Optimal Allocation of Renewable Energy for the Mining Industry: From Diesel Dependency to Sustainable Autonomy

3rd Semester Master's Project

AAU Energy

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STUDENT REPORT

AALBORG UNIVERSITY

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3rd semester Master's at AAU Energy
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Title:

Optimal Allocation of Renewable Energy for the Mining Industry: From Diesel Dependency to Sustainable Autonomy

Project Theme:

Interaction between hybrid wind power generation units and electrical loads or power system

Project period:

04/09-19/12 2025

Participants:

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Pages: 52
Due Date: 19-12-2025

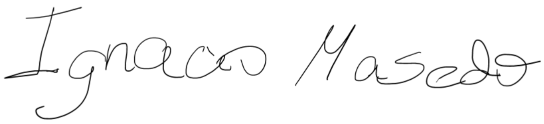
Synopsis:

Remote mining relies on diesel microgrids with high logistics costs and emissions. Replacing them requires a reliable renewable supply capable of covering night-time demand and operational variability. This project designs and evaluates an island PV–BESS system for a mining site, with the aim of obtaining realistic power/SOC profiles and a dispatch capable of minimising dependence on fossil fuels. REopt is used on an annual horizon with 15-minute resolution, modelling power and energy limits, efficiencies and SOC bands. The approach is technical (not economic) and generates consistent sizes and profiles, with and without curtailment. The scenarios analysed are: 1) comparison of four PV sizes under two operating modes, with and without curtailment, to explore the trade-off between curtailment and BESS requirements, 2) sensitivity to the initial SOC of the year (high/medium/low) with and without curtailment, evaluating how the optimal size of the BESS and its management changes, 3) inclusion of a diesel generator with an annual usage quota to limit the energy/power of the BESS and analyse behaviour in critical weeks of low irradiance. Overall, PV–BESS achieves configurations to meet demand. Allowing curtailment and choosing an appropriate initial SOC reduces the demand on the BESS, while a backup diesel generator reduces sizes but puts pressure on the renewable autonomy objective.

Preface

The following project is written by 3rd semester MSc Hybrid Wind Power Systems student Ignacio Masedo Arana, from Aalborg University. This is a semester project intended to teach students about an aspect of engineering, the theme of this semester is the interaction between generating units, battery energy storage systems, electrical loads and the electrical power system.

The author would like to express their gratitude to group supervisors Daniel-Ioan Stroe and Diptish Saha from the Department of Energy, Aalborg University, for their valuable guidance on modelling and their continuous support in project writing throughout the project period.



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19th of December 2025, Aalborg University

Nomenclature

Symbol	Definition	Unit
P_{pv}	PV system power output	[MW]
P_{load}	Site load power	[MW]
E_{bess}	Battery energy capacity	[MWh]
P_{bess}^{ch}	Battery charge power	[MW]
P_{bess}^{dis}	Battery discharge power	[MW]
SOC	State of Charge	[%]
DoD	Depth of Discharge	[%]
ENS	Energy Not Served	[MWh]
η_{ch}	Charge efficiency	[-]
η_{dis}	Discharge efficiency	[-]
GHI	Global Horizontal Irradiance	[W/m^2]
DNI	Direct Normal Irradiance	[W/m^2]
POA	Plane-of-Array Irradiance	[W/m^2]
T	Temperature	[°C]
$C\text{-}rate$	Charge/discharge rate	[h^{-1}]
End of Table		

Acronyms

Acronym	Definition
RES	Renewable Energy Sources
WT	Wind Turbine
PV	Photovoltaic
BESS	Battery Energy Storage Systems
RE	Renewable Energy
HES	Hybrid Energy System
SOC	State of Charge
CAPEX	Capital Expenditures
LCOE	Levelized Cost of Energy
DoD	Depth of Discharge
ENS	Energy Not Served
GLM	Greenbushes Lithium Mine
MPPT	Maximum Power Point Tracking
MILP	Mixed-Integer Linear Programming
REopt	Renewable Energy Optimization (NREL)
NREL	National Renewable Energy Laboratory
ARENA	Australian Renewable Energy Agency
AAU	Aalborg University
GHI	Global Horizontal Irradiance
DNI	Direct Normal Irradiance
POA	Plane of Array
O&M	Operation and Maintenance
LCOE	Levelized Cost of Energy
WA	Western Australia
SA	South Australia
WA	Western Australia

Contents

1. Introduction

1.1 Background

The mining industry is crucial to contemporary economies by providing essential raw materials for the energy, manufacturing, and infrastructure sectors. At the same time, mining is one of the most energy-intensive industrial processes and a significant contributor to greenhouse gas (GHG) emissions. According to recent estimates, mineral mining accounts for about 1,7 % of global *final* energy consumption, while the total GHG footprint across ranges from roughly 4–7% of global emissions. These figures highlight both the sector's systemic importance and its decarbonization challenge. [1, 2]

A global sustainable energy transition (SET) in mining is being driven by climate policy (e.g Paris agreement), which aims to prevent an increase in global temperatures beyond 2 [°C] above pre-industrial levels, and pursue efforts to limit it to 1.5 [°C] [3, 4]. While preserving dependability and safety, SET in the mining industry refers to the transition from on-site fossil fuels (such as coal and diesel) to low-carbon electricity based on renewables and supporting technologies (particularly solar PV and battery energy storage) [5]. Thus, switching to cleaner energy has become not only an environmental need but a strategic necessity for the industry's long-term future. In line with these policies, techno-economic trends increasingly support the viability of energy transition in mining operations [6].

In parallel with these regulatory commitments, declining costs and improvements in renewable and storage technologies have opened up feasible pathways to reduce fossil fuel use at mine sites, particularly where power must be self-generated or the connection to the grid is weak. Analyses show that decarbonising mining's power demand would require significant amounts of clean energy, S&P Global estimates on the order of 180 TW h per year [7]. Figure 1.1 shows the use of clean energy in mining projects during the year 2023, showing that Chile and Australia account for over half of it.

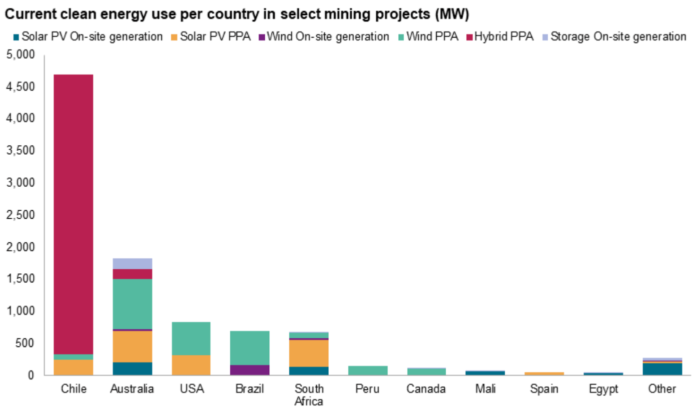

Figure 1.1: Overview of the 2023 clean energy use per country in mining projects [7].PPA = Power Purchase Agreement: a long-term contract where the mine buys electricity at an agreed price from a third-party generator.

However, significant challenges remain. Many mines are located in remote areas and operate either islanded or with limited grid connection, so integrating renewable energy without compromising safety, power quality, and high availability remains a technically demanding task. It is important to size renewables and storage correctly to avoid both energy deficits and excess capacity. This requires realistic representations of critical and deferrable loads, prioritising the former and scheduling the latter, and simple, robust control that uses short-term forecasts of solar output and demand. From an operational perspective, the performance, safety, and availability of batteries under high ambient temperatures, dust, and cyclic load peaks remain practical constraints. In practice, realistic, high-resolution battery power profiles are needed to understand these trade-offs and to monitor state of health over time. Realistic, high-resolution battery power profiles are necessary in practice to comprehend these trade-offs and track the state of health over time.

In light of these challenges, it is important to develop a practical framework with site-specific guidelines for energy management that coordinate solar generation and battery storage, prioritise critical loads and schedule deferrable loads, while developing realistic, high-resolution battery energy profiles, with the ultimate goal of reducing dependence on diesel generators.

1.2 Motivations

Due to their ease of deployment and operator familiarity, diesel-only microgrids continue to be the standard option for remote mining locations. However, this reliance exposes operations to fluctuating fuel prices, complex logistics, greenhouse gas emissions, noise, and higher maintenance. A practical solution to decrease diesel runtime and fuel consumption is to incorporate photovoltaic (PV) generation and battery energy storage systems (BESS). In this project, the focus is on a PV–diesel–BESS microgrid. This is referred to as a *hybrid energy system (HES).* A proper academic definition for HES is given by [8], stating:

> *"Systems involving multiple energy generation, storage, and/or conversion technologies that are integrated—through an overarching control framework or physically—to achieve cost savings and enhanced capabilities, value, efficiency, or environmental performance compared to the independent alternatives."*

It is expected of mining corporations to keep production stable while reducing expenses and emissions. Every litre of diesel avoided in remote areas lowers pollutants and exposure to fuel logistics and price fluctuations. PV is mature and cost-effective in many mining regions. When combined with a BESS, it can cover daytime variability and help ride through short cloud events without compromising safety or throughput. Understanding how the site uses power over the day (including short ramps and scheduled activities) is therefore essential to plan a feasible hybrid.

In addition, a mine does not have one homogeneous electrical demand. It consists of a combination of near-continuous process equipment, safety-critical services, and adaptable ancillary uses. Separating these into operational classes (critical, deferrable, and non-critical) is useful for three reasons:

- Aligns energy planning with safety and production priorities: Critical aspects are always guaranteed.

- Reschedule flexible tasks around solar availability and short BESS support, this way there is a reduction in diesel use and logistics risk.
- Helps produce realistic daily power profiles for the site, which make the rest of the analysis more credible.

The primary motivation of this project is to develop a comprehensive and sustainable energy management framework for HES in the mining sector that eliminates dependence on diesel generators. In practice, this study structures the site's demand into operational classes and combines it with PV and BESS so that the microgrid can operate reliably with a predominantly renewable supply, progressively reducing diesel and, where possible, removing it entirely.

1.3 State of the Art

This section reviews current practice and evidence for HES based on PV, BESS and diesel generation supplying remote mining sites and analogous microgrids, with the aim of reducing diesel generator use. First, it summarises field results from projects that achieved quantifiable diesel displacement and identifies recurring battery functions in operation. Next, operational load distinctions and the Australian practice approach that determine dispatch flexibility and realistic battery operating profiles are outlined. Furthermore, optimisation software commonly used to reduce diesel use,generate battery power and energy time series is surveyed. This section ends with a summary on the State of the Art.

1.3.1 Literature Review

1.3.1.1 Diesel displacement in remote microgrids and mining

Evidence from operating mines and remote microgrids shows that PV combined with BESS reduces generator starts, mitigates solar ramps, and enables short-duration displacement, reducing diesel consumption without compromising reliability. Field testing at Australian installations shows a consistent pattern of diesel reduction with PV and BESS. At DeGrussa, ramp-rate control and dynamic spinning reserve enabled by batteries in an islanded diesel system reduced generator starts and protected the continuity of critical services, with reported savings of approximately 5 million litres of diesel per year [9, 10]. At Coober Pedy, by combining PV, Wind, and BESS, a penetration rate of over 70% of renewable energy was achieved during the first 5 years of the poject, and 2,189 kL of diesel were saved [11, 12]. Agnew's hybrid microgrid, in mining, reported significant reductions in emissions and fuel consumption, achieving to deliver up to 60% renewable energy to the mine and reduce the emissions by 42% (elec + diesel) [13, 14]. Flinders Island was reliant on expensive diesel fuel to supply the island's electricity needs. By implementing a hybrid system, the annual contribution of renewable energy nowadays is up to 60%, and is able to run for periods of continuos zero-diesel operation (nearly 100 hours continuosly and for approximately 50% of the year) [15, 16]. Table 1.1 below provides a summary of the various projects mentioned.

Table 1.1: Selected Australian hybrid microgrids and mining sites with PV-BESS.

Site	Sector	Configuration	Installed capacity	Reported saving	Source
DeGrussa (WA)	Mining	PV + BESS + diesel (islanded)	PV: 10,6 MW BESS: 6 MW/1,8 MWh Diesel: existing	≈5 million litres of diesel/year	[9, 10]
Coober Pedy (SA)	Remote microgrid	Wind + PV + BESS + diesel	PV: 1 MW Wind: 4 MW BESS: 1 MW/0,5 MWh Diesel: 4,15 MW	75.3% renewable penetration, 2,189 kL of diesel saved (first 5 years)	[12, 11]
Agnew (WA)	Mining	Wind + PV + BESS + thermal	Wind: 18 MW PV: 4 MW BESS: 13 MW/4 MWh Gas: 16 MW	42% emissions reduction	[13, 14]
Flinders Island (TAS)	Remote microgrid	Wind + PV + BESS + diesel	PV: 200 kW Wind: 900 kW BESS: 750 kW/266 kWh Diesel: UPS 850 kVA	60% diesel reduction, 100 h continuous diesel-off capability	[16, 15]

Expanding the dataset beyond four projects suggests that hybridation of technologies correlates to local site conditions. In particular, islanded or coastal sites usually include wind (Rottnest, King Island, Flinders Island) [17, 18], whereas inland mining sites show different configurations: PV-only (e.g., DeGrussa, Granny Smith) and PV–wind (e.g., Agnew, Coober Pedy). This points to local wind resource, remoteness and fuel logistics as the main drivers of mix selection. Given the small sample, statistical claims are avoided, a controlled analysis using measured wind/PV capacity factors, distance to coast, and project scale would be required to confirm tendencies. Figure 1.2 shows the locations of the different projects.

