Universidade de São Paulo - USP
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Reduction of CO₂ Emissions in Isolated Power Systems Using Energy
Storage.

São Paulo, Brasil
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Storage.

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Storage.

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To my parents, brothers and my nieces

To my family and friends

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Resumo

Atualmente, a grande maioria da energia utilizada em sistemas isolados é gerada por meio de combustíveis fósseis. Este trabalho faz a avaliação do potencial de redução das emissões de CO₂ em dois sistemas escolhidos como teste, o sistema de Fernando de Noronha e o sistema de um navio de suprimentos para plataformas de petróleo (do inglês, *Platform Supply Vessel*), utilizando sistemas de armazenamento de energia. Além disso, como contribuição principal, propõe-se uma metodologia para encontrar a combinação ideal e de menor custo de geração de energia renovável para se atender um dos critérios específicos de projeto: nível de penetração de renovável, percentual de redução das emissões de CO₂ e uma combinação dos dois.

A análise em sistemas isolados é realizada usando energia solar e energia eólica, estas fontes renováveis contribuem para a diminuição da dependência de combustíveis fósseis desses sistemas. A variabilidade dessas fontes é atenuada com o uso de sistemas de armazenamento de energia, permitindo o aumento do nível de participação das energias renováveis. A metodologia aplicada aos sistemas de energia insulares é baseada na consideração de múltiplos cenários com diferentes potências nominais de geração fotovoltaica, turbinas eólicas e sistemas de armazenamento de energia. Esses cenários são analisados usando o software HOMER.

Os resultados mostraram que um mesmo nível de penetração das energias renováveis pode ser alcançado por múltiplas combinações de energia solar, energia eólica e a energia armazenada nas baterias. Além disso é mostrada uma avaliação econômica do sistema isolado permitindo escolher a combinação com o melhor custo benefício, que atenda o nível de penetração desejado, considerando preço de combustível, dos equipamentos para renováveis, das baterias, imposto sobre as emissões de CO₂ e envelhecimento das baterias. A metodologia proposta neste trabalho permite que a seleção da combinação entre energia renovável e baterias seja feita de forma independente da análise preliminar, na qual as soluções que atendem os requisitos são selecionadas.

Por fim, é mostrado que o uso de baterias em sistemas de potência de navios, movidos a geradores a diesel, promove uma diminuição das emissões de CO₂. Essa análise também mostra o impacto da variação de diferentes parâmetros de bateria e diferentes tecnologias de baterias de Li-ion como Lithium Iron Phosphate e Lithium Titanate.

Palavras-chave: Emissões de CO₂, Sistemas de armazenamento de energia, sistemas isolados, Sistemas de navios, energia solar, energia eólica.

Abstract

Today, the vast majority of energy used in isolated systems is generated from fossil fuels. This paper assesses the potential for reducing CO₂ emissions in two test systems, the Fernando de Noronha system and the platform supply vessel system using Energy storage. In addition, as a major contribution, a methodology is proposed to find the ideal and lowest cost combination of renewable energy generation to meet one of the project-specific criteria: renewable penetration level, percentage reduction of CO₂ emissions and a combination of the two.

The analysis in isolated island systems is performed using solar and wind energy, these renewable sources contribute to the reduction of fossil fuel dependence of these systems. The variability of these sources is attenuated with the use of energy storage systems, allowing the increase of the participation of renewable energies. The methodology applied to island power systems is based on the consideration of multiple scenarios with different rated photovoltaic power, wind turbines and energy storage systems. These scenarios are analyzed using the HOMER software.

The results showed that the same level of renewable energy penetration can be achieved by multiple combinations of solar energy, wind energy and the energy stored in batteries. In addition, an economical assessment of the isolated system is shown, allowing to choose the most cost-effective combination that meets the desired penetration level, considering fuel price, renewables equipment, batteries, CO₂ emissions tax and aging batteries. The methodology proposed in this paper allows the selection of a combination of renewable energy and batteries that can be made independently of the preliminary analysis, in which the solutions that meet the requirements are selected.

Finally, it is shown that the use of batteries in diesel-powered ship power systems promotes a reduction in CO₂ emissions. This analysis also shows the impact of varying different battery parameters and different Li-ion battery technologies such as Lithium Iron Phosphate and Lithium Titanate.

Keywords: CO₂ emissions, Energy Storage Systems, isolated systems, Ship systems, solar energy, wind energy.

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1. INTRODUCTION

Discussions around greenhouse gas emissions have taken an important place in the worldwide agenda. On 2018 CO₂ emissions grew at the same time that the growth of energy demand did. From 2015 to 2017 the growth of energy demand had small increments or no variation. ^[1]

In order to reduce CO₂ emissions, changes are needed in the way we generate and consume energy. Renewable energies have been playing an important role in energy supply and have a high potential to reduce our dependence on non-renewable energy sources, such as fossil fuels, as well as reducing the emission of greenhouse elements, with increased potential when paired with energy storage ^{[2][3]}.

Two of the main sources of renewable energy are wind power and solar energy ^{[4][5]}. A characteristic of these two sources (or one of their main problems) is the variability of available primary energy. They are energies with high intermittency and poor reliability indices ^{[6][7]}. It is a necessity to guarantee minimum energy capacity levels and minimum power quality levels in power grids ^[8].

There is also an associated important factor, in addition to the continuous changes in the available energy: the difference between available resources and variation of load ^[9], which means uncertainty in energy production. Studies of possible changes in the regulatory market, and also estimation of prices, have been discussed ^[9], suggesting solutions as they create hydroecolic pools between participants to increase season complementarity as a mitigation tool.

An option to this inconsistency on wind and solar energy is improving and developing equipment capable of storing energy properly during low

consumption periods in the system and during peaks of renewable generation [2][10][11]. It is required to compare different types of energy storage elements and how they are integrated, connected and controlled with the electricity network. For example, a possible action against variability on wind energy is the use of batteries parallel to wind farms [12]. Wind energy could have a more predictable and controllable use with these batteries. It is possible, also, selling stored energy when energy price is higher. This service is known as Electric Energy Time-shift [13] [14] [15].

There are many different energy storage mechanisms, depending on the required *power* and *backup time* that would ensure a satisfactory response for the intermittent renewable energy. Among the storage systems, we can mention PHS (Pumped Hydro Storage), CAES (Compressed Air), EDLC (Double Layer Capacitors), sodium sulfide, nickel-cadmium, nickel-metal hydride, and vanadium-redox and lithium-ion batteries [16].

Each ESS (Energy Storage System) have its own characteristics and specific uses for electrical networks. It is possible to:

- Improve frequency regulation.
- Optimize generation with traditional energy resources during peak demand.
- Reduce CO₂ emissions.

At the end, electricity storage technologies can increase the penetration of renewable energies that have intermittent generation [17].

1.1 ISLAND POWER SYSTEMS

Balance between load and generation is very important for electrical systems and is required to achieve a safe operation of the power grid. This balance is instantaneous and is analyzed through frequency. A range of safe frequency is defined for all systems and different types of frequency control systems are implemented. Integration of Variable Generation in power systems has an important role nowadays and has a high interest for governments and public utilities [18]. Aside from frequency related problems, Variable Generation

has an unpredictable behavior increasing uncertainty about energy supply. As it can be seen in Figure 1 the solar radiation has high variability:

Figure 1. Solar radiation in Fernando de Noronha Island in an hourly basis

Source: Created in HOMER software. Data found in [19].

On this case, the total Global Horizontal Irradiance (GHI) for the five days was 21,19 kWh/m²; if all five days had a similar GHI to the third day, the total irradiance would have been around 38.8 kWh/m².

A special case of power grids are "off-grid systems", e.g. island power systems. They have their own characteristics and problems to solve.

Specific problems with island power systems and with research interest are [20][21][22][23]:

- Traditional electricity supply in these territories is more expensive because they face high fuel transport costs.
- Voltage levels have a significant effect on the whole network compared to the management of a larger system.

- The first frequency control adjustment between power and frequency is more difficult to achieve. Isolation makes it necessary to keep more reserve capacity to ensure large spinning reserve.
- It is very hard to define standards and even clear safety rules for island power systems because each network is extremely specific.

An example of island power systems is the U.S. Virgin Islands project. They have a pilot project for clean energy development that could be replicated around the world on other islands [24]. USVI electricity cost is almost three times the U.S. average cost. This group of islands have the same problem than almost every island system in the world: nearly 100% dependency on fossil fuels. One goal for 2025 is to reduce 60% of energy generation from fossil fuels. Renewable energies must play an important role since almost half of the 60% reduction would come from wind and solar energy.

1.2 SHIP POWER SYSTEMS

In 2016 the Paris Agreement came into force to reduce greenhouse gas emissions, and to keep global warming increase under 2 °C [25]. Although most of the countries participate on this agreement, emissions from shipping were not considered. Currently shipping accounts for 2% of the total worldwide emissions, having a participation similar to Canada, as it can be seen in Figure 2[26].

Figure 2. Global CO₂ emissions ranking

Source: Data from [26] and figure from [27]

To keep the raise under 2 °C of global temperature, CO₂ emissions from shipping should be reduced 13% and 63% by 2030 and 2050 respectively [28]. Difficulties to achieve this goal arise since 90% of total global trade is transported by shipping, and trade continues growing [29] as it can be seen in Figure 3:

Figure 3. Annual world seaborne trade from 1970 to 2017

Source: Data from [29] figure from [27]

There are multiple approaches to reduce emissions from shipping ^{[30][31]}, including the use of energy storage, fuel cells, and to change from diesel to liquified natural gas (LNG) ^[32]. These technologies can also make the operations more flexible and reliable. Overall, energy storage allows ship power systems to reduce consumption by storing energy from generators when they operate at high efficiency (high demand), and use it during periods when they operate at low efficiency (low demand).

1.3 BATTERY SYSTEMS

For years researchers have suggested that a possible action against variability on wind energy is the use of batteries in parallel to wind farms ^{[12][6]}. Industry has made progress on battery usage and energy storage systems of wind power generation, however, it's necessary to choose different battery technologies and configurations. It's desirable to analyze the behavior of batteries in load variations, their response to faults, and benefits obtained in terms of power quality. There are important challenges in the full implementation of energy storage systems:

- Analysis and improvement of control systems (network frequency control against wind gust, moderate wind speed variations, solar radiation reduction with clouds) ^[20].
- Location of storage systems (on terminals of the renewable power plant, on the terminals of each turbine, on the converters) ^[20].
- Adequate sizing of energy storage system to enhance flexibility of intermittent generation ^[33].

Some specific benefits using storage technologies are ^{[13][20]}:

- Conditioning power electronic tools, required for the integration of electrochemical batteries, can also control and improve the quality of the power signal.

- Some storage technologies exhibit temporal dynamics that allow them to participate actively on the balancing of generation and load. They help to flatten the load curve and thereby reduce the need to run peak load generation units that generate significant CO₂ emissions.
- There is a disadvantage when the ESS is located in the center of the grid: it is the creation of transit flows on some parts of the network.
- The electrochemical storage devices are technologies best suited for the need of island power systems with growing integration of intermittent renewable energy in the absence of hydraulic sources.
- The life time of existing transmission lines could be extended. Analyses in the U.S. ^[34] show that 70% of their lines have more than 25 years. From the point of view of distributed storage, it is possible to reduce line congestion and power losses, mainly because storage moves power at off-peak times.

Challenges

Regardless of the mentioned benefits from energy storage systems, they still have important issues to improve, multiple investigations and advances have been carried out during the last decade. Although ESS have a great opportunity to improve, researchers ^[14] concluded, for example, that in three European markets (France, Scandinavia, and the Netherlands) storage facility is not profitable, despite the benefits that can be achieved with them.

Also, authors in source ^[35] developed an initial reflection on a business model. According to them, the main idea of the model "lies in organizing an auction chain in which the right to use available storage capacities is auctioned among different actors". They suggest that a storage system can recover the investment in a better way when they aggregate its value to diverse actors or services.

According to source ^[34], main challenges for energy storage systems are:

- Cost competitive technology: life-cycle cost, efficiency, energy density, capacity fade.
- Validated reliability and safety: it is very important for user confidence.

- Equitable regulatory environment: It is important that grid storage has regulatory levels similar to other grids components.
- Industry acceptance: or that industry accepts storage because it has shown a behavior according to expectations.

1.4 OBJECTIVES

Main objectives:

To develop a methodology to select the most suitable and cost effectively combination of solar power, wind power, and batteries that meet the prescribed requirements for an island system.

Secondary objectives:

- To assess isolated electrical systems comparing CO₂ emissions and fuel consumption, and determining the effect of energy storage systems.
- To evaluate and compare the impact of energy storage parameters on ship power systems CO₂ reduction, including sensitivity analysis.
- To develop a methodology to calculate the total cost of an island power system that includes photovoltaic power, wind power, diesel generation, and energy storage.
- To evaluate CO₂ emissions on ship power systems using diesel generators and auxiliary generators compared to systems with diesel generators and energy storage.

1.5 CONTRIBUTION

The main contribution of this thesis is the development of a new methodology to evaluate more attractive configurations of island power systems based on diesel generation, considering CO₂ emission and renewable energy penetration. This methodology allows the selection of a combination of photovoltaic, wind power generation and energy storage capacity to supply the electricity demand. The specific contribution is that the energy dispatch

evaluation is performed at the beginning of the study to select a large group of possible configurations that meet the requirements. The cost assessment is done on the second stage of the methodology to allow the use of current equipment prices without losing the selected configuration founded on the first part of the methodology. With the real cost of the equipments, investors could choose the cheapest configuration that achieves the required goals (a certain amount of CO₂ emissions reduction or a certain value of renewable energy penetration).

