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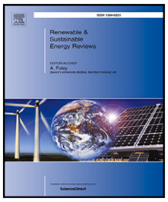

The carbon footprint of island grids with lithium-ion battery systems: An analysis based on levelized emissions of energy supply

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ABSTRACT

Electrical energy storage systems are key to the integration of intermittent renewable energy technologies such as photovoltaic solar systems and wind turbines. As installed battery energy storage system capacities rise, it is crucial that the environmental impacts of these systems are also positive. In this work, a methodology to ascertain the effect and effectiveness of integration of energy storage on the carbon footprint of isolated island grid energy systems and its reduction is presented. Two metrics are introduced — the Levelized Emissions of Energy Supply (LEES), and the reduction in emissions per additional unit of energy storage (R). The proposed methodology is applied to an island grid scenario to ascertain the variation in the LEES value with the peak power and energy storage capacity of the BESS. A simplified LCA of a utility-scale Lithium-ion BESS is also carried out for this purpose. It is found that for the considered scenarios, incorporation of battery systems is always effective in reducing emissions, with a maximum possible reduction of nearly 50% compared to no storage. With the help of the metric R, the proposed methodology is also useful in identifying isolated energy systems which should be prioritized for incorporation of additional energy storage capacity.

1. Introduction

The global shift from fossil-based energy sources toward clean energy produced by renewable energy sources is now well underway with installed renewable generation capacity worldwide, having more than doubled in the last decade of 2010–19, standing at an impressive 2, 532, 866 MW at the end of 2019 [1]. As the share of installed capacities of intermittent power generators such as PV and WTs in the global energy system rises, provisioning of measures to ensure quality and security of energy supply at a larger scale becomes inevitable. These measures include time-shifting of renewable energy generation — ensuring supply in times of generation shortfalls, mitigating excessive power flows in places with weak grid infrastructure, and containing the frequency and voltage fluctuations in the electricity grid to within the stipulated tolerances [2].

The energy sector, as a whole, is the single largest emitter of GHG in the world [3]. In isolated island grid energy systems, conventional power generation technologies, such as DGs and gas turbines are the major source of GHG emissions [4]. The environmental impact of techno-economically feasible energy storage technologies, which have the potential for large-scale adoption, should be diligently investigated. Electrochemical energy storage systems, such as Battery Energy Storage Systems (BESSs), are already the leading energy storage technology class in terms of the number of projects installed worldwide [5]. It is worth noting that there exists economic potential for the deployment of electrical energy storage systems to provide services in several applications [6]. A thorough analysis of these systems should hence be carried out in order to ensure that the base rationale behind the system installation — which is to enable the energy system to operate at lower emission levels, is not inadvertently defeated. Most prevalent performance assessment methodologies focus on techno-economic evaluation of energy storage systems, and the environmental aspects thereof do not play a central role in the decision process. This observation is corroborated by Pellow et al. [7]. The probable factors which explain this tendency have been identified — the complexity associated with the meticulous tracing of material, energy, and emissions streams while carrying out a Life Cycle Analysis (LCA), and the availability of reliable and sufficiently detailed Life Cycle Analysis (LCA) data (particularly primary data) in the public domain. Few et al. report that experts themselves express low confidence in carrying out environmental and energetic analyses of the processes for battery production and decommissioning. They also identify this area as one in need of greater focus within the scientific community [8].

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Abbreviations

BESS	Battery Energy Storage System.
CO_2eq	Carbon Dioxide equivalent.
DG	Diesel Generator.
DOD	Depth of Discharge.
ECM	Equivalent Circuit Model.
EFC	Equivalent Full Cycles.
EMS	Energy Management System.
EOL	End-of-Life.
EPR	Energy-to-Power Ratio.
ESN	Energy System Network (Simulation Tool).
FU	Functional Unit.
GHG	Greenhouse Gases.
GWP	Global Warming Potential.
HVAC	Heating, Ventilation, Air Conditioning.
LCA	Life Cycle Analysis.
LEES	Levelized Emissions of Energy Supply.
LFP	Lithium Iron Phosphate.
OCV	Open Circuit Voltage.
PV	Photovoltaic Solar.
SimSES	Simulation of Stationary Energy Storage Systems (Simulation Tool).
SOC	State of Charge.
SOH	State of Health.
VRFB	Vanadium Redox Flow Batteries.
WT	Wind Turbine.

Parameters

C_n	Installed Energy Storage Capacity in Energy System Configuration *n*.
E_{BESS}	Rated BESS Energy Capacity.
$E_{load\ center,a}$	Total Useful Energy at Load Center *a* years.
P_{PV}	Photovoltaic Solar Power Generation.
P_{WT}	Wind Turbine Power Generation.
P_{BESS}	Rated BESS Peak Power.
P_{load}	Load Power.
$P_{residual}$	Residual Power.
$R^{unit\ storage}_{n,n-1}$	Reduction in System Emissions per Additional Unit of Energy Storage Capacity.
ϵ_{EOL}	End-of-Life Phase Emissions.
$\epsilon_{op,a}$	Operation Phase Emissions *a* years
ϵ_{prod}	Production Phase Emissions.

A review of existing literature in this area has been conducted to examine the existing metrics and environmental performance evaluation methodologies in the context of decarbonization. Some of the findings are discussed in the following paragraphs.

The *time to ecological amortization* of an energy storage technology is the time required for a cumulative energy equal to its embodied energy footprint to be discharged from it [9]. The *Energy Stored on Energy Invested (ESOI)* is defined as the ratio of the amount of energy stored over the lifetime of an energy storage technology and the energy required to produce it [10]. The *Energy Return on Energy Invested (EROI)* metric from the *Net Energy Analysis* concept can also be modified to incorporate the analysis of energy storage [11]. The *Life Cycle Greenhouse Gas Emissions*, which is the emissions analog of the Levelized Cost of Energy Storage (LCOS), can be used to quantify the GHG emissions per kWh of energy stored by the system, calculated over its entire lifetime [12]. These metrics are applicable to the energy storage system level, and are ideal to compare two competing technologies, but do not capture the effect of the energy storage technology on the net energy system emissions. Metrics and evaluation methodologies applicable at the energy system level are required to study decarbonization of energy systems.

Energy storage technologies such as BESSs, when deployed to provide grid-services in grids with large conventional generation capacities (i.e. high carbon intensities), lead to higher energy input and net energy systems emissions as compared to existing solutions due to the energetic losses [13]. Energy storage technologies, when used to replace conventional generation technologies for the provision of a grid-related service, may in some cases lower the net energy system emissions [14], especially if the grid carbon intensity is low, indicating high shares of renewable generation capacities and curtailment [15,16]. These outcomes are also highly dependent on the round-trip efficiency of the energy storage technology and its lifetime in addition to the factors mentioned earlier [17]. The boundaries for analysis also ostensibly influence this inference. Charging the energy storage directly instead of feeding-back the energy into the grid is detrimental to the reduction in net energy system emissions, as a greater amount of energy is lost due to losses. Charging on energy which could otherwise be curtailed is the most beneficial [18,19].

This work restricts itself to the evaluation of the environmental performance of lithium-ion BESSs providing renewable time-shifting services in isolated island grid energy systems. Time-shifting of renewable energy generation in large grids with energy storage is subject to the inferences discussed above. Renewable time-shifting is particularly crucial in isolated island grid energy systems. Incorporation of energy storage in isolated island grid with high shares of renewable generation capacities and conventional backup power generation always results in a reduction in the net energy system emissions by partially displacing the conventional power generation from the energy mix. This finding holds true for Vanadium Redox Flow Batteries (VRFB) [20], as well as for lithium-ion BESSs [4]. The present work builds upon existing literature in this area by presenting a holistic evaluation methodology, which enables the comparison of the effectiveness of various energy storage configurations in reducing the net emissions in island grid energy systems. This work is also able to confirm results presented in the reviewed literature sources.

The prominent questions which arise in the context of carrying out such evaluations are:

1. How large are the GHG emission footprints for the production, operation, and decommissioning of lithium-ion BESSs?
2. How effective are lithium-ion BESSs at reducing the net GHG emissions of the island grid energy system?
3. What energy storage capacities ought to be installed to maximize the reduction in emissions, and to justify the resources invested?

Addressing the first question is an indispensable step, and is specific to the scenario and energy storage technology under consideration. presents a simplified LCA for a utility-scale lithium-ion BESS. The impact category Global Warming Potential (GWP) is used throughout this work to quantify the carbon footprint of technologies and the entire energy system. The results from this analysis are used in the simulative analyses carried out in the subsequent sections. To answer the second question, a performance evaluation methodology is presented in Section 2.1. The proposed methodology introduces two metrics — the first metric *Levelized Emissions of Energy Supply (LEES)* fixes an emissions value for every unit of useful energy supplied by the energy system to its load center. The second metric $R^{unit\ storage}_{n,n-1}$ denotes the reduction in energy system emissions per additional unit of energy storage capacity. These metrics enable the third question to be addressed in a quantifiable manner. As the research questions raised are relevant to a wide range of scenarios and energy storage technologies, the methodology is also correspondingly general enough. The methodology is demonstrated through simulative analyses in the context of provision of renewable energy time-shifting services in isolated island grid energy systems with lithium-ion BESSs. The simulation results are discussed in Section 3. The emissions of the island grid energy system, the energetic behavior of the energy system, the effect on the BESS, and the influence of other parameters on the LEES are examined. Section 4 summarizes the major conclusions and achievements of this work. The limitations and the future outlook of this work are also touched upon.

