air Storage System:

Storage Type	Name
Sodium Sulfur	NaS
Sodium Nickel Chloride	NaNiCl
Hybrid LA & DL-CAP	Hybrid
Compressed-Air ES, cavern	CAES-c
Valve Regulated Lead Acid	VRLA
Adv. Vanadium Red. Flow	A-VRFB
Advanced Lead Acid	LA-adv
Zinc Bromide	ZnBr
Lithium Ion - High Energy	LIB-e
Vanadium Redox Battery	VRFB

As a first step, the feasibility of the technologies is calculated for utility back-up at transmission level. Of the studied technologies, Compressed Air Energy Storage (with total annual value of €80-€330/kW/year) is the only viable option. If in addition to utility back-up, a secondary use for the storage system such as frequency support, other technologies like Nickel and Hybrid LA & DL-CAP become economically feasible.

In a second step, simulations with DER-VET tool were carried out to assess whether the energy storage systems are capable of covering a shortage of a 2h duration in the existing transmission line. According to the Net Present Value analysis, Compressed Air Energy Storage system is economically viable for a single application (Utility reliability-based backup) with Day-ahead spot prices for charge tariffs.

Efficient sizing of ESS requires detailed modelling and assessment of the dispatch, finance, and reliability analyses of the grid. Several input data are necessary to evaluate stacking of different revenue streams to enhance the energy storage system's business model. Frequency support services are proposed as the second use case considering their synergy with the utility reliability back-up application while without the frequency price and requirements data, the assessment is not feasible.

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Acronyms

ADN	Active Distribution Node
CAES	Compressed Air Energy Storage
ENS	Energy Not Supplied
ESS	Energy Storage System
IR	Inflation Rate
IRR	Internal Rate of Return
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NPV	Net Present Value
PHES	Pumped Hydro Energy Storge
RP	Recovery Period
TEP	Transmission Expansion Planning
VBRA	Value Based Reliability Assessment

I. Introduction

Background

La Palma's transmission grid has a unique design. Transmission lines go from west to east, but do not complete the loop—meaning power can only flow both ways between west and east with the generation units mainly concentrated in the eastern part. This makes managing and operating a secure system that tries to minimise cost of generation very complex leading to significant price differences between the states and blocking renewable energy from being exported from specific pockets in the island.

La Palma grid is a completely isolated island within Canary Islands interconnection to other islands is less evident due to the great depth of the seabed in the archipelago. A Reliability-oriented transmission expansion project, namely:

- 66kV Las Breñas L / Guinchos-Aridane Valley (Double Circuit): The existing circuit at 66kV Guinchos-Aridane Valley and circuits at 66kV Guinchos-Las Breñas and 66kV Las Breñas-Aridane Valley
- 66kV Guinchos - Las Breñas 2 (Simple circuit).
- 66kV Las Breñas - Aridane Valley 2 (Simple Circuit)

has been issued by the System Operator to satisfy the existing or new reliability criteria. 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 may get obstructed due to different perspectives on need, benefits, and cost responsibility.

Without such a transmission, there is potential for reliability-related problems and failure to meet the established N-1 security criteria[6]. An estimate of the ENS (Energy Not Supplied) has been made in the area that would mean the non-realisation of the network proposed in this report. Assuming the unavailability of the current circuit Aridane-Guinchos Valley 66 kV of about 40 h/year (according to statistics of unavailability of the last 8 years), an ENS of 510 MWh is estimated that valued at €6,350/MWh (reference ENTSOE) gives a cost Estimated annual ENS avoided of €3.24 million. The economic indicators of Internal Rate of Return (IRR) and Investment Recovery Period (RP) are calculated as 10% and 10 years, respectively. Solving the equation below with the €23.3 million mentioned in the previous study done by 3E for La Palma as the total investment costs:

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

where:
C_t = Avoided cost during the period t
C_0=Total initial investment costs
NPV=Net Present Value
gives the IR (Inflation rate) estimated as 3.3% which seems rational.

Motivation

It should be stated that addition of a new parallel 66 kV circuit to the current one doesn't mean 100% reliability and availability of the customer supply, while common mode failures [1] may still cause simultaneous outage of both lines and consequently, load curtailment and ENS. It is believed that 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 operating scenarios. 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 transmission lines [2]. In this way, the incremental cost of providing

[6] Basic criteria of security of supply and suitability of the Transport Network (POSEIE 1 and POSEIE 13) according to which the system must support simple contingencies (N-1) without affecting the quality and security of supply.

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 the normal operation according to the capacity of the existing line and the maximum power needed to be transferred to demand connected to Aridane 66 kV.
- Integration of more energy resources into Aridane 66 kV and 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 the energy storages when they are not used for the main application (Utility reliability improvement) in the transmission line outage circumstances (40 h/year).
- ESS-based solutions are modular and can be scaled and relocated in future to fit the needs.
- 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 [3].
- The avoided cost of interruption is used widely for mitigating short duration outages, reaching as high average benefit value as $719/kW-year. As a comparison, average benefit values for specific use cases of ESS range from under $10/kW-year for voltage support to roughly $100/kW-year for capacity and frequency regulation services. However, there is no agreement when it comes to make money from increasing the grid resilience [4].

Contribution

A comparative analysis of ESS and N-1 Network Security in Transmission Expansion Planning (TEP) is designated to coordinate ESS with transmission expansion planning in a system like La Palma. This system is characterised by base load generators and expensive peaking power plants. The objective of this study is to minimise the operational cost of the generators as well as the transmission line and storage investment costs over several demand levels.

In section II of this report, a methodology for ESS valuation is established. The initial step of the valuation framework is presented in section III on the relation assessment of technologies and business models of the ESS for the use case of La Palma using the ES-SELECT Tool. The sizing of the ESS with detailed analytical and simulation methods are presented and analysed in section IV for a single-application and multi-application ESS including dispatch, design, financial, and reliability evaluations. In Section V, we will conclude the report by reviewing the main findings, limitations of our study, and opportunities for future research.

II. Energy Storage System Valuation

Two of the first solutions to increase the share of renewables and at the same time guaranteeing electricity supply are energy storage systems and improving the operation and control practices of the grid. The hierarchical controller of an ESS should interact in different timeframes with the business and energy management systems of the System Operator and of the Market Operator, as shown in Figure 1 to provide flexibility and energy services to the local system and, consequently, to the grid.