Other assessments of island power systems use cost calculation to determine the cheapest solution at the beginning of the evaluation, invalidating results in the close future with new costs. This methodology can ease the evaluation process of the decision makers giving scenarios independent of time, with more possible configurations.

A second contribution is presented in an extensive evaluation for ship power systems performance, comparing the CO₂ emissions for different operational parameters of battery energy storage system. The methodology works like a map of CO₂ emissions for the battery parameters as round trip efficiency, rated capacity, C-rate and Li-ion chemistry. The CO₂ emissions are evaluated for a 120 hours during a ship mission (loading in port, laden voyage, DP operation, partial load voyage and stand-by).

Other researches about ship power systems and batteries evaluate one part of the mission for one parameter scenario only, and not for multiples. This map of CO₂ emission can be useful for the shipping sector to achieve better performance.

The next chapters are structured as follows:

- Chapter 2: how the modeling is done. Presenting state of the art on isolated systems, also presenting modeling of solar power, wind power, energy storage, and diesel generators.

- Chapter 3: discusses the methodology implemented to define the scenarios to be simulated, and cost definitions for each element of the isolated power system.
- Chapter 4: It has complete evaluation of an island power system, and a hypothetical case based on the island Fernando de Noronha including total system cost calculation
- Chapter 5: Presents the evaluation of a platform supply vessel system integrating Li-ion batteries. Several scenarios are simulated for different battery parameters.
- Chapter 6: Conclusions and future work

2. MODELING

Equipments, demand curves, energy resources, and batteries are modeled and implemented in HOMER Software. HOMER (Hybrid Optimization of Multiple Energy Resources)^[36] is a software that simulates energy balance using combinations of different sources such as diesel generators, wind turbines, solar panels, as well as energy storage elements (batteries, flow batteries, flywheels). HOMER performs simulations of the system using an optimization approach with two possible goals: being the most economic or lowering fuel consumption, always meeting power requirements set by the user for the different established combinations of energy sources and storage systems. HOMER performs hourly system simulations over a year and extends these results to the whole life time of the project to determine the total net present cost. The software only performs energetic balance and does not comprises dynamic simulations.

2.1 STATE OF THE ART

Like isolated systems, island electrical systems are prime candidates to change their traditional way of generating electricity and move towards renewable energy systems. Energy assessments in two islands were analyzed in order to determine a suitable procedure for an isolated system. Lanai Island (Hawaii) ^[37] desires to reach 100% renewable generation, though not in the short term. Similarly, the Virgin Islands plan ^[24] to reduce by 60% its dependence on fossil fuels by 2025.

The NREL (National Renewable Energy Laboratory) elaborated two documents (^[37]^[38]) in which a possible high integration of renewables in the

Virgin Islands and Lanai is analyzed using HOMER. They defined a model of the electric load of the island, which was implemented together with other elements such as diesel generators, PV generators, wind turbines and a battery system. The implemented scenarios are: Base Case, base+PV, base+wind, base+PV+Wind+batteries.

Where base case is a system configuration using only-diesel generators as primary energy source. Results highlight mainly saved penetration of renewables and the reduction of CO₂.

Main steps followed are:

- To define elements and parameters of the system (*i.e.* diesel generators, load curve, wind and solar data, etc).
- To define scenarios to simulate different configurations of the available elements. Usually used: Base Case, Base+PV, Base+PV+wind, Base+PV+Wind+ batteries.
- To simulate scenarios.
- To collect results, comparing mainly saved diesel, penetration of renewables, and reduction in CO₂ emissions.

The selected system to develop a methodology of evaluation is based on Fernando de Noronha Island. This system has similar elements to the Fernando de Noronha Island such as a demand curve, wind speed, and solar radiation.

2.2 DATABASES FOR WIND SPEED AND SOLAR RADIATION

Currently there are multiple sources of information to get the data of solar radiation and wind speed on different zones of the world.

A compilation of databases for sources like solar, wind, tidal, and wave power are made in source [39]. Additionally, the authors mention the difficulty of comparison, and also try to determine errors between these databases. The difficulties are caused by differences in the way data methods are taken, the different times in which measurements were made, among others. With the different datasets many forecasts were made, finding that no database maintains a constant error over the range of time.

Different databases were analyzed to determine the most suitable for our project.

2.2.1 Overview

After evaluating the characteristics of different datasets, a group of datasets is pre-selected, their name and main features are listed in Table 1:

Table 1. Main characteristics of pre-selected datasets for wind and solar

Dataset	Resource	Time range	Time resolution	Space resolution	Covered area
European Center for Medium-Range Weather Forecasts (ECMWF) [40]	Wind, solar	1979-onwards	6 h	0,75 °	Worldwide
Renewable Resource Data Center (NREL) [41]	Solar	1961-2010	1 h	Data collected from 239 stations in U.S.	U.S.A.
Giovanni (NASA EarthData) [42]	Wind	1979-onwards	1 h	0,5 °x0,67°	Worldwide
Atmospheric Science Data Center (NASA) A.K.A HOMER dataset [19]	Solar	1983-2005	1 month	0,5 ° x0,5 °	Worldwide
	Wind	1983-1993	1 month	0,5 ° x0,5 °	Worldwide
Solar Anywhere [43]	Solar, wind	1998-2011	1 min 0,5 h 1 h	1 km - 10 km	U.S.A.
Meteonorm [44]	Solar, wind	1991-2001	1 min 1 h 1 month	Anypoint	Worldwide

Source: [19] [40] [42] [43] [44]

The selected compilation of datasets are Giovanni ^[42] and ASDC ^[19]. Among points taken into consideration to discard other datasets we found: need of specialized software to access data (ECMFW and Meteonorm), few available years (SolarAnywhere and Meteonorm), and required payment (ECMWF and Meteonorm).

2.2.2 Dataset comparison

By plotting average monthly data for databases Giovanni ^[42] and HOMER ^[19], we have the curves shown in Figure 4:

Figure 4. Average monthly wind speed in Fernando de Noronha for datasets ^[42] and ^[19]

Source: Adapted ^[42] ^[19]

As it can be seen in Figure 6, differences between datasets are not negligible. HOMER and Giovanni curves show bigger differences during the first half of the year and closer speeds during the second half. The biggest difference between Giovanni and HOMER on the same period is of 41%. Annual average wind speed difference is 13% for the 83-93 period. Difference between HOMER and Giovanni for the 93-13 period is 3%. The plot of wind speed for each single year from 1993 to 2013 of Figure 7 is used to see dispersion and the comparison between averaged lines. As it can be seen in Figure 7, the variation

of subsequent years and average years has the potential to change the results of incoming simulations.

2.3 WIND POWER GENERATION

The wind turbine modeled in HOMER is based on the Enercon 330 kW turbine [45]. Main parameters used for simulations are shown in Table 2.

Table 2. Main parameters turbine Enerco 330 kW modeled in HOMER.

Name	Enercon E-33
Rated power	330 kW
Hub height	37 m
Electrical bus	AC

Source [45]

Power curve is shown in Figure 5

Figure 5. Power output turbine Enerco E-33

Source: [45]

2.4 SOLAR POWER GENERATION

The photovoltaic system is based on the generic flat panel from HOMER [36]. Parameters used are shown in Table 3:

Table 3: Main parameters photovoltaic panels modeled in HOMER.

Panel type	Flat panel
Ground reflectance	20%
Tracking system	Horizontal
Rated capacity	100 kW
Derating factor	80%
Electrical bus	DC

Source: [36]

2.5 BATTERY SYSTEM

The implemented battery system is based on a generic Li-ion battery [36]. Parameters used for simulations are shown in Table 4:

Table 4. : Parameters Li-ion battery modeled in HOMER

Battery model	Idealized
Rated voltage	480 V
Rated capacity	100 kWh
Rated capacity	209 Ah
Roundtrip efficiency	90%
Max charge current	209 Ah
Max discharge current	600 A
String size	1
Initial state of charge	100%
Minimum state of charge	20%

Source: [36]

2.6 DIESEL GENERATORS

Diesel generation is modeled through two main elements, generator and fuel. Characteristics of fuel used in simulations is presented in Table 5:

Table 5: Fuel parameters for HOMER simulations

Type	Diesel
Lower heating value	4,2 MJ/kg
Density	820 kg/m ³
Carbon content	88%
Sulfur content	0,33%

Source: [36]

Generators can be modeled using parameters shown in Table 6:

Table 6: Parameters for diesel generators and emissions used in HOMER

Intercept coefficient (900 kW and 1200 kW)	0,08 L/h/kW
Slope (900 kW and 1200 kW)	0,25 L/h/kW
Intercept coefficient (600 kW)	0,0167 L/h/kW
Slope (600 kW)	0,225 L/h/kW
Carbon monoxide	6,5 g/L
Unburned hydrocarbons	0,72 g/L
Particulate matter	0,49 g/L
Proportion of fuel sulfur converted to PM	2,2 g/L
Nitrogen oxides	58 g/L

Source: [36]

2.7 PARTIAL CONCLUSIONS

Main elements to model isolated systems in HOMER have been presented. Solar radiation and wind speed are not obtained through direct measurements *in-situ* but using global datasets from satellital data. The selected datasets are chosen because of their coverage, space resolution and time resolution, having access to wind speed and solar radiation with one hour resolution make these dataset appropriate for this research.

Equipments used in isolated systems were also modeled and simulated. Among these elements we have generators, photovoltaic panels, wind turbines, Li-ion batteries and diesel fuel. Since simulations evaluate energetic parameters such as generated energy, fuel consumed, CO₂ emissions, most electrical parameters do not need to be modeled except for batteries since voltage, charge current and discharge current are used to determine their state of charge.

3. METHODOLOGY

The methodology is developed to determine a suitable combination of solar power, wind power, and energy storage that meets the specified requirements, such as to increase renewable penetration or to reduce CO₂ emissions. Figure 6 presents the flowchart containing the main steps of the methodology. As can be seen, there are fixed and flexible inputs when considering a specific location. The fixed ones are related to the available wind and solar resources at that specific location. The flexible items are economic related and can be changed at any point of the analysis, which is a very important feature of the methodology, since the costs of these technologies still present a considerable variation.

It is important to highlight that it is possible to find in the literature optimization methodologies for isolated systems, renewable energy implementation, and energy storage installation considering fixed prices, which can not be easily updated after the analysis is completed. In the methodology proposed in this document allows updating system costs very easily, once the sceneratios generated in the first stage of the methodology can be reassessed in the second stage, which is the responsible for selecting the solution with the minimum cost.

Figure 6. Flowchart of general procedure methodology to select the most suitable solution

Source: Author

3.1 GENERAL APPROACH

Decision makers and researchers have different expectations and restrictions for the design renewable energy implementation in isolated systems. Some of them aim at solutions to increase renewable penetration [46], [47], [48], [49], others to reduce system cost [50], [51], [52] or to reduce CO₂ emissions [53], [54], [55]. These solutions are studied individually or combined but optimized

to achieve the minimal cost. In this chapter we show the implementation of a methodology to find suitable solutions that achieve desirable level of renewable penetration or CO₂ emissions, analyzing system cost and performing sensitivity analysis after some feasible solutions are selected.

Since the cheapest solution does not necessarily means a result meeting the required CO₂ reduction or renewable penetration, we designed a methodology that first evaluates and determines a set of solutions evaluating energy and emission requirements.

Several simulations, calculations and cost assessments are performed to implement the methodology. During the chapter are show elements to be installed in the system; possible combinations of them to achieve CO₂ reduction or renewable penetration goals; considerations to estimate cost of elements; calculation cost for solar, wind, battery system and fuel. Additional considerations are introduced such as battery degradation and taxes on CO₂ emission to evaluate impact in the final cost.

3.2 SENSITIVITY ANALYSIS

To calculate renewable penetration and CO₂ emissions the first step is to define the range of solar power, wind power and battery storage to be installed in the isolated system. Thus, these parameters are evaluated by a sensitivity analysis, simulating several cases with different levels of installed photovoltaics, wind power and energy storage. Based on previous analyses of island power systems [56], [35], [37], [38], steps from 10 % to 20 % of the maximum demand were considered in the simulations. For example if the peak demand is 1 MW, solar power, wind power and storage capacity could range from 100 kW to 1 MW in steps of 100 kW or 200 kW.

3.3 SCENARIOS DEFINITION

Based on sensitivity analysis, the values and ranges for diesel generation, solar power, wind power and energy storage are defined. The rated power of

solar and wind power are considered taking into account the capacity of the available equipments.

Once the maximum rated power for each element of the system is established, the sensitivity analysis is used to evaluate the maximum number of each equipment considering the benefits, such as CO₂ emissions or renewable penetration.

3.4 SIMULATION

An important element about this strategy (doing a sensitivity analysis, defining scenarios and simulations), is the lack of dependance on economic parameters. This first step can be considered as a pre-project that is independent of cost variations. Usually, studies for island power systems [56], [35], [37], [38] perform an optimization process based on economic restraints from the beginning of the analysis. These studies consider just a small group of feasible solutions since the objective is reduction of the total project cost.