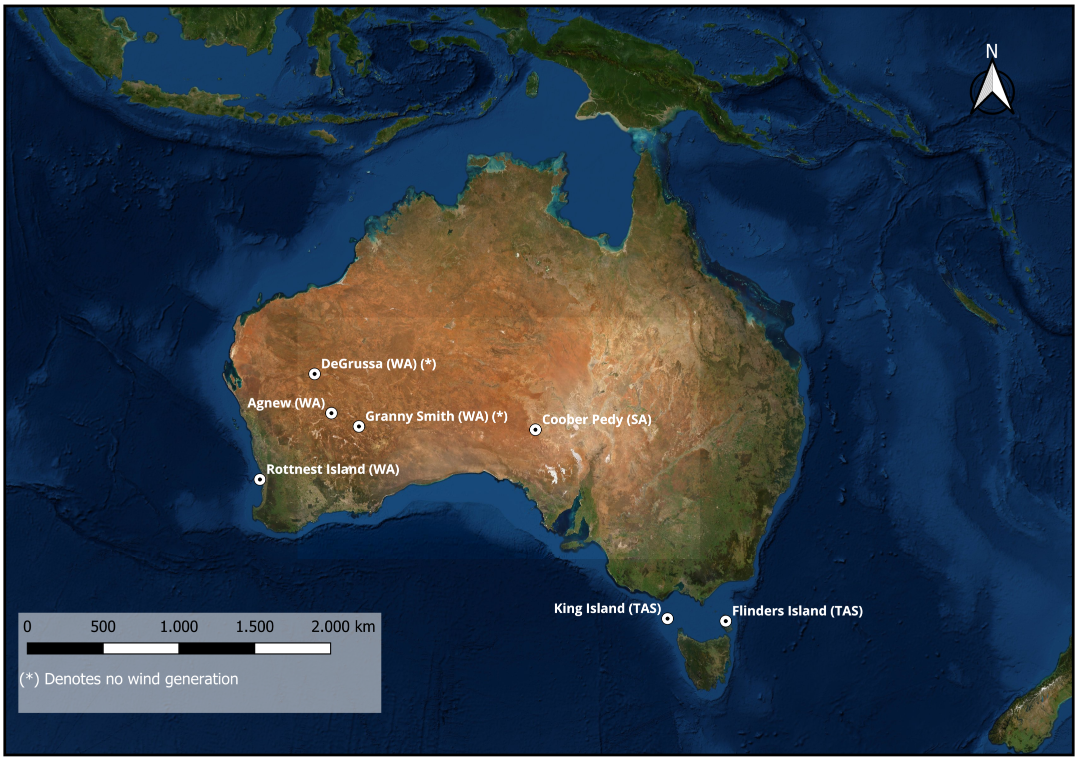

Figure 1.2: Locations of representative projects in Australia. (*) denotes no wind generation. Map produced by the author using QGIS software [19].

1.3.1.2 Operational load distinctions

In Australian practice, electricity demand is classified by criticality. Security and compliance services (e.g., underground ventilation, mandatory monitoring, etc.) are considered non-deferrable and require continuous supply according to current normative [20, 21, 22]. Hybrid projects in Western Australia indicate that, in operation, the aim is to maintain the stability of the process and only non-critical loads are shifted when there is a margin [23, 24]. Thus, in Coober Pedy and Flinders Island, diesel-off capability is enabled without compromising power quality, with deferrable loads aligned to renewable availability [12, 15].

1.3.2 Optimisation Software

1.3.2.1 Commercial products

Within this project, optimisation is used primarily to minimise the use of diesel generators use. The aim is to create guidelines through realistic, sub-hourly BESS power, energy and SOC profiles across multiple sizing and different scenarios, and to use such profiles to draw operational conclusions. Priority is given to tools that are widely used or well documented that export time series of battery power, energy and SOC suitable for cycle counting and SoH metrics.

Table 1.2 shows the different tools reviewed. REopt offers a clear basis with hourly dispatch and useful resilience scenarios for extracting battery cycles. When accessed via API/REopt.jl, it supports inputs below one hour, but not for all functions. HOMER Pro prioritises speed and easy-to-use rule-based dispatch, but does not guarantee global optimisation. Open source tools, such as PyPSA and oemof, allow the application of constraints for specific characteristics (e.g., minimum reserve for ventilation, deferrable windows, C-rate limits, and depth of discharge) with user-defined resolution, making it easy to generate sub-hour profiles. These implementations are biased and require a hard learning curve. Finally, DER-CAM combines investment and operation and returns dispatch series consistent with cost and emissions targets. It is less suitable for sub-hourly profiles.

Table 1.2: Characteristics of common PV–BESS–diesel tools for sizing technologies.

Tool	Optimisation type	Temporal resolution	Cons	Source
REopt (NREL)	MILP, techno-economic	Hourly (web), 15-30 min via API/REopt.jl	Sub-hourly not fully supported	[25]
HOMER Pro	Rule-based simulation with heuristic search	5-60 min (user-defined)	Not guaranteed global optimum	[26, 27]
PyPSA	LP / MILP, multi-period	User-defined (minutes to hours)	Higher modelling effort	[28]
oemof	LP / MILP, framework	User-defined (minutes to hours)	Higher modelling effort	[29]
DER–CAM	MILP, investment + operation	Hourly (typical)	Not suited for sub-hourly	[30, 31]

1.3.2.2 Academic studies

This subsection reviews studies that size or dispatch PV–BESS–diesel systems and report (or allow to export) BESS power, energy, and SOC time series for cycle counting and basic SoH analysis. These papers guide the choice of time-step, constraints, and post-processing of battery profiles.

Table 1.3: Selected academic studies on PV–BESS–diesel sizing and dispatch.

Study	System and solver	Time-step	Cons	Source
Ellabban and Alassi, IET RPG	Mining microgrids, MILP techno-economic framework	Hourly	Hourly only, no aging model	[32]
Ranjbar et al., Optimization Letters	Remote mining microgrid, two-stage plan and schedule, MOEAs with BESS aging	Hourly	Hourly schedule, high compute	[33]
Marqusee et al., Advances in Applied Energy	PV–BESS with networked diesels, REopt-based outage analysis	Hourly	Not mining-specific, hourly only, simple battery model	[34]
Vergara-Zambrano et al., Journal of Cleaner Production	Copper mining integration, multi-objective optimisation with storage	Hourly	Aggregated inputs, no battery aging, time series not shared	[35]
Sufyan et al., PLOS ONE	Isolated microgrid, economic scheduling with DoD-based degradation cost	Sub-hour	Simplified DoD aging, not mining, small cases	[36]

The studies cover mining and isolated microgrids with methods that help produce usable BESS profiles. Ellabban and Alassi provide a MILP framework with Australian mining cases that yields dispatch aligned with cost and reliability, its main limits are the hourly step and the lack of an explicit battery aging model. Ranjbar and co-authors use a two-stage workflow with evolutionary algorithms (MOEAs) and a battery aging term, it produces useful schedules but remains hourly in the scheduling stage and can be computationally heavy. Marqusee and co-authors study PV, battery storage, and networked diesels with REopt under outage events, it is not mining-specific, works at hourly resolution, and uses a simple battery model. Vergara-Zambrano and co-authors apply a multi-objective method to copper mining, battery aging is not modeled, and detailed time series are not provided. Sufyan and co-authors include a degradation cost per interval based on depth of discharge (DoD), the model is simplified, the cases are not mining, and the test systems are small.

1.3.3 Summary on State of the Art

In microgrids with photovoltaic energy and BESS, data in Australia shows that batteries reduce diesel consumption mainly by smoothing solar ramps and providing reserve capacity, enabling short-term isolation and shifting of some energy within the day. Australian regulations distinguish between non-deferrable and deferrable loads, requiring reserves and a minimum SOC to be maintained, thereby limiting how the battery can be deployed. The choice of optimisation tool is not straightforward, as the literature does not select a single method for HES operation in a mine. In this work, the objective is to find an operational dispatch that minimises diesel use and maintains a secure supply, rather than extensive and accurate sizing. In general, the literature supports the replacement of diesel with well-defined battery functions and highlights the need for minute-level modelling.

Based on the Literature Review, several research gaps can be identified. While scientific articles have been able to fill some of these gaps, none of the papers in the Literature Review have covered all of the gaps.

Research gaps:

- Lack of sub-hourly BESS profiles.
- Lack of smart energy management (SEM) of the BESS based on local production and consumption.

- Degradation not integrated into operation: Usually analysed afterwards.
- Thermal management not represented in dispatch.

1.4 Problem Formulation

Many remote mines rely on diesel-based microgrids to ensure continuous operation and security of supply. This entails volatile fuel costs, complex logistics, and high emissions. A hybrid system with PV and BESS offers a clear path to reducing diesel use without compromising reliability. For this to work, it is necessary to classify site loads (critical, deferrable, non-critical) and obtain high-resolution battery power profiles that represent daily operation.

Therefore, the objective of this project is to define a practical planning and dispatch technique for a PV-BESS hybrid system in mining, with the reduction of diesel reliance as the main goal. Thus, the study focuses on load prioritisation and the calculation of sub-hourly dispatch that respects power and energy limits, efficiencies and SOC levels, generating high-resolution power and SOC profiles for further analysis.

The statement for the project can be expressed as follows:

> *How is a sub-hourly isolated HES modelled and dispatched to supply prioritised mining loads, and what operational conclusions can be drawm from the resulting profiles under different BESS sizes?*

1.5 Objectives

To address the thesis statement, the following objectives are pursued:

- Develop a HES framework at sub-hourly resolution that prioritises mining loads and minimises diesel use.
- Calculate comparable indicators in different scenarios in order to draw operational conclusions.

1.6 Methodology

The optimiser chosen in this project is REopt (an open source software developed and deployed by NREL). The choice follows the considerations described in Section 1.3. REopt is suitable for scenario runs with few design parameters and has extensive documentation and usage. Optimisation is realized using Python scripts that prepare the inputs, call REopt and process the results.

Weather data is obtained from Open-Meteo website, obtaining irradiance and ambient temperature with a 1-hour resolution. Then, this data is resampled to a 15-minute resolution.

PV datasheet for modeling production is taken from commercially available products.

The load profile used in this study was provided by the project supervisor and represents the total demand of the mining site with hourly resolution. Pre-processing is performed to convert it to sub-hourly resolution and verify that it reflects daily variation.

The diesel generator parameters are taken from EIA for diesel cost, Wärtsilä and Caterpillar technical notes for efficiency and ADFC for energy content.

The initial sizes used as starting points are based on estimates consistent with the operating model of a mine in Australia. Then, the final sizes and results are returned by REopt under the specified constraints and data.

1.7 Scope & Limitations

As the investigated project is complex, several limitations were considered in order to limit its scope. These are in the form of simplifications and assumptions listed below:

- The battery degradation and state of health are not considered within this report.
- The battery charging and discharging power is considered equal.
- Particularities (e.g., voltage limits, self-discharge etc.) of different battery technologies were not considered
- Smart Energy Management is not implemented when controlling the battery.
- Complex modelling of PV production is outside the scope of this project.
- Power-system aspects such as protection, harmonics, voltage regulation are not considered.
- Exhaustive techno-economic analysis, such as CAPEX and LCOE, is not considered.

2. System Characterization

2.1 Model Overview

2.2 System Description

2.2.1 Case Study

Greenbushes Lithium Mine (GLM), located in South-Western Australia, is selected for the study since it offers a representative industrial context for HES integration, being a large open-pit hard rock mine [37, 38]. The site has a history of underground activity for other commodities, but current lithium extraction is carried out in open pit. The former underground mines are reportedly in a state of maintenance [39].

From a methodological point of view, this mine is also chosen because it has large differences between daily minimum and maximum temperatures throughout the seasons. These variations are useful for this study because they allow to observe how PV production varies by operating temperature and how the BESS adjusts its charge/discharge limits in cold and hot conditions. In extreme thermal conditions battery performance is reduced and the results will serve as the basis for realistic power profiles.

2.2.2 HES Configuration

The Greenbushes mine is primarily supplied from the South West Interconnected System (SWIS) at 132 kV. An overhead transmission line from the substation located in Bridgetown feeds the GLM on-site substation, with a cable length of approximately 14 km [40, 41]. At the mine, the power is transformed at a 132/22 kV substation. This substation is equipped with two transformers designed for N-1 redundancy, ensuring that the site can continue to receive power even if one unit is out of service due to maintenance or failure. Then, a 22 kV medium voltage bus distributes power to the different technologies and loads in the mine, such as the processing plant, mining services, workshops and ventilation [42, 43]. Furthermore, the mine has diesel-powered generators connected to a Low-Voltage/22 kV step-up transformer for backup and contigency [44, 45].

The study introduces two behind-the-meter assets at the 22 kV bus:

- A utility-scale PV plant.
- A Battery Energy Storage System (BESS).

Figure 2.1 shows the topology of the HES, clearly highlighting the existing assets on site and the new technologies incorporated in to the project. Detailed ratings are defined in later sections.