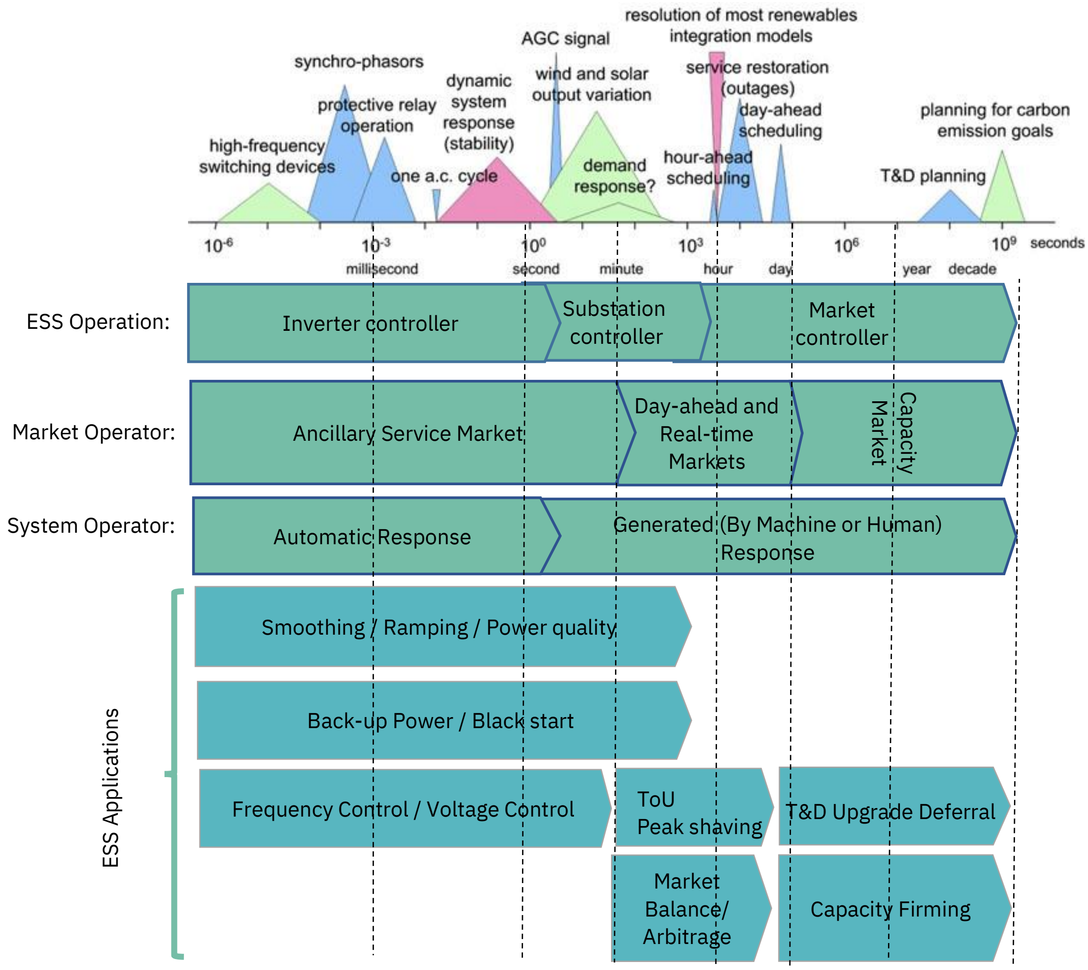

Figure 1 Time scales and phenomenon in power system and ESS planning and operations.

The more utility-scale battery storage systems installed, the greater share of variable renewable energy could be integrated into the island power grid and the more cost saving opportunities will come to the renewable marketplace for multiple stakeholders. Energy Storage System valuation deals with four main threads responding main issues as regards services, technologies, economics, and gaps, itemised below:

- Services:
  - What services exist to improve the current business model?
  - What other peripheral services could we deliver?
- Technologies:
  - Which storage technologies are a fit?
  - What are their associated costs?
- Economics:
  - System level: Comparing with other alternative measures, such as demand response, more flexible generation, or even stronger network connection, is ESS still justifiable?
  - ESS Asset level: Assuming optimal operation, would a project be financially viable under a specified market setting?
- Gaps:
  - Is there any missing money?
  - How to bridge the gap?

An ESS project needs consistency in design and operation to hedge the risk of investment with stacking several revenue streams and cost saving. This can be achieved through load shifting and ancillary services provision. Revenue streams, investor's role, and value propositions forming ESS's possible business model are presented in

Figure 2. Considering complexities of ESS business models, a battery is just as valued as the software that operates it.

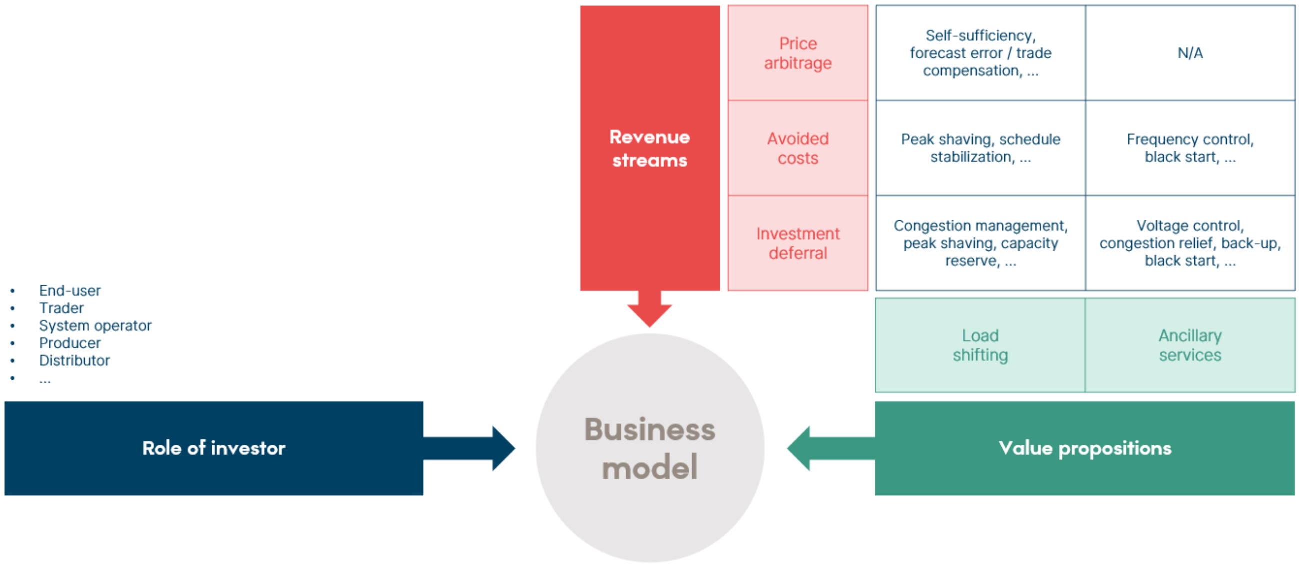

Figure 2 ESS's possible business model realisation[7].

Business models should be carefully matched to the available technologies as each business model involves specific operational requirements that not all storage technologies can run into. Matching plays on an intersection in three operational parameters:

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

The cycle capacity and round-trip efficiency are not encouraged parameters in line with their reflection in the technology's cost efficiency. The summarised operational requirements for business models from previous reviews is presented in Figure 3 [5].

Although there are some commercially available technologies that can serve all the identified business models, certain combinations of technologies and applications may move toward a slipping point on their profitability and preference in comparison with the alternative solutions. The power rating of an energy storage system impacts system pricing, where larger systems are typically lower in cost (on a €/kWh basis) than smaller ones due to volume purchasing [6].