For this project, the first steps consist in defining scenarios, perform simulations and select a group of results that meet the desired objective. In this case, the desired goal can be a specified reduction in CO₂ emissions or fuel consumption, it can also be a desired renewable penetration level.

After results from all simulations are collected and the scenarios that meet the defined objective are separated, a cost evaluation can be implemented. This cost evaluation can be done months and even years later after the initial simulations considering that these have energetic results and technological changes are not impacting the obtained results.

3.5 COST DEFINITION

As it has been shown in previous chapters, isolated systems have higher electricity cost and CO₂ emissions compared to systems connected to the grid [24][37]. Installation of solar power, wind power, and energy storage can increase the initial cost of an electric system [17]; however, taking into account savings during the life time of the project, it is possible to reduce the total cost, as a

consequence of lowering diesel consumption. At the same time, using renewable energy and energy storage systems reduces CO₂ emissions.

Costs estimation for each element (solar, wind, diesel, and batteries) are presented, and a total system cost is calculated for the possible combination of scenarios of such elements (180 cases). In the end, it is possible to compare the cost of two feasible solutions with similar outputs in terms of renewable penetration or CO₂ emission. Below we show the main considerations to take into account to calculate the total cost of each element on the project.

3.5.1 Solar system cost

Solar power systems have many elements that affect the final cost of an installed system. Among these elements there are: the cost of modules, the inverter, the electrical and structural construction, land acquisition, the installation labor and equipment, and the line connection. A detailed cost segmentation for solar system in the U.S. from [57] is shown next in Figure 7:

Figure 7. Photovoltaic associated cost for 2017 in U.S. [USD/Wdc]

Source: [57]

A first approach to solar cost varies from 1.38 USD/Wdc to 1.49 USD/Wdc depending on the tracking system used. The total cost for an isolated system tends to be higher. Additional data is required to evaluate the cost of a solar system in an isolated grid in Brazil. An average of total installation cost for solar power in the globe can be seen in Figure 8^[58], power size is determined by the diameter of circles in each case.

Figure 8. Total installed costs for utility-scale solar PV projects and the global weighted average, 2010-2017

Source: [58]

As it can be seen, costs are overall higher for systems with smaller installed power when they are calculated as USD/kWp. According to Figure 33, total installed global cost for 2016 and 2017 can be seen in Table 7:

Table 7. Total solar power installation cost per kWp for 2016 and 2017. Global weighted average

Total installed cost global						
Year	Average	95th percentile	5th percentile	Max	Min	Unit
2016	1500	3400	1100	7250	800	2016 USD/kWp
2017	1400	3350	900	5300	800	

Source: [58]

Although this data shows a range for solar cost, it is still possible to refine the total cost of solar power. Data for South America is shown in Figure 9[58]:

Figure 9. Regional total cost for solar PV

Source: [58]

From Figure 9 we have the solar costs in South America as shown in (Table 8):

Table 8. Total installation cost solar PV in South America in 2016 U.S. Dollars

Min cost solar power in SA (\$/kW)	Max cost solar power in SA (\$/kW)
1200	2700

Source: [58]

With a 3% of inflation rate, the calculated maximum cost for 2017 is of 2781 USD/kW in South America. This value is used in this project for isolated systems in Brazil.

For operation and maintenance costs (O&M), since the only available data is O&M cost from U.S. [57], we calculated a factor between solar installation costs in U.S. and Brazil and multiplied that factor to the O&M cost in U.S. Factor is calculated in Table 9:

Table 9. Relation between solar cost in U.S and Brazil

Solar cost in USA	1100
Solar cost in Brazil	2781
Factor	2,53

Source: Author based on [57] [58]

Since O&M cost in U.S is 18.5 USD/kW-year [57], estimated O&M for Brazil is 46,7 USD/kW-year. Total solar cost (Tsc) can be calculated using Equation 1:

$$Tsc = S_{kW} * \frac{\$_s}{kW} \quad (1)$$

Where:

S_{kW} : Solar installed power

Tsc: NPC for CAPEX and OPEX solar power

NPC: Net Present Cost. CAPEX: Capital expenditure. OPEX: Operational expenditure.

The net present cost of CAPEX and OPEX for solar power used in these calculations are already considering all the elements affecting the final installation cost such as panels, interconnections, fees, land acquisition, etc.

3.5.2 Wind power costs

Similar to solar system, the data cost for wind systems has installation costs and operation costs that overall can be grouped as shown in Table 10 ^[59]:

Table 10. Wind cost segmentation

Cost element	Element	Fraction of cost
CAPEX	WTG	52 %
	Grid connection	8 %
	Construction	5 %
	Others	5 %
OPEX		30 %
Total		100 %

Source: ^[59]

Global weighted average cost for onshore wind projects in the world can be seen in Figure 10^[58]:

Figure 10. Total installed costs for onshore wind projects, global weighted average 1983-2017

[58]

Source: [58]

Taking into account that the total installed cost of wind power by region in 2017, we have the values shown in Figure 11:

Figure 11. Regional total cost for solar wind power

Source: [58]

From Figure 10 and Figure 11 is extracted the data presented in (Table 11):

Table 11. Weighted average of total installed cost for onshore wind global and South America

Global Average (\$/kW)	Global 5th percentile (\$/kW)	Global 95th percentile (\$/kW)	Min cost wind power in SA (\$/kW)	Max cost wind power in SA(\$/kW)
1477	1310	2800	1300	2400

Source: [58]

Finally, O&M cost are defined according to [58] as shown in Table 12:

Table 12. O&M cost for Central and South America, and rest of the world.

Region	Max USD/kW/year	Min USD/kW/year	Avg USD/kW/year
Cost in Central and South America	52	35	16
Cost rest of the world	58	37	50

Source: [58]

Similar to solar power, wind total cost (T_{wc}) can be calculated using Equation 2:

$$T_{wc} = W_{kW} * \frac{\$_w}{kW} \quad (2)$$

Where:

W_{kW} : Solar installed power.

$\frac{\$_w}{kW}$

: NPC for CAPEX and OPEX wind power.

3.5.3 Energy storage system cost

Battery system cost has two main steps to be considered for the calculation. The first step calculates annuities costs, and the second step calculates NPC for the storage system. For annuities cost it is used the

methodology proposed by IRENA in [60]. The total cost is calculated using Equation 3:

$$A_{Storage\ System} = A_{ESU} + A_{PCU} + A_{Other} \quad (3)$$

Where:

$A_{Storage\ System}$: Total investment-related annuities for battery system.

A_{ESU} : Annuity for the energy storage unit.

A_{PCU} : Annuity for power converter unit.

A_{Other} : Annuity for other investment costs.

All annuities are calculated with the next expression on Equation 4:

$$A_{ESU} = C_{ESU} * \frac{(1+i)^{l_{ESU}} - 1}{l_{ESU}} \quad (4)$$

Where:

A_{ESU} : Annuity for energy storage elements.

C_{ESU} : Investment cost of the energy storage unit.

l_{ESU} : Lifetime for the energy storage element.

i : Interest rate.

To calculate each annuity, the first step is to calculate the investment cost denoted by letter C. For the energy storage unit the investment cost is defined by Equation 5:

$$C_{ESU} = P_{Application} * \left(C_{EIC,ESU} * E/P_{ratio} + C_{PIC,ESU} \right) \quad (5)$$

Where:

C_{ESU} : Investment cost of the energy storage unit (USD).

$P_{Application}$: Power demand of the given application (kW).

$C_{EIC,ESU}$: Energy installation cost of the selected energy storage unit (USD/kWh).

E/P_{ratio} : Relationship between power and energy capacity in the given application (kWh/kW).

$C_{PIC,ESU}$: Power installation cost of the selected energy storage unit (USD/kW).

For electrochemical storage systems, the power installation cost is set to zero, as their capacity and power cannot be separated. Only vanadium redox flow batteries, whose energy and power capacities can be designed independently, are implemented separately.

Similar to the energy storage unit, the investment cost of the power conversion unit is calculated using Equation 6:

$$C_{PCU} = P_{Application} * C_{PIC,PCU} \quad (6)$$

Where:

C_{PCU} : Investment cost of the power conversion unit (USD).

$P_{Application}$: Power demand of the given application (kW).

$C_{PIC,PCU}$: Power installation cost of the selected power storage unit (USD/kW).

Since the calculation of each C cost has included the power of the specified application, annuities costs need to be calculated separately for each energy size of the battery system.

A project cost breakout for a Li-ion battery of 500 kW-1000 kWh is shown next in Table 13:

Table 13. Project cost breakout for Li-ion battery 500kW-1000 kWh

Project Cost	Fraction of total cost
Battery	60 %
Hardware	20 %
Engineering, construction	9 %
Develoment-Soft cost	11 %

Source: [61]

In source [62], the global energy capital cost of Li-ion batteries is estimated in 1110 USD/kWh. For the U.S. the total installation cost is 883 USD/kWh [61]. The International Renewable Energy Agency estimates ESS costs varie globally from 473 USD/kWh to 1260 USD/kWh.

3.5.4 Fuel costs

Diesel costs for isolated systems in Brazil is approximately 1.6 USD/L [63]. Using the total fuel consumed for every combination of diesel generators, wind power, solar power and Li-ion batteries, is possible to calculate the total cost of the diesel consumed during a fixed life cycle using Equation 7:

$$\text{\$}f_{lit} = \text{PMT} \times ((1 - (1 / (1 + r)^n)) / r) \quad (7)$$

Where:

PMT: Present cost of fuel. For current evaluation in Brazil isolated system is used 1.6 USD/L.

r: Discount rate.

n: Number of years.

$\text{\$}f_{lit}$: Cost of fuel per liter.

3.5.5 Total present cost calculation for the methodology

Values and methodology for the calculation of solar, wind, and energy storage systems has been presented in this chapter, in the same way that the diesel cost during the full life cycle of the system. All this elements are condensed in Equation 9:

$$S_{kW} * \frac{\text{\$}_S}{kW} + W_{kW} * \frac{\text{\$}_W}{kW} + B_{kW} * \frac{\text{\$}_B}{kW} + F * \frac{\text{\$}_F}{lit} = TC \quad (8)$$

Where:

S_{kW} : Solar installed power

$\frac{\$S}{kW}$: NPC for CAPEX and OPEX solar power

W_{kW} : Wind installed power

$\frac{\$W}{kW}$: NPC for CAPEX and OPEX wind power

B_{kW} : Batteries installed power

$\frac{\$B}{kW}$: NPC for CAPEX and OPEX batteries

F : Total fuel consumption in liters

$\frac{\$F}{lit}$: NPC of fuel

TC : Total Cost of the project

With Equation 9, it is possible to calculate the installation and O&M costs for any combination under consideration of solar, wind and BESS all together with the consumed fuel by diesel generators.

Since diesel generators are already installed in the isolated system, their capital cost is not considered in the calculations. Only the total cost of diesel systems is 134.4 million dollars for a 20 year system's life.

3.6 PARTIAL CONCLUSIONS

A methodology to evaluate island power systems is presented. Main steps can be summarized as define location; implement equipment models in HOMER software; perform sensitivity analysis to define scenarios to be evaluated with different combinations of photovoltaic, wind and batteries; simulate all scenarios and separate combinations that meet a defined objective (CO₂ emissions or fuel consumption or renewable penetration); calculate total project costs for the selected scenarios. In the next chapter we present the implementation of the methodology for a fictional isolated system based on parameters from island Fernando de Noronha. Current values for demand and generators in Fernando de Noronha are not the same presented here.

4. EVALUATION OF ISLAND POWER SYSTEM

Generation systems using renewable energy are becoming more common around the world; in the case of Brazil and its Ten Years Expansion Plan ^[64], it is expected to increase participation in the energetic matrix of wind energy from 2% in 2014 to 8% in 2024, (*i.e.* an increase by 20 GW of wind energy). Brazil seeks to diversify its energy generation increasing the power generated by wind, solar, thermal biomass, and SHP to 35 GW by 2024.

Renewable energy in the vast Brazilian territory can offer benefits for its implementation in isolated systems, bringing energy to remote areas that have no grid connection to the national grid and have a high dependence on fossil fuels. A place of special interest is the Fernando de Noronha island located to the northeast of the country, which began working with wind energy in 1993 ^[65].

A goal for the Administration of the island is to implement sustainable technologies. Working with renewables would make Fernando de Noronha an example for Pernambuco state to follow ^[66].

For this project some parameters are used for the simulations, although real current parameters could differ. The island approximately has 3000 ^[67] inhabitants, the maximum peak load used is 2 MW ^[68]; two photovoltaic systems were opened in the island: a 400 kWp system (2014), and a 500 kWp system (2015) ^[69].

In Figure 12 and Figure 13 are shown a monthly average for wind speed and solar radiation, respectively, for a whole year in Fernando de Noronha.

Figure 12. Average wind speed per month in Fernando de Noronha

Source: [42]

Figure 13. Average solar radiation per month in Fernando de Noronha

Source: [19]

Regarding the electrical characteristics of the island, the average daily load curve used is based on source [70] and is shown in Figure 14:

Figure 14. Daily load curve for island system under analysis

Source: [70]

4.1 SENSITIVITY ANALYSIS

Island system is simulated with five diesel generators (total power 4200 kW), a load with a peak power of 2 MW, and 1.4 MW as the lowest power during the day Results of base case (only-diesel generation) are shown in Table 14:

Table 14. Results of simulations with only-diesel generation. Base case

Generator	Production (kWh/yr)	Fraction (%)
900 kW	4.240.570	29
600 kW	5.256.000	35
1200 kW	3.963.900	27
600 kW	1.370.210	9
Total	14.830.680	100

Source: author

Total consumed diesel: 4'671,272 l/year

CO₂ emissions: 12'300,995 kg/year

The simulation results (consumed diesel, CO₂ emissions, and produced energy) are used as base case for comparison when the additional technologies are introduced in simulations. Sensitivity analysis is performed for each element (photovoltaic, wind, battery).