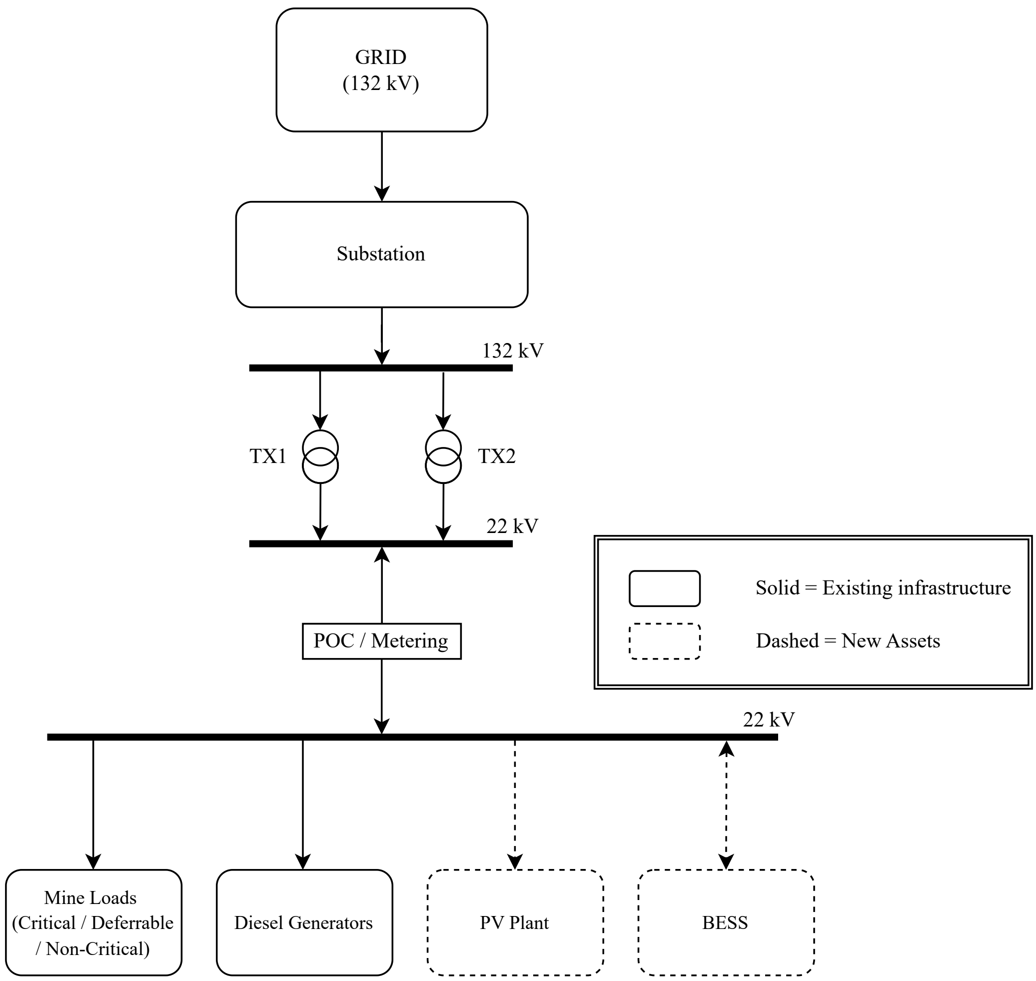

Figure 2.1: Single-line diagram for the GLM. Solid lines show existing infrastructure, while dashed lines show the new assets behind the meter, each connected via a 22 kV step-up transformer.

2.3 System Characterization

2.4 Modelling

The following sections describe models for active power production of the RE systems. Then, BESS modelling and the associated equations are shown. The methodology for load classification and generating the load profile is discussed in Section 2.6 .

2.4.1 Photovoltaic

A PV generator transforms sunlight into electrical power due to the photovoltaic effect. The instantaneous PV power output (P_{pv}) depends on various factors including the solar irradiance and the operating temperature of the cells [46, 47]. In this study, PV arrays are assumed to be equipped with maximum power point tracking (MPPT). The real power output can be calculated through the Equation (2.1).

$$P_{pv} = f_{pv.derating} P_{pv.r} \frac{G}{G_{STC}} \left[1 + \alpha_T (T_{pv} - T_{STC})\right] \tag{2.1}$$

Where:
P_{pv} - PV system power output [MW];
$f_{pv.derating}$ - PV derating factor [%];
$P_{pv.r}$ - rated power output of PV system [MW];
G - solar irradiation [W/m^2];
G_{STC} - solar irradiation under standard test conditions [W/m^2];
α_T - PV temperature power coefficient [%/°C];
T_{pv} - operating cell temperature [°C];
T_{STC} - operating PV cells temperature under standard test conditions [°C].

The PV derating factor ($f_{pv.derating}$) is a coefficient that considers the expected real world operating conditions of the solar panels. It takes into account losses due to soiling, partial shading, snow cover, wiring losses, high temperature etc. [48]. Typical values are near 90%, but in hot, dusty climates can be reduced to 80% or 70% [49, 50]. In South-West Australia, this problem is generally mild compared with arid interior sites because winters are cooler and wetter. Studies around the area report relatively low average soiling losses, though some dust events can occur [51, 52]. The PVWatts Calculator of the National Renewable Energy Laboratory estimated a general 14% reduction in the PV output with different assumptions to match the site condition. Therefore, for this project it is assumed a value for $f_{pv.derating}$ of 92%.. $P_{pv.r}$ is the rated PV power output under standard test conditions (STC) as reported on the datasheet. G is the actual solar irradiance in a given time and G_{STC} is the irradiance at STC (1000 W/m^2). T_{pv} is the actual operating temperature while T_{STC} is the STC cell temperature (25 °C). Weather inputs (temperature and solar irradiance) are obtained from the Weather Data reported in Section 2.5.1. All the rest of the PV module parameters can be found on the datasheet of a commercially available PV panel [53].

2.4.2 BESS

Due to the characteristics of chemical and electrical processes taking place in battery cells, some losses and constraints need to be taken into account. The efficiency of a BESS is dependent on the battery, in addition to the power converter and thermal management system. Battery efficiency depends on technology type and can further vary based on C-rate [54]. In a study on a grid-connected BESS, the one-way efficiency is found to be 96.1 % and a round-trip efficiency of 92.5 % [55]. In this project, a one-way efficiency of 90 % for charge and discharge is assumed, and 81 % for round-trip efficiency. This is assumed for the entire BESS. The battery modelling is therefore not specific to a specific technology, but a surface-level black box modelling of a battery. The assumed efficiency is low compared to the paper.

Due to the chemical and electrical characteristics of batteries, a BESS has both losses and operational limitations. Overall efficiency reflects not only the battery pack, but also the power converter and thermal management system. Battery efficiency depends on the type of technology and varies with the C-rate [54]. For reference, a study on grid-connected BESS reported a unidirectional efficiency of 96.1% and a round-trip efficiency of 92.5% [55]. In this project, a one-way conservative value of 90% efficiency is adopted for both charging and discharging, implying a round-trip efficiency of 81%. This value is applied to the entire BESS. In this way, the battery model is not specific to a certain technology and can be treated as a black box. This decision is based on not overestimating the efficiency, which can lead to undersizing of the battery. The Equation (2.2) shows the maximum energy exchange possible for the battery. With the power reference defined on the system bus, only a fraction η of the load power effectively reaches the battery, hence the factor η is multiplied. On the other hand, in the case of discharge, the battery must supply more energy to cover the losses, resulting in η being divided in the discharge.

$$\Delta E_B^{\max} = \begin{cases} \eta \, P_{B.max} \, \Delta t, & \text{(charge)} \\ \dfrac{1}{\eta} \, P_{B.max} \, \Delta t, & \text{(discharge)} \end{cases} \tag{2.2}$$

Where:
$\Delta E_B^{\max}$ - maximum energy change within a single time period [MWh];
η - efficiency of the BESS [-];
$P_{B.max}$ - maximum discharging and charging power [MW];
Δt - time step [h] (e.g., 0,25 h for 15-minute data).

SOC limits can be seen in Equations (2.3). These limits are applied to ensure that energy storage is fully utilised. When using sub-hourly time resolution, having the full range of SOC can provide more precise information of the required C-rating.

$$\begin{aligned} SOC_{Min} &= 0\% \\ SOC_{Max} &= 100\% \\ SOC_{Min} \leqq SOC &\leqq SOC_{Max} \end{aligned} \tag{2.3}$$

Where:
SOC_{Min} - minimum SOC permitted for the battery [%];
SOC_{Max} - maximum SOC permitted for the battery [%];
SOC - current SOC of the battery [%].

Equations (2.4) describe how charging and discharging power is calculated.

$$\begin{aligned} P_{B.dis} &\leqslant \min\left\{ P_{B.max}, \; \frac{\eta \, (SOC - SOC_{min}) \, E_{B.max}}{\Delta t} \right\}, \\ P_{B.cha} &\leqslant \min\left\{ P_{B.max}, \; \frac{(SOC_{max} - SOC) \, E_{B.max}}{\eta \, \Delta t} \right\}. \end{aligned} \tag{2.4}$$

Where:
$P_{B.dis}$ - discharging power for the battery, to reach SOC_{min} [MW];
$P_{B.cha}$ - charging power for the battery, to reach SOC_{max} [MW];
$E_{B.max}$ - capacity of the battery [MWh];
$\Rightarrow$ - indicates that the equations are subject to not having values larger than the maximum power capability of the battery.

2.5 Input Time Series

Weather data is used to evaluate the PV production during the considered period. A load profile is used to accurately show the impact of a variable load in conjunction with RES.

2.5.1 Weather Data

To calculate photovoltaic production, time-varying meteorological data are required. In this study, hourly global tilted irradiance (GTI) and air temperature at 2 m are downloaded for the GLM location using the Open-Meteo API [56]. The data is obtained with a resolution of 1 h for the entire analysis window, timestamps are aligned with local time, night-time irradiance is set to zero and basic continuity checks are applied so that there are no gaps in the data. The profiles obtained are exported to CSV and used as inputs for the PV model.

The PV and BESS models operate at 15-minute intervals, so the meteorological data is converted from 60 minutes to 15 minutes using a simple routine. The idea is to keep the hourly energy exactly the same, while creating a sub-hourly profile that looks realistic:

1. For each hour and the next, a straight line is drawn between these two
2. Four 15-minute samples are taken within the hour at the centres of the four sub-intervals
3. A small random 'oscillation' is applied around the line, limited by a tolerance $\pm$tol. This creates a 'natural' variation
4. These samples are rescaled so that their average within the hour is exactly the original value.
5. Physical limits are applied: values are clipped to zero when necessary (for night-time irradiance) and negative values are not allowed.
6. The final 15-minute series are exported to CSV for direct use in the PV model.

To make the method simple but credible, jitter tolerance is set seasonally based on typical variability within an hour: in summer, 5% is used (clearer skies, less variability), in spring and autumn, 10-12% (intermediate variability) and in winter, 15% (more clouds). The air temperature is linearly interpolated to 15 minutes without fluctuations. Figure fig. 2.2 compares, for each season, the first day of the series at 1 hour and at 15 minutes to verify that the sub-hourly curve is smooth and that the hourly average is preserved.

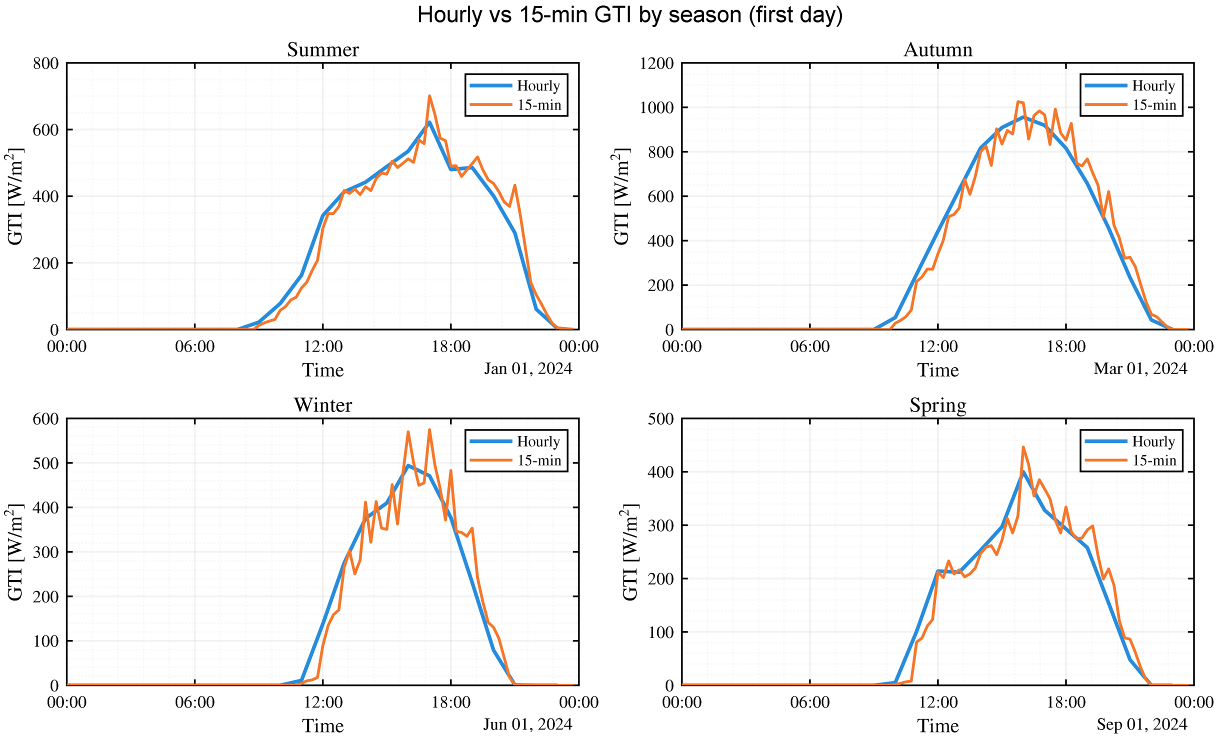

Figure 2.2: Hourly-to-15 min conversion shown for the first day of each season.

2.5.2 Photovoltaic Production

PV production is calculated with a resolution of 15 minutes using meteorological data and the model described in Section 2.5.1. For plotting and scaling, a base size of 20 MW is adopted, as this is consistent with recent PV installations at comparable mines in Western Australia, such as DeGrussa (around 10.6 MW), Granny Smith (around 7.7 MW, with plans to expand to 19 MW), Kathleen Valley (around 16-17 MW) and Tropicana (around 24 MW) [9, 57, 58, 59]. Therefore, 20 MW provides a benchmark that can be linearly rescaled later if necessary.

Figure 2.3 shows a heat map of PV power by hour of the day (rows) and day of the year (columns). The maximum is reached around midday and is higher and broader in summer (December-February in Australia), while winter profiles are shorter and lower. Cloudy days appear as visible reductions.