2. Methods

Section 2.1 describes the proposed methodology and the two metrics, which are key features of this performance evaluation methodology. Section 2.2 discusses the modeling procedure for the island grid, the Lithium-ion BESS, and the power generation components. The calculation procedure for the indirect and direct GHG emissions for the components in the island grid energy system is presented in Section 2.3.

2.1. Proposed methodology for evaluation of impact of energy storage on system emissions

BESSs, like PV panels and WTs, belong to a class of technologies which cause almost no direct emissions during operation, but whose production and decommissioning at the end of life can cause substantial emissions. The GWP footprint of generated energy consists of two components, one – a fixed component dependent on the production and decommissioning processes for the components in the energy system, and the other – an operation-dependent component. A carbon intensity calculation based solely on the operation-dependent emissions, as is currently the case [21], risks completely overlooking the emissions impact of PV and WT installations on power generation, as the operation-dependent component is negligible in this case. Incorporation of a BESS into the system leads to a further uncertainty in accounting of emissions, as this is neither a power generation technology, nor is it directly responsible for emissions during operation. In cases wherein the input energy to a BESS has an operation-dependent component in its footprint, additional emissions can be attributed to the BESS on account of energy lost in the conversion processes. For an island grid system without a conventional grid connection, once the production and decommissioning emissions for PV panels, WTs, and BESS, which is charged by surplus renewable energy, is taken into account, the operation-dependent emissions emanate from the DG alone, that steps in every now and then to cover load which the renewable generators and the BESS are unable to cover.

For energy systems with predominantly renewable power generation, such as solar PV and WTs with fluctuating power generation, not all power produced can be put to use at all instants of time. The generators can also not be relied upon to be able to supply sufficient power at all instants. This leads us to the concept of *useful energy* which is actually supplied to the load centers. This section outlines a modified methodology to obtain the resultant carbon intensity for the energy supplied by an energy system with a high share of renewable energy generators, energy storage and some conventional generation as backup. Production of PV panels, WTs, and BESS components is highly energy-intensive, resulting in substantial emissions, which makes the inclusion of this phase highly relevant. The process for determination of electrical energy storage system capacity ranges with the highest impact on emissions reduction is also explained briefly. The steps outlined in this methodology can be applied to any energy storage technology providing a similar service in a comparable use-case.

2.1.1. Levelized Emissions of Energy Supply (LEES) : A modified carbon intensity measure for energy systems

The *Levelized Emissions of Energy Supply (LEES)* is formulated and defined in this section for use in the proposed methodology. The *LEES* metric takes into account direct and indirect emissions within an energy supply system. Additionally, this metric is based on the *useful energy* supplied by the power generators plus supporting components such as energy storage (if present) to the load centers rather than the energy generated (see Fig. 1). In an isolated energy system with predominantly renewable generators, the losses due to energy conversion in the BESS do not result in any additional emissions in the operations phase, as the BESS is charged with renewable energy sources exclusively, and the emissions in the production and decommissioning phase for the renewable generators are explicitly factored in. This metric, *LEES*, fixes an emission value (in $\mathrm{kg\ CO_2eq}$) to each unit (kWh) of useful energy supplied by the energy system to its load center over a pre-defined period of time. It is mathematically defined in Eq. (1).

$$LEES = \frac{\Sigma\varepsilon_{prod} + \Sigma\varepsilon_{op,a} + \Sigma\varepsilon_{EOL}}{E_{load\ center,a}} \tag{1}$$

where:

$\Sigma\epsilon_{\mathrm{prod}}$ denotes the sum total of the emissions entailed on account of production of all components included in the energy system

$\Sigma\epsilon_{\mathrm{op,a}}$ denotes the emissions entailed on account of operating all the components making up the energy system during the considered simulation period of *a* years

$\Sigma\epsilon_{\mathrm{EOL}}$ denotes the sum total of the emissions entailed on account of EOL treatments for all the components making up the energy system

$\mathrm{E_{load\ center,a}}$ denotes the total useful energy supplied by the system to the load center over the simulation period of *a* years

The values of ε_{prod} and ε_{EOL} for each component are a fraction of the total production and EOL emissions if the component does not reach the end of its estimated/projected service life at the end of the simulation period. The value of the fraction is obtained from aging/degradation models or from lifetime estimates, and is equal to the ratio of the utilized service capacity/metric to the estimated/projected service capacity/metric. In the case of lithium-ion BESSs, this fraction can be conveniently based on the State of Health (SOH) metric. Other ways of assigning emissions to the simulation period may also be possible.

Some key features of the Levelized Emissions of Energy Supply (LEES) metric:

- *Zero load-shedding condition:* The metric is calculated under the constraint of zero load-shedding — i.e. power supplied by the generation and storage equipment together must, at least, be equal to the demand at all instants of time
- *Internalization of losses:* All energetic losses in the energy system, such as curtailment, generation and transmission losses, and losses on account of energy storage operation are lumped together and internalized in the metric. The useful energy, which is considered for the calculation is directly affected by any changes in these loss mechanisms. These losses are directly reflected in the LEES value, with higher losses reflecting in a higher value of LEES, and vice-versa
- *Identification of sub-optimal sizing:* Sub-optimally sized systems can also be identified, if a change in system sizing is found to fulfill the zero load-shedding condition at a lower LEES value

Once the value of LEES for a particular system configuration is obtained, the manner of its variation with system configuration can be examined. We are primarily interested in the impact of energy storage capacities on our stated goal of emissions reduction. The steps involved in such an analysis are depicted in Fig. 2. In the backdrop of limited resources, a method to be able to quantify this impact for every unit of monetary and material investment made is an absolute necessity.

2.1.2. Reduction in system emissions per additional unit of energy storage capacity

The *Reduction in system emissions per additional unit of energy storage capacity* $\mathrm{R_{n,n-1}^{unit\ storage}}$ is defined as the ratio of reduction in the LEES value

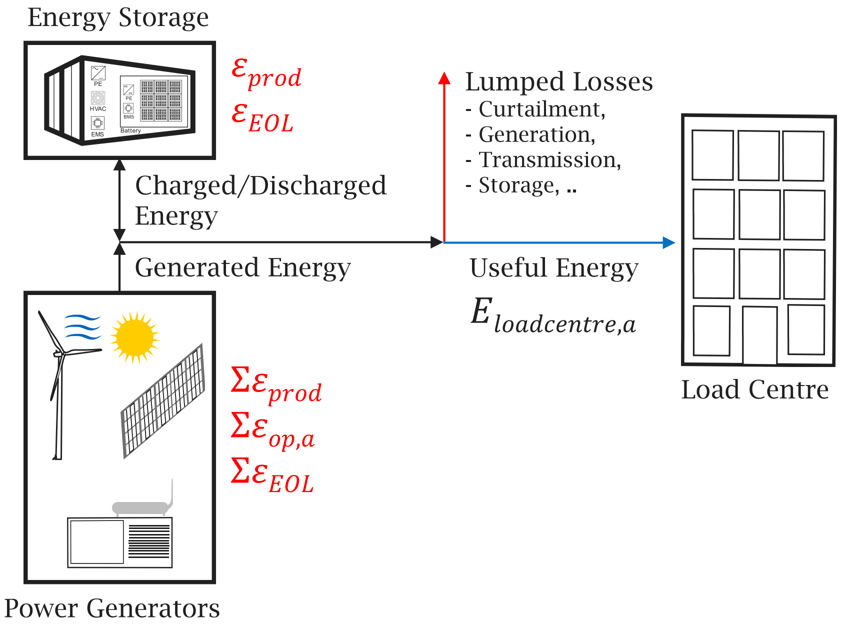

Fig. 1. Depiction of the lumped losses, and the useful energy supplied to the load center.

per additional unit of energy storage with respect to that of a previous configuration. It is mathematically defined as:

$$R_{n,n-1}^{unit\ storage} = \frac{\Delta LEES_{n,n-1}}{(C_n - C_{n-1})} \tag{2}$$

where:

ΔLEES$_{n,n-1}$ denotes difference in LEES values of system configurations n and n-1, wherein configuration n has a larger energy storage capacity.

C$_n$ denotes the energy storage capacity for system configuration n, $C_n > C_{n-1}$.

The reciprocal of $\mathrm{R}_{\mathrm{n,n-1}}^{\mathrm{unit\ storage}}$ is the *Energy Storage Capacity per Unit Reduction in System Emissions*, which is defined as the ratio of the additional energy storage capacity required to bring about a unit reduction in the LEES value with respect to that of a previous configuration.

Identification of capacity ranges exhibiting the highest environmental benefits is possible using the metric $\mathrm{R}_{\mathrm{n,n-1}}^{\mathrm{unit\ storage}}$. Large negative values signify high emissions reduction potential, whereas positive values indicate a worse configuration with respect to the previous configuration. This metric is thus, a complementary metric to the LEES in analyses of total emissions in island grid energy systems, and can aid in obtaining the best return in terms of emissions reduction for the invested resources.