4.1.1 Diesel+PV, Diesel+Wind

Different scenarios were simulated by varying the installed capacity of renewables. First, several cases with available diesel generators and at different levels of installed solar power were simulated, as can be seen in Figure 15, as well as a similar case with multiple simulations but using wind energy. For both cases, the renewable penetration level and the excess energy are shown.

Figure 15. Systems using solar wind and diesel

Source: author

Working with each technology (solar and wind) independently, shows that wind energy has higher energy excess and penetration than solar power. On one hand the penetration level of wind energy is close to 50% at 2 MW of installed power, but, on the other hand, solar power does not reach 30% of the penetration of 2 MW of installed power. It is interesting to note that for both technologies, the energy excess is almost zero under 1 MW of renewable installed power.

4.1.2 Study with Different Levels of Mixed Solar and Wind Power

A mixture of the two renewable energies is implemented to determine their impact on the system. We choose as a comparison parameter the economized diesel, which in turn gives also a sample of the reduction in CO₂ emissions. In Figure 16, for fixed values of wind power (colored lines), solar installed power is varied in the horizontal axis. For Figure 17 similar simulations are done, while maintaining fixed values of solar power, the wind on the horizontal axis is varied.

Figure 16. Saved diesel varying solar power for fixed wind power values

Source: author

Figure 17. Saved diesel varying wind power for fixed solar power values

Source: author

According to Figure 16 and Figure 17, wind energy has a higher impact (compared to solar energy) in the overall fuel reduction and renewable generation. Although the slopes of every curve decrease for higher values, it is possible to estimate the slope for the first part of the graph. Saved diesel in

Figure 13 has a slope of 1.5% for every 100 kW and 2.9% for Figure 17. The increment of saved diesel, when the first group of solar generators is added, is about 9%. For the first wind generator this increment is close to 18%.

Wind energy has higher impact in the system. Compared to solar energy, wind energy has almost twice the amount of fuel savings. Although energy and diesel savings are fundamental, it is important to note that more aspects should be taken into account when selecting the feasible solution of renewable energy and batteries to be implemented in the system. The aspects to take into account on electrical systems for islands are: the type of maintenance, the maximum speed of winds and typhoons, the humidity, the salinity, among others [71].

4.1.3 Implementation of Batteries

The effect of this implementation of batteries in the system is shown in Figure 15. The use of ESS increases the penetration of renewable power systems [12]. ESS helps to reduce the variability of the energy available [6][72][73] from wind and solar power.

For the simulations were used Li-ion batteries with 100 kW of power and 100 kWh of energy. Battery parameters are (Table 15):

Table 15: Li-ion parameters used in HOMER

Parameter	Value
Nominal voltage (V)	480
Nominal capacity (kWh)	100
Nominal capacity (Ah)	209
Roundtrip efficiency (%)	90
Maximum charge current (A)	209
Maximum discharge current (A)	600

Source: author

Simulation results including batteries for the island system with 2 MW of installed photovoltaics and 2 MW of installed wind power is shown in Figure 18:

Figure 18. Saved diesel using batteries (2 MW solar, 2 MW wind)

Source: Author

The use of batteries increases saved diesel in more than 10% per year. However, the use of batteries has a practical limit, as it can be seen in Figure 15. To increase saved diesel beyond 15 % is necessary to use more than 5 MWh of installed energy storage.

4.1.4 Assessment for multiple database

In Figure 19 we can see the results in Fernando de Noronha system when using wind speed as input data for specific years. Since we have access to wind speeds on almost any location and for every year, from 1979 until the first months of 2016, we simulated many scenarios using only-wind data for every year since 1994 to 2013. Results are shown in Figure 19.

Figure 19. Saved diesel and energy production for Fernando de Noronha system simulated per year.

Source: author

Additional simulations were made per year with and without ESS. The maximum difference of saved diesel between years is 4.38%, which equals 538,000 kg/year less of CO₂ in the atmosphere and 205,000 l/year of saved diesel. Using the data per year to evaluate a system could lead to major savings and improved management.

Plotted data shows a pattern in the values of saved diesel and energy production through the years. Extensive analysis and simulations would be necessary to find a relationship for this behavior and it is not within the scope of the current research.

4.1.5 Performance Variation Changing Energy Storage Parameters

There are some parameters that can be changed in the ESS to achieve better results on the system. Using the same group of batteries, but doing multiple simulations with different levels of maximum allowed discharge per battery is the first approach.

The system was configured to stop the discharge process in the batteries at certain levels, so the dispatch of diesel generators takes them into consideration, and decides if it is necessary to increase generation using fossil fuels.

As it can be seen in Figure 20, allowing a deeper discharge on batteries increases saved diesel up to an additional 3%; however, discharge levels can

shorten the battery life so in some cases is not worthwhile. Most of the initial simulations were done with a minimum discharge level of 20%, so an additional 1% of savings per year can be achieved just by changing the level of discharge to 10%-5%. Avoiding total discharge of the ESS will preserve batterie life and will maintain round-trip efficiency.

Figure 20. Energy assessment varying minimum discharge level of ESS

Source: author

A better use of available energy is also identified through excess energy. On this case the excess energy variation is lower (1%) but the effect of that energy is higher when other factors are analyzed, such as the saved diesel and the CO₂ reduction.

Another way to affect available energy is directly through the rated energy capacity of batteries. For the next case we will change only the battery energy, power will be unaffected (see Figure 21):

Figure 21. Energy assessment varying the energy capacity of every battery

Source: author

Energy capacity is affected by variations in the discharge current of batteries. As it can be seen in Figure 21, increasing the energy capacity more than 1.25 times has a reduced impact on the rated energy than at lower levels. Slope before 1.25 is approximately 4.7 % of saved diesel per energy unit, after 1.25 slope is almost halved to 2.3 %. The renewable fraction has a similar pattern that saved diesel with a lower change rate overall.

4.1.6 Effect of Battery Discharge Level on CO₂ Emissions and on Battery Lifespan

Further analysis, taking into account the effect of allowable discharge levels in batteries, are used to assess CO₂ emission and battery lifespan. Before we used a discharge level of 25%. It means that the dispatch strategy tries to meet the demand, using first renewable energy and stored energy unless batteries state of charge is equal or less than 25%.

On this analysis were simulated multiple scenarios with Depth of Discharge between 70% and 100% [74]. A realistic model of battery cells was used in order to determine the impact on a battery lifespan. A Modified Kinetic Model was used following numeral 5.14 from [22]. No temperature effect was taken into consideration. The lifetime curve used for this battery is shown in Figure 22.

Figure 22. Cycles to failure vs Depth of Discharge in Li-ion battery

Source: author

In Figure 23, the reduction of CO₂ emissions and the increasing of expected battery lifespan is presented. An additional reduction around 4% in CO₂ emissions could be achieved, however, under this circumstance, the expected lifespan of the ESS decreases to almost half the initial at 70% of DoD.

Figure 23. Annual CO₂ emissions and overall battery lifespan variation with discharge level.

Source: author

4.2 SCENARIOS DEFINITION

The available diesel generators are the same used in previous chapters; solar power, wind power, and batteries used in this assessment are shown in Table 16:

Table 16. Rated parameters for elements used during simulations

Element	Rated power	Simulated values
Diesel generators	Various	600 kW, 600 kW, 900 kW, 900 kW, 1200 kW
Solar panels	200 kW	0 kW, 200 kW, 400 kW, 600 kW, 800 kW, 1000 kW
Wind turbines	330 kW	0 kW, 330 kW, 660 kW, 990 kW, 1320 kW
Li-ion batteries	100 kW/100 kWh	0 kW, 100 kW, 300 kW, 500 kW, 700 kW, 900 kW

Source: Author

Several simulations were performed using combinations of wind, solar, and batteries alongside diesel generators. The total number of cases are determined by:

- Solar power values: 6.
- Wind power values: 5.
- Battery values: 6.
- Total simulated scenarios: $6 \times 5 \times 6 = 180$.

HOMER software was used to simulate all cases. A special Matlab script was written to collect and classify the desired parameters from the csv files generated by HOMER for each simulation. Load curve on Fernando de Noronha takes into account seasonal variation, as shown next in Figure 24:

Figure 24. Seasonal load on Fernando de Noronha system

Source: Modified from [68] [76]

4.3 SIMULATIONS

Total fuel consumption for all cases is shown next in Figure 25:

Figure 25. Fuel consumption for multiple combinations of renewable energies and BESS in Fernando de Noronha Island

c) Fuel consumption with 300 kW BESS

d) Fuel consumption with 500 kW BESS

e) Fuel consumption with 700 kW BESS

f) Fuel consumption with 900 kW BESS

Source: Author

As it can be seen, wind energy has greater impact compared to solar energy, since fuel consumption decreases faster with the use of wind power. BESS impact in fuel consumption varies from less than 20,000 L/year to more than 280,000 L/year.

Additional results information, such as renewable penetration and CO₂ emissions, are used during this chapter to assess and apply the methodology.

4.4 COST DEFINITIONS

The general cost variation and the impact of batteries in the system cost is discussed before showing an example of the methodology applied to one desired penetration level of a renewable. First, in Table 17 is shown the total system cost reduction for each simulated scenario.

Table 17. Total Cost reduction (%) compared to an only-diesel system

Battery 0 kWh							Battery 100 kWh						
Wind-Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	Wind-Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	0	2	3,9	5,9	7,8	9,8	0 kW	-0,5	1,9	3,8	5,8	7,8	9,7
330 kW	8,2	10,1	12	14	15,9	17,8	330 kW	8,1	10,1	12	14	15,9	17,8
660 kW	16	18,2	20,2	22	23,9	25,7	660 kW	16,2	18,2	20,1	22	23,9	25,7
990 kW	24	26,2	28	29,8	31,5	32,9	990 kW	24,2	26,1	28	29,8	31,5	32,9
1320 kW	32	33,7	35,3	36,6	37,8	38,7	1320 kW	32	33,8	35,4	36,8	38	39

Battery 300 kWh							Battery 500 kWh						
Wind-Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	Wind-Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	-0,2	1,8	3,7	5,7	7,6	9,5	0 kW	-0,1	1,8	3,7	5,7	7,6	9,5
330 kW	8	9,9	11,9	13,8	15,7	17,6	330 kW	7,9	9,8	11,8	13,7	15,5	17,4
660 kW	16	18	19,9	21,8	23,7	25,5	660 kW	16	17,9	19,8	21,7	23,5	25,3
990 kW	24	26	27,9	29,7	31,5	33	990 kW	23,9	25,8	27,7	29,5	31,3	33
1320 kW	32	33,8	35,5	37	38,3	39,4	1320 kW	31,9	33,8	35,6	37,2	38,6	39,8

Battery 700 kWh							Battery 900 kWh						
Wind-Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	Wind-Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	-0,3	1,7	3,6	5,5	7,5	9,3	0 kW	-0,74	1,3	3,3	5,2	7,2	9,1
330 kW	7,9	9,8	11,7	13,6	15,4	17,2	330 kW	7,8	9,7	11,6	13,5	15,3	17,1
660 kW	16	17,7	19,5	21,4	23,3	25,2	660 kW	15,6	17,5	19,3	21,2	23,2	25,1
990 kW	24	25,6	27,5	29,4	31,3	33,1	990 kW	23,4	25,3	27,3	29,3	31,3	33,1
1320 kW	32	33,7	35,6	37,3	38,8	40,1	1320 kW	31,7	33,7	35,7	37,5	39,1	40,5

Source: Author

As it can be seen in Table 17, the cases that use batteries and no renewables increased the total cost up to 0.7% compared to an only-diesel scenario. Renewable energy allows the reduction of consumed fuel with other combinations, and, for instance, a reduction in total cost of the system over the whole life cycle, with the highest cost reduction of 40.5%. That means that on most of the cases the implementation of renewable energies and energy storage results in saving money, when compared to only-diesel traditional generation.

IMPACT OF ONLY-BATTERY INSTALLATION IN TOTAL SYSTEM COSTS

Next, we analyze the impact of the system cost each time batteries are installed. In this analysis we compare the cost of all combinations of solar, wind, and diesel on two cases, with and without batteries. For example, the case with solar power 400 kW, wind power 330 kW, and no batteries is compared against the same combination, but with every set of available storage (i.e. 100 kWh, 300 kWh, etc.).

Cost variation can be seen next in Table 17, negative values represent reduction of the total system cost.