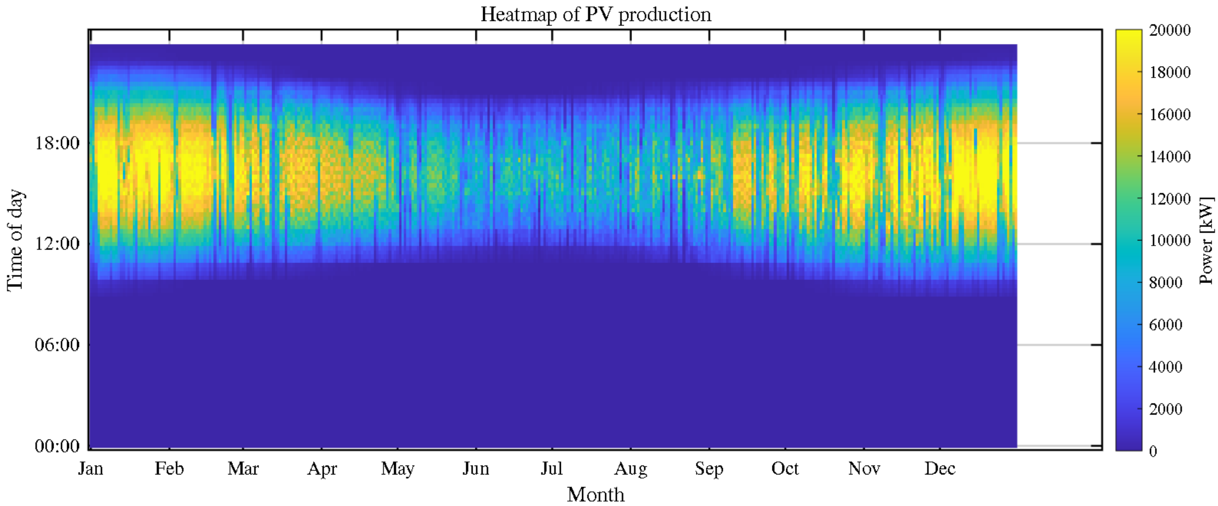

Figure 2.3: Heat map of PV production across time of day and day of year (15-minute resolution).

Figure 2.4 shows quarterly box plots of PV production. The distribution follows the expected seasonal pattern: Q1 and Q4 have higher medians and wider ranges, in line with longer days and higher irradiation, while Q2 and especially Q3 show lower values and smaller dispersions. The numerous high values in the second and third quarters indicate brief intervals of clear skies around midday that boost production. Overall variability within the quarter is considerable, reflected by the 15-minute resolution.

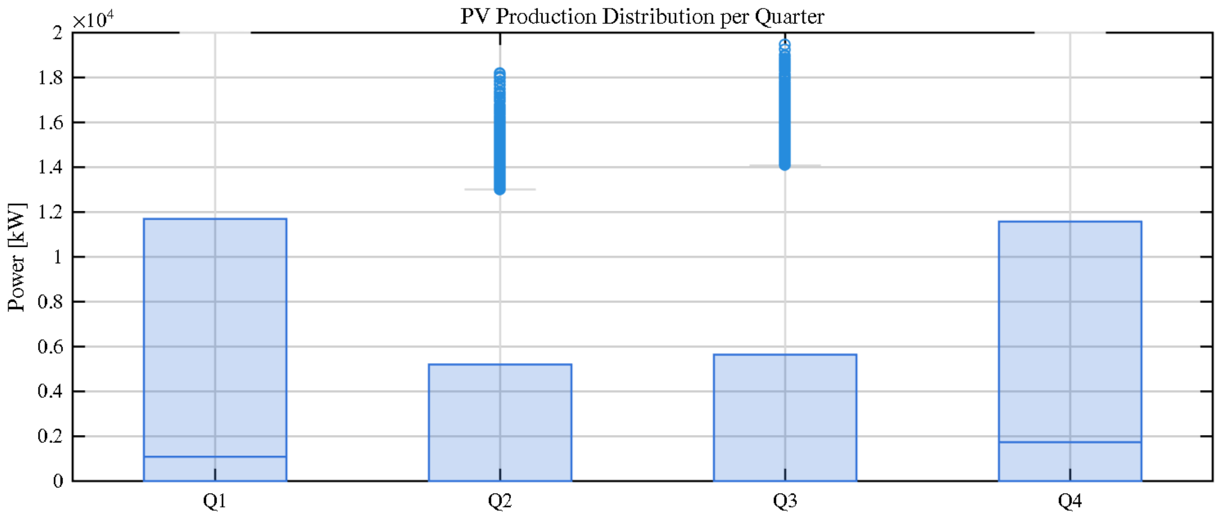

Figure 2.4: Quarterly box plots of PV production (15-minute resolution).

2.6 Load model

The load time series is provided by AAU Energy as an anonymized site demand profile. No additional preprocessing was applied prior to the process described below. The hourly demand series is converted to a 15 min profile using the same routine described in section 2.5.1. Hourly energy is preserved and a fixed $\pm 10\%$ jitter adds realistic variation.

The resulting 15 min profile tracks the hour-to-hour trend smoothly and introduces modest variability that is useful for BESS operation studies. The hourly means of the 15 min series match the original series to numerical precision.

2.6.1 Load Profile

To represent a realistic magnitude of the site, the hourly series is scaled to a target average of 15 MW and the maximums are limited to 28 MW. The use of 15 MW as an annual average maintains a credible operating level for current conditions, and the MW cap avoids unrealistic peaks that would exceed the contracted grid limit, while maintaining consistency with the site's connection and expansion path. Figure 2.5 shows the hourly and 15 min load profiles for a week.

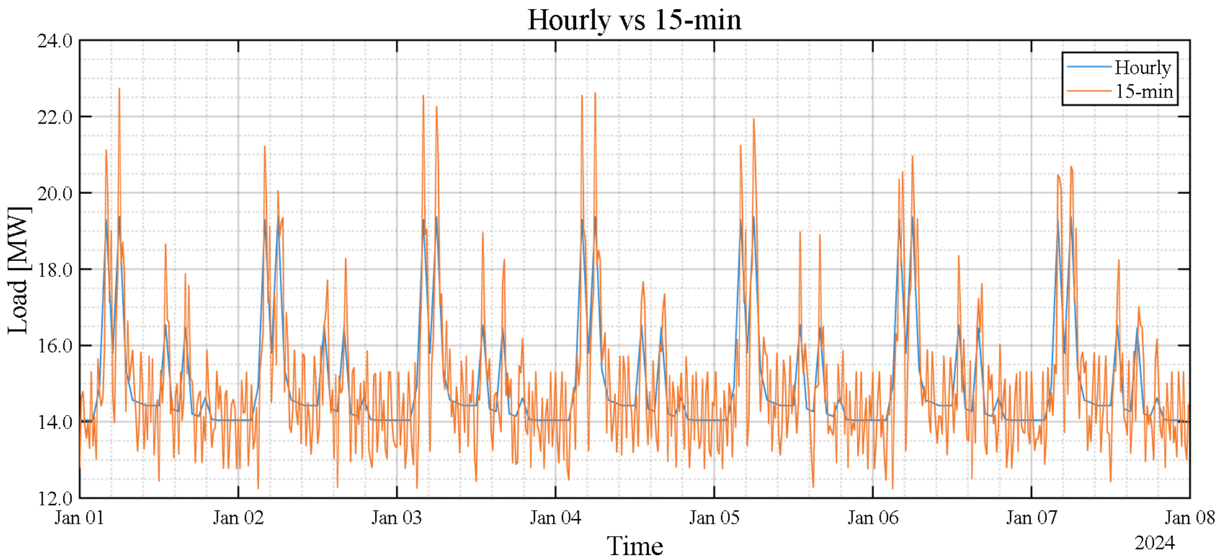

Figure 2.5: Hourly load and 15 min profile for the first week. The 15 min curve transitions linearly within each hour and shows small deviations due to the ±10% jitter.

2.6.2 Criteria to distinguish loads

The site load is divided into four classes: critical, non-restrictive, deferrable, and non-critical, so that dispatch and storage can maintain safety and performance while, as far as possible, taking advantage of temporary displacement. The classes refer to a GLM-type mine.

Classes are ordered from highest to lowest priority. Depending on the situation, they are maintained or restored in this order.

- *Critical services*: Necessary for safety, legal compliance, and protection of personnel and equipment. These include control and communications, mandatory ventilation where applicable, and drainage to prevent flooding risks. They must continue to receive uninterrupted supply during network failures and incidents.
- *Non-curtailable process units*: Continuous units essential to ensure production. Stopping them causes large losses or long restart times. Typical examples are crushing and grinding chains in the mine.
- *Deferrable loads*: Loads with time windows that allow limited displacement without affecting production. Some examples are storage conveyor belts and some auxiliary services. They can be shifted in time within defined limits so that their operation is aligned with PV availability and BESS usage.

- *Non-critical loads*: Their uses are related to comfort, so they can be reduced or limited for long periods within agreed limits. Examples include air conditioning systems, non-essential lighting, and certain office activities.

This classification follows established practices and regulations regarding microgrid prioritisation and is consistent with mining data. [60, 61, 62].

2.6.3 Load classes

The total load for the mine has been scaled up to an average of approximately 21 MW. Based on the Greenbushes flow diagram and standard prioritisation, the model uses:

- *Critical (20%)*: conservative value to cover safety/compliance requirements in a mine such as GLM, consistent with microgrid prioritisation guidance.
- *Non-curtailable (60%)*: reflects the main continuous process block; crushing is reported to consume the most electricity, and the Greenbushes flowsheet is conventional and stable.
- *Deferrable (15%)*: moderate allowance for time-shifting without creating bottlenecks.
- *Non-critical (5%)*: residual share after allocating the other blocks; reasonable where process dominates site demand.

Table 2.1: Summary of load classes for GLM mine.

Class	**Subsystems**	**Importance**	**Mean**	**Source**
Critical	Control & comms, essential services, mandated ventilation, base dewatering	Safety/compliance and integrity	20%	[60, 61]
Non-curtailable	Primary crushing, grinding, flotation	Continuous dominant block	60%	[62, 63]
Deferrable	Water transfer to storage, tailings pumps, scheduled EV charging	Buffers/windows allow shifting within limits	15%	[60, 61]
Non-critical	Admin HVAC/lighting, non-essential workshops, area lighting	Comfort/convenience, curtailment acceptable within bounds	5%	[60, 61]

2.6.4 Reconstruction of load profiles by class

This procedure splits the one-year, 15-minute total load into four classes by annual energy share and priority: Critical (20%), Process non-curtailable (60%), Deferrable (15%), and Non-critical (5%). The percentages refer to energy over the year, not fixed power at each timestep. The procedure is:

- Set annual energy targets for the four classes using 20/60/15/5.
- Place Critical first as a nearly flat baseline (around 4–5 MW for a 21 MW average) and adjust it slightly so it totals 20% of annual energy. The remaining load is used by the next classes.
- Build the Non- Critical profile from the remaining load as a smooth, slowly varying profile (daily/seasonal shape) and scale it so it totals 60% of annual energy.

- Allocate Deferrable day by day with a daily quota consistent with 15% over the year, filling first the valleys (hours with more headroom) and respecting a simple power cap and basic time windows.
- Fill Non-critical last load adjusting so it totals 5% of annual energy.

The original load was not aligned to the solar cycle. Demand stayed relatively flat while PV rose and fell, leading to daytime charging nightime discharging of the battery. To address this, a reshaping is first applied so the load leans toward daylight hours without changing annual energy. Then, the deferrable portion is placed during a daytime window, prioritising hours with both space in the residual and PV availability. The resulting classified profile shows a clear "belly" during mid-day, meaning that there is more use when the sun is up and less in the rest of the hours. This creates a load profile that is better matched to PV, and therefore, more realistic. Figure 2.6 shows the comparison between the original load and the reshaped one.

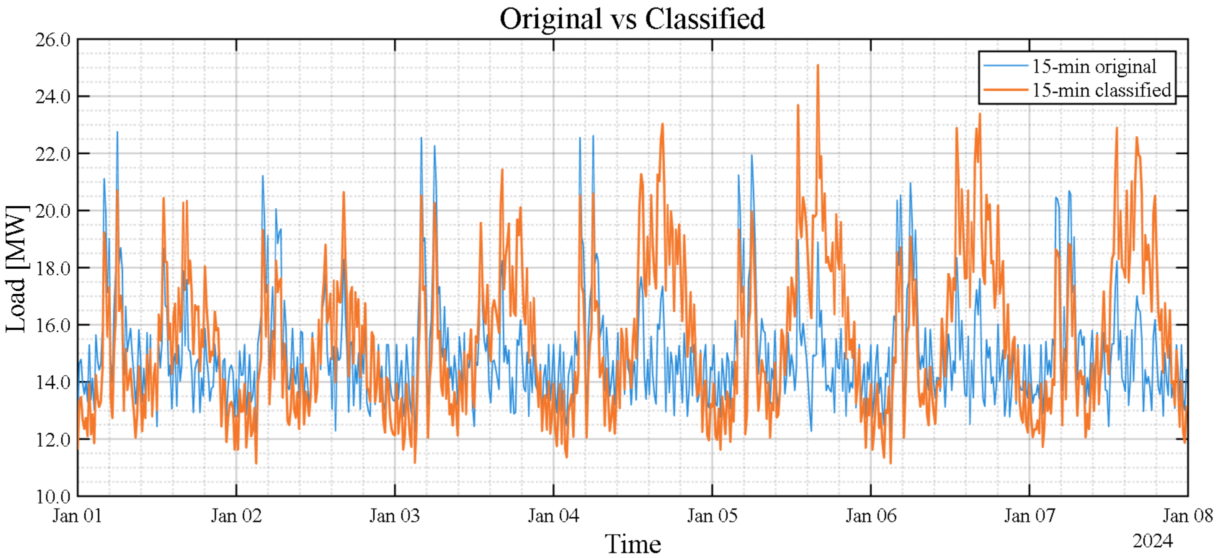

Figure 2.6: Comparison of the original load (blue) and the final classified profile (yellow). The classified one produces a realistic "belly" aligned with PV.

2.7 Scenarios & Cases

This section presents three scenarios with the aim of studying an isolated HES system. A full year is simulated with 15-minute resolution. PV production and load profile use the dataset indicated and there is no grid support.

The first scenario compares four PV plant sizes in two operating modes: with curtailment disabled and enabled. Its purpose is to evaluate the trade-off between curtailment and BESS requirements, while maintaining the annual load supply. The main objective is to understand how different PV sizes and the possibility of curtailment modify parameters such as the BESS size (energy and inverter), and how the most balanced PV-BESS combinations are selected.