A comparative assessment of the characteristics of ESS flexibility options potential in different timeframes is presented in Figure 4. While ESS with short duration captures the intra-day variability, ESS with long duration is fit for extreme events that last for multiple hours and 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 (up to a day) and large capacity.

[7] From 3E's webinar on "*MARKET TRENDS IN SOLAR & WIND*". More information: https://3e.eu/webinars/webinar-market-trends-solar-wind

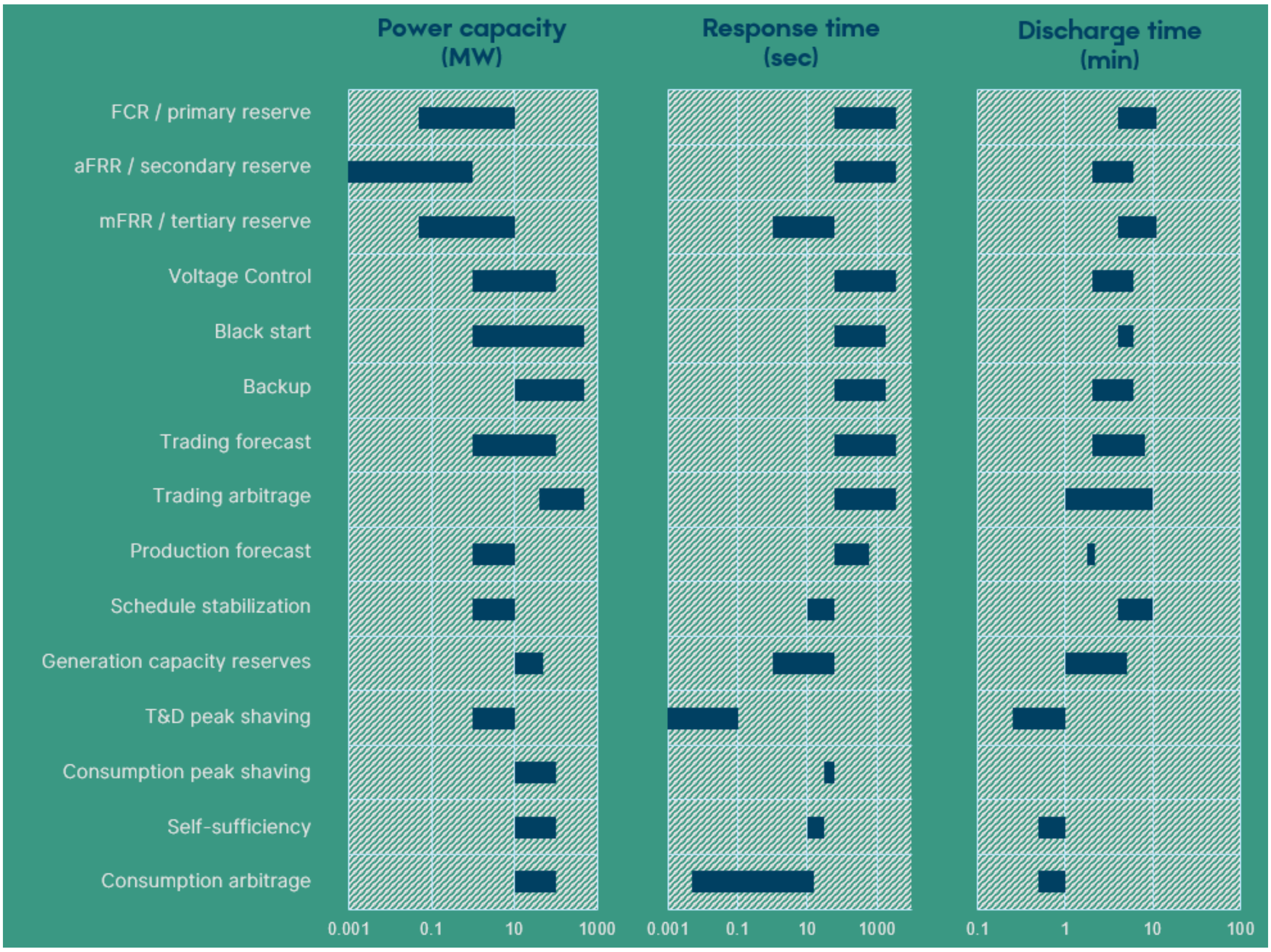

Figure 3 ESS's applications technological requirements review.

Figure 4 Comparative review of common ESS technologies.

According to IRENA storage valuation framework [7], four main steps are designated to assess the applicability of ESSs for the utility reliability use case of La Palma (N-1 security), as below:

1- Initial technology selection for the primary use case (using ES-SELECT Tool of SANDIA[8])
2- Sizing studies of ESS for the primary use case (using DER-VET[9] Tool of EPRI)
3- Financial evaluation and comparative studies
4- Stacking revenues either to bridge the gap or to enhance the business model

[8] https://www.sandia.gov/ess-ssl/ESSelectUpdates/ES-Select_Documentation_and_User_Manual-VER_2-2013.pdf
[9] https://storagewiki.epri.com/index.php/DER_VET_User_Guide#Index

III. Business Model mapping to Technology

ES-SELECT Tool is used for selecting the technology for the primary use case, i.e. utility backup application for T&D operators interconnection points. The ES-Select™ Tool aims to improve the understanding of the different electrical energy storage technologies and their feasibility for intended applications in a simple, visually comparative form.
ES-SELECT is used to:

- Calculate Feasibility Scores of technologies based on the role, applications, and technologies
- Analysing and mapping technology to the business model

In the application's initial screen, users choose from the five main locations for energy storage in a power grid, from central or bulk storage facilities with a capacity of 50 MW or more to residential and community storage of 100 kW or less. Based on the load level of Aridane substation, studies are executed at transmission substation level.

Service Reliability (Utility Backup) defined in ES-SELECT is one of the ESS applications that focuses on the need for back-up power systems at the utility side of the electric meter like the case of La Palma. This application needs long discharge (high energy) requirements with occasional use with high compatibility with other applications for stacking. The choice of technology depends on:

1. CaPEx, per kW & kWh (kWh is chosen due to higher feasibility scores)
2. Maturity of technology (readiness for commercial deployment)
3. Appropriateness for locations (considers availability, mobility, size, weight, scalability, etc.)
4. Capability to meet application requirements (considers discharge duration, cycle life, efficiency, etc.).

The top ten ESS options and feasibility scores for Utility Backup single-application are presented in Table 1. CaPEx, per kW & kWh in ES-SELECT Tool is shown in bubble charts in Figure 5 for the feasible technologies.