Table 17. System cost variation (%) caused by batteries installation

Battery 100 kW							Battery 300 kW						
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	0.05%	0.09%	0.07%	0.02%	0.04%	0.05%	0 kW	0.21%	0.21%	0.19%	0.19%	0.21%	0.24%
330 kW	0.10%	0.06%	0.04%	0.06%	0.06%	0.06%	330 kW	0.22%	0.20%	0.20%	0.22%	0.23%	0.29%
660 kW	0.04%	0.07%	0.09%	0.05%	0.05%	0.06%	660 kW	0.22%	0.30%	0.30%	0.32%	0.33%	0.34%
990 kW	0.10%	0.10%	0.02%	-0.01%	-0.04%	-0.09%	990 kW	0.30%	0.28%	0.22%	0.15%	0%	-0.23%
1320 kW	-0.05%	-0.15%	-0.21%	-0.35%	-0.40%	-0.52%	1320 kW	0.02%	-0.21%	-0.37%	-0.65%	-0.85%	-1.14%

Battery 500 kW							Battery 700 kW						
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	0.11%	0.17%	0.20%	0.20%	0.25%	0.30%	0 kW	0.38%	0.34%	0.33%	0.36%	0.38%	0.52%
330 kW	0.34%	0.32%	0.32%	0.40%	0.46%	0.58%	330 kW	0.33%	0.34%	0.41%	0.50%	0.62%	0.77%
660 kW	0.34%	0.38%	0.50%	0.47%	0.57%	0.56%	660 kW	0.58%	0.69%	0.79%	0.87%	0.87%	0.78%
990 kW	0.52%	0.57%	0.51%	0.42%	0.22%	-0.22%	990 kW	0.78%	0.82%	0.75%	0.58%	0.24%	-0.38%
1320 kW	0.07%	-0.20%	-0.45%	-0.89%	-1.35%	-1.82%	1320 kW	0.20%	-0.09%	-0.42%	-1.12%	-1.7%	-2.32%

Battery 900 kW						
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	0.74%	0.68%	0.69%	0.65%	0.71%	0.77%
330 kW	0.46%	0.44%	0.48%	0.63%	0.77%	0.88%
660 kW	0.73%	0.91%	1.05%	1.08%	1.00%	-0.79%
990 kW	1.18%	1.16%	1.01%	0.70%	0.25%	-0.41%
1320 kW	0.31%	-0.06%	-0.57%	-1.40%	-2.06%	-2.92%

Source: Author

Although Li-ion batteries implementation allows to decrease CO₂ emissions up to an additional 5%, system cost can be higher in many cases. They can vary from 0.01% up to 1.18% more expensive when compared to a system with the same renewable installed power and no batteries. Although batteries present a slight increase in the system cost, the total associated cost of renewables and batteries is always lower compared to an only-diesel system. Additional consideration to analyze the impact of batteries could be taken into consideration, such as the reduction of CO₂ emissions and the possible cost variation, due to the taxation of these emissions.

EXAMPLE OF THE METHODOLOGY APPLIED AND THE SENSITIVITY ANALYSIS

In order to find the impact of possible variations in the initial cost of solar, wind, and ESS elements we perform a sensitivity analysis. The chosen renewable penetration level is $20\% \pm 2\%$.

Table 18 shows renewable penetration for every scenario combination of renewables and batteries. The highlighted are renewable penetration levels that meet the criteria ($20\% \pm 2\%$).

Table 18. Renewable penetration level for all 180 simulated cases.

Batteries	0 kW					
Wind/Solar kW	0	200	400	600	800	1000
0	0,00%	2,51%	5,02%	7,53%	10,04%	12,55%
330	9,96%	12,47%	14,98%	17,49%	20,00%	22,51%
660	19,92%	22,43%	24,94%	27,45%	29,95%	32,40%
990	29,88%	32,39%	34,87%	37,28%	39,52%	41,50%
1320	39,70%	42,01%	44,15%	46,02%	47,67%	49,10%

Batteries	100 kW					
Wind/Solar kW	0	200	400	600	800	1000
0	-0,68%	2,30%	4,81%	7,32%	9,83%	12,34%
330	9,75%	12,26%	14,77%	17,28%	19,79%	22,30%
660	19,71%	22,22%	24,73%	27,24%	29,75%	32,22%
990	29,67%	32,18%	34,68%	37,12%	39,42%	41,48%
1320	39,54%	41,91%	44,12%	46,08%	47,79%	49,29%

Batteries	300 kW					
Wind/Solar kW	0	200	400	600	800	1000
0	-0,63%	1,89%	4,40%	6,90%	9,42%	11,92%
330	9,34%	11,84%	14,35%	16,86%	19,37%	21,88%
660	19,29%	21,80%	24,31%	26,82%	29,34%	31,84%
990	29,25%	31,77%	34,28%	36,77%	39,17%	41,39%
1320	39,21%	41,66%	43,96%	46,08%	47,93%	49,55%

Batteries	500 kW					
Wind/Solar kW	0	200	400	600	800	1000
0	-0,61%	1,70%	4,18%	6,67%	9,17%	11,67%
330	8,99%	11,49%	14,00%	16,50%	19,01%	21,52%
660	18,92%	21,42%	23,93%	26,45%	28,97%	31,50%
990	28,88%	31,40%	33,92%	36,44%	38,91%	41,23%
1320	38,90%	41,40%	43,80%	46,02%	48,01%	49,72%

Batteries	700 kW					
Wind/Solar kW	0	200	400	600	800	1000
0	-0,49%	1,70%	4,16%	6,64%	9,13%	11,61%
330	8,90%	11,37%	13,85%	16,34%	18,83%	21,34%
660	18,66%	21,16%	23,66%	26,17%	28,71%	31,25%
990	28,59%	31,11%	33,64%	36,19%	38,70%	41,09%
1320	38,67%	41,20%	43,65%	45,98%	48,05%	49,83%

Batteries	900 kW					
Wind/Solar kW	0	200	400	600	800	1000
0	-0,46%	1,72%	4,18%	6,67%	9,15%	11,64%
330	8,95%	11,42%	13,90%	16,38%	18,85%	21,35%
660	18,57%	21,07%	23,56%	26,07%	28,61%	31,16%
990	28,40%	30,93%	33,48%	36,03%	38,55%	40,97%
1320	38,50%	41,06%	43,56%	45,93%	48,06%	49,95%

Source: Author

Twenty results meet the desired 20% of renewable penetration. The total system cost is calculated again, this time performing a sensitivity analysis varying the initial cost of the three elements (solar, wind, and storage) one at the time.

Initial cost is varied at three stages: low, medium, and high. Related costs for each element are shown in Table 19:

Table 19. Initial costs for ESS, solar, and wind power

Initial cost level	Battery cost (\$/kWh)	Solar cost (\$/kW)	Wind cost (\$/kW)
Low	473	900	1200
Medium	840	1400	1994
High	1260	3350	2369

Source: [57] [58] [59] [62]

Figure 26 shows the results of the sensitivity analysis. Each vertical set of data corresponds to a defined cost level for every technology (*i.e.* ESS, solar, wind).

Figure 26. Total system cost of three initial cost levels for combinations with 20% of renewable penetration

Source: Author

Although the ESS has a smaller initial equipment cost range, in some cases it has higher costs than wind power and almost the same cost with solar

power which has a higher high-cost than the ESS high-cost (3350 USD vs. 1260 USD). Table 20 shows the detailed costs for all chosen cases:

Table 20. Total system costs for all cases for low, medium and high initial costs of solar, wind and batteries.

Case (battery-solar-wind)	Battery cost sens			Solar cost sens			Wind cost sens			CO2 reduction
	ESS Low cost	ESS medium cost	ESS high cost	Solar Low cost	Solar medium cost	Solar high cost	Wind Low cost	Wind medium cost	Wind high cost	
B0-S800-W330	111,7	111,7	111,7	111,3	111,7	113,3	111,5	111,7	111,9	18,7%
B0-S0-W660	112,3	112,3	112,3	112,3	112,3	112,3	111,8	112,3	112,5	17,7%
B100-S800-W330	111,5	111,6	111,8	111,2	111,6	113,2	111,4	111,6	111,8	19,0%
B100-S0-W660	112,0	112,2	112,3	112,2	112,2	112,2	111,7	112,2	112,4	18,1%
B300-S800-W330	111,1	111,5	112,0	111,1	111,5	113,1	111,2	111,5	111,6	19,6%
B300-S1000-W330	108,3	108,7	109,2	108,2	108,7	110,7	108,4	108,7	108,8	22,0%
B300-S0-W660	111,6	112,0	112,5	112,0	112,0	112,0	111,5	112,0	112,3	18,7%
B300-S200-W660	108,7	109,2	109,7	109,1	109,2	109,6	108,6	109,2	109,4	21,1%
B500-S800-W330	110,7	111,4	112,3	111,0	111,4	113,0	111,2	111,4	111,6	20,1%
B500-S1000-W330	108,0	108,7	109,5	108,2	108,7	110,6	108,4	108,7	108,8	22,5%
B500-S0-W660	111,1	111,9	112,7	111,9	111,9	111,9	111,3	111,9	112,1	19,3%
B500-S200-W660	108,2	108,9	109,8	108,8	108,9	109,3	108,4	108,9	109,2	21,8%
B700-S800-W330	110,3	111,3	112,4	110,9	111,3	112,8	111,0	111,3	111,4	20,7%
B700-S1000-W330	107,6	108,6	109,7	108,1	108,6	110,5	108,3	108,6	108,7	23,1%
B700-S0-W660	110,8	111,8	112,9	111,8	111,8	111,8	111,3	111,8	112,0	19,8%
B700-S200-W660	107,9	108,9	110,1	108,8	108,9	109,3	108,4	108,9	109,2	22,2%
B900-S800-W330	109,8	111,1	112,6	110,7	111,1	112,7	110,9	111,1	111,2	21,4%
B900-S1000-W330	107,1	108,4	109,9	107,9	108,4	110,3	108,1	108,4	108,5	23,7%
B900-S0-W660	110,3	111,6	113,1	111,6	111,6	111,6	111,1	111,6	111,9	20,4%
B900-S200-W660	107,6	108,9	110,3	108,8	108,9	109,2	108,3	108,9	109,1	22,8%
USD millions										

Source: Author

All cases with a small amount or no batteries installed (0 kWh and 100 kWh) present a total cost over 111 million of USD. When the cases with low initial cost are compared to the high initial cost ones, the batteries present an overall higher impact on the total cost, having a raise from 0.3 million of USD up to 2.8 million USD. Similarly, the solar cost increment range goes from 0.5 million USD up to 2.5 million USD. In contrast, wind energy presents a lower impact with 0.8 million USD of maximum increment. The impact of wind power in CO₂ emissions prevail over the total cost when it is combined with at least a 300 kWh battery system and any installed solar power.

IMPACT OF INITIAL PRICE VARIATION

In order to evaluate the impact of the price variation of each element (solar, wind, ESS) in the final cost of the project, we calculate the ratio between the variation of the final cost of the project and the variation of the price of each element, using Equation 9:

$$VAR_{TC} = \frac{TC_H - TC_L}{IC_H - IC_L} \left[\frac{\$}{\$/kWh} \right] \quad (9)$$

Where:

VAR_{TC} : Variation of total cost per variation of initial equipment price.

TC_H : Total cost for high initial cost.

TC_L : Total cost for low initial cost.

IC_H : High initial cost.

IC_L : Low initial cost.

For example, taking into consideration the data from Table, the case B300-S800-W330 is calculated in Equation 10:

$$VAR_{TC} = \frac{TC_H - TC_L}{IC_H - IC_L} = \frac{112 - 111,1 \text{ million\$}}{1260 - 473 \text{ \$/kWh}} = 1178 \quad (10)$$

Next, in Figure 27 we can see how the overall wind energy price has a lower impact on the final project cost, with approximately a maximum of 700 USD of variation for every dollar variation on the initial cost.

Figure 27. Variation of total project cost and variation of initial equipment installation cost

Source: Author

Energy storage shows the highest increment of the ratio, having an impact twice and up to three times higher than solar and wind technologies.

There is a special issue when analyzing CO₂ emissions. As it can be seen in Figure 27 although the ESS has a higher impact in the total cost, there is a tendency of reduction on the emissions with the installation of ESS.

When comparing both extreme cases on Figure 27

(B0-S800-W330 and B900-S200-W660), around 4% of additional CO₂ reduction is achieved. The amount of 1% of CO₂ emission is equivalent to 150 Ton/year.

Figure 28 has a representation of CO₂ reduction using the size of the circles. As it can be seen, the lowest emission points are not always for the more expensive system configurations.

Figure 28. Total project costs and CO₂ reduction for each case with 20% of renewable penetration.

Source: Author

Total CO₂ reduction for each case.

COST SYSTEM CALCULATION CONSIDERING BATTERY DEGRADATION

Additional analyses are performed in order to establish the impact in the total project cost when the discharge-recharge cycles are considered to be affecting degradation of the storage system.

For each scenario was accounted the total energy cycled through the battery system. This energy value is used to calculate the number of total equivalent full cycles using Equation 11.

$$N_c = \frac{\text{Total cycled energy per year}}{0,7 \times \text{rated ESS capacity}} \quad (11)$$

Where:

Total cycled energy per year: Is the cycled energy through the energy storage system during a full operation year.

Rated ESS capacity: Is the rated energy capacity of the selected battery system.

0,7: This value represent 70% of the total battery capacity since batteries have a state of charge limited to 90% at maximum 20% at minimum.

It is important to clarify some limitations of this method. This degradation is considered outside HOMER simulations, accounting the total number of cycles per year for the battery system, and calculating the time needed to replace the whole battery system. The temperature effects were not considered on battery life estimations.

A replacement is considered when a battery reaches 20,000 cycles (International Renewable Energy Agency (IRENA), October 2017) and a new battery is included in the total number of batteries for a 20 year life system, affecting at the end the total cost of the system. Table 21 shows calculated cycles per year on the storage system for each considered case.