2.2. Modeling: island grid energy system and components

The modeling and simulation of the system is carried out with two python-based simulation tools - *Energy System Network (Simulation Tool) (ESN)*, and *Simulation of Stationary Energy Storage Systems (Simulation Tool) (SimSES)*[1] [22]. Both the tools have been developed in-house. The tool Energy System Network (Simulation Tool) (ESN) is capable of modeling and simulating several user-defined energy system configurations and scenarios. In scenarios which include energy storage systems, ESN operates in conjunction with the tool Simulation of Stationary Energy Storage Systems (Simulation Tool) (SimSES), which can model and simulate the electro-thermal behavior of BESSs in a very detailed fashion. The degradation of the Lithium-ion cells under operation in the given load scenario is also considered.

Table 1
Island grid system simulation parameters.

	Parameter	Value
Simulation	Sample time (s) Duration of simulation (years)	900 20
Load	Annual load (MWh) Peak load (MW) Minimum load (MW) Mean load (MW) Peak residual load (MW)	10 000 1.59 0.72 1.14 1.59
Wind	Installed capacity Wind Turbines (WTs) (MW$_p$) Capacity factor (%)	3.25 26.62
Photovoltaic Solar (PV)	Installed capacity Photovoltaic Solar (PV) (MW$_p$) Capacity factor (%)	2.00 22.65
Diesel Generator (DG)	Rated power (MW)	1.60

The energy system considered consists of Wind Turbine (WT) and Photovoltaic Solar (PV) generators as the sources of primary energy. A Diesel Generator (DG) picks up the slack when renewable generation is inadequate. Excess generation from the renewable power generators is simply curtailed. This configuration represents the base case. The load and renewable energy generation curves are based on those of Tenerife, the largest of the Canary islands, situated off the northwest coast of Africa in the Atlantic ocean. The annual load and renewable energy generation time series have been normalized and used for this study. The profiles are available on the website of the utility company serving these areas [23]. Values for the year 2016 are used in this study. The hypothetical island system differs from the original energy supply system of Tenerife in several respects. Firstly, the system is largely down-scaled, and secondly, the proportions and types of various generators in the system have been altered. The configuration of this hypothetical energy system is presented in Table 1.

The influence of integration of a BESS into this hypothetical island grid is then investigated. The island grid can be understood to consist of the components depicted in Fig. 1. The methodology for the calculation of the LEES metric, which was presented earlier in Section 2.1.1, is applied to a hypothetical island grid system in this section.

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[1] SimSES open-source code repository: https://gitlab.lrz.de/open-ees-ses/simses

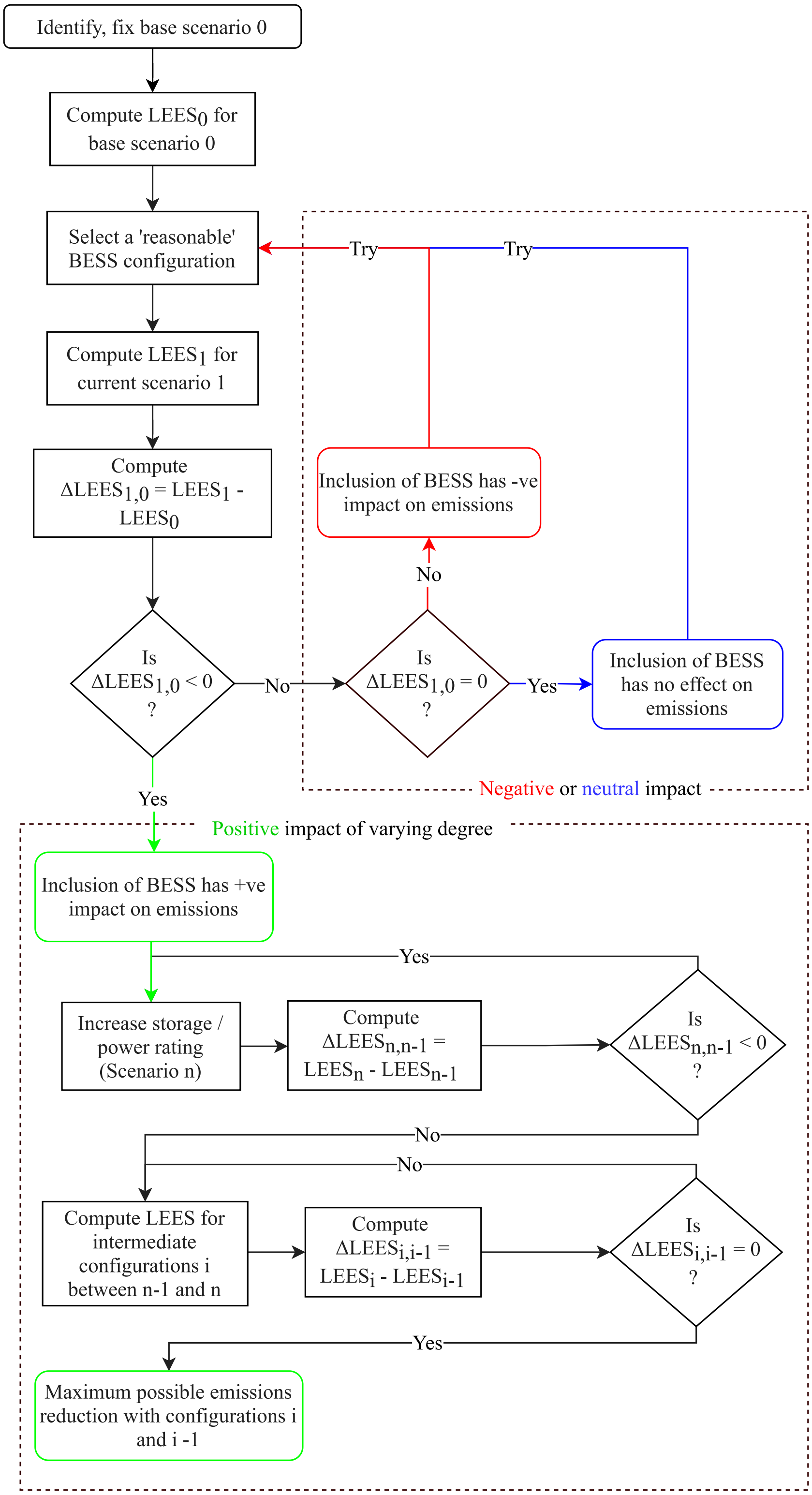


Fig. 2. Process flowchart outlining the steps involved in conducting a Levelized Emissions of Energy Supply (LEES) analysis for an isolated energy system. *+ve* stands for positive, and *-ve* stands for negative. The choice of a 'reasonable' Battery Energy Storage System (BESS) configuration is arrived at by conducting a sizing exercise based on the application requirements for performance indicators, such as the fulfillment ratio.

2.2.1. Energy management

A simple rule-based operating strategy implemented in ESN, termed 'Simple Deficit Coverage', is utilized to simulate the interplay between the operations of the BESS and the DG. The residual load at each instant of time is defined as the difference between the sum of power generation from the renewable generators and the load. The residual load at each time-step is then represented as:

$$P_{residual} = (P_{PV} + P_{WT}) - P_{load} \tag{3}$$

where:

$P_{residual}$ denotes the residual power, at each time-step
P_{PV} denotes the generation from the PV installation

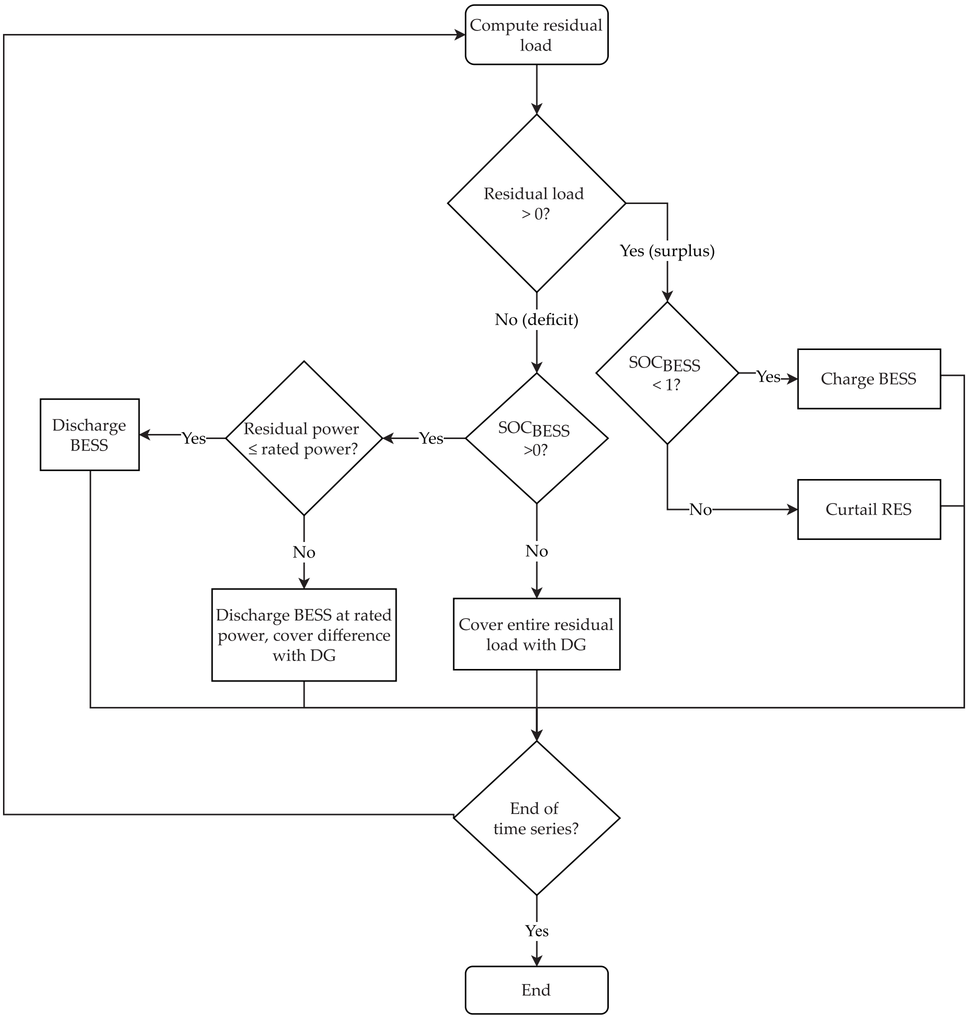


Fig. 3. Rule-based operating strategy for the Battery Energy Storage System (BESS) and the Diesel Generator (DG) operating in tandem to cover the load in the absence of sufficient renewable power generation.