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

Storage Type	Name	Feasibility scores
Sodium Sulfur	NaS	74%
Sodium Nickel Chloride	NaNiCl	58%
Hybrid LA & DL-CAP	Hybrid	57%
Compressed-Air ES, cavern	CAES-c	56%
Valve Regulated Lead Acid	VRLA	56%
Adv. Vanadium Red. Flow	A-VRFB	54%
Advanced Lead Acid	LA-adv	54%
Zinc Bromide	ZnBr	53%
Lithium Ion - High Energy	LIB-e	52%
Vanadium Redox Battery	VRFB	51%

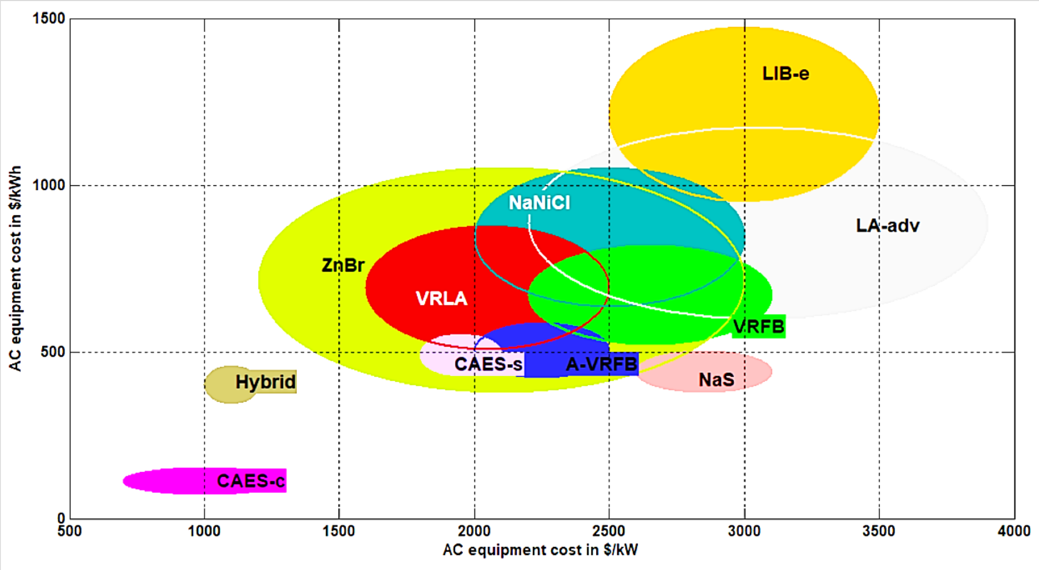

Figure 5 CaPEx, per kW & kWh of feasible ESS technologies for utility back-up from ES-SELECT.

Using previous financial parameters, ES-Select™ provided cash flows and payback analyses considering the uncertainty in both the cost of ownership of the ESS and its benefits over the years. Amongst different analyses, the probability of having a payback within the project lifetime is presented in Figure 6 in which CAES (with total annual value of €80-330/kW/year) is the only viable option amongst technically available technologies. It is evident that batteries should be a choice by profitability rather than by default.

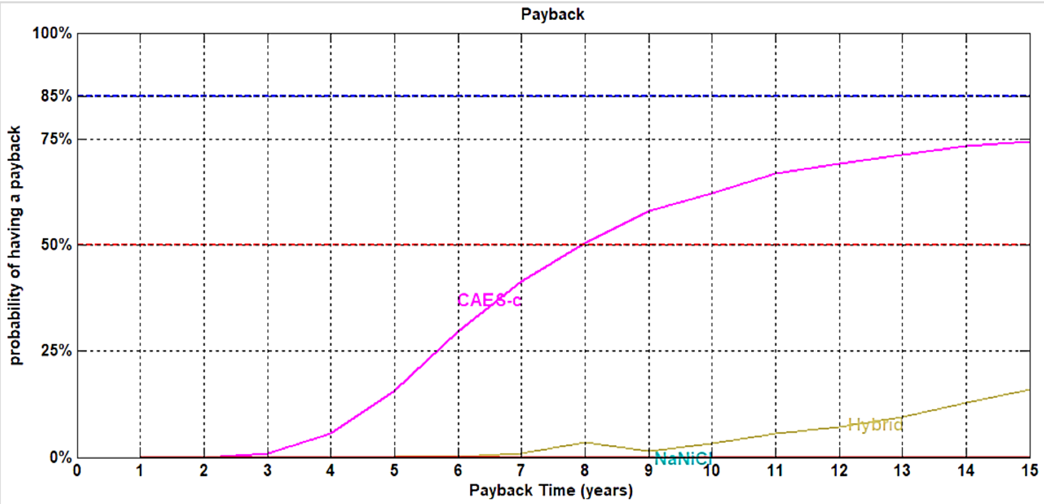

Figure 6 Probability of having a payback within the project lifetime for utility back-up.

Adding more applications to the business model will possibly lead to different storage options and score ranking. It is generally expected to have further profitability from a business model with stacked synergetic applications. Several secondary use cases could be integrated into the business model of the ESS such as arbitrage, voltage support, smoothing, firming, etc. Considering the level of annual value and synergy with the primary application, area regulation is chosen. Area regulation is an hourly product that uses ESS to rapidly change its output (MW/min) to follow minute-to-minute variations in loads generations (to maintain the grid frequency).

Table 2 ESS options and feasibility scores for multiple applications: utility back-up and regulation

Storage Type	Name	Score
Sodium Sulfur	NaS	72%
Sodium Nickel Chloride	NaNiCl	58%
Hybrid LA & DL-CAP	Hybrid	56%
Advanced Lead Acid	LA-adv	52%
Lithium Ion - High Energy	LIB-e	51%
Adv.Vanadium Red. Flow Batt.	A-VRFB	50%
Zinc Bromide	ZnBr	49%
Valve Regulated Lead Acid	VRLA	48%
Vanadium Redox Battery	VRFB	47%
Compressed-Air ES, cavern	CAES-c	46%
Compressed-Air ES, small	CAES-s	44%
Ni batt. (NiCd, NiZn, NiMH)	Ni-batt	40%

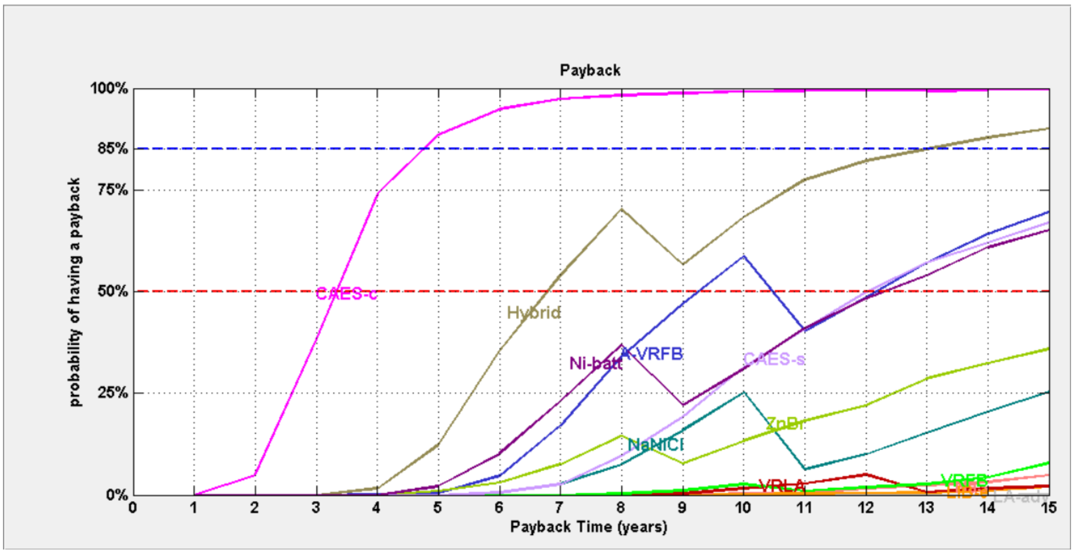

Figure 7 Probability of having a payback within the project lifetime for utility back-up and area regulation.