The second scenario assesses how different SOC values at the beginning of the year affect the optimal size of the BESS with and without curtailment. The objetive is to see how the initial SOC changes the dispatch and different BESS parameters throughout the year.

The last scenario implements a diesel generator in order to limit the size of the BESS. A generator power is set and an annual usage cap is calculated by using a fuel quota. This scenario allows to see how the use of the generator can change the BESS size, the PV distribution and the behaviour of the system in critical weeks with low irradiance.

3. Optimisation Design

3.1 Selected optimisation method

This chapter presents the selected optimiser, called REopt [64]. Its use in this project is based on energy management in an islanded system with PV and BESS. It is selected for its reliability, simplicity of configuration and reproducibility, and for considering a full year at 15-minute resolution without overcomplicating the model. REopt optimizes the power generation and storage by considering energy and power limits, SOC and efficiencies, maintaining consistency between intervals. The simulation parameters are controlled with minimal options and parameters, which simplifies its use and the review of parameters.

In this project, REopt is mainly used as an PV-BESS system sizing.BAsed on the sizes obtained, then the aim is to obtain consistent power and SOC profiles from established data on demand and PV resources, without analysing costs or economics. The operation is off-grid, with a 15-minute interval over one year. The PV plant operaates in MPPT by default, but curtailment is allowed when necessary.

The inputs and settings that REopt provides are deliberately minimal to reduce complexity: the required CSV files obtained in the previous chapters are taken, 'off-grid' mode is enabled and the time resolution is set, then the basic and fixed storage parameters (power, energy and SOC ranges) are set. REopt offers a good balance between operational realism, simplicity, and repeatability. It provides the basis for further analysis of battery behaviour without going into detailed sizing.

3.1.1 REopt as a MILP with Gurobi

REopt uses an optimization model known as a mixed-integer linear programme (MILP) and solves it using Gurobi software [65]. In general terms, a MILP is a large spreadsheet that searches for an optimal combination that complies with simple rules expressed as linear relationships. Within it, some decisions can take continuous values and others must be integer values. A subset of these integer values are binary to encode yes/no decisions.

To solve this type of model, Gurobi uses a step-by-step process. First, it temporarily ignores the 'integer' part and solves a simpler version of the problem. Then, when it identifies that certain decisions should be 0 or 1, it divides the problem into smaller cases and discards regions that it knows will not be useful. As it progresses, Gurobi reports how close it is to the optimal result using a measure called the 'optimality gap'. A balance between speed and quality is achieved by using two parameters: the required gap and the maximum time.[66].

This approach has certain advantages. The model is simple, as all rules are written using linear operations that are easy to review. It is also transparent: if the gap is reduced to zero, it is known that there is no better solution under the data and assumptions provided. If the gap is small, it is known how close the result is to the optimum. Furthermore, setting up these conditions is usually as simple as adding or adjusting a linear rule, without changing tools [67].

The model also has certain limitations. In order to use a MILP, it is necessary to consider some simplifications of behaviours that are non-linear in reality and accept that the model does not reflect all physical aspects. Furthermore, the model assumes that all input series are already known and will not undergo modifications, which means that uncertainty is not modelled within REopt. Finally, as the size of the problem or the number of integer decisions grows, so does the computation time. Therefore, it is advisable to set reasonable limits on the variables to facilitate the solver's work.[64].

REopt operates sizing and dispatch with a techno-economic objective that minimises the total cost. In island mode, unserved energy receives a high penalty, so REopt tries to meet the demand whenever it is technically possible. In this project, the objective is to obtain the sizing and other battery characteristics without performing a deep economic analysis.

3.2 REopt Scope and assumptions

In order to determine the scope of the model and establish the working assumptions used throughout this chapter, an island mode case with sub-hourly resolution and predefined inputs has been chosen, using the tools provided by REopt.[64]

- System limits: Isolated HES with PV and BESS. No grid connection and no diesel generators.
- Resolution: One full year with 15-minute intervals (35,040 intervals).
- Data inputs: the load and PV series defined in Chapter [**?**] are used.
- Unsupplied energy: allowed with high penalty to reflect island operation.
- Battery: power and energy limits, efficiencies, and SOC according to parameters in Section 2.4.2.

3.3 REopt Configuration

This section describes how to configure, parameterise, and run REopt. It explains how file paths, series formats, and basic solver parameters work. To avoid repetition, the models are not re-explained; only the inputs and settings necessary to obtain the results are specified. [64]

File structure and format

- Working directory: contains CSV files for load and PV production factor, plus a script that builds the payload and runs the optimisation.
- Load: a numerical column in [kW] with 35,040 rows (15 minutes over one year).
- PV production factor: series representing the fraction of PV power available relative to its nominal value (range between 0 and 1). It must have 35,040 values and be aligned in time with the load. REopt reads this file in this format and uses it as a factor to multiply it.
- Year of analysis: must match the calendar of the series (e.g., 2024). REopt uses the year to mark the time steps internally.

- Payload: JSON file[1] with the input data for REopt: year, loads, PV production factor and the BESS parameters.

Minimum payload parameters

- Settings: `time_steps_per_hour` = 4 (15 minutes) and `off_grid_flag` = `true`. Also set `timeout_seconds` and `optimality_tolerance` to control computation time and the optimality gap.
- Site: `latitude` and `longitude`.
- ElectricLoad: `loads_kw` with 35 040 values, calendar `year`, and `critical_load_fraction` = 1.0 in islanded mode.
- PV: `production_factor_series` (35 040 values) and basic technology parameters such as `dc_ac_ratio` and `inverter_efficiency`. To disable curtailment, set `can_curtail` = `false`.
- ElectricStorage: limits `min/max_kw` and `min/max_kwh`, fractions `soc_min_fraction/soc_max_fraction`, and efficiencies as per the specification. If grid charging is not desired, set `can_grid_charge` = `false`. [64]

REopt summary and execution

To summarise, the execution of the script is described below. The chosen REopt method is utilized in a python script through the REopt API [68]. The script configures optimisation in island mode with a resolution of 15 minutes. Next, the power and energy ranges for the PV and BESS are defined. Then, the script loads the demand and production factor series in CSV format and sends the request to the service, waits and periodically queries until a solution is obtained. When finished, it reports the status and saves the results in JSON. The expected keys and types of the payload are summarised in chapter B.

3.4 Dispatch logic

In island mode and without curtailment, the REopt result reads as follows: in each interval, the PV first supplies the demand and charges the battery (within its limits) if there is surplus energy. The battery then provides the energy needed to cover the rest of the demand when the PV is not sufficient, respecting its power and energy capacities and SOC ranges. In the event that the demand cannot be met by either PV or BESS, the missing (unmet) energy is recorded with a high penalty to reflect the priority of supply in island operation. When a diesel generator is implemented, REopt optimizes PV, BESS and now diesel. The generator supplies energy if there is still a shortage of energy after the PV-BESS dispatch. Unsupplied energy is recorded only when none of the three sources can cover the demand. Since that situation carries a high penalty, diesel is used before leaving unmet load. PV curtailment occurs when the load is covered and the battery cannot charge any more.

Under this logic, REopt returns series of effectively used PV power, battery power (with its sign), state of charge, and unserved energy per interval. These outputs allows to build the operation management profiles for PV-BESS islanded system.

[1] JSON is a text format for data with key:value pairs and lists. Example: `{"year": 2024, "loads_kw": [120.5, 118.2]}`.

3.5 Output interpretation & workflow

The results obtained from REopt consist of two types of outputs: optimal resource sizes and operation management time series. In terms of sizes, the model returns the nominal power of the photovoltaic system and the power and energy of the battery. In terms of series, it provides PV per unit production series, battery power, the state of charge and the energy not served per interval. To facilitate understanding of the optimiser, a workflow diagram 3.1 is provided that summarises the entire process.

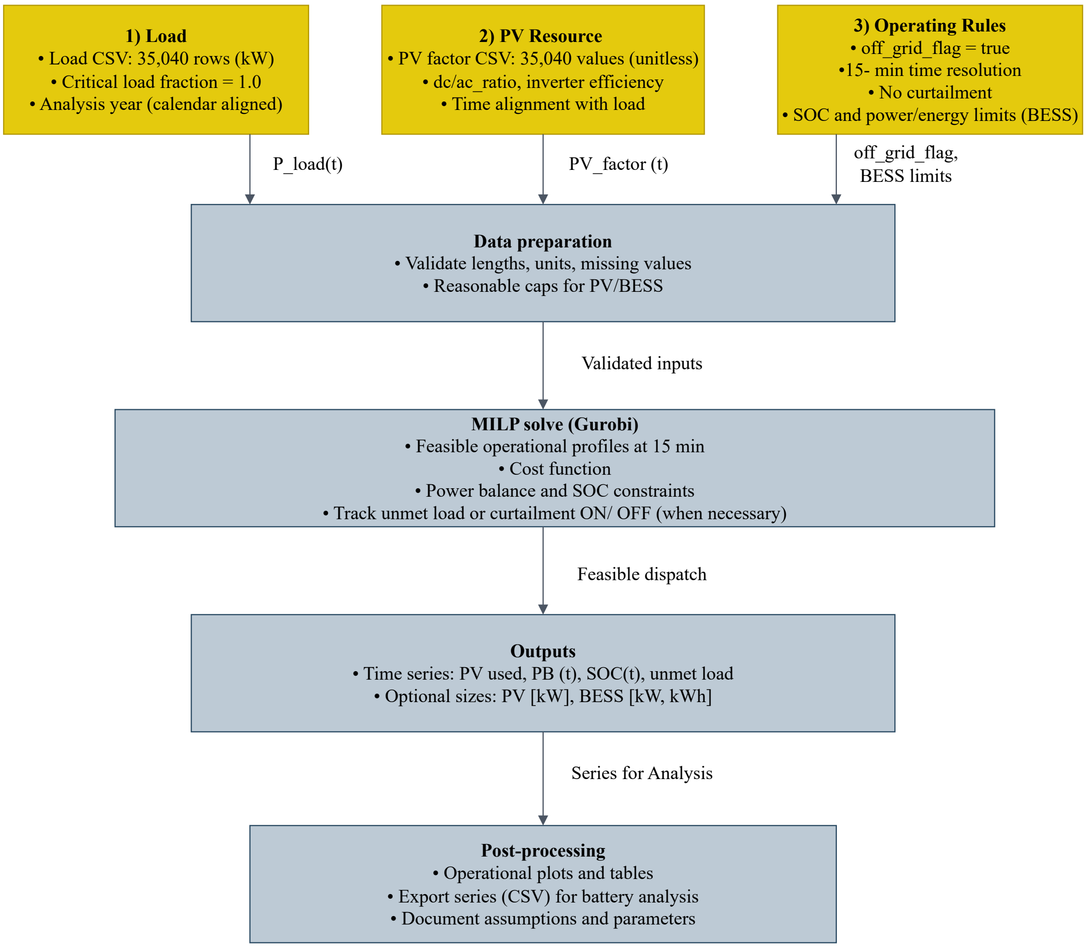

Figure 3.1: REopt workflow adapted to this project.

4. Optimisation Results

4.1 Verification of HES model

Before presenting the sizing results and comparation of scenarios, a verification that the HES operates in a coherent way is carried on. In order to do this, two representative days are used with an average consumption power of around 15 MW, without curtailment and with an initial SOC of 95%. Thus, one day of lower PV production and another of high PV production are analysed.

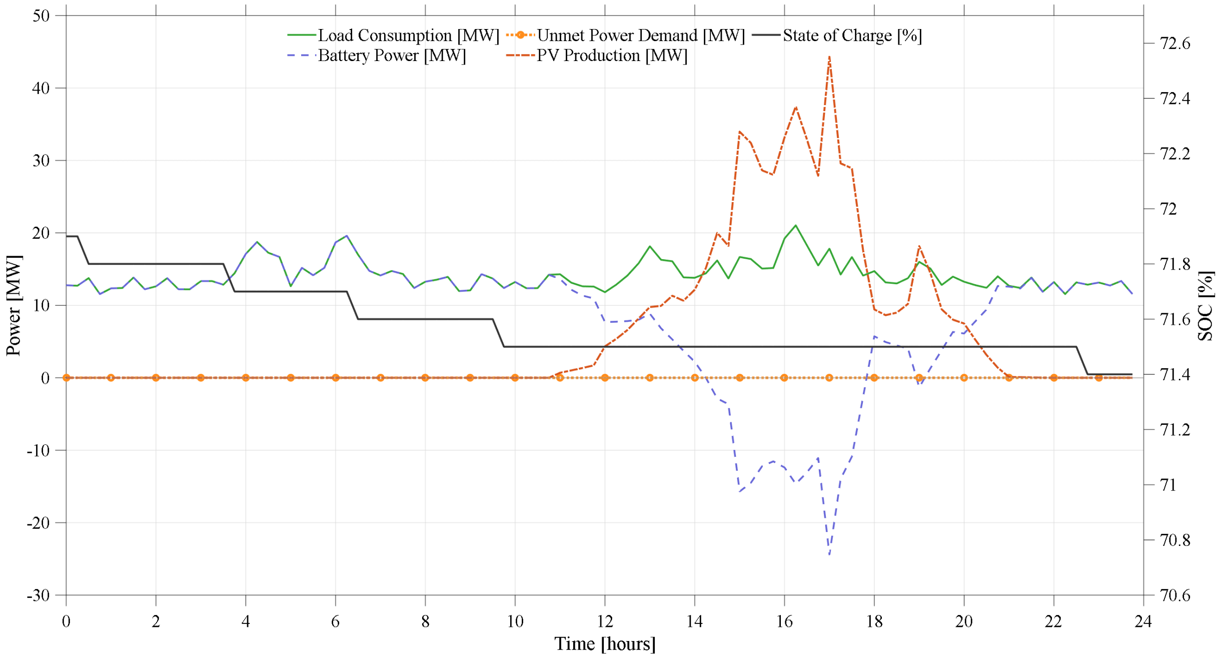

Figure 4.1: Verification on a low irradiance day. Load, BESS power (discharge >0, charge <0), PV production and SOC are shown.