P_{WT} denotes the generation from the WT installation

P_{load} denotes the load power

This rule-based Energy Management System (EMS) deploys the BESS as frequently as possible to cover the residual load (Eq. (3)), which the PV and WT generators are unable to cover. In the event that the BESS is incapable of covering the residual load, owing to power or energy constraints, the DG is brought online to cover the deficit. The BESS is charged exclusively with surplus generation from the PV and WT installations. This rule-based decision-making algorithm is depicted in Fig. 3.

2.2.2. *Component models*

The power generation, storage, and load components present in the energy system are simulated based on models found in literature. The models for the PV and WT generators are relatively simple, and the values of power generation are directly based on their generation profiles. Similarly, the load is also modeled as a demand profile. The models for the BESS and the DG are modeled to a much greater level of detail. These are described in the following subsections.

Battery Energy Storage System (BESS)

The BESS model is based on a 'R-int', or internal resistance Equivalent Circuit Model (ECM), which consists of a voltage source in series with an ohmic resistance. The values of both the voltage of the source and the ohmic resistance at any instant of time are dependent on the State of Charge (SOC) at any particular instant. The model has been parameterized based on experimental data from a commercial 'new' Lithium Iron Phosphate (LFP) cylindrical 26650 cell (see Fig. 4) [24,25]. The State of Health (SOH) is defined as the ratio of the cell's charge capacity in 'new' condition to its charge capacity at any later point in time. At an SOH value of 80%, the cell is said to have reached its End-of-Life (EOL). As the sample time and simulation duration of the time series analysis simulations is 15 min and 20 years respectively, the R-int ECM representation of the battery is adequate in light of simulation speed and desired detail of simulation results. The degradation model for the Lithium Iron Phosphate (LFP) cells is semi-empirical in nature, and is based on extensive aging tests for calendric and cyclic degradation carried out in-house [26,27]. The models for the BESS subcomponents, such as for the battery, power electronics, are all modeled in *SimSES*. The model for the AC/DC converter efficiency is based on a model found in literature [28]. The BESS is assumed to operate under a constant ambient temperature of 298.15 K, and the thermal behavior thereof is not considered in this paper (see Table 2).

Diesel Generator (DG)

The model of the DG is based on a model found in published literature [29]. This model estimates part-load DG efficiencies for a range of power values below its rated peak power. Based on the electricity generated, this model permits the calculation of fuel consumption and the corresponding emissions on account of fuel combustion for

Table 2
Battery Energy Storage System (BESS) parameters for the R-int Equivalent Circuit Model (ECM) model used.

	Parameter	Value
BESS	Battery type	Lithium Iron Phosphate (LFP)
	Battery format	Cylindrical, 26 650
	Rated energy capacity (MWh)	0.1 - 192
	Rated power (MW)	0.1 - 1.6
	Initial State of Charge (SOC)	0%
	Initial State of Health (SOH)	100%
	End-of-Life (EOL) SOH criterion	80%
	Battery model	R-int ECM (based on [24,25])
	Aging model	Semi-empirical calendric and cyclic (based on [26,27])

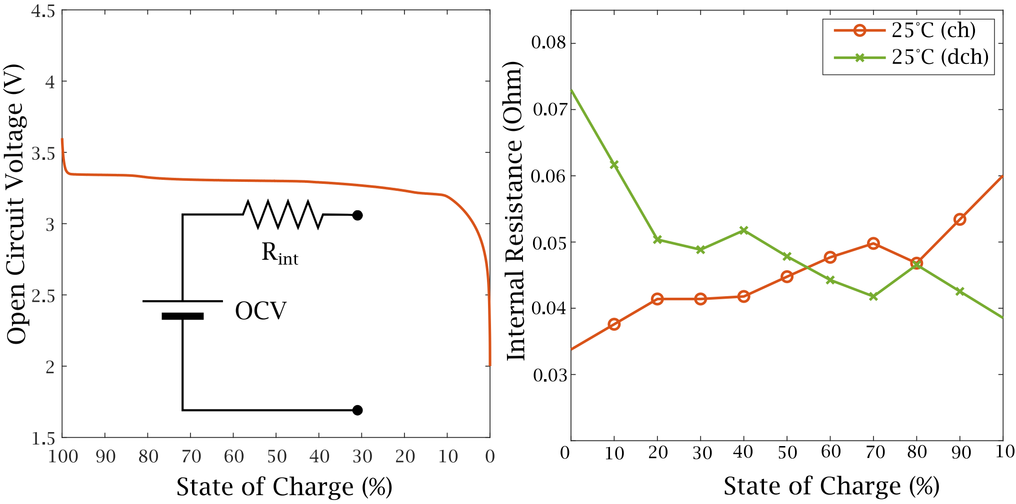


Fig. 4. Open Circuit Voltage (OCV) curve vs. State of Charge (SOC) for the considered Lithium Iron Phosphate (LFP) cell (left), and the R-int Equivalent Circuit Model (ECM) (inset, left). Values of the charging (ch) and discharging (dch) internal resistance versus the SOC for the considered cell type (right).

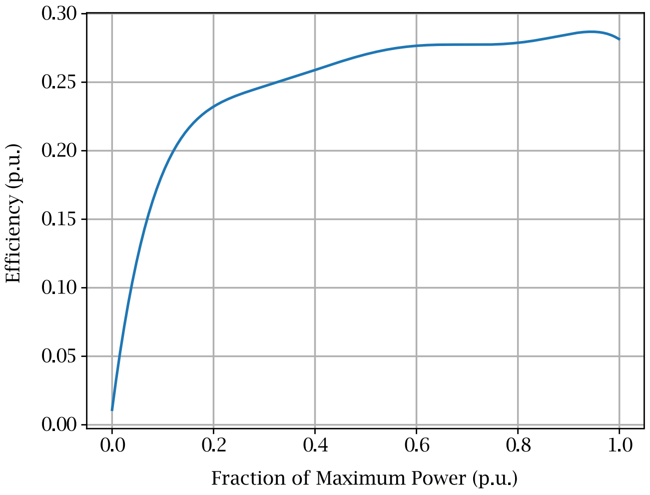


Fig. 5. Efficiency curve with respect to the normalized power for the Diesel Generator (DG) model .
Source: Based on [29].

each time step. The efficiency curve for the DG with respect to the normalized power is depicted in Fig. 5.

2.3. Modeling of Greenhouse Gases (GHG) emissions

Indirect emissions associated with the major components relevant for this study — the BESS and its sub-components, the PV and WT installations, and the DG, have been determined from various literature sources , which were reviewed during the course of this study. The only source of direct emissions is the DG, which emits GHGs as a by-product of the combustion process. Except for the PV panels, whose production emissions can be scaled up linearly with power owing to the visibly modular nature of the technology, the values for WTs and the DG are non-linear. A more rigorous treatment with regards to this feature of the data is beyond the scope of this work, and the values taken here are representative, and are not applicable to WTs and DGs of all sizes, as the specific production emissions (in $\mathrm{kg\ CO_2eq/kW}$) for large systems are not identical to those for small systems. The reader is requested to bear in mind that the presented analysis can be thought of as a simplified LCA at best, as it is neither based on primary data, nor is it as comprehensive as a full-fledged LCA can be expected to be as per the ISO standards 14040, 14041, 14042, and 14043. But, it is deemed to be sufficient for the purpose of this work, wherein the focus lies on the *LEES* methodology presented, and not on the LCA itself.

Battery Energy Storage System (BESS)

An in-house experimental container BESS is studied, and a simplified LCA has been carried out based on this system as a reference point [30]. The production and EOL phase emissions for its components have been obtained from published literature sources. An overview of the lifecycle phases for a utility-scale container BESS is depicted in Fig. 6.