Like the single-application case, results are presented in Figure 7 and Table 2, showing higher economic viability (with total annual value of €233-531/kW/year) for more of the feasible storage options.

IV. ESS sizing to Address Grid Reliability and Customer Resilience

The data and model form the previous study done by 3E for La Palma[10] is utilised in this study. While only total historical load of the grid has been provided by La Palma, the total load of the island is supposed to be distributed evenly among two main 66 kV substations of the island, namely Guinchos and Aridane. Studies are executed for 30 minutes interval data of load and day-ahead price of 2017-2019.

Assumptions and Inputs

The methodology is tailored with the data available from the island's grid operation while considering possible scenarios and uncertainties. Avoiding or deferring installation of a new 66 kV transmission line between Guinchos

[10] This study was performed as part of the Clean energy for EU islands secretariat Project Specific Support in 2020

and Aridane to build up a N-1 secured grid is achievable by reserving some energy capability at Aridane substation (stored energy in a storage system) that would not be used by economic services. On the one hand, ESS can guarantee reliability of the grid and resilience of the customers connected to the downstream in case of the line outage, and on the other hand, the increased reliability could be compromised with the investment cost with Value-Based Reliability assessment.

The reliability of an asset such as a transmission line would be defined as its ability to fulfil its function (i.e. continuous operation), corresponding to its risk, which is defined as the product of probability and effect. In the case of La Palma, the outage of the line happens expectedly 40 h/year with 510 MWh × €6,350 /MWh equal to €3.24 million annual avoided cost, while other operational performance indicators of on the utility asset (the 66 kV transmission line) were not publicly available.

Essentially, for calculating techno-economic performance of the existing transmission line and to assess the economic impact their forced outages on the La Palma grid reliability planning [8] *Reliability*, *Maintainability*, and *Availability* parameters would be required to be estimated for being measured in the storage sizing problem inputs as targets [9]:

- *Reliability*: Mean Time Between Failures (MTBF) or the failure rate (λ) as its reciprocal or the probability that the line will be available (i.e., will not fail) within a specified period, with no concern about the time to repair or back to service,
- *Maintainability*: Duration of maintenance outages or Mean Time to Repair (MTTR) or probability of a failed transmission line to be restored or repaired to an operating condition within a specified period, as repair rate (μ) which is the reciprocal of the MTTR,
- *Availability*: Up-time for operations as a measure of how often the line is alive and in service as function of MTBF and MTTR ($Availability = {}^{\mathrm{MTBF}}/_{\mathrm{MTBF+MTTR}}$)

For these estimations, several data per outage including date and time, line outage duration, protection action, restoration (or repair) time, interrupted MW and duration are required. Failure rate should be approximated as the division of the total number of failures experienced by the total service years. Type and location of failures, available logistics, human skills, and different environmental conditions affect the time required for restoring the failed line. A random variable can represent the down time (outage duration) of the line associated with a probability density function. In many instances, if the failure rate of a transmission line is constant, the down time is exponentially distributed. For non-constant failure rates other distributions such as Weibull or lognormal are used.

The Unavailability indicator (estimated as 40 h / 8760 h = 0.0046, i.e., 0.9954 as for the Availability index), does not always implicate high reliability or maintainability. If the failure frequency or repair time is high, i.e. the system fails either frequently or with high duration and impact, it has a negative effect on the system user and higher capacity of storage system may be required.

Therefore, installing an ESS (instead on a new transmission line) for N-1 conditions of La Palma grid should be treated as a back-up use case for reliability-based sizing of a utility-owned ESS for coverage of target hours of guaranteed outage or guaranteed availability for the utility customers. In the two forthcoming sections, two different methods, Analytical and Simulation, are described and implemented.

Analytical Reliability-based Sizing of ESS

The Aridane 66 kV substation load at the downstream is supplied by the primary source (i.e. the utility resources and connection) of availability/Unavailability $A_0 = 0.9954, U_0 = 0.0046$ showing that power will be served to the load with probability in steady state. It is assumed that the total system load connected to this substation ($P_{max}\ MW = 22.6\ MW$) should be served in case of grid connection failure (i.e. Critical load is equal to the total Load) to comply with intended N-1 security condition.

It is presumed to add sufficient capacity of storage to boost/reduce the Availability/Unavailability of power supply to Aridane load from A_0, U_0 to A_1, U_1 (as the intended reliability criteria) of the island at Aridane 66 kV node. This targeted reliability criteria could be mandated by the grid code or calculated from the reliability cost-worth analysis.

The power capacity of the required storage unit should be at least P_{ESS}^{max} MW, while energy capacity or duration should be calculated. Average load not supplied per one hour outage duration is another option to be considered as for P_{ESS}^{max} as $12.75\ \mathrm{MW}$ (as a mean value). Average load not supplied per one hour outage duration could be approximated as $12.75\ \mathrm{MW} = {}^{510\ \mathrm{MWh}}/_{40\mathrm{h}}$ if MW peak load is not available throughout the year.

Assuming:
- D_{tl}: disturbance of the existing transmission line failure.
- F: disturbance of unsupplied load.
- T: Duration for which the ESS unit should serve the load.
- $MTTR$: random variable for the outage duration or down time of the existing 66kV transmission line.
- $f_{MTTR}(r)$: probability density function of R,

the event F occurs when the 66 kV transmission is down for a period longer than T, and its probability is given from [9] by:

$$U_1 = 1 - A_1 = P\{F\} = P\{\{F > T\} \cap D_{tl}\}$$
$$= P\{\{F > T\} \cap D_{tl}\}$$
$$= (\int_{t=T}^{\infty} f_{MTTR}(r)dr) \,.\, P\{D_{tl}\}$$
$$= (\int_{t=T}^{\infty} f_{MTTR}(r)dr)\,(1 - A_0) = U_0 \int_{t=T}^{\infty} f_{MTTR}(r)dr$$
$$\Rightarrow \frac{U_1}{U_0} = K = \int_{t=T}^{\infty} f_{MTTR}(r)dr$$