As seen in Figure 4.1, at the start of the day (during the night) there is no PV production and the battery covers the entire demand. This can be observed in a positive battery power and a slight decrease in SOC. When the sun rises, PV production increases and starts to meet the instantaneous demand. When there is a surplus, it is supplied to the battery and the battery power goes negative (charging).

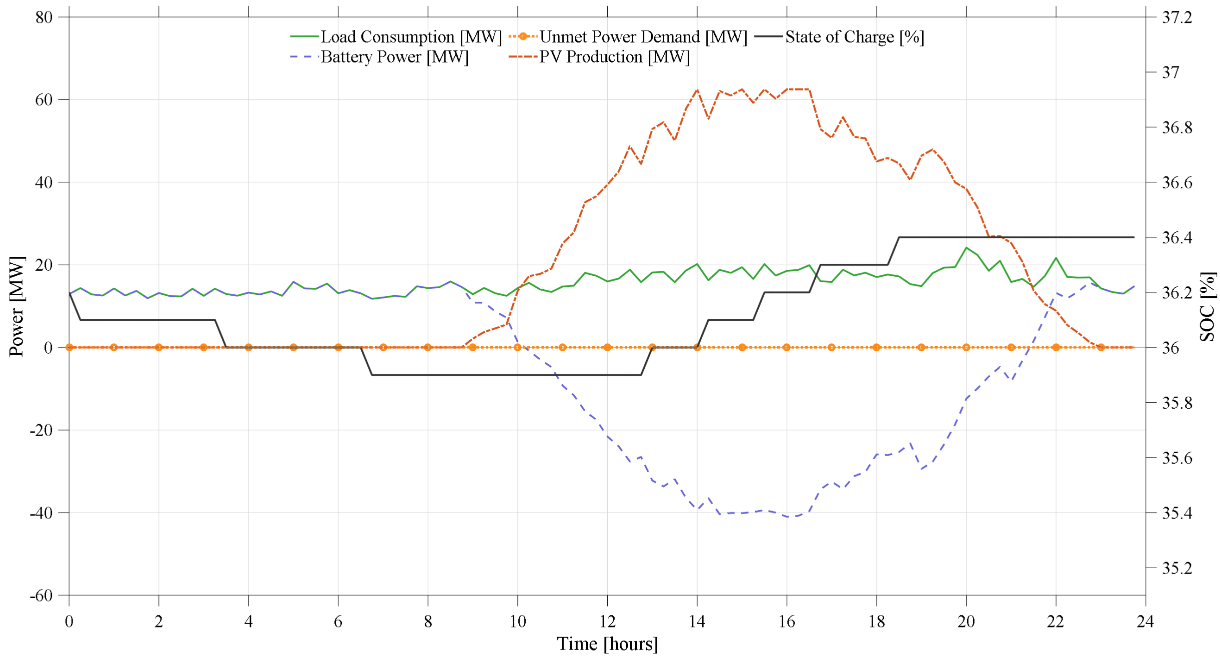

Figure 4.2: Verification on a high irradiance day. Load, BESS power (discharge >0, charge <0), PV production and SOC are shown.

Throughout the afternoon, the optimization prioritises PV over charging, and the BESS varies its power accordingly, reducing the charging power (the curve approaches zero) when the PV must cover increases in demand, and entering discharge mode when PV is not sufficient (positive power). On the high PV day in Figure 4.2, the BESS charges continuously until sunset, while on the low PV day the transition to discharge happens earlier. At dusk, PV completely drops and BESS takes over by supplying power to the plant.

Observing the SOC curve, the behaviour observed is that when the BESS is discharging, the SOC drops slightly, while when it is charging, the SOC curve increases. On the low PV production day, the charging window is shorter and the magnitude of the BESS charge is lower, so the SOC recovers less and ends the day below the first hour's value. On the other hand, on the high PV day, the SOC recovers more and ends the day above the previous value. As can be seen, the variation in SOC is barely noticeable. This is because the figures show how SOC varies in a single day, while the model measures a full year that must fully cover the demand. This annual horizon leads to very large battery sizes. Thus, such SOC variations are hardly noticeable in the figures.

On both days, the unmet demand is zero when operating without curtailment and with the considered sizing. The sum of PV to load and BESS covers the demand in each interval, and when necessary, BESS compensates for transitions. Overall, the instantaneous balances and SOC evolution are consistent with the model scheme, confirming that the implemented optimization reproduces a valid behaviour of the HES.

4.2 Optimisation Results

The different scenarios and cases presented in Section 2.7 are analysed in this section. The load considered in all scenarios has an average value of 15 MW computed over the full dataset (1 full year).

4.2.1 Influence of PV size on BESS size

This scenario compares four PV plant sizes in two operating modes: with (ON) and without (OFF) curtailment. The aim is to compare how much PV is curtailed and how much is required by the BESS, ensuring that the site's annual demand continues to be met. An annual summary is presented in the following table with the obtained results. The curtailment percentage is calculated as the curtailed PV energy (reported by REopt) divided by the annual available PV energy.

Table 4.1: Annual summary of the PV sizes Scenario. For each case, the size of the BESS (energy and inverter power), the PV production, the curtailment relative to PV and the peak discharge of the BESS are reported.

PV (MW)	**Mode**	**Curtail. (%PV)**	$E_{\mathbf{BESS}}$ **(GWh)**	$P_{\mathbf{BESS}}$ **(MW)**	**PV→load (%PV)**	**Discharge peak (MW)**
50	OFF	0.00	63.25	23.74	69.24	20.56
	ON	0.00	63.25	23.74	69.24	20.56
75	OFF	0.00	46.48	83.60	41.94	24.49
	ON	1.77	30.85	38.93	50.31	20.72
90	OFF	0.00	147.37	95.57	30.67	24.75
	ON	6.76	21.33	45.05	43.00	20.72
100	OFF	0.00	245.66	103.51	26.41	24.75
	ON	11.97	17.58	40.64	39.19	20.72

Table 4.1 shows the trade-off between curtailment and storage based on six indicators. For a solar PV size of 50 MW, the six indicators are independent of the curtailment mode. This is because at 50 MW, PV production rarely exceeds the demand, so there are no surplus excesses. Therefore, even though curtailment mode is active, there is no energy to curtail.

The first results that stands out is the remarkable difference between BESS power and energy. Power (MW) reflects the instantaneous rate at which the BESS can charge or discharge, while energy (GWh) marks the total volume it can store over time. Even though the power is in the tens of MW, the annual throughput reaches tens or huncdreds of GWh. This shows that the use is focused on moving energy over many hours, charging during periods of high PV production and discharging at night or during periods of lower irradiance. Thus, the system prioritises energy over power, approaching a more seasonal storage behaviour.

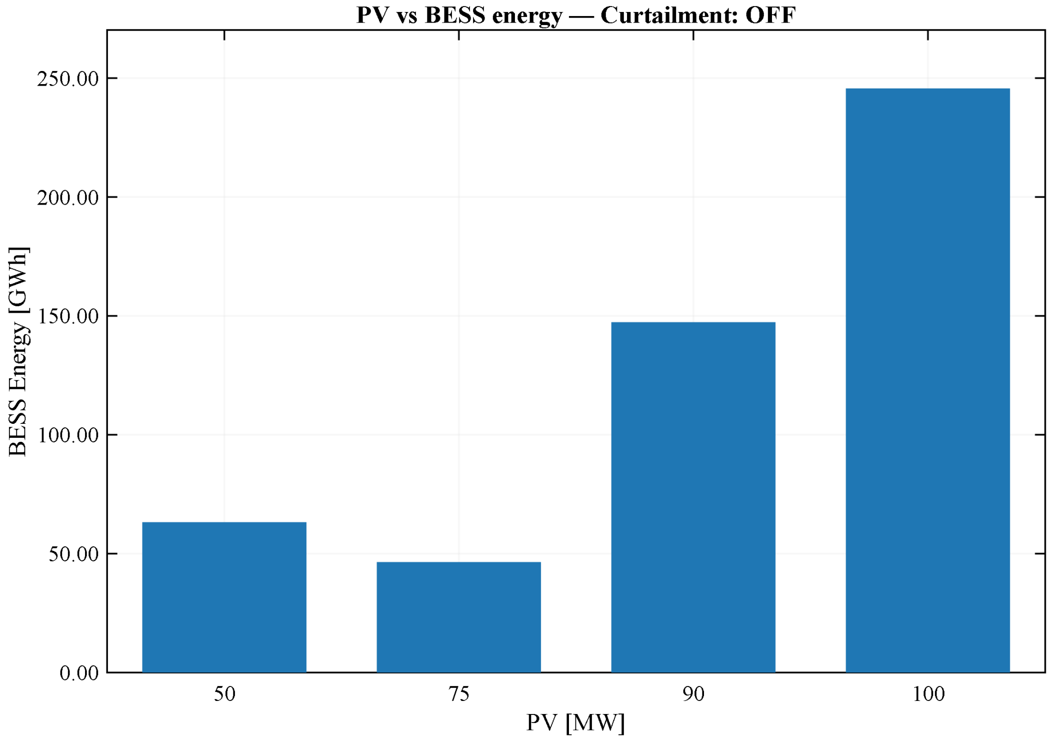

Figure 4.3: PV Power versus nominal BESS energy when curtailmet is desactivated
.

As can be seen, increasing the size of PV without curtailment (Figure 4.3) increases the size of the BESS, as it needs to storage all the energy coming from the PV. When curtailment is activated (Figure 4.4), there is a percentage of PV production that is not used, which increases with the size of the plant. Curtailment is a small value when PV is 75 MW and increases significantly at 90 and 100 MW. In return, the BESS energy capacity decreases significantly and the BESS power is also reduced. This behavior is explained by the fact that, with curtailment, the fraction of energy that is supplied directly to the load increases and the necessity to shift energy between hours using the battery decreases.

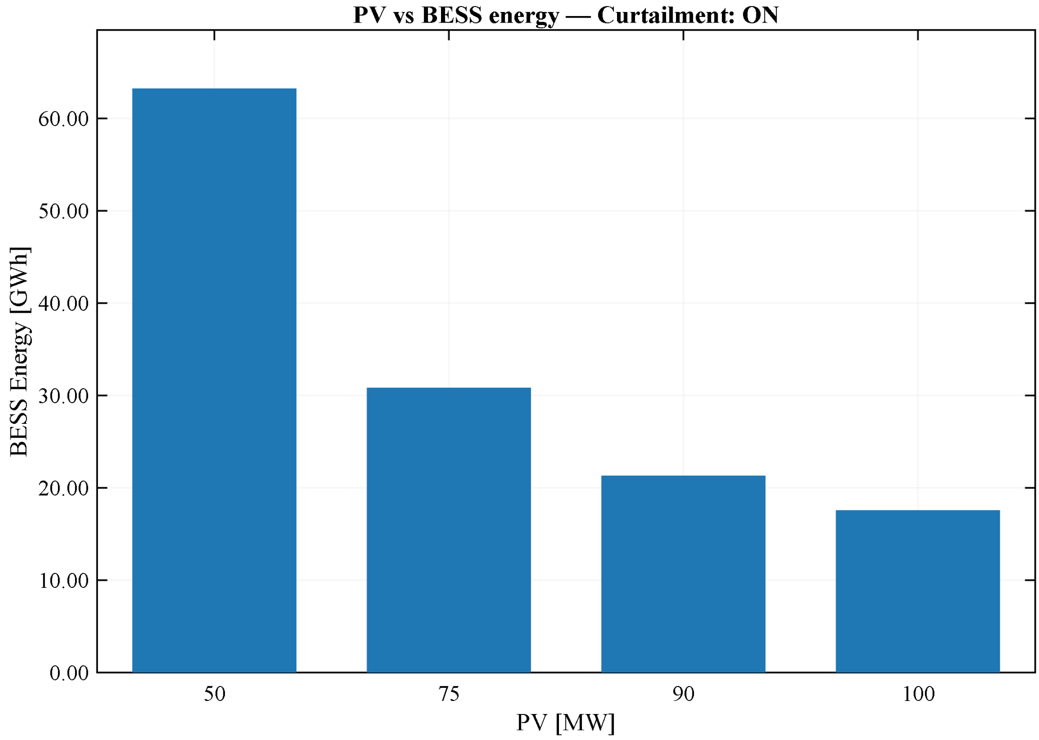

Figure 4.4: PV Power versus nominal BESS energy when curtailmet is activated
.

When PV capacity increases and curtailment is not allowed, there are more hours with solar surplus just when demand does not need it. To avoid wasting it, this surplus PV energy is charged into the BESS. Thus, the energy amount supplied directly from PV to the load stops rising and declines as a fraction of the total PV output. If curtailment is activated, the control prioritises using the PV at that moment and allows the small surplus to be curtailed, increasing the PV that goes to the load and decreasing the one that goes to the BESS.

The discharge peak of the BESS varies for the same reason. Here, P_{BESS} is the nominal power of the inverter on the AC side, while 'discharge peak' is the maximum discharge power observed in the results. Without curtailment, when accumulating more energy for hours without sunlight, the battery has to 'work harder' in the afternoon and its discharge peaks are higher. With curtailment, there is less energy to shift and the battery does not need to deliver as much power at once, so the discharge peaks decrease. Note that BESS power is still higher than the discharge peak since the rating is conditioned by the peak load and not by the maximum discharge.

Overall, when there is no curtailment, increasing the PV from 50 to 100 MW causes the BESS size to increase: the annual energy is multiplied by approximately 4 and the power increases 4.5 times. On the other hand, with curtailment activated, the scenario changes: for the same PV; the system needs to move much less energy and requires more moderate power. At 100 MW, the energy drops 14 times and the power 2.5 times with a 11.97% of curtailment. It can be seen that the case of 75 MW with curtailmet represents a balance: curtailment is low (1.77%) and the reduction of the size of the BESS is substantial (approximately 16 GWh and 45 MW are cut). At 90-100 MW, the BESS is further decreased, leading to higher curtailment.