For the considered LFP cell technology, the GHG emissions in the production phase for the Functional Unit (FU) kWh of energy storage capacity, amount to around $161\,\mathrm{kg\ CO_2eq/kWh}$ on average [31]. The GWP impact of the EOL phase for the processing of each kWh

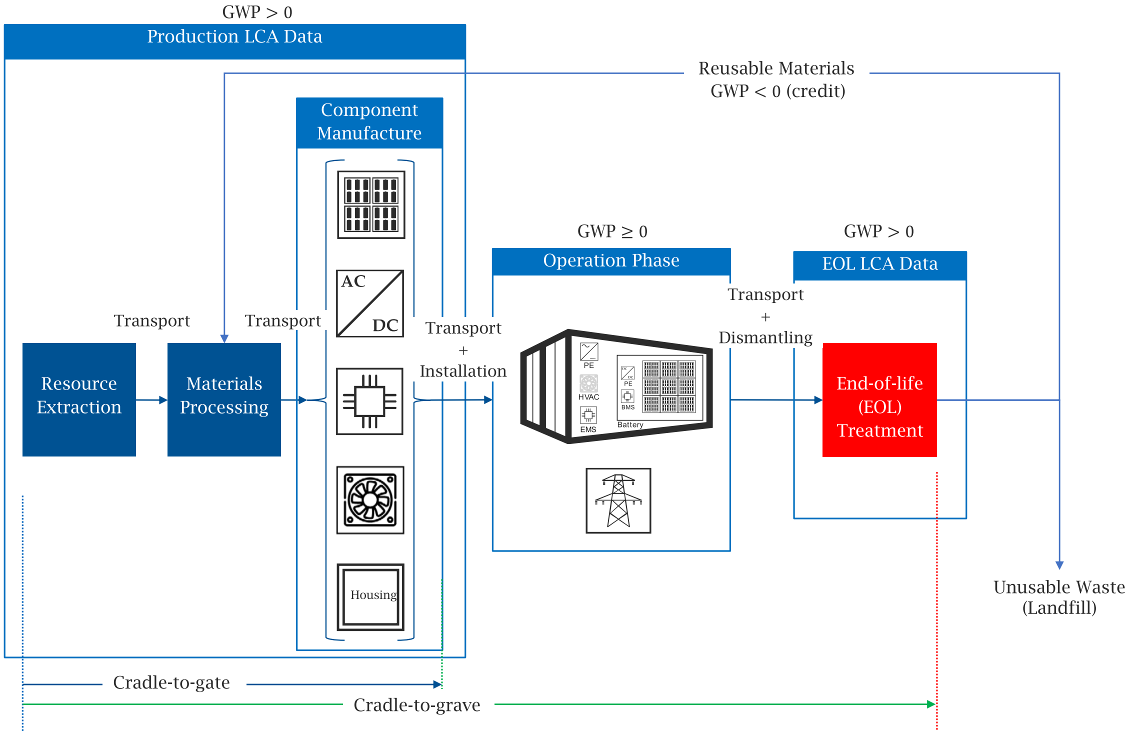


Fig. 6. Overview of lifecycle phases of a container utility-scale Battery Energy Storage System (BESS). The impact factor category Global Warming Potential (GWP) is considered.

of LFP cells varies from 0.45 kg of additional emissions for the pyrometallurgical process to −11.70 kg of reduction in emissions for the advanced hydrometallurgical process [32]. We consider the advanced hydrometallurgical process in the current analysis , which represents an optimistic scenario.

The carbon footprint of the production phase for each Functional Unit (FU) (kW of power conversion capability) of the power electronics is non-linearly dependent on the power rating, as the power density of these devices increases non-linearly with the power. Based on multiple literature sources, including the *Ecoinvent* database, a function to determine the GWP footprint for a functional unit of 1 kW has been obtained [33–35]. The EOL phase for electronics components, for optimal recycling, results in a reduction in the overall emissions to the tune of −9.45 kg CO_2eq/kW assuming an average power density of 1000 W/kg for the power electronics [36].

For the peripheral electronic components such as circuit breakers, relays, monitoring equipment, and other circuitry in the considered experimental BESS, based on values from the *Ecoinvent* database,it can be expected that these components make up around 7% of total production emissions [33]. The EOL phase is understood to result in reduced emissions overall on account of effective recycling. The resultant emissions reductions, for lack of better data, are assumed to be comparable to those for the power electronics at around −14.49% of production emissions [36].

For utility-scale BESSs, a standard shipping container is generally used to house all the components. Production of a 20 ft steel container with a mass of around 2400 kg is estimated to emit around 15 720 kg CO_2eq [33]. With the understanding that shipping containers are constructed from abundant materials such as steel, and other metals, which are already largely recycled, no additional emissions or emissions reductions are allocated to the EOL phase. With a preliminary estimate that 20% of a container's volume may be occupied by the cells, around 1600 kW h of LFP cells with a specific volumetric density of 278 kWh/m^3 may be installed in one such container [2].

The production of the Heating, Ventilation, Air Conditioning (HVAC) system is estimated to cause around 426.16 kg CO_2eq of emissions for the floor area of the 20 ft standard shipping container [37]. Similar to the Housing, the EOL phase for the HVAC components is assumed to cause no additional emissions, due to the ubiquitous materials used therein.

Table 3
Production and End-of-Life (EOL) phase emissions for a container Battery Energy Storage System (BESS) with a rating of 1 MW/1 MW h in kg CO_2eq.

Component	Production	EOL	Net
Cells	161 000	−11 700	149 300
Power Electronics	28 170	−9450	18 720
Housing (20 ft. Container)	15 720	0	15 720
Misc. Electronics	15 454	−2239	13 215
Heating, Ventilation, Air Conditioning (HVAC)	426	0	426
Total (kg CO_2eq)	220 770	−23 389	**197 381**

Based on the values presented in this section, the net emissions of a BESS for any given rating for the two lifecycle phases of production and EOL may be roughly estimated. As an example, the emissions of a system with a power/energy rating of 1 MW/1 MW h is presented in Table 3. One 20 ft container is used to house all the components, including the LFP cells. The power electronics consist of two inverters of 500 kW each.

Photovoltaic Solar (PV)

For the production of PV panels, assuming an average grid carbon intensity of 500 g CO_2eq/kWh for each kW h of electrical energy consumed in the production processes, an average emissions value of 1100 g CO_2eq per Functional Unit (FU) (kW_p (peak power)) of PV generation capacity is obtained for crystalline Silicon modules, averaged over multiple energy efficiencies [38]. The EOL treatment of PV panels is understood to cause net emissions of 7.40 kg CO_2eq/kW_p. This value is calculated by combining the GWP value for the recycling process from a published research article [39] with the value of power density for PV panels obtained from another literature source [40]. This analysis, for the sake of simplicity, solely considers the PV panels themselves, and not other auxiliary components such as the power electronics.

Table 4
Indirect and direct emissions for other island grid energy system components for the production and EOL lifecycle phases.

	Parameter	Value
Photovoltaic Solar (PV) Panels	Production emissions (kg CO_2eq/kW$_p$)	1100.00 [38]
	EOL emissions (kg CO_2eq/kW$_p$)	7.40 [39]
Wind Turbine (WT)	Production emissions (kg CO_2eq/kW)	683.70 [41]
	EOL emissions (kg CO_2eq/kW)	−227.90 [41]
Diesel Generator (DG)	Production emissions (kg CO_2eq/kW)	47.84 [42]
	Diesel combustion emissions (kg CO2/liter)	2.63 [43]
	Diesel upstream emissions (kg CO_2eq/liter)	0.53 [43]
	EOL emissions (kg CO_2eq/kW)	0

Wind Turbine (WT)

Owing to the non-linear behavior of the power scaling with respect to the materials used in a WT, the production emissions per FU (kW of power generation capacity) are strictly valid only in the neighborhood of the original data point. For the considered WT power rating of 3.25 MW, this value is determined from a publicly available LCA report for a WT of a comparable power rating [41]. The production GWP footprint for the WT in the current analysis is estimated to be around 683.70 kg CO_2eq/kW. The recycling and EOL treatments cause a reduction of 227.90 kg CO_2eq/kW, thereby improving the lifetime GWP of the technology.

Diesel Generator (DG)

The production emissions for an exemplary DG are obtained from the Ecoinvent database, and similar to the WT, are not as readily scalable [33]. A value of 47.84 kg CO_2eq per FU (kW of power generation capacity) is determined and used in this study. The GWP impact of the EOL process for the DG, which largely contains abundant metals such as Iron and Aluminum, is assumed to be negligibly low, and is subsequently not considered. The direct emissions due to combustion of diesel are obtained for each time step with the help of theDG model explained in .

The values of the indirect and direct emissions for all components used in the simulations are tabulated in Table 4.

3. Simulation and discussion of results

The island grid energy system is simulated for a variety of scenarios with variations in the BESS parameters. A parameter sweep is carried out by varying the rated energy capacity and peak power of the BESS to investigate the influence of the integration of energy storage into the energy system. The system operation and the energy flows are governed by the operating strategy discussed earlier (Fig. 3). Transmission losses and energy conversion losses in the PV and WT installations, which are not modeled in the current work, are disregarded. If modeled, however, additional loss mechanisms could easily be incorporated within the analysis, and will be reflected in a higher value of the LEES metric. The power generation components such as the PV panels, the WT, and the DG are considered to have a service lifetime of 20 years, after which they are decommissioned [44,45]. The base case does not include a BESS. The LEES value of the base case (without energy storage) over a period of 20 years is 0.5450 kg CO_2eq/kWh. The energy flows in the base case are depicted in Fig. 7.

To concisely capture the information contained in the parameter variation, we make use of the term *Energy-to-Power Ratio (EPR)*. The EPR is defined as the ratio of the rated energy capacity (E_{BESS} to the rated peak power (P_{BESS}).

$$EPR = \frac{E_{BESS}}{P_{BESS}} \tag{4}$$

Table 5
Simulation matrix: Variation in parameters of the BESS, grouping of the 52 simulated scenarios into six categories based on the EPR of the BESS.