K is defined as *reliability target decrease rate*. Assuming exponential distribution of R with $\overline{mttr}$ for outage duration (down time) probability density function is a normal case for transmission lines. Therefore:

$$T = -\bar{r} \times \ln\left(\frac{1 - A_1}{1 - A_0}\right) = -\overline{mttr} \times \ln\ K$$

As an example, to improve the unavailability to 10% of the initial value ($K = 0.1$; 40 h to 4 h total duration; 0.0046 to 0.00046 unavailability):

$$T = -\ln\left(\frac{0.00046}{0.0046}\right) \times \overline{mttr} = 2.3 \times \bar{r}$$

Having the mean down time of the transmission line, it would give us the minimum energy requirement of the ESS for $2.3 \times \bar{r}$ hours. Assuming 2h as $\overline{mttr}$, the storage energy rating is calculated as 103.96 MWh and 22.6 MW inverter's power rating. For reliability cost-worth analysis and Value Based Reliability Assessment (VBRA), 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 [6]:[11]

$$Reliability\ worth = \sum_{t=1}^{\mathrm{PR}} \frac{C_t(1+IR)^t}{(1+IRR)^t} = \sum_{t=1}^{10} \frac{3.24(1+0.033)^t}{(1+0.1)^t} = €23.31\, million$$

[11] RP, IRR, and IR in this report are assumed like the ones from the planned transmission line cost-benefit analysis as the base case to benchmark.

$$Reliability\ cost = A \times P_{ESS}^{max} + B \times E_{ESS}^{max} = 103.96\ \text{MWh} \times 120\ \frac{k€}{\text{MWh}} + 22.6\ \text{MW} \times 1200\ \frac{k€}{\text{MW}} = €39.60\ \text{million}$$

that explicates:

$$Reliability\ worth < Reliability\ cost$$

If the optimal reliability target is not achieved in the first step, calculations would be repeated for a new reliability target[12] till convergence. The new reliability target is supposed to be a less than A_1 in case of over investment.

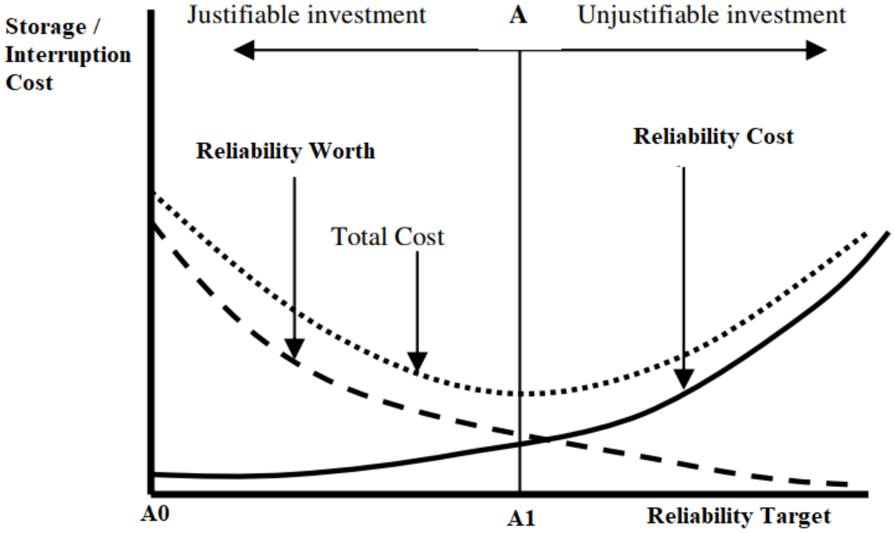

Figure 8 Reliability cost-worth analysis and convergence.

If instead of availability, we want to use a target in terms of mean down time (for which the data is not currently available) from $\bar{r}$ to $K.\bar{r}$ for $0 < K < 1$, T should be calculated from:

$$\int_{t=T}^{\infty} r f_R(r) dr = K.\overline{mttr}$$

It is instinctively noticeable this equation would produce somewhat similar results to $\int_{t=T}^{\infty} f_R(r) dr = \frac{1-A_1}{1-A_0}$ for small value of T. Appropriately, we could say that if the storage targets an improvement in the availability index, somewhat similar effect would be expected to be seen in the mean down time.

In this approach, details such as degradation, maintenance, charging, and other cost terms, common cause failures, failures of storage, or time-dependent factors like state of charge are neglected. In the next section, using DER-VET, reliability-based sizing of the ESS is presented in more details as opposed to the analytical method.

Simulated Reliability-based Sizing of ESS

DER-VET uses load and other site-specific data to optionally optimise the size of the ESS concurrently with its dispatch optimisation. It has a detailed analysis capability, expanding the reliability service to include dynamic, time-varying energy reservations, size constraints, and reconfigurability.

Reliability and resiliency are defined as the ability of ESS to supply power to (critical) loads at all times at Aridane 66 kV substation. In DER-VET the (critical) load coverage probability approach in which the probability of the ESS having enough energy and power capability to cover the transmission line outage of a specified duration is modelled (2 hours, herein). In this case, operation of ESS will be constrained such that, it will be able to meet or surpass the coverage probability requirement. To size ESS for always supplying the (critical) load for 2 hours target

[12] The return period (PR) could be also extended to the life time of the storage as for CAES to 40 years.

outage length, all possible outage scenarios of 2-hour length within the given load profile are considered with equal probability of outage occurrence at all time steps.

Inputs and Setting

Studies are executed for 30 minutes interval data of load and day-ahead price of 2017. Load of 2017 is assumed to be distrusted evenly among two main 66 kV substations of La Palma.

Figure 9 Day-Ahead Price time series and heatmap of 2017 in La Palma.

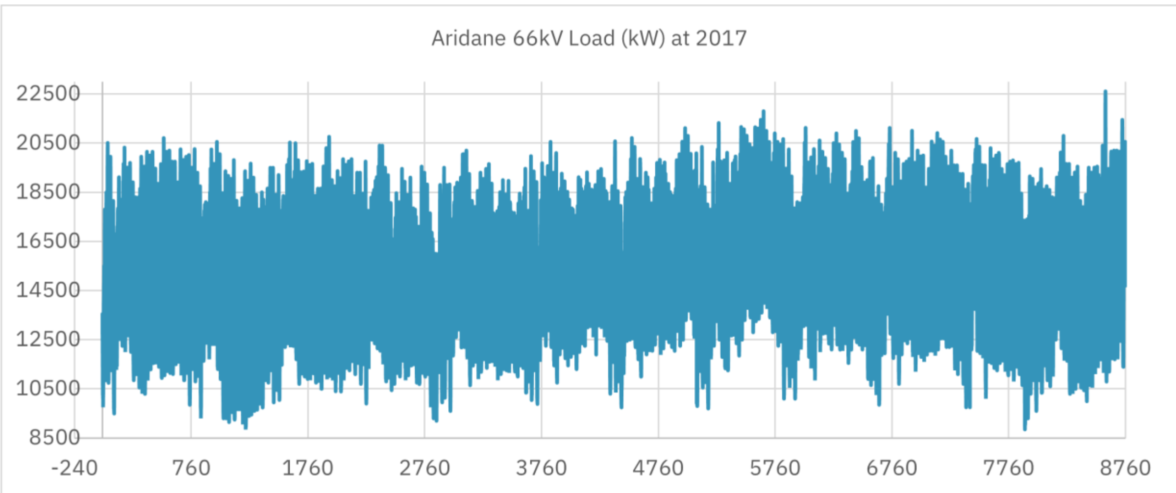

Figure 10 Aridane 66kV (critical) Load (kW) in 2017.