Table 21. Number of full cycles per year for Li-ion batteries

Battery equivalente full cycles															
Batteries		0 kW						Batteries		100 kW					
Wind/Solar		0	200	400	600	800	1000	Wind/Solar		0	200	400	600	800	1000
0		--	--	--	--	--	--	0		1333	3455	3428	3400	3397	3391
330		--	--	--	--	--	--	330		3520	3440	3419	3393	3395	3382
660		--	--	--	--	--	--	660		3520	3444	3418	3402	3391	3336
990		--	--	--	--	--	--	990		3520	3450	3393	3323	3206	3044
1320		--	--	--	--	--	--	1320		3400	3231	3076	2917	2783	2686
Batteries		300 kW						Batteries		500 kW					
Wind/Solar		0	200	400	600	800	1000	Wind/Solar		0	200	400	600	800	1000
0		4416	3441	3449	3463	3466	3471	0		2646	2849	2860	2940	2995	3018
330		3511	3508	3510	3513	3512	3507	330		3229	3243	3268	3307	3320	3311
660		3513	3507	3511	3505	3523	3533	660		3372	3345	3363	3358	3325	3258
990		3510	3510	3509	3523	3492	3399	990		3374	3310	3270	3206	3122	3014
1320		3578	3503	3450	3315	3157	2973	1320		3160	3052	2975	2916	2761	2649
Batteries		700 kW						Batteries		900 kW					
Wind/Solar		0	200	400	600	800	1000	Wind/Solar		0	200	400	600	800	1000
0		1895	2247	2263	2323	2400	2432	0		1473	1804	1823	1860	1902	1923
330		2548	2653	2708	2739	2782	2771	330		1999	2054	2098	2127	2192	2182
660		3010	3038	3050	3027	2962	2880	660		2495	2503	2527	2505	2460	2375
990		3081	3066	2993	2898	2822	2718	990		2703	2661	2578	2496	2414	2352
1320		2771	2710	2638	2549	2470	2371	1320		2443	2368	2277	2218	2151	2058

Source: Author

A total of 3000 cycles per year is equivalent to 8.2 full cycles per day. Taking into account this information, we calculate battery life in years. The results are presented in Table 22:

Table 22. Expected battery life for each simulated case (years)

Expected life (years)												
Batteries		0 kW										
Wind/Solar	0	200	400	600	800	1000						
0	--	--	--	--	--	--						
330	--	--	--	--	--	--						
660	--	--	--	--	--	--						
990	--	--	--	--	--	--						
1320	--	--	--	--	--	--						
Batteries		300 kW										
Wind/Solar	0	200	400	600	800	1000						
0	4,5	5,8	5,8	5,8	5,8	5,8						
330	5,7	5,7	5,7	5,7	5,7	5,7						
660	5,7	5,7	5,7	5,7	5,7	5,7						
990	5,7	5,7	5,7	5,7	5,7	5,9						
1320	5,6	5,7	5,8	6,0	6,3	6,7						
Batteries		700 kW										
Wind/Solar	0	200	400	600	800	1000						
0	10,6	8,9	8,8	8,6	8,3	8,2						
330	7,8	7,5	7,4	7,3	7,2	7,2						
660	6,6	6,6	6,6	6,6	6,8	6,9						
990	6,5	6,5	6,7	6,9	7,1	7,4						
1320	7,2	7,4	7,6	7,8	8,1	8,4						

Batteries		100 kW					
Wind/Solar	0	200	400	600	800	1000	
0	15,0	5,8	5,8	5,9	5,9	5,9	
330	5,7	5,8	5,9	5,9	5,9	5,9	
660	5,7	5,8	5,9	5,9	5,9	6,0	
990	5,7	5,8	5,9	6,0	6,2	6,6	
1320	5,9	6,2	6,5	6,9	7,2	7,4	
Batteries		500 kW					
Wind/Solar	0	200	400	600	800	1000	
0	7,6	7,0	7,0	6,8	6,7	6,6	
330	6,2	6,2	6,1	6,0	6,0	6,0	
660	5,9	6,0	5,9	6,0	6,0	6,1	
990	5,9	6,0	6,1	6,2	6,4	6,6	
1320	6,3	6,6	6,7	6,9	7,2	7,6	
Batteries		900 kW					
Wind/Solar	0	200	400	600	800	1000	
0	13,6	11,1	11,0	10,8	10,5	10,4	
330	10,0	9,7	9,5	9,4	9,1	9,2	
660	8,0	8,0	7,9	8,0	8,1	8,4	
990	7,4	7,5	7,8	8,0	8,3	8,5	
1320	8,2	8,4	8,8	9,0	9,3	9,7	

Source: Author

Batteries with minor capacity have a lower expected life since they are cycled faster each day in order to compensate the variability of renewable energies. Lifespan increases from 40% up to 70% on some cases when they compare a 100 kWh battery against a 900 kWh storage system.

From Table 7 it is possible to estimate the number of total battery systems needed for the project, including replacements and the first battery group installed in the year 1. On each simulated case, this battery number is shown in Table 23:

Table 23. Total battery system purchases during a project with a duration of 20 years, considering ESS degradation

ESS total replacements															
Batteries		0						Batteries		100 kWh					
Wind/Solar		0	200	400	600	800	1000	Wind/Solar		0	200	400	600	800	1000
	0	--	--	--	--	--	--		0	2,3	4,5	4,4	4,4	4,4	4,4
	330	--	--	--	--	--	--		330	4,5	4,4	4,4	4,4	4,4	4,4
	660	--	--	--	--	--	--		660	4,5	4,4	4,4	4,4	4,4	4,3
	990	--	--	--	--	--	--		990	4,5	4,5	4,4	4,3	4,2	4,0
	1320	--	--	--	--	--	--		1320	4,4	4,2	4,1	3,9	3,8	3,7
Batteries		300 kWh						Batteries		500 kWh					
Wind/Solar		0	200	400	600	800	1000	Wind/Solar		0	200	400	600	800	1000
	0	5,4	4,4	4,4	4,5	4,5	4,5		0	3,6	3,8	3,9	3,9	4,0	4,0
	330	4,5	4,5	4,5	4,5	4,5	4,5		330	4,2	4,2	4,3	4,3	4,3	4,3
	660	4,5	4,5	4,5	4,5	4,5	4,5		660	4,4	4,3	4,4	4,4	4,3	4,3
	990	4,5	4,5	4,5	4,5	4,5	4,4		990	4,4	4,3	4,3	4,2	4,1	4,0
	1320	4,6	4,5	4,5	4,3	4,2	4,0		1320	4,2	4,1	4,0	3,9	3,8	3,6
Batteries		700 kWh						Batteries		900 kWh					
Wind/Solar		0	200	400	600	800	1000	Wind/Solar		0	200	400	600	800	1000
	0	2,9	3,2	3,3	3,3	3,4	3,4		0	2,5	2,8	2,8	2,9	2,9	2,9
	330	3,5	3,7	3,7	3,7	3,8	3,8		330	3,0	3,1	3,1	3,1	3,2	3,2
	660	4,0	4,0	4,0	4,0	4,0	3,9		660	3,5	3,5	3,5	3,5	3,5	3,4
	990	4,1	4,1	4,0	3,9	3,8	3,7		990	3,7	3,7	3,6	3,5	3,4	3,4
	1320	3,8	3,7	3,6	3,5	3,5	3,4		1320	3,4	3,4	3,3	3,2	3,2	3,1

Source: Author

To calculate the total cost of the project, we changed the number of batteries purchased from one to the values shown on Table 23. The battery number was rounded down. The result of the total cost for all cases considering battery degradation is shown on Table 24:

Table 24. Total project cost for all 180 simulated cases considering battery degradation
(millions USD)

Batteries	0 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	134,4	131,4	128,5	125,7	122,8	119,9
330 kW	123,3	120,5	117,6	114,7	111,9	109,0
660 kW	112,5	109,6	106,7	103,9	101,1	98,4
990 kW	101,7	98,9	96,1	93,5	91,0	88,8
1320 kW	91,4	88,8	86,4	84,3	82,5	81,0

Batteries	100 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	134,6	132,3	129,5	126,5	123,6	120,7
330 kW	124,3	121,4	118,5	115,6	112,8	109,9
660 kW	113,4	110,5	107,6	104,8	102,0	99,3
990 kW	102,6	99,8	97,0	94,3	91,8	89,6
1320 kW	92,2	89,5	87,0	84,5	82,7	81,0

Batteries	300 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	138,1	134,1	131,3	128,4	125,5	122,6
330 kW	126,1	123,2	120,3	117,4	114,6	111,8
660 kW	115,3	112,4	109,5	106,7	103,9	101,2
990 kW	104,5	101,6	98,8	96,1	93,5	91,1
1320 kW	93,9	91,1	88,6	86,3	84,3	81,5

Batteries	500 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	137,0	134,1	131,3	128,4	125,5	124,3
330 kW	127,9	125,0	122,1	119,3	116,5	113,8
660 kW	117,0	114,1	111,4	108,5	105,8	103,1
990 kW	106,4	103,6	100,8	98,0	95,3	92,7
1320 kW	95,6	92,8	88,5	86,1	83,8	81,9

Batteries	700 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	136,0	135,3	132,4	129,6	126,7	124,0
330 kW	127,2	124,4	121,6	118,7	116,0	113,3
660 kW	119,0	116,1	113,3	110,6	105,4	102,6
990 kW	108,3	105,5	100,3	97,5	94,7	91,9
1320 kW	95,1	92,2	89,5	86,8	84,5	82,5

Batteries	900 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	136,8	133,8	130,9	128,0	125,1	122,3
330 kW	125,4	125,5	122,6	119,9	117,2	114,4
660 kW	117,8	115,0	112,3	109,5	106,6	103,6
990 kW	107,4	104,5	101,6	98,6	95,7	92,9
1320 kW	96,2	93,2	90,4	87,6	85,2	83,0

Source: Author

Finally, the total cost increase for energy storage implementation and battery degradation is shown on Table 25.

Table 25. System cost increase by energy storage replacement, due to battery degradation
(expressed on millions)

Batteries	0 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	-	-	-	-	-	-
330 kW	-	-	-	-	-	-
660 kW	-	-	-	-	-	-
990 kW	-	-	-	-	-	-
1320 kW	-	-	-	-	-	-

Batteries	100 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	0,2	0,9	0,9	0,9	0,9	0,9
330 kW	0,9	0,9	0,9	0,9	0,9	0,9
660 kW	0,9	0,9	0,9	0,9	0,9	0,9
990 kW	0,9	0,9	0,8	0,8	0,8	0,7
1320 kW	0,8	0,7	0,6	0,2	0,2	0,1

Batteries	300 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	3,7	2,8	2,7	2,7	2,7	2,8
330 kW	2,7	2,7	2,7	2,7	2,7	2,8
660 kW	2,7	2,8	2,8	2,8	2,8	2,8
990 kW	2,8	2,8	2,7	2,6	2,5	2,3
1320 kW	2,5	2,3	2,1	1,9	1,8	0,5

Batteries	500 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	2,6	2,7	2,7	2,7	2,8	4,5
330 kW	4,5	4,5	4,5	4,6	4,6	4,8
660 kW	4,5	4,5	4,7	4,6	4,7	4,7
990 kW	4,7	4,7	4,6	4,5	4,3	3,9
1320 kW	4,2	3,9	2,1	1,7	1,3	1,0

Batteries	700 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	1,7	3,9	3,9	3,9	3,9	4,1
330 kW	3,9	3,9	3,9	4,0	4,2	4,3
660 kW	6,4	6,5	6,6	6,7	4,4	4,2
990 kW	6,6	6,6	4,2	4,0	3,7	3,1
1320 kW	3,6	3,4	3,1	2,5	2,0	1,6

Batteries	900 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	2,5	2,4	2,4	2,3	2,4	2,4
330 kW	2,0	5,0	5,0	5,2	5,3	5,4
660 kW	5,3	5,5	5,6	5,6	5,5	5,2
990 kW	5,6	5,6	5,4	5,1	4,7	4,1
1320 kW	4,7	4,4	4,0	3,3	2,7	2,0

Source: Author

The total system cost on the case using only-diesel is 134.4 million dollars. Energy storage implementation and battery degradation increase the total cost from 0.2 million of USD to 6.7 million of USD.

COST SYSTEM CALCULATION CONSIDERING TAX ON CO₂ EMISSIONS

One final assessment for isolated system is the inclusion of taxes on CO₂ emissions. As stated by the Organization for Economic Cooperation and Development (OECD) "Pricing carbon emissions allows countries to smoothly steer their economies towards, and along, a carbon-neutral growth path" (Organisation for Economic Cooperation and Development (OECD). , Sep 2018). In order to evaluate if an additional cost (*i.e.* emission tax) on renewable technologies and battery implementation could affect economically the current isolated system under study, a CO₂ tax is included in the calculation of the total system cost. The associated cost is 60 EUR per tonne of CO₂ emitted.