EPR	Parameter	Value	# Simulations
0 (base case)	Power (MW) Energy capacity (MWh)	0 0	1
0.5	Power (MW) Energy capacity (MWh)	0.2 - 1.6 0.1 - 0.8	5
1.0	Power (MW) Energy capacity (MWh)	0.1 - 1.6 0.1 - 1.6	9
2.0	Power (MW) Energy capacity (MWh)	0.2 - 1.6 0.4 - 3.2	10
4.0 - 100.0	Power (MW) Energy capacity (MWh)	1.6 6.4 - 160	25
120 (extreme case)	Power (MW) Energy capacity (MWh)	1.6 192	1

Table 5 lists the peak power–energy capacity ratings of the BESS in the simulated scenarios. The scenarios can be grouped into six categories - *the base case* (with EPR = 0, i.e. no storage), EPR = 0.5, EPR = 1.0, EPR = 2.0, EPR > 2.0, and *the extreme case (with EPR = 120)*. The peak power rating of the BESS in all the simulations is varied from 0.1 MW - 1.6 MW. The rated peak power is not increased beyond 1.6 MW, as this is the value of the maximum power deficit that either the DG or the BESS are expected to cover (even in the case of zero renewable generation) at any given point in time. Between EPR = 4 to 100, the energy capacity of the BESS is increased in steps of 6.4 MW h, with the peak power remaining constant. The extreme case of EPR = 120 (E_{BESS} = 192 MW h) is simulated to see if any of the parameters change in unexpected ways. Each system configuration is simulated for 20 years. The results are grouped into the aforementioned six categories, and each of the categories are represented as a separate series in the graphical results.

3.1. Effect on the emissions of the island grid energy system

The LEES parameter is calculated for the entire island grid energy system over the simulation period for each scenario from Table 5. Fig. 9 plots the LEES values versus the corresponding BESS energy storage capacity (E_{BESS}) for each of the scenarios. For each of the simulated scenarios, excluding the base case, it can be seen that $\Delta LEES_{n,0} < 0$ - where n varies from 1 to 50. This implies that the incorporation of energy storage capacity in the energy system results in a reduction of the total energy system emissions with respect to the base case (without energy storage). The value of LEES decreases monotonically as the peak power (P_{BESS}) and energy capacity (E_{BESS}) of the BESS increase.

It is also worth noting that the values of reduction in system emissions per additional unit of energy storage capacity ($R^{\text{unit storage}}_{n,n-1}$) decrease monotonically when evaluated for any two scenarios as the energy storage capacity rises. The value of its reciprocal ($1/R^{\text{unit storage}}_{n,n-1}$), the energy storage capacity per unit reduction in system emissions increases monotonically. Alternatively, the magnitude of the slope of the LEES vs. E_{BESS} curve, which represents the quantity $R^{\text{unit storage}}_{n,n-1}$,

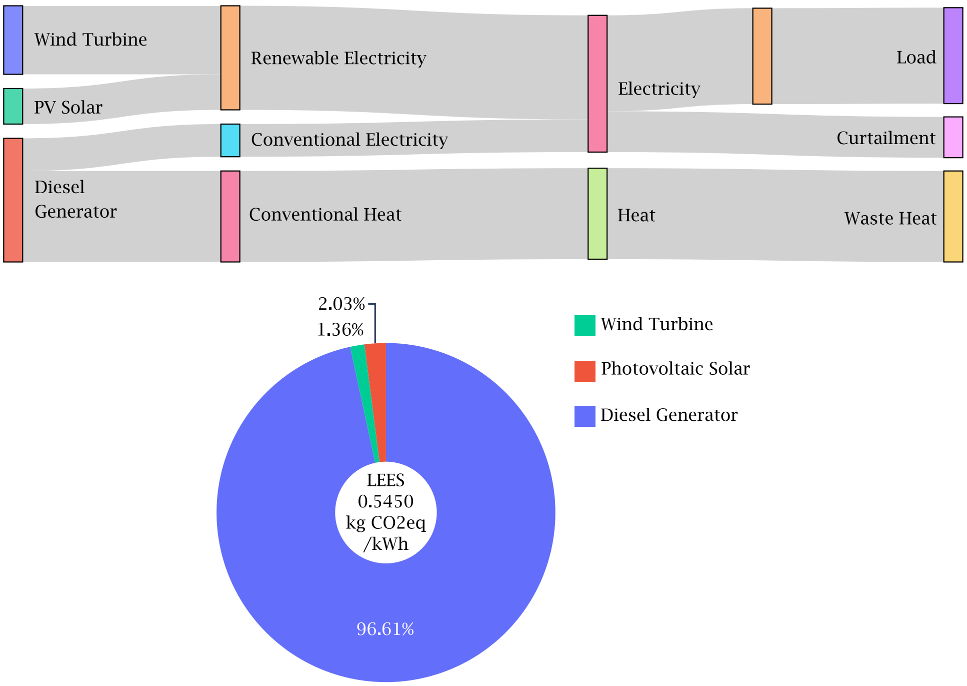


Fig. 7. Energy flows among the various energy system components in the **base case** without energy storage (top). Component-wise distribution of net emissions for the island grid energy system in the **base case** with its calculated Levelized Emissions of Energy Supply (LEES) value (bottom).

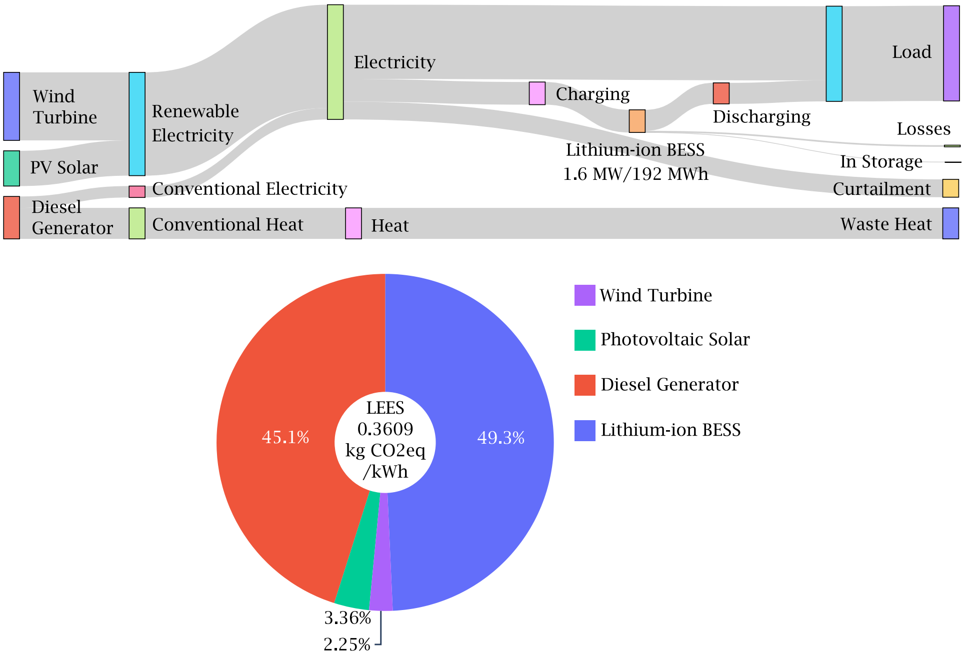


Fig. 8. Energy flows among the various energy system components in the island grid energy system for the **extreme case** with a 1.6 MW/192 MWh Lithium-ion Battery Energy Storage System (BESS) (top). Component-wise distribution of net emissions attributable to the island grid energy system in the **extreme case** with its calculated Levelized Emissions of Energy Supply (LEES) value (bottom).

decreases monotonically. The highest values of $R^{\text{unit storage}}_{n,n-1}$ are observed in the energy capacity range of 0.1 MW h - 1 MW h. As the energy capacity is further increased, values of $R^{\text{unit storage}}_{n,n-1}$ are modest up to roughly 10 MW h of energy storage capacity, after which the slope of the curve becomes increasingly gentle. The slope of the LEES vs. E_{BESS} curve, $R^{\text{unit storage}}_{n,n-1}$, eventually touches zero at a capacity of 51.2 MW h and a power rating of 1.6 MW (EPR = 32). This implies that it takes impractically large amounts of additional energy storage capacity to achieve a further 1 kg reduction in system emissions. Any further increase in the energy storage capacity slowly results in a reversal of the sign of the slope from negative to positive - i.e. a further installation of energy storage capacity in the energy system results in a rise in the LEES value with respect to the lowest possible value attained at EPR = 32. As a consequence, beyond this lowest attainable LEES value, every additional unit of energy storage capacity increases the LEES value of the system, and is sub-optimal. The diminishing energetic benefit of additional energy storage capacity is overshadowed by its increasing GWP footprint.