Setting of the financial and technical parameters are decided similar to the previous study scenarios except for the analysis horizon which is extended to 20 years as the minimum lifetime of the ESS.

Result analysis

ESS Design:

Power Specifications		Energy Specifications	
Discharge Rating (kW)	Charge Rating (kW)	Energy Rating (kWh)	Duration (hours)
22,600	22,600	89,151	3.95

ESS Rated Power and Energy Costs:

Cost of the ESS		
Total Cost	€37,818,120	
Cost per kW	22,600kW x €1,200/kW	€27,120,000
Cost per kWh	89,151kWh x €120/kWh	€10,698,120

ESS NPV:

Year	Capital Cost [€]	NPV of Day-Ahead market [Benefits € over 20 years]	NPV of the ENS avoided [cost € over 20 years]	Net NPV [€]
2017	-37,818,120	559,544	35,739,803	-1,518,773

ESS Dispatch (Only the first month):

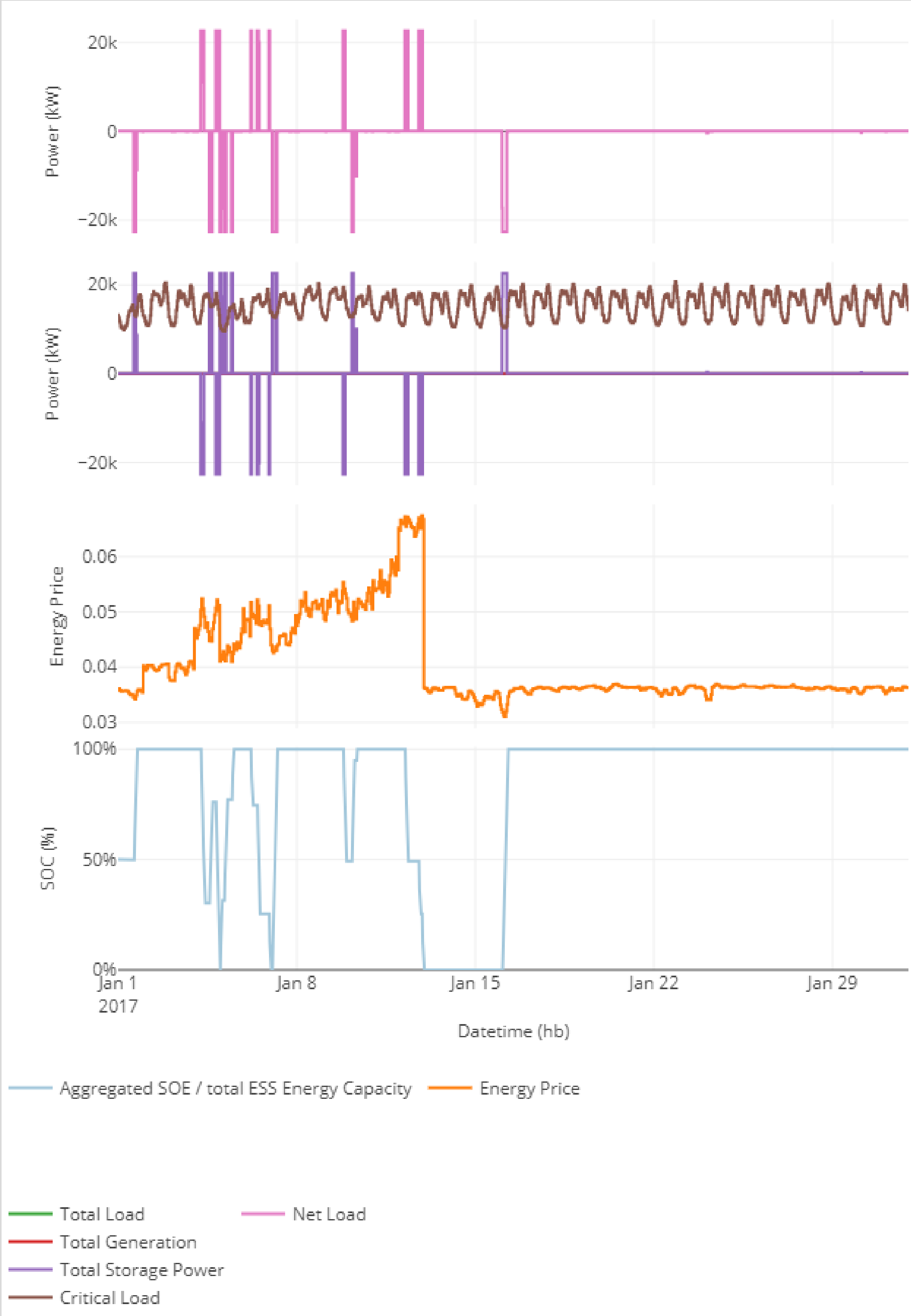

Figure 11 First month's dispatch results in ingle-application BESS for Reliability.

While net present value of the project is yet negative, it could be considered as acceptable with regard to the overestimation of risk in input parameters.

Reliability:

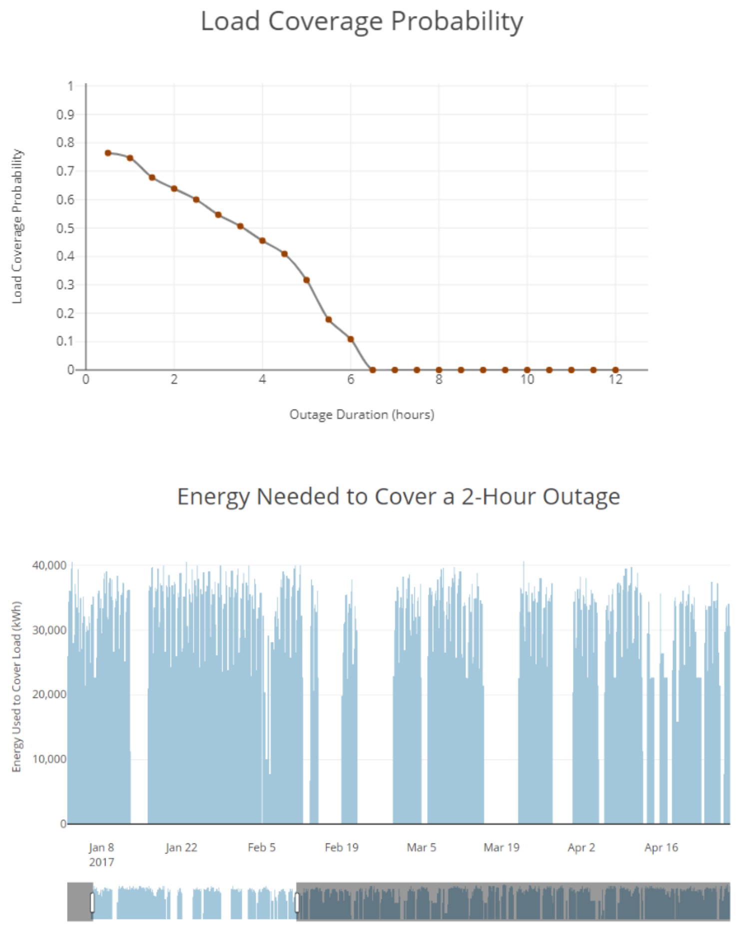

Figure 12 Reliability simulation results of a single application BESS.