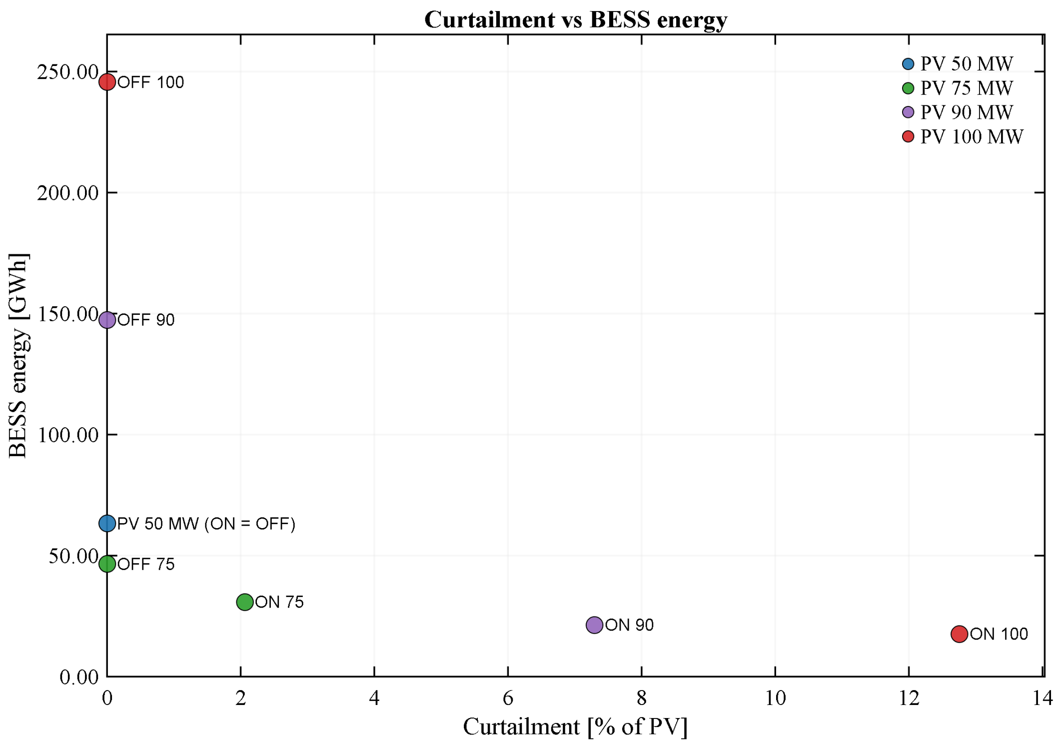

Figure 4.5: PV Curtailment versus nominal BESS energy (scatter plot). Each point is a case (ON = Curtailment/OFF = No curtailment due to PV size). Identical cases (e.g., PV 50 MW) are shown as a single marker(ON = OFF)

.

Figure 4.5 shows the scatter plot, which represents curtailment on the horizontal axis and BESS energy on the vertical axis. The preferred region is located at the lower left corner, where curtailment is low and the battery is small. Without curtailment, the cases remain on the left but increase the battery size as the size of PV increases. When allowing curtailment, the points begin to shift slightly to the right but clearly decrease, indicating significant reductions in BESS energy. The 75 MW case with curtailment approaches the 'sweet spot' thanks to reduced curtailment, which already provides a significant decrease in storage. The 90 and 100 MW sizes descend even further on the vertical axis, at the cost of accepting higher curtailment percentages.

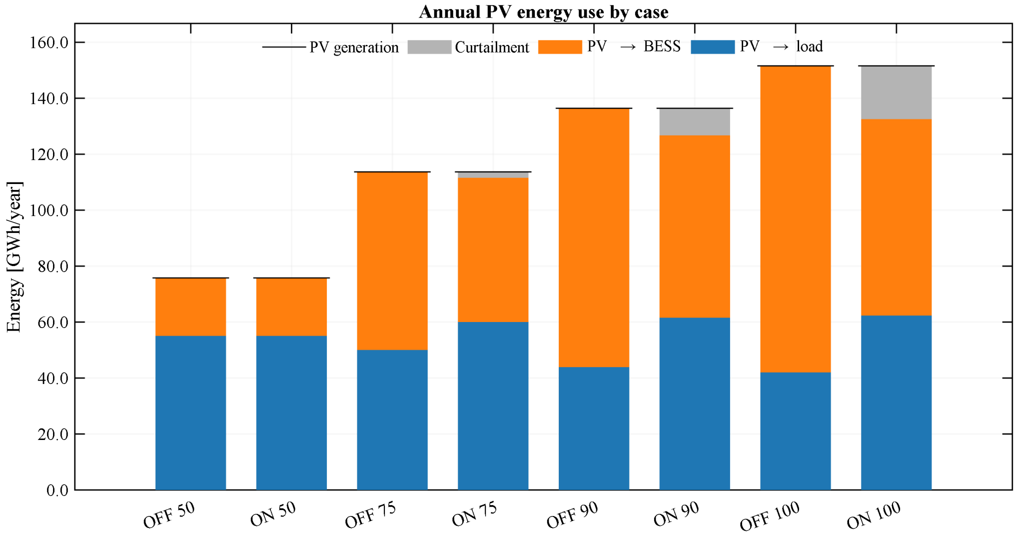

Figure 4.6: Annual PV energy usage per case: PV→load (blue), PV→BESS (orange) and curtailment (grey). The horizontal black line on each bar indicates the total PV generation for every case.

Figure 4.6 shows energy usage per case. The stacked bars break down annual PV usage into three categories: PV to load, PV to BESS and curtailment. With curtailment active, the PV-to-load energy increases only slightly, whereas most of the change comes from less PV-to-BESS charging and more curtailment. The black reference line indicates that the total generation in each case remains the same, what changes is the internal distribution. This change is explained by the reduction in energy capacity and power of the BESS. As less shifting between hours is required, the storage can be scaled down and operate with lower power peaks.

4.2.2 Influence of BESS initial SOC on BESS size

This scenario evaluates the effect of the initial BESS SOC state at a PV power of 100 MW in two operating modes: with (ON) and without (OFF) curtailment. The PV size has been selected based on having sufficient curtailment to obtain distinguishable cases, since in the previous scenario with 100 MW a higher percentage of curtailment was obtained. The objective is to compare how different variations affect the optimal size of the BESS (energy and inverter power), the distribution of PV power between direct consumption and battery charging, curtailment and other indicators, while maintaining coverage of the site's annual demand.

Table 4.2: Annual summary of the initial SOC Scenario.

SOC_0	Mode	Curtail. (%PV)	$E_{\mathbf{BESS}}$ (GWh)	$P_{\mathbf{inv}}$ (MW)	PV→BESS (%PV)	cycles/yr	$SOC_{\min}$ (%)
0.10	OFF	0.00	31.18	63.22	58.90	2.19	0.0
	ON	0.00	31.18	62.90	58.90	2.19	0.0
0.25	OFF	0.00	17.58	63.22	66.76	4.56	0.0
	ON	2.03	17.58	49.59	56.83	3.88	0.0
0.35	OFF	0.00	18.91	98.96	72.27	4.69	7.0
	ON	4.58	17.58	43.09	54.27	3.88	0.0
0.50	OFF	0.00	24.57	99.65	72.28	3.60	28.5
	ON	6.97	17.59	40.94	51.91	3.88	0.0
0.75	OFF	0.00	49.14	101.01	72.29	1.80	64.2
	ON	10.11	17.59	40.64	48.80	3.88	0.0
0.85	OFF	0.00	81.89	102.29	72.30	1.08	78.5
	ON	11.33	17.59	40.64	47.53	3.88	0.0
0.95	OFF	0.00	245.67	103.51	72.31	0.36	92.8
	ON	12.56	17.59	40.64	46.32	3.88	0.0

Table 4.2 summarises, for each mode and SOC_0, the PV curtailment, the energy of the BESS, the inverter power, the PV→BESS fraction, the equivalent full cycles per year and the minimum SOC reached. When curtailment is OFF, the optimiser tends to increase the size of the BESS when the SOC_0 is high. The reason is that, with less space available at the beginning of the year, the battery must be larger to absorb the PV surpluses without curtailing. Furthermore, as SOC_0 increases, the minimun SOC no longer reaches 0% since the BESS is oversized at high SOC levels during winter season. This is consistent with the equivalent annual cycles shown in the table, which decrease as SOC_0 increases, meaning that a very large battery is used more for seasonal storage than for daily cycling. Overall, this can be seen in the Figure 4.7, where cases with high SOC_0 maintain higher SOC in winter and doesn't reach the minimum, while low SOC_0 are discharged more easily.

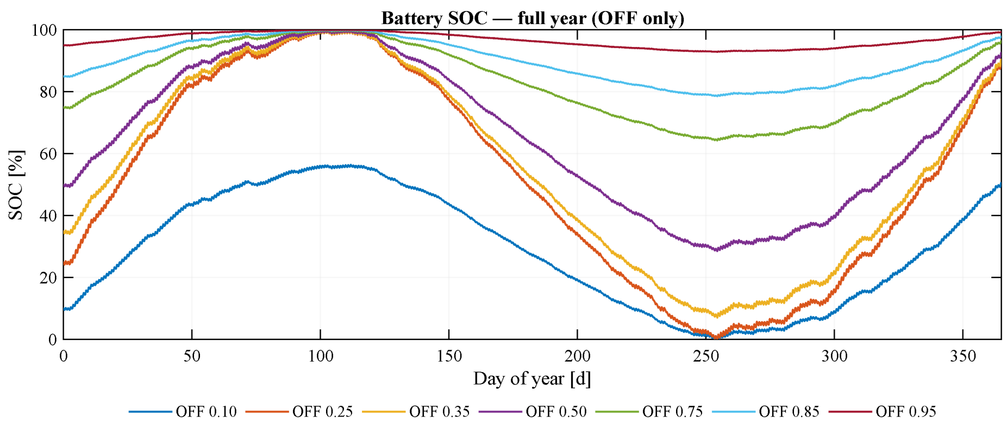

Figure 4.7: Annual evolution of the SOC without curtailment (OFF).

When curtailment is ON the behaviour changes. From $SOC_0 = 0.25$, curtailment increases with the initial SOC (from 2.03% to 12.56%). This allows the BESS size to no longer depend on SOC_0 since the battery energy capacity is around 17.6 GWh and inverter power 40-50 MW for all SOC_0 between 0.25 and 0.95. The equivalent cycles also stabilise, close to 3.88 cycles/year and the $SOC_{\min}$ is 0% in all cases. Thus, with curtailment the optimiser does not oversize the battery to cover the winter season, but prefers to cut part of the PV and allows the battery to complete deep cycles. The SOC trajectory in Figure 4.8 shows this tendencies.

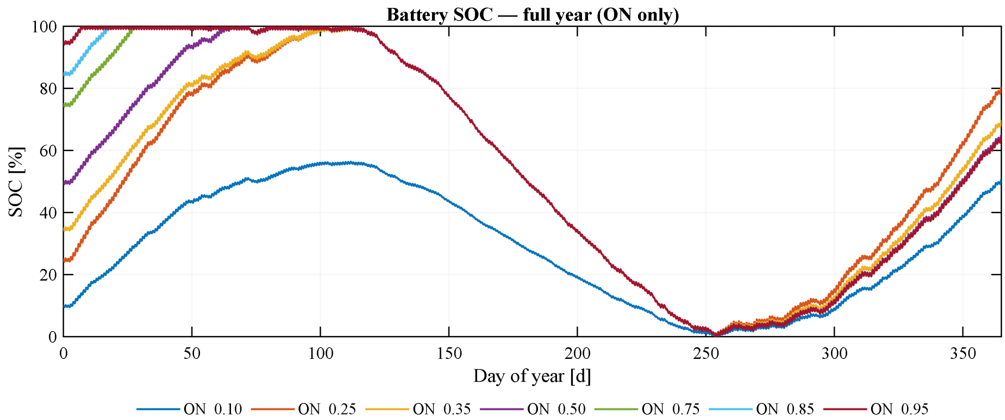

Figure 4.8: Annual evolution of the SOC with curtailment (ON).

Unlike the other cases, in the case of $SOC_0 = 0.10$, a different approach is adopted for both OFF and ON: a higher BESS energy and a more moderate inverter power. REopt finds it cheaper and more robust to increase energy (31.18 GWh) and maintain a moderate power (63 MW) than to reduce energy and to curtail later or increase power sigfnificantly. The starting point is very low and it leaves room to absorb surpluses without the need for curtailment. That is why curtailment is zero in both cases. With this combination, the SOC increases gradually and does not necessarily reach 100%.

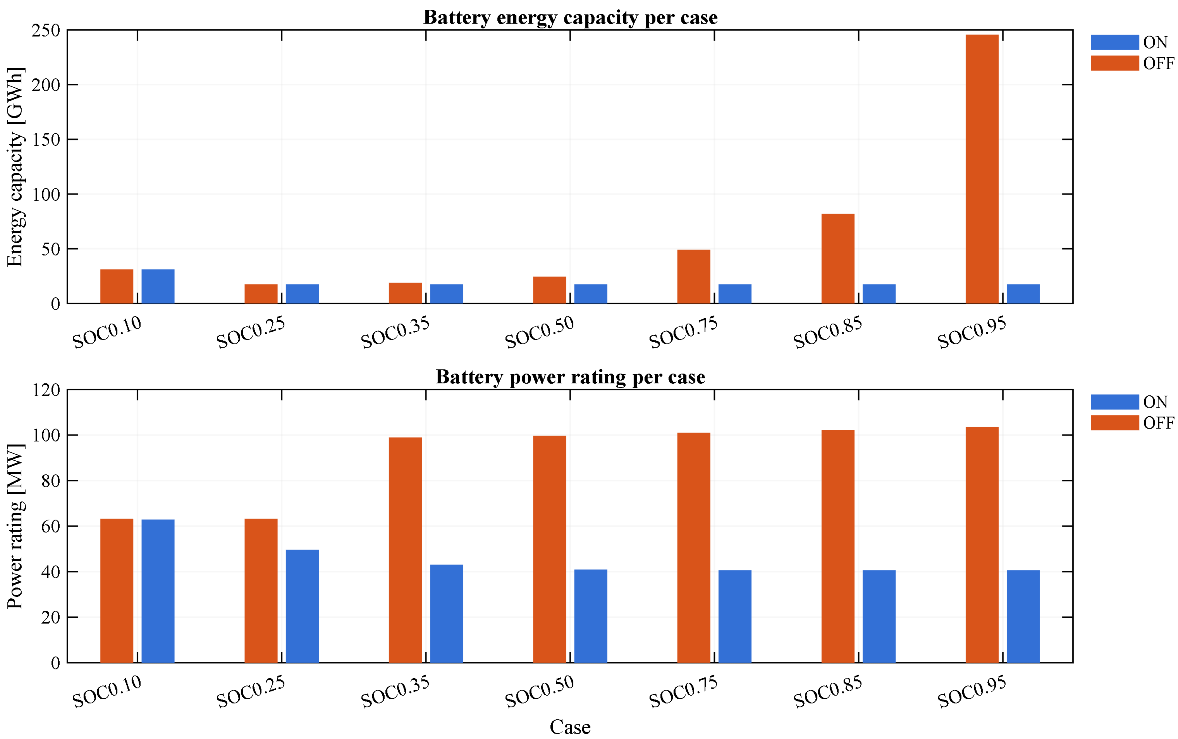

Figure 4.9: BESS sizes based on the different initial SOC. Top: nominal power of the inverter. Bottom: energy capacity.