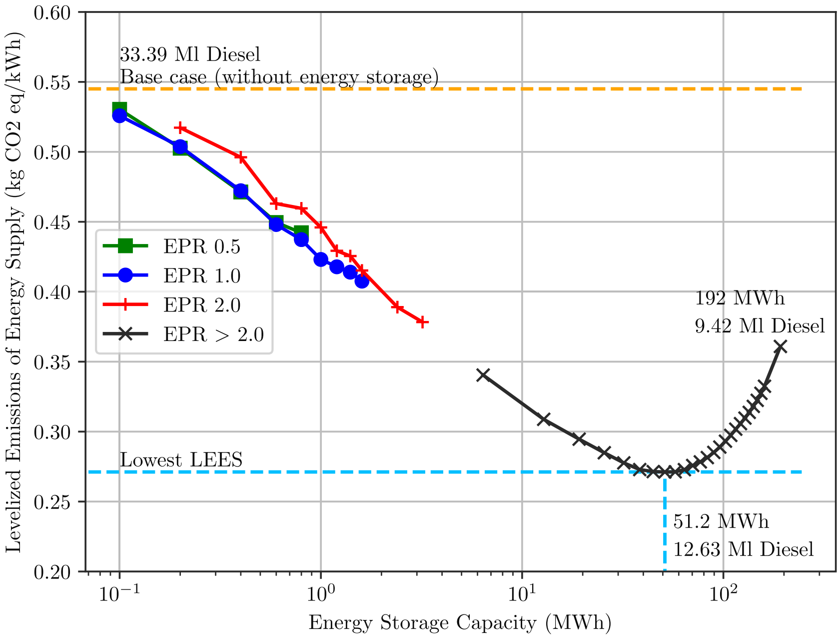


Fig. 9. Evolution of the value of Levelized Emissions of Energy Supply (LEES) for the island grid energy system with varying energy storage capacities. The magnitude of the slope of the curve $R^{\text{unit storage}}_{n,n-1}$ gradually decreases, underlining the falling effectiveness of each additional unit of energy storage capacity in reducing emissions. The slope is eventually zero at the minimum LEES, then changes sign and rises again, leading to a counter-productive increase in the LEES. The annotations for the three highlighted scenarios also depict the quantity of diesel consumed in each case (in Megalitres).

3.2. Effect on the energetic behavior of the island grid energy system

The energy flows in the extreme case (E_{BESS} = 192 MW h, EPR = 120) are graphically depicted in Fig. 8. It can be observed that despite the presence of an extremely high energy storage capacity within the energy system, curtailment cannot be avoided completely, and that the DG must run for some periods. This finding is particularly significant when considered in conjunction with Figs. 10A and 10B. The extent of curtailment in the system reduces incessantly with each additional MW h of energy storage system capacity, albeit at an increasingly gentler rate. An identical trend is also observed in the case of energy supplied by the DG. Within the range of values assumed by E_{BESS} (0 - 192 MW h), which are covered by the simulated scenarios, the curtailed energy, as well as the energy supplied by the DG both continue to drop.

This observation can be explained by the fact that more of the energy which would have otherwise been curtailed, is absorbed by the BESS in times of surplus generation, and is discharged to the load center in times of generation deficits. This results in more such instances wherein the BESS is able to supply the required energy, and the system's reliance on the DG drops correspondingly, while maintaining the no load-shedding condition. In the absence of Fig. 9, an isolated assessment of Fig. 10A could be misinterpreted to mean that increasing E_{BESS} in an unbounded fashion is environmentally beneficial, given that the curtailed energy and the operating hours of the DG keep reducing. A quick glance at Fig. 9 shows that the LEES value is nearly equal for systems with E_{BESS} = 25.6 MW h and 89.6 MW h. The only difference in the two scenarios is the lower curtailment and diesel generation values in the latter. The additional 64 MW h of energy storage capacity is then difficult to justify from the perspective of resource and material utilization, in the absence of any tangible benefit in terms of reduction in emissions.

Fig. 10B highlights the diminishing efficacy of the BESS as a tool to reduce curtailment. The energy throughput of the BESS gradually stagnates despite the larger E_{BESS} value and the prevalence of energy curtailment. This finding agrees well with the findings of Palmer et al. [11].

3.3. Effect on the Battery Energy Storage System (BESS)

Fig. 11A depicts the number of Equivalent Full Cycles (EFC) witnessed by the BESS at the given average Depth of Discharge (DOD) in each of the simulated scenarios. Evidently, for scenarios with higher values of E_{BESS}, the number of Equivalent Full Cycless (EFCs) over the 20 year period decreases at a diminishing rate. With the falling number of EFCs witnessed by the BESS, the stress induced by these cycles (represented by the mean depth of discharge, $\overline{DOD}$), also drops simultaneously. The share of cyclic aging in the total aging witnessed falls, and calendric aging becomes the dominant aging category. The total shares of the two dominant aging categories — calendric and cyclic, are depicted in Fig. 11B. Calendric aging, which in the scenario with the lowest E_{BESS} = 100 kW h, contributes just less than 50% to the total aging, is observed to be the dominant aging category for energy system scenarios with large energy storage capacities. The aging model used in this work superimposes calendric and cyclic aging to obtain the total aging. Among the simulated scenarios, the shortest lifespan observed for the LFP battery is for the scenario with E_{BESS} = 100 kW h and P_{BESS} = 200 kW (EPR = 0.5). In this scenario, the cells last for about 7.75 years, during which they endure 3046 EFCs at $\overline{DOD}$ = 63.84%. the share of calendric aging in the total aging at EOL is 41.78%. The longest lifespan of 19.5 years is observed in the scenario with E_{BESS} = 153.6 MW h and P_{BESS} = 1.6 MW (EPR > 2). During this period, the cells endure 283 EFCs with $\overline{DOD}$ = 2.5%. The share of calendric aging at the EOL = 99.47%. Given that at least one, or more replacements of the batteries are necessary during the simulated period of 20 years, there remains some residual useful service life at the end of each simulation. The GWP footprint of the BESS is adjusted to account for this remaining capacity, so that the LEES metric only reflects the capacity that has been lost to degradation. This adjustment is necessary to ensure comparability of the scenarios. As all the other components are considered to have reached the end of their service lives after 20 years, no adjustments have to be made to their values of production and EOL phase GWP footprints.