While the ESS's requirements obtained from this simulation is not unlike the one resulted from analytical calculations, but it is lower due to better modelling and operation of the ESS with DER-VET tool. As it could be seen from the NPV analysis, the ESS is considered economically viable with a single application (Reliability-based backup sizing) and improvement of the business model would be easily applicable to bridge the modest financial gap.

Simulated Value-stacking Analysis of ESS

The economic viability gap assesses the difference between the cost and the monetisable benefit that could be greater than zero due to:

- High storage capital costs, or
- Unfavourable market mechanisms.

Solutions to bridge the possible gap are:

- Compensating storage for offsetting the need for other investment/cost
- Creating new revenue streams achieved with a value proposition/market in which storage is allowed to participate.
- Evaluating other technology options or combinations as per their feasibility.

In DER-VET; ESS can be used to improve grid reliability, improve customer resilience by providing backup to local critical loads, decrease the electricity bill incurred by the site, participate in wholesale energy or ancillary services markets, provide demand response or resource adequacy, or some allowable combination of these. In contrary to the pre-dispatch services such as reliability that happens before the optimisation, DER-VET "Optimisation services" determine economic value of the service and the amount the ESS by the optimisation problem. Frequency regulation service could be chosen as the second use case considering its synergy with the reliability application while without the frequency regulation price data, the assessment is not feasible.

V. General Conclusions and Recommendations

A methodology for utility-scale Energy Storage System (ESS) valuation is established for technology selection and cost-benefit evaluation of a virtual transmission line project for reliability-based planning purposes in La Palma, Spain. First, the relation of technologies and business models of the ESS have been assessed for the use case of La Palma (Utility back-up) using ES-SELECT Tool. CEAS-c has been chosen as the economically and technically viable technology in this use case. By stacking the revenue streams, more technologies with higher viability and payback period have become viable.

Sizing of the ESS with detailed analytical and simulation methods is presented and analysed for a single-application and day-ahead prices leading to dispatch, design, financial, and reliability evaluations. With regards to the overestimated reliability requirements and underestimated benefits of the ESS, mitigating short duration outages with ESS could be justified in a 20-year horizon analysis.

The ESS also demonstrated high average yearly benefit value for multiple applications in simulations with ES-SELECT, while without the relevant data, detailed assessment is not practicable in DER-VET. Gathering required formation for stacking other revenue streams of ESS is highly recommended.

The following state-of-the-art recommendations are proposed for further investigations:

(1) A preliminary study on the role of energy storage in [10] suggests that implementing load rationing even partially and limited by the enthusiastic customers could potentially reduce significantly this estimated energy storage capacity. Load rationing is about replacing load shedding during difficult hours, with providing a minimum amount of electricity supply to some customers with incentives and cut off their electricity if they go beyond our limit.
(2) Enhancing failure rate and outage duration of the existing transmission line with smart grid technologies and data analytics in the asset operation and asset management would be also recommended to reduce the required size of the ESS.
(3) For the sake of reliability, the proposed utility-scale ESS concentrated at Aridane is recommended to be distributed by providing proper regulatory support and incentives in distribution grid with sufficient controllability and observability, as well as price signals for guiding investment directions. While in most member states of EU, TSOs and DSOs are prohibited from ownership of ESS, with some expectations in the regulatory framework, there should be a clear regulatory and market framework through which they can be benefit from services provided by other ESS owners [11].
(4) Integration of Renewable energy resources all over the island and, especially into the downstream grid of Aridane 66 kV primary substation would be encouraged both technically and financially with installation of ESS. Nevertheless, smart grid functionalities and solutions are required to guarantee safe, secure, and efficient operation of the transmission grid of La Palma in high level of renewable penetration.
(5) Power-to-X storage[13] have extensive seasonal to short-term applications tailored for back-up applications and stacking revenue streams, while other consumptions of Hydrogen like gas grid in the system should be also considered.
(6) Active Distribution Node (ADN) implementation[14] at Aridane substation in co-operation of ESS and either DERs in the downstream grid or the aggregated net LV Load in a coordinated manner with the System and Market Operators. Cooperative operation of the ADN needs transactive system operation and distributed control approaches.

[13] https://irena.org/innovation/Toolbox
[14] http://www.flexitranstore.eu/Demo-1

(7) Tools and databases deployed in this report all have been developed by US national and independent research and innovation institutes. To the author's knowledge similar open-source tools and databases are encouraged to be made available by corresponding authorities for special needs of EU member states on regulatory, economical, and technological considerations[15].

[15] A database for EU-wide projects is https://data.europa.eu/data/datasets/database-of-the-european-energy-storage-technologies-and-facilities?locale=en

References

[1] M. Eliassi, H. Seifi, and M.-R. Haghifam, "Incorporation of protection system failures into bulk power system reliability assessment by Bayesian networks," *IET Gener. Transm. Distrib.*, vol. 9, no. 11, 2015, doi: 10.1049/iet-gtd.2014.0365.

[2] 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.

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

[4] 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.

[5] 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.

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

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

[8] M. Abdelfatah, M. EL-Shimy, and H. Ismail, "Reliability and maintainability analysis of medium voltage transformers in Egypt," *Int. Conf. Electr. Eng.*, vol. 8, no. 8, pp. 1–17, 2012, doi: 10.21608/iceeng.2012.32720.

[9] J. Mitra, "Reliability-based sizing of backup storage," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 1198–1199, 2010, doi: 10.1109/TPWRS.2009.2037516.

[10] A. Menati and L. Xie, "A Preliminary Study on the Role of Energy Storage and Load Rationing in Mitigating the Impact of the 2021 Texas Power Outage," 2021, doi: 10.1109/naps52732.2021.9654452.

[11] S. A. R. Mir Mohammadi Kooshknow and C. B. Davis, "Business models design space for electricity storage systems: Case study of the Netherlands," *J. Energy Storage*, vol. 20, no. August, pp. 590–604, 2018, doi: 10.1016/j.est.2018.10.001.

Appendices