A full calculation of the system cost is done, taking into account the emission taxes and battery degradation. The total project cost is shown on Table 26:

Table 26. Total project cost for all 180 simulated cases, considering battery degradation and CO₂ emission tax of 60 EUR/Ton

Batteries		0 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	
0 kW	137,2	134,2	131,3	128,3	125,3	122,4	
330 kW	125,9	123,0	120,1	117,1	114,2	111,3	
660 kW	114,9	111,9	108,9	106,1	103,2	100,4	
990 kW	103,8	100,9	98,1	95,4	92,8	90,6	
1320 kW	93,3	90,6	88,1	86,0	84,1	82,6	

Batteries		100 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	
0	137,4	135,1	132,2	129,1	126,2	123,2	
330	126,9	123,9	120,9	118,0	115,1	112,1	
660	115,8	112,8	109,8	106,9	104,0	101,3	
990	104,7	101,8	99,0	96,2	93,6	91,3	
1320	94,1	91,3	88,8	86,2	84,3	82,6	

Batteries		300 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	
0 kW	140,9	136,9	134,0	131,0	128,1	125,1	
330 kW	128,6	125,7	122,8	119,8	116,9	114,0	
660 kW	117,6	114,6	111,7	108,8	105,9	103,2	
990 kW	106,6	103,6	100,8	97,9	95,3	92,8	
1320 kW	95,8	92,9	90,2	87,9	85,9	83,1	

Batteries		500 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	
0 kW	139,8	136,8	133,9	131,0	128,1	126,8	
330 kW	130,4	127,5	124,5	121,6	118,8	116,0	
660 kW	119,4	116,4	113,5	110,6	107,8	105,0	
990 kW	108,4	105,6	102,7	99,8	97,1	94,5	
1320 kW	97,4	94,5	90,2	87,7	85,4	83,4	

Batteries		700 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	
0 kW	138,8	138,0	135,1	132,1	129,2	126,4	
330 kW	129,7	126,9	124,0	121,1	118,3	115,5	
660 kW	121,3	118,3	115,5	112,7	107,5	104,6	
990 kW	110,3	107,4	102,2	99,3	96,4	93,6	
1320 kW	96,9	93,9	91,2	88,4	86,1	84,0	

Batteries		900 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW	
0 kW	139,6	136,5	133,6	130,5	127,6	124,7	
330 kW	127,9	127,9	125,0	122,2	119,4	116,6	
660 kW	120,1	117,2	114,4	111,6	108,6	105,6	
990 kW	109,4	106,4	103,5	100,4	97,4	94,6	
1320 kW	97,9	94,9	92,0	89,2	86,7	84,5	

Comparing the total cost with battery degradation and CO₂ tax (Table) against the total cost with only-battery degradation has an increased cost that varies from 1.5 million USD to 2.8 million USD.

Finally, evaluating the impact of both CO₂ tax and battery degradation, we compare all cases against the only-diesel case, which is the same as not having solar power, wind power, and energy storage system. This comparison is shown on Table 27.

Table 27. Cost comparison against an only-diesel case, including battery degradation and CO₂ emission tax.

Batteries	0 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	0,0	-3,0	-6,0	-8,9	-11,9	-14,8
330 kW	-11,3	-14,2	-17,1	-20,1	-23,0	-26,0
660 kW	-22,3	-25,3	-28,3	-31,2	-34,1	-36,8
990 kW	-33,4	-36,3	-39,1	-41,9	-44,4	-46,6
1320 kW	-43,9	-46,6	-49,1	-51,2	-53,1	-54,7

Batteries	100 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	0,2	-2,1	-5,0	-8,1	-11,0	-14,0
330 kW	-10,3	-13,3	-16,3	-19,2	-22,1	-25,1
660 kW	-21,5	-24,4	-27,4	-30,3	-33,2	-35,9
990 kW	-32,5	-35,4	-38,3	-41,1	-43,6	-45,9
1320 kW	-43,2	-45,9	-48,5	-51,0	-52,9	-54,6

Batteries	300 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	3,7	-0,3	-3,3	-6,2	-9,2	-12,1
330 kW	-8,6	-11,5	-14,5	-17,4	-20,3	-23,2
660 kW	-19,6	-22,6	-25,5	-28,4	-31,3	-34,0
990 kW	-30,6	-33,6	-36,4	-39,3	-41,9	-44,4
1320 kW	-41,5	-44,3	-47,0	-49,3	-51,4	-54,2

Batteries	500 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	2,6	-0,4	-3,3	-6,2	-9,1	-10,4
330 kW	-6,8	-9,7	-12,7	-15,6	-18,4	-21,2
660 kW	-17,9	-20,8	-23,7	-26,6	-29,4	-32,2
990 kW	-28,8	-31,7	-34,5	-37,4	-40,1	-42,7
1320 kW	-39,8	-42,7	-47,1	-49,6	-51,8	-53,8

Batteries	700 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	1,6	0,8	-2,1	-5,1	-8,0	-10,8
330 kW	-7,5	-10,4	-13,3	-16,1	-18,9	-21,7
660 kW	-16,0	-18,9	-21,7	-24,5	-29,8	-32,6
990 kW	-26,9	-29,8	-35,0	-37,9	-40,8	-43,6
1320 kW	-40,3	-43,3	-46,1	-48,8	-51,2	-53,2

Batteries	900 kWh					
Wind/Solar	0 kW	200 kW	400 kW	600 kW	800 kW	1000 kW
0 kW	2,4	-0,7	-3,7	-6,7	-9,6	-12,5
330 kW	-9,3	-9,3	-12,2	-15,0	-17,8	-20,6
660 kW	-17,1	-20,0	-22,8	-25,6	-28,7	-31,6
990 kW	-27,8	-30,8	-33,7	-36,8	-39,8	-42,6
1320 kW	-39,3	-42,3	-45,2	-48,1	-50,5	-52,8

Source: Author

As it can be seen on Table 12, on most cases the total cost is inferior to the only-diesel cost system. In very few cases the implementation of batteries increased the total cost of the system, especially for systems with zero or low renewable penetration levels. For all cases with wind energy there is a reduction in the system cost. Overall, it is possible to install energy storage systems with Li-ion batteries saving from 0.3 million of USD to 50 million of USD during a 20

years life cycle, reducing at the same time CO₂ emissions from 1% to 50% per year and to be able to pay CO₂ emission taxes.

SELECTION OF A SUITABLE SOLUTION

Different approaches have been considered in this chapter to evaluate the suitable solutions to be implemented in an isolated system such as the Fernando de Noronha, in order to reduce costs and CO₂ emissions. There are multiple combinations of wind power, solar power, and energy storage that could meet the user requirements. We introduced the idea of approaching to a solution by selecting an objective such as renewable penetration, and then performed a sensitivity analysis to evaluate the differences between the selected solutions.

To facilitate this task, we developed a simple Matlab script that allows the comparison between the selected cases. It is important to clarify that this script relies on results already simulated in HOMER, performing mainly cost calculations and comparisons on different initial equipment costs, considerations of battery degradation, and inclusion of CO₂ taxes.

A starting window (Figure 29) allows us to change the basic entry data used in calculations such as the initial installation cost of solar power, wind power, and batteries. It is possible to change the fuel cost, the project life, the interest rate, and the inflation. Also, we can determine if the first analysis would include battery degradation and CO₂ emission tax.

Figure 29. Starting window Project cost calculator in Matlab

Project cost calculator

Cost

Wind cost (\$/kW) 2300

Solar cost (\$/kW) 1300

Battery cost (\$/kWh) 1000

Fuel cost (\$/L) 1,6

CO2 tax (\$/Ton) 0

Battery degradation Off

Battery life (kWh) 0

Project life (years) 20

Annual interest rate (%) 5

Inflation (%)

Select simulation results

Cost calculation

Source: Author

Most common cost values are presented when the window is opened, and it is advisable to use them for the first iterations. After we click *Cost calculation*, a .xls file is created where all results, including the total costs, renewable penetration, consumed fuel and CO₂ emissions, are shown. Additionally, a graphical representation of the results is created as it can be seen in Figure 30.

Figure 30. Matlab window of graphical representation of the total cost, calculated for all 180 simulated cases

Source: Author

Finally, an additional window opens allowing the selection of the desired renewable penetration level and the change of variables for the sensitivity analysis.

Evaluating the results of a 20% of the desired renewable penetration level we can summarize all available results as shown on Table 28:

Table 28. Results at 20 % of renewable penetration level in Fernando de Noronha Island for three cases. i) No CO₂ tax, No ESS degradation, ii) No ESS degradation, iii) With ESS degradation and CO₂ tax

Case	CO ₂ reduction	Total cost No CO ₂ tax No ESS degradation	Total cost with ESS degradation	Total cost ESS degrad and CO ₂ tax
B0-S800-W330	18,7%	111,9	111,9	114,2
B0-S0-W660	17,7%	112,5	112,5	114,9
B100-S800-W330	19,0%	111,8	112,8	115,1
B100-S0-W660	18,1%	112,4	113,4	115,8
B300-S800-W330	19,6%	111,6	114,6	116,9
B300-S1000-W330	22,0%	108,8	111,8	114,0
B300-S0-W660	18,7%	112,3	115,3	117,6
B300-S200-W660	21,1%	109,4	112,4	114,6
B500-S800-W330	20,1%	111,6	116,5	118,8
B500-S1000-W330	22,5%	108,8	113,8	116,0
B500-S0-W660	19,3%	112,1	117,0	119,4
B500-S200-W660	21,8%	109,2	114,1	116,4
B700-S800-W330	20,7%	111,4	116,0	118,3
B700-S1000-W330	23,1%	108,7	113,3	115,5
B700-S0-W660	19,8%	112,0	119,0	121,3
B700-S200-W660	22,2%	109,2	116,1	118,3
B900-S800-W330	21,4%	111,2	117,2	119,4
B900-S1000-W330	23,7%	108,5	114,4	116,6
B900-S0-W660	20,4%	111,9	117,8	120,1
B900-S200-W660	22,8%	109,1	115,0	117,2
USD Millions				

Source: Author

All 60 presented cases in Table have 20% of renewable penetration in the Fernando de Noronha system, so the first requirement has been met. The lowest cost is 108.5 million of USD for the B900-S1000-W330 case, so a first evaluation could lead to select this solution. However, this case lacks important elements such as battery degradation and a possible incorporation of CO₂

emission tax in the electrical market. When these two elements are considered, the solutions with lowest cost change are the B300-S1000-W330 case. Although the total cost is different when CO₂ tax is considered, and, when is not, the technical solution is the same for both.

If an additional requirement is added, for example, looking for at least 20% of the emissions reduction, some proposed solutions from Table do not fulfill the requirement. The three highlighted solutions found before still satisfy this new requirement, and, in fact, have a high reduction of the emissions with 22% and 23.7% of CO₂ emission reduction.

4.5 PARTIAL CONCLUSIONS

A complete evaluation of an island system was performed following the proposed methodology. The objective was 20 % of renewable penetration. A total of 180 scenarios were defined, they are composed by combinations of photovoltaic power, wind power and Li-ion batteries. Twenty combinations meet the desired renewable penetration level. An extensive evaluation is performed calculating total project cost for the twenty selected cases.

The cheapest scenario can be selected from the twenty defined scenarios. Additional elements impacting the total cost of the project are implemented in the methodology to adapt additional restriction that a user of the methodology could have. These elements are a tax for CO₂ emissions and battery aging by energy cycle through them. Finally, a Matlab tool is developed to calculate the total project cost, allowing to change the initial cost of equipments such as energy storage, photovoltaic system and wind power system. Also, the Matlab tool allows to calculate the project cost considering the implementation of CO₂ emission tax and storage aging.

5. EVALUATION OF SHIP POWER SYSTEMS

Multiple authors have proposed methodologies to reduce greenhouse gas emissions in ship power systems ^{[77][78][79]}, although these methodologies show reduction, we extended the range of these evaluations.

In source ^[77], authors achieve 45% of CO₂ reduction, however it is not clear which part of the mission they are using. We decided to evaluate the whole mission of the ship (see Figure 31). Similarly, in source ^[78] authors use batteries with roundtrip efficiency between 80% and 100%. Our simulations do not take into account 100% of the round trip efficiency but 96%, and the lower value analyzed is 70%. Finally, the algorithm used in source ^[79] considered variables such as power balance, GHG emissions, and ramp rates; however, it did not evaluate the influence of minimum load level of generators and neither the possible impact of different system configurations and hybrid systems.

Implemented energy storage systems study the effect of multiple parameters such as the battery round trip efficiency, the part of the mission where the ship generators are working, the hybrid system configurations, and the minimum load level, at which can be loaded any generator.

5.1 METHODOLOGY

A PSV (Platform Supply Vessel) was selected to determine the impact of Li-ion battery system on the consumption of diesel by the generators on board. The power demand on each time step during the whole mission is shown next in Figure 31:

Figure 31. Power demand during the different parts of the mission.

Ship power system has the topology shown in Figure 32. The main elements are four 1850 kW diesel generators, and a main bus with connected loads such as service load, thrusters and batteries. There are two additional auxiliary generators for further analysis.

Figure 32. Power system diagram of the Platform Supply Vessel (PSV).

Base case is in black. Components connected to the base case to evaluate the potential of the auxiliary generators are in red. Elements related to batteries are in blue.

Source: [27]

The base case uses a load demand of Figure 31 with three 1850 kW diesel generators, set with minimum load level of 50% and the last 1850 kW set at 10% of the spinning reserve.

Additional configurations are simulated as it can be seen next in Table 29.