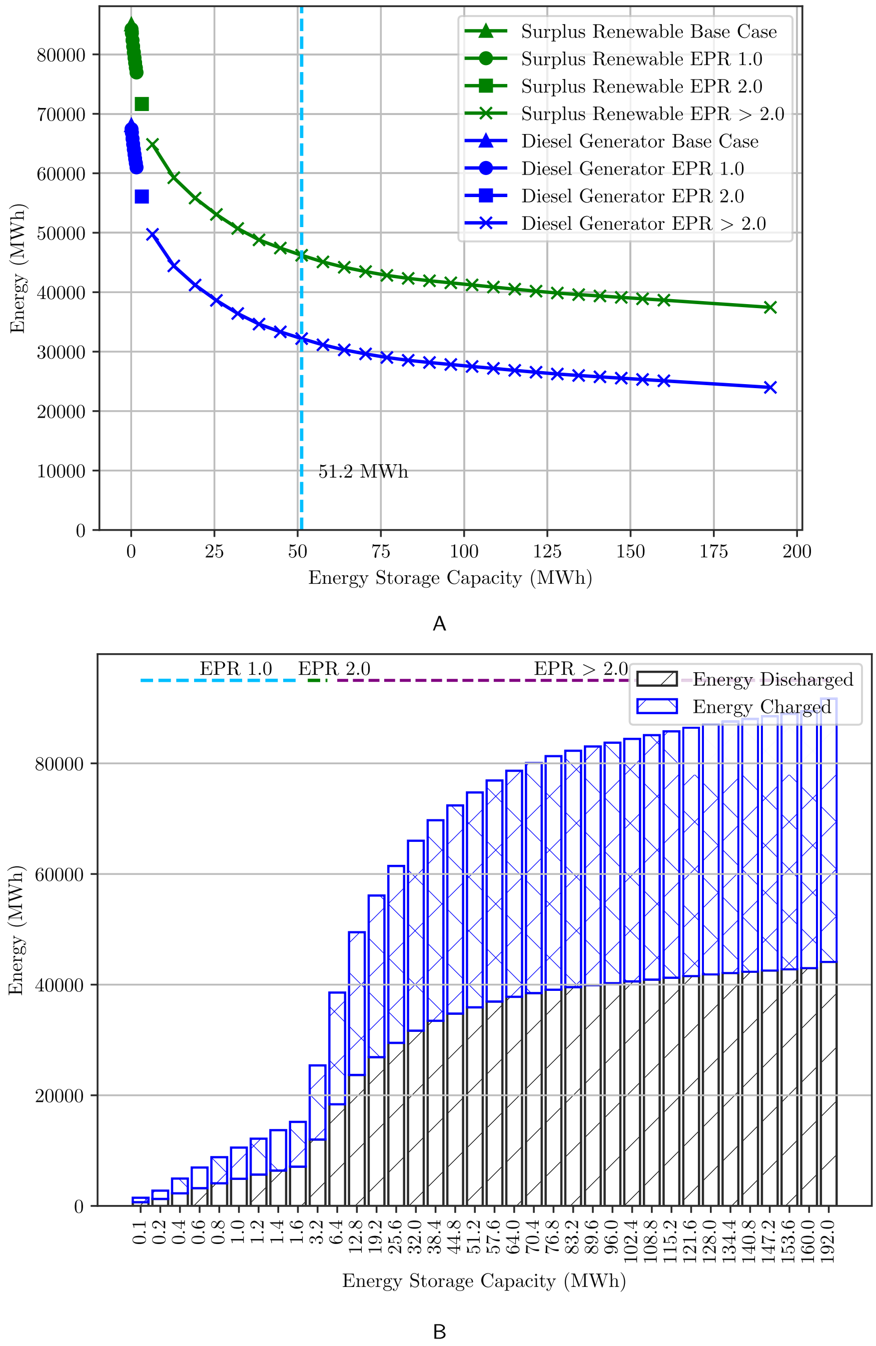
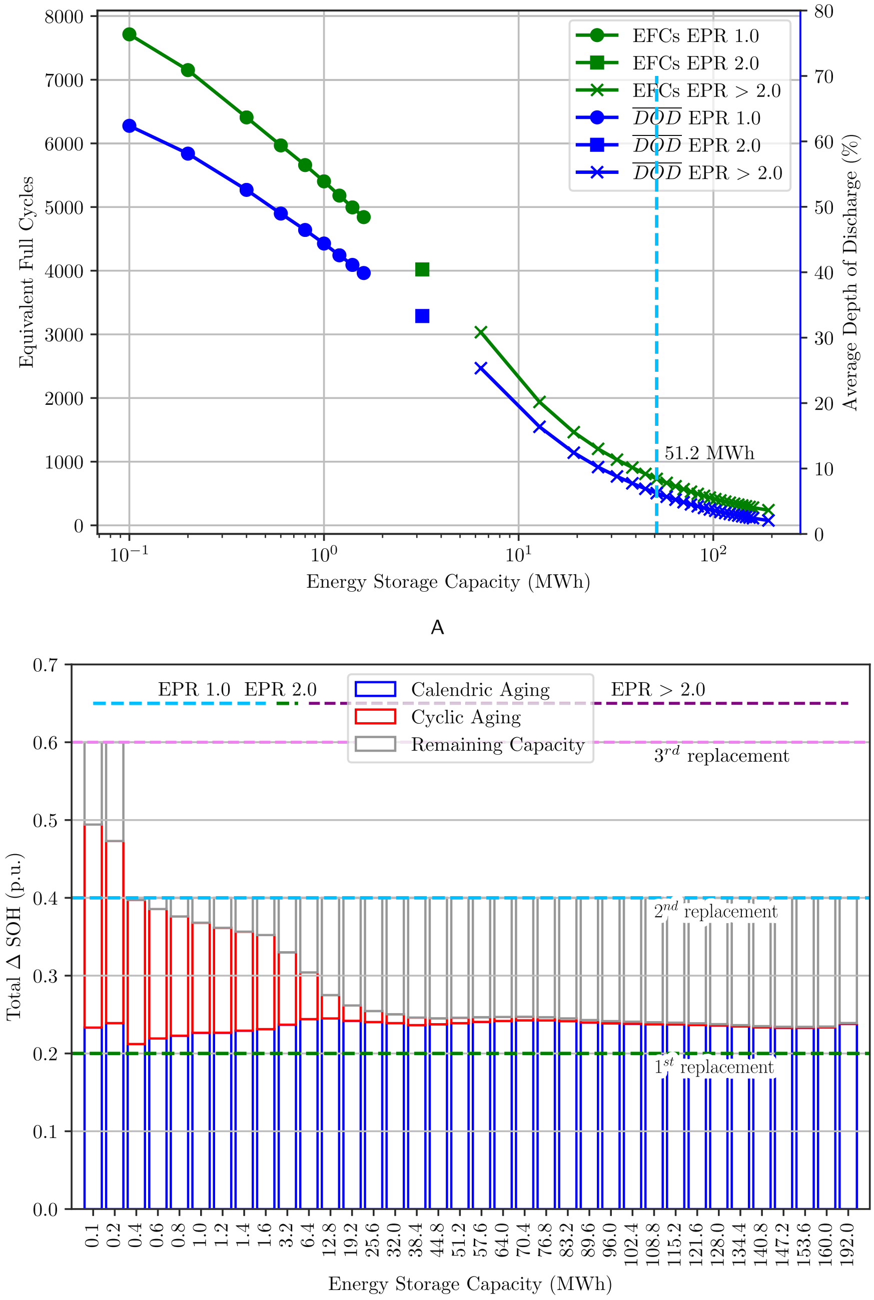


Fig. 10. Surplus renewable energy generation and energy generation from the Diesel Generator (DG) drop continuously with respect to energy storage capacity (A). Limited effectiveness of energy storage at completely eliminating curtailment, despite extremely large energy storage capacities, stagnating BESS energy throughput (B).

3.4. Effect of variation in other parameters: a short discussion

The present work introduces the metric LEES, and investigates the effect of BESS peak power and energy storage capacity on the value of LEES for the island grid energy system. Incorporation of energy storage is clearly not the only path to attaining a lower value of LEES vis-a-vis the base case. As an example, an alternative energy system with twice the renewable generation capacity as the base case and the same diesel generation capacity is also simulated - i.e. 6.5 MW of WT capacity, and 4 MW_p of PV generation capacity. The values of LEES for this energy system with E_{BESS} = 200 kW h and P_{BESS} = 200 kW is 0.4558 kg CO_2eq/kWh, as compared to 0.5037 kg CO_2eq/kWh for the original energy system. The LEES value with a BESS of 1.6 MW / 1.6 MW h rating is 0.3101 kg CO_2eq/kWh, as compared to 0.4076 kg CO_2eq/kWh for the same E_{BESS} in the original energy system. This oversized system has much higher levels of curtailment, but the curtailed energy, as already discussed, should not be the sole yardstick of comparison. This finding agrees well with results obtained by Arbabzadeh et al. who suggest that over-building WT capacity is a more effective method of reducing net energy system emissions [20]. Some other possible ways to achieve a reduction in the LEES value may be deduced directly from the expression for the LEES metric, and are not simulated in the current work. These are: higher lifetimes for all components, higher component efficiencies, cleaner production processes with lower carbon footprints, a greater degree of recycling, right-sizing of the installed capacities of renewable energy generators and the BESS. These remarks are comparable to those presented by Jones et al. [17].



A

B

Fig. 11. Equivalent Full Cycles (EFC) and average Depth of Discharge (DOD) seen by each BESS configuration over the simulation period (A). Total calendric and cyclic aging experienced by the BESS with replacements (B).

The stochastic variations in the power outputs of the renewable energy sources could also add to the uncertainty and variability in the calculations. This work assumes perfect foresight for the calculation of the LEES for an energy system. The accuracy of forecasts may, however, affect the planned operation patterns of the various energy system components, and further aggravate the problem of mismatch between generation and demand [46]. In the worst case, curtailment and the operation hours of the DG may increase, and the energy throughput of the BESS may decrease. Occurrence of these effects together can lead to a higher value of LEES. Low response times and large permissible ramp-rates of the DGs can also counteract negative impacts of inaccurate renewable generation forecasts.

The LEES metric can prove to be useful when used in conjunction with other metrics for performance comparisons. A more detailed investigation into the variation of other parameters is not presented in the current work, but will be addressed in subsequent works. This concluding section serves to prove the utility of the LEES metric as a holistic evaluation parameter for island grid energy systems.

4. Conclusion and outlook

This work presents an environmental performance evaluation methodology to assess the reduction in the total GHG emissions of an island grid energy system. Two metrics — the LEES and $R^{\text{unit storage}}_{n,n-1}$ are introduced to better describe and discuss the incorporation of energy storage in such island grid energy systems. A simplified LCA of a Lithium-ion BESS is carried out to demonstrate the methodology. The methodology and the results from the simplified LCA are applied to an island grid energy system.

It was shown that for the considered conditions, the inclusion of a BESS in an isolated island grid energy system always leads to lower overall emissions than in the base case. It is found that the maximum achievable reduction in total emissions through the incorporation of energy storage capacity in an island grid energy system is bounded by a value which is a function of the characteristics of the energy system and all its components. Focusing solely on minimizing the curtailed energy, or the power generation from the DG through incorporation of energy storage capacity does not necessarily lead to lower total emissions.

The prudent selection of nameplate energy storage capacities can be achieved by considering the value and sign of $R^{\text{unit storage}}_{n,n-1}$ - large negative values indicate higher reductions in emissions, positive values indicate a sub-optimal configuration. From a global perspective, for a given amount of material and monetary investment, a higher total global reduction in emissions can be expected if energy storage capacities are installed in energy systems exhibiting a high $R^{\text{unit storage}}_{n,n-1}$ value, rather than building-up large energy storage capacities in energy systems with substantial pre-existing energy storage capacities, and which exhibit a low $R^{\text{unit storage}}_{n,n-1}$ value.

There exists scope for future works to build upon and further refine the results of this work. Improving the level of detail of the LCA could help enhance the accuracy of the calculation. The current work uses simple energy flow models for the island grid energy system and its components, which do not consider the variations in voltages and frequencies. Transmission losses are entirely disregarded, and the loss mechanisms in the PV, WT, and DG are not modeled. The challenge of obtaining a minimum possible LEES value by varying all possible energy system parameters to yield an optimal system configuration could be formulated as an optimization problem. Uncertainties stemming from the forecasts of renewable energy generation could also potentially be incorporated in future works, and confidence-bounds for the LEES value may be obtained.

CRediT authorship contribution statement

Anupam Parlikar: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Software, Visualization, Writing - original draft and editing. **Cong Nam Truong:** Methodology, Data curation, Writing - review & editing. **Andreas Jossen:** Funding acquisition, Resources, Supervision, Writing - review & editing. **Holger Hesse:** Funding acquisition, Formal analysis, Visualization, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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