Figure 4.9 helps to observe these sizes. Without curtailment, E_{BESS} and P_{inv} grow with SOC_0 because the BESS must handle all the energy shifting. When curtailment is activated (except for case 0.1), all SOC_0 have practically the same size in energy and power because now the degree of freedom used by the optimiser is no longer the BESS size but the percerntage of curtailment.

Overall, without curtailment, an optimal point (the minimum size of BESS that meets the demand) appears around SOC_0=0.25, with 17.6 GWh of energy and 63 MW of power. When the SOC_0 is higher, there is less margin to absorb daytime surpluses and the model ends up oversizing the battery (SOC_0=0.95 $\rightarrow$ 245.7 GWh and 103.5 MW). On hte other hand, at SOC_0=0.10, the power remains around 63 MW but the energy increases to 31 GWh to cover the initial deficits.

4.2.3 Influence of Diesel Generator Integration on BESS Size

The obtained sizes in the previous scenarios are unrealistic and not coherent with a Li-Ion battery. With the aim of reducing such sizes without complicating the model, a diesel generator is introduced into the HES, acting as "unmet demand". The generator is used with different annual utilisation rates, by using a fuel cap. REopt respects this maximum but not always decides to operate the generator over the PV and BESS. The initial SOC in this case is set to 0.5 to avoid start-up biases. In this scenario, curtailment is activated, preventing oversizing of the BESS and thus reducing sensitivity to SOC_0.

Table 4.3: Generator parameters and practical ranges.

Parameter	**Value**	**Practical range / note**	**Sources**
Generator power	15 MW	Fixed size	–
Target share	15% / 20% / 30% / 40%	Implemented as annual fuel cap	–
Electric cost	0,25 $/kWh	$0.25–0.45/kWh	[69]
Average electric efficiency	0.35 (fraction)	0.30–0.40	[70, 71]
Diesel energy content	36 kWh/gal	35-37 kWh/gal	[72]

Table 4.3 shows the parameters that have been utilised to operate the generator. Generator size is fixed to 15 MW in order to ensure enough power at critical times. The annual target share (15/20/30/40%) does not require the exact use of that value. It translates into an annual fuel quota (in gallons) using an average electrical efficiency (0.35) and the diesel energy content (36 kWh/gal). With this quota. REopt can never surpass the percentage, but can stay lower if PV+BESS are cheaper than the generator or the generator size is not enough to cover the target. The variable cost is set as $0.25/kWh (minimum value within permissible range) so that the generator is competitive without forcing its use at all hours, observing so how the BESS size changes as the target share is increased. The calculation of fuel cap is described in eq (4.1).

$$F_{\text{cap}} = \frac{s\,E_{\text{load}}}{\eta\,q} \tag{4.1}$$

Where:
F_{cap} — annual fuel cap [gal];
s — target share [%];

E_{load} — annual demand of the mine [kWh];
η — average electrical efficiency of the generator (p.u.);
q — calorific value of diesel [kWh/gal].

Table 4.4: Battery and generator results for each target-share case.

Case	**BESS size (MW)**	**BESS energy (GWh)**	**Generator share (%)**	**Fuel used (gal)**	**GEN clipping (%)**
0%	40.94	17.586	0.00	–	0.00
15%	42.183	11.937	15.60	1 554 274	2.85
20%	38.928	2.199	20.80	2 072 366	3.80
30%	26.814	0.178	24.03	2 393 624	4.14
40%	26.814	0.178	24.03	2 393 624	4.14

Table 4.4 shows the results obtained in this scenario. By adding a diesel generator, the required BESS energy decreases significantly as the target increases, because a fraction of the demand is now covered directly by the generator during the critical hours. On the other hand, BESS power not always decrease. In the 15% case, the BESS power size increases more than in the no-gen case, as the generator introduces ramps in the profile that force the battery to supply more power in less time. Furthermore, in the cases of 30-40% it can be observed that the annual target share is not fully achieved, the actual percentage falls short of the target, only reaching 24%.

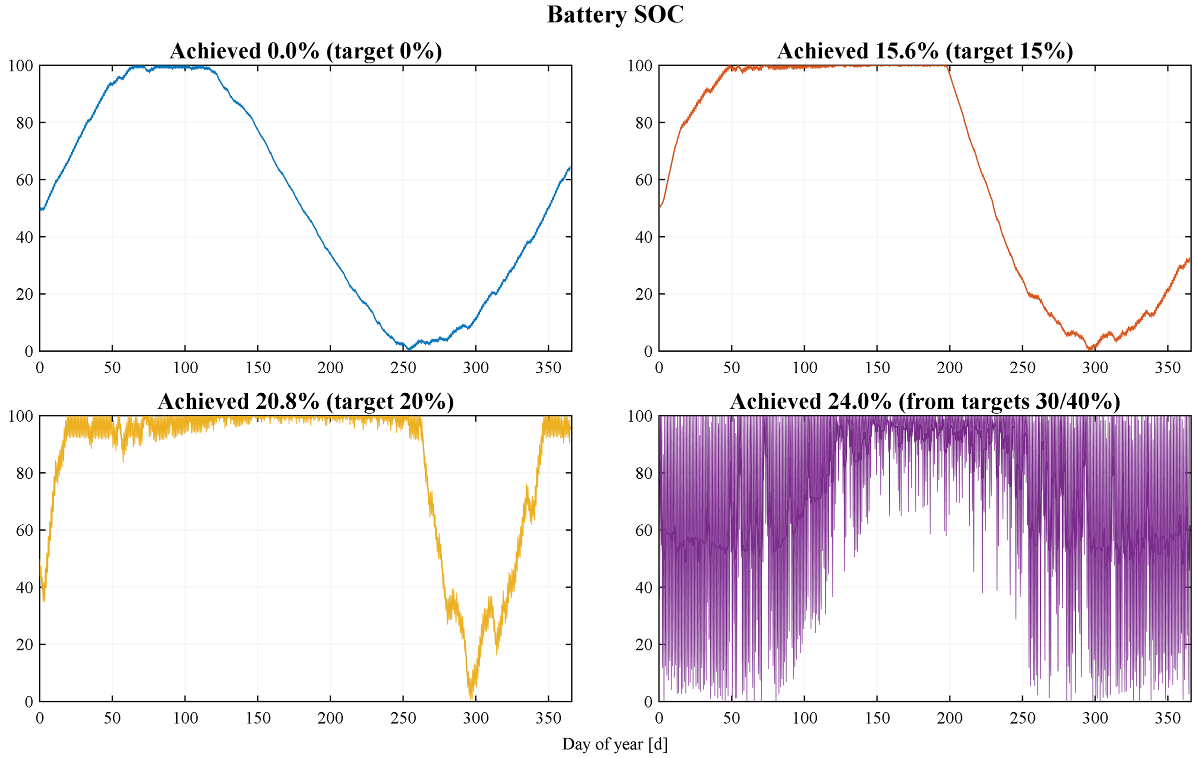

Figure 4.10: Annual SOC curves for each target share case.

Figure 4.10 shows how the generator changes the role of the BESS throughout the year. Without diesel generation, the battery acts as a 'seasonal storage facility': SOC increases during the high PV season and the battery is deeply discharged in winter until it reaches 0% of SOC. When switching to 15% and 20%, the generator helps when PV production is low, so the BESS discharges more slowly and takes longer to reach 0%. On many days, it does not even empty, because the generator covers part of the demand when there is no sun.

Furthermore, more cycles appear in the 20% and 24% diesel generation cases. This is because the BESS stops shifting as much seasonal energy and starts to absorb daily ramps. The depth of these cycles also varies. At 20% target share, shallow cycles predominate (the SOC ranges between 80 and 100%) as the battery adjusts for daily imbalances. On the other hand, at 24% target share, there are deep cycles (oscillations between 0% and 100%) because the system can recharge strongly the next day (enough PV and generator support at midday). Thus, the optimal strategy is to empty the battery at night and recharge it the next day during peak generation hours. In the 24% case, the observed interval from 100 to 250 days shows lower BESS usage, although it corresponds to winter months. Although the irradiance is lower during those weeks, the SOC behaviour is not only determined by the PV, but also by the use of the generator.

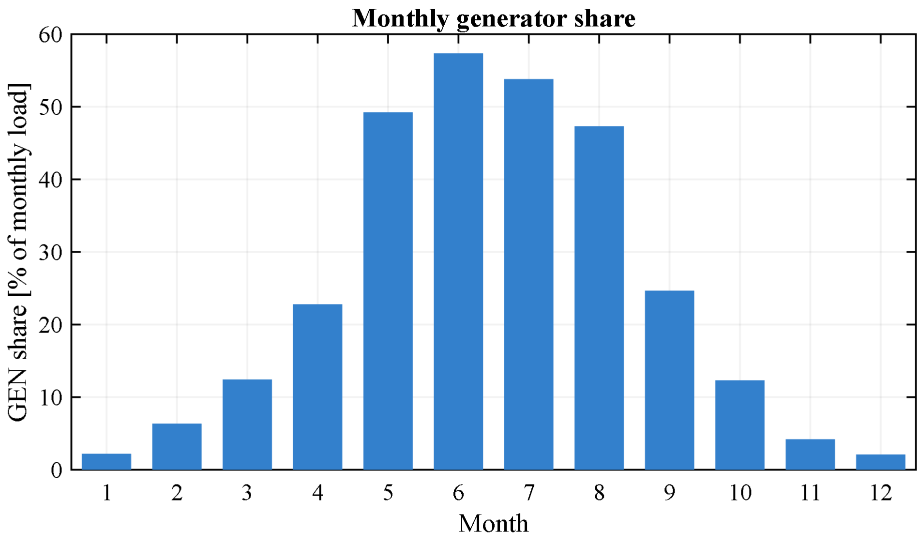

Figure 4.11: Monthly share of the diesel generator (percentage of the monthly demand covered by the generator). Use of generator increases during the winter (May-August in Australia) and is lower during the rest of the year.

As seen in 4.11, REopt uses more generator power during the critical weeks avoiding deep discharges. As a result, SOC remains high with fewer long discharges during this period.

Figure 4.12 shows how the size of the BESS varies when more use of the generator is asked. BESS power does not drop suddenly: at a target share of 15% it even increasis slightly due to the fact that, when the generator is turned on, there are ramps in the demand and the battery has to compensate such peaks in less time. From a target share of 20% onwards there is a clear drop to 27 MW at 30-40%. On the other hand, the BESS energy decreases as generator use increases, meaning that the BESS stops 'storing' seasonal energy and starts to cycle more frequently between day and night. The fact that 30% and 40% cases have the same sizes is because the model ends up using the generator in the same way.

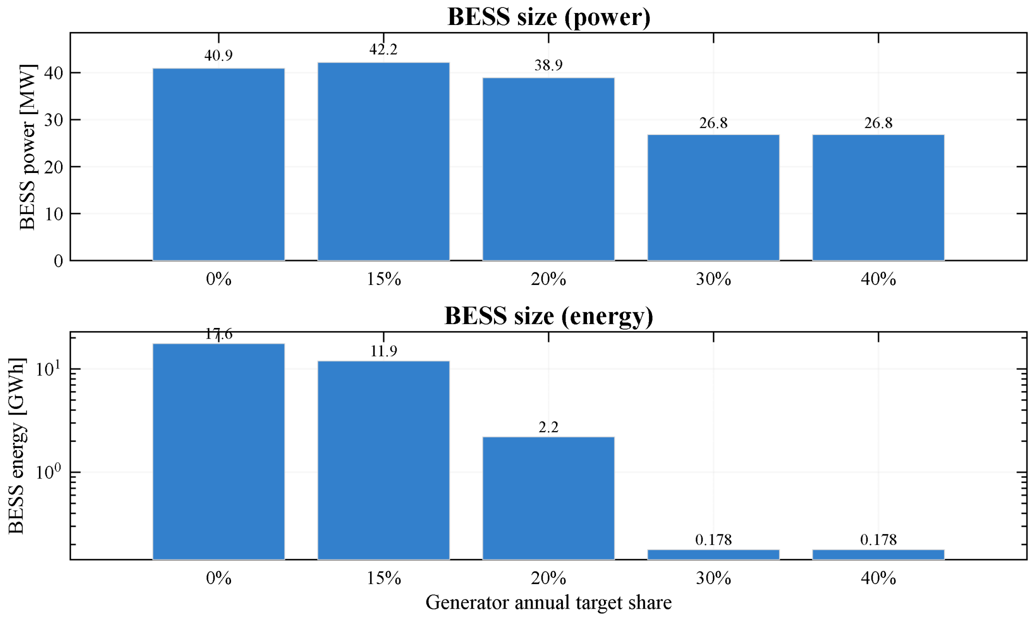

Figure 4.12: BESS sizes based on the generator's target share. Top: nominal power of