Table 29. Configurations under evaluation

Configuration	Additional information
Diesel + battery	Four 1850 diesel generators and a 1000 kW - 1000 kWh Li-ion battery
Diesel + Diesel Aux	Four 1850 diesel generators and two 450 kW aux generators connected during the loading-in-port and standby operations
Diesel + Battery + Diesel Aux.	Four 1850 diesel generators, two 450 kW aux generators connected during the loading-in-port and standby, and a 1000 kW - 1000 kWh Li-ion battery

Source: author

Four main parameters are analyzed:

- Round trip efficiency: from 70% to 96%.
- Minimum load level of diesel generators: 30%, 40% and 50%.
- Battery C-rate: 0.2 up to 2.0 for a 1000 kWh battery.
- Battery energy capacity: Discharge times varying from 12 min to 120 min for a 1000 kW Li-ion battery.

Equation 12 is used to calculate the total full charge-discharge cycles of batteries, this is used to evaluate the expected battery lifespan.

$$\text{Number of cycles} = \frac{E_T}{E_{90\%} - E_{20\%}} \quad (12)$$

Where:

E_T : Total cycled energy through the battery (kWh)

$E_{90\%}$: Battery capacity at 90% SoC (kWh)

$E_{20\%}$: Battery capacity at 20% SoC (kWh)

To avoid excessive detrimental battery lifespan effects for depth of discharge and overcharge, the state of charge is limited to 90% and 20% [80].

5.2 SIMULATION RESULTS

Results for different parameters such as roundtrip efficiency, C-rate, battery capacity, type of chemistry, are presented in this part of chapter 5.

5.2.1 ROUNDTrip EFFICIENCY VARIATION

Several cases were simulated for each parameter discussed previously. CO₂ emissions and a number of battery cycles for each value of roundtrip efficiency simulated are shown next in Figure 33 .

Figure 33. Changes in CO₂ emissions and number of cycles caused by a variation in the round trip efficiency.

Battery power and capacity fixed at 1000 kW–1000 kWh. In red: CO₂ emission reduction in the case of four diesel generators with batteries, in comparison to the base case (four diesel generators and no batteries). In black: Number of battery cycles

Source: [27]

Although the number of cycles stays almost unchanged, there are higher CO₂ emission reduction for the increase of round trip efficiency reaching almost 9% of the reduction.

CO₂ emission reduction for variation of the minimum load level of diesel generators is shown in Figure 34.

5.2.2 MINIMUM LOAD LEVEL

As one can see in Fig. 34, the round trip efficiency is kept at 92% for the three minimum load levels simulated. The generators minimum load levels simulated are 30%, 40%, and 50%, the equivalent number of battery cycles during the operation are 43.8, 41.9, and 41.6, respectively.

Figure 34. CO₂ emission reduction and a total increase of generated energy for the case with four diesel generators and batteries in comparison to the case with four diesel generators without batteries.

Source: [27]

Diesel generators have manufacturer recommendations to operate at 50% or higher energy levels in order to avoid incomplete fuel combustion [81] that reduces their efficiency. In cases where generators operate under 50% for a long

time, manufacturer recommend to operate the generator for 30 minutes at 50% of the rated power.

Since generators that work at low load levels are operating at lower efficiency, this approach to analyze the impact was suitable for energy storage implementation and topology configuration. However results show no strong correlation between load levels and CO₂ reduction. At this point it is not recommended to implement this approach to reduce GHG emissions due to the increase of inconveniences, like operating for extra time the diesel generator at 50% load level.

5.2.3 C-RATE VARIATION

CO₂ emissions and number of cycles for different C-rate batteries are shown in Figure 35

Figure 35. CO₂ emission reduction in the case of four diesel generators with batteries in, comparison to the base case.

The battery is fixed at 1000 kWh, with round trip efficiency of 92%

Source: [27]

In the simulations of C-rate batteries it is limited the maximum charge and discharge power of the energy storage system. For C-rate below 0.6 the reduction of CO₂ emissions is under 2%. This reduction starts to grow after a C-rate of 0.6 reaching 9%. The implementation of batteries with C-rate over 1.4 seems not needed for the current configuration since the emissions reduction reaches a cap. Higher value C-rate entail batteries operating at higher power. Depending on the power levels it might be needed to be operated with an additional equipment of refrigeration, increasing the cost and required space.

5.2.4 BATTERY ENERGY CAPACITY

Finally, for this sensitivity analysis, results for battery energy capacity variation are shown in Figure 36.

Figure 36. CO₂ emission reduction to the base case for battery rated power 1000 kW and rated capacity variation from 200 kWh (12 min.) to 2000 kWh (120 min.)

Source: [27]

A 200 kWh battery system is unlikely used according to these results, meaning that for the current dispatch process is not worth to operate this battery size. CO₂ reduction starts to increase rapidly and, again, reaches a

limit. At 1000 kW battery power, an available discharge time of 72 minutes seems enough to achieve the maximum CO₂ reduction.

5.2.5 COMPARISON OF LITHIUM IRON PHOSPHATE AND LITHIUM TITANATE BATTERIES

With the limited space in ships and the low flexibility to create new structures, a suitable and popular solution to install an energy storage system in ships is the use of containers. As it can be seen in Figure 37 there are multiple installed projects using Lithium Iron Phosphate and Lithium Titanate batteries around the world.

Figure 37. Li-ion battery technologies from 500 kW to 5 MW of power and 10 to 180 min. of operation duration that are in operating worldwide

Source: [27] [82]

The 20 ft. container used in the analysis has the following dimensions:

L: 6.058 m W: 2.438 m H: 2.591 m

Li-ion batteries general specification are shown next in Table 30.

Table 30: Li-ion batteries specifications

Li-ion battery	Volumetric energy (kWh/m ³)	Cycle Life [83] [60]	Round Trip Efficiency (%) [60]	Recharge rates [84]
LiFePO ₄	211-620 [60] [85]	1000-2000	92	2C-1C
LiTiO	120-620 [83] [60]	3000-7000	96	3C-1C

Source: [27]

In order to determine the power and capacity of a 20 ft container with an energy storage system that includes any of these two chemistries, we calculate elements related to space used by battery cells, and converters. Taking into account the typical distribution inside containers [86][87][88] and the battery racks arrangement [89][90][91], the typical layout of a Li-ion energy system in a 20 ft container is shown in Figure 38:

Figure 38. Plane view of a typical arrangement of battery racks in a 20 ft container.

Source: [27]

Considerations related to the space occupied by battery cells and battery racks are followed by the calculation of the appropriate total power and the

capacity of the energy storage system. Battery cells need additional space inside the racks for installation, considering electrical and thermal isolation ^[92], the estimated effective space of cells in each rack is 57%. Depending on battery racks configurations, effective space ^{[83][60][84]} varies from 30% for two battery racks to 52% for three battery racks. Considering the losses in converters and other electronic elements, an additional and conservative 2% of losses was added to the round trip efficiency of each chemistry, since depending on the topology of electronic losses varies from 0.4% to 1.56% ^[93]. Using effective space for two racks and the battery cells inside each rack, the Li-ion parameters used in the analysis is shown in Table 31.

Table 31. Parameters for Li-ion energy storage system in a 20 ft container

Li-ion battery	Rated power (kW)	Energy capacity (kWh)	Total round trip efficiency (%)
LiFePO4	1285	1285	90
LiTiO	948	948	94

Source: ^[27]

Simulation results in HOMER are shown in Figure 39:

Figure 39. Variation of CO₂ emissions and total energy production using Lithium Titanate (LiTiO) and Lithium Iron Phosphate (LiFePO₄) batteries in a 20 ft container.

Source: 27

Both battery technologies presented reduction in the total CO₂ emissions from the PSV generators. Although LiFePO₄ system presents a higher reduction, both results are close with less than 0.5% of difference. Additional considerations should be taken into account when these two technologies are compared, such as maintenance and replacement cost.

5.2.6 Part of the mission and CO₂ emissions

In Figure 21 we can see variation of the demand for each part of the mission. We simulated four cases to evaluate CO₂ emissions independently. The simulated cases are:

- Diesel generators
- Diesel generators + battery
- Diesel generators + Diesel generators auxiliary
- Diesel generators + Diesel generators auxiliary + battery

Results are shown next in Figure 40:

Figure 40. Accumulated CO₂ emissions for the four simulated cases.

Source: [27]

From Figure 40 we can see that laden voyage and partial load voyage have the highest slope for CO₂ emissions, this means that these two sections have a great impact in the total CO₂ emissions. At the end, the fourth case (Diesel + batt + diesel aux) has the lowest CO₂ emissions.

Additional analysis for each part of the mission is presented in Figure 41, in this case we evaluate the reduction not accumulated but total for each part of the mission.

Figure 41. CO₂ emission reduction for each part of the mission

Source: [27]

The two parts of the mission with the lowest power demand also have the highest relative emission reduction (loading in port and standby). This can be attributed to the low point of operation of diesel generators during these periods. When generators are forced to operate at lower power levels, their efficiency is also lower. Having available energy storage increases the overall efficiency of the system since generators are forced to operate at higher efficiency levels to charge batteries and this energy can be used later without the need to connect an additional generator that could work at a low efficiency level.

An special case can be seen in the standby operation where the system with auxiliary generators and no batteries has lower CO₂ emissions when compared to the system diesel + battery.

Finally, during laden voyage and partial load voyage, diesel generators are operating close to their rated capacity. In this case generators are operating close to their optimal efficiency points, making energy storage to have lower impact in the CO₂ emissions reduction.

5.3 PARTIAL CONCLUSIONS

The impact of implementation of energy storage in platform supply vessels was evaluated, analyzing different elements of Li-ionn batteries such as roundtrip efficiency, battery capacity, battery C-rate, and minimum load level of diesel generators.

It was also evaluated the performance of lithium titanate and lithium iron phosphate batteries. For these cases, some considerations were followed in order to determine the available capacity to install in a 20 ft container which is a common container size used to implement energy storage in shipping.

Finally, an evaluation for each part of the mission was followed to analyze which part presents more emissions variation depending on the topology to be used, with batteries and auxiliary generators. To the author knowledge, not any other study has considered all these elements when evaluating energy storage and its impact in shipping.

6. CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

In this work a new methodology to evaluate the more attractive configurations of island power systems based on diesel generation, considering CO₂ emission and renewable energy penetration was proposed. The methodology allows the selection of a combination of photovoltaic, wind power generation and energy storage capacity to supply the electricity demand subjected to a required CO₂ emission or renewable penetration level.

An important feature of the methodology consists on the two-stage analysis. In the first one, a group of possible configurations that meet the requirements is selected and in the second one, the cost assessment is performed. As a result, in case the costs have changed after the study, the second stage allows updating the equipment costs without losing the selected configuration on the first part of the methodology.

In the first stage of the methodology, several scenarios are evaluated considering the objective defined (*e.g.* renewable penetration level, CO₂ emissions). These scenarios present combinations of photovoltaic, wind power and energy storage in order to meet the objective. In the second stage of the methodology, the total cost of the project is obtained, allowing the user to select the most suitable solution from the first stage. Additional parameters to determine variations in the total project cost such as battery aging and tax on CO₂ emissions, are considered also to expand the applicability of the methodology in real case scenarios.

A MatLab tool was developed to calculate the total project cost. This tool requires to have results obtained from HOMER software according to the modeling and methodology presented in this document.

The methodology was validated for two isolated power systems, an island power system and a platform supply vessel. For the island power system, multiple scenarios were analyzed considering wind and solar power and storage systems. For the platform, a methodology to model ship power systems and batteries was presented and elements such as battery round trip efficiency, rated capacity, C-rate were analyzed.

Further analysis of lithium titanate and lithium iron phosphate, permits to evaluate their impact in the reduction of CO₂ emissions. Also, an evaluation of emissions for each part of the mission for the platform supply vessel serves to determine in which parts, energy storage has higher.

6.2 FUTURE WORK

Analysis of ship power systems using batteries has potential to be a wide area of research, investigations related to this topic are starting to be more frequent. Additional analysis considering more load missions profiles can increase the real scope of the proposed solutions, not only for this work but also for other works found in the related literature. Other parameters that have interesting impacts to be analyzed are efficiencies of diesel generators, customization on the operation time at which batteries can be connected.

When the energetic results (fuel consumption, energy generated, CO₂ emissions) are available, the methodology applied to island power systems can be easily applied, it is recommended to develop a web-based script where the user can change parameters and calculate total project cost under considerations similar to the proposed in the document. Additional refinements to the evaluation are the implementation of thermal effect on the expected battery life, energy demand growth, changes in the available renewable resources per year.

Published Works on conferences:

C. O. Peralta and M. B. C. Salles, "Advanced energy storage systems to increase the penetration of renewable energies in Fernando de Noronha Island," in 2017 6th International Conference on Clean Electrical Power (ICCEP), Santa Margherita Ligure, Italy, 2017.

G. T. T. Vieira ; C. O. Peralta ; M. B. C. Salles ; B. S. Carmo, "Reduction of CO₂ emissions in ships with advanced Energy Storage Systems" in 2017 6th International Conference on Clean Electrical Power (ICCEP) , Santa Margherita Ligure, Italy, 2017.

Vale, R. J., Peralta, C. O., Vieira, G. T. T., Salles, M. B. C., & Carmo, B. S. (2018, October). Assessment of CO₂ Emissions on Platform Supply Vessels for Distinct Battery Dispatch. In 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA) (pp. 1287-1291). IEEE.

Published Work on journal:

Peralta, P., César, O., Vieira, G. T., Meunier, S., Vale, R. J., Salles, M. B., & Carmo, B. S. (2019). Evaluation of the CO₂ Emissions Reduction Potential of Li-ion Batteries in Ship Power Systems. *Energies*, 12(3), 375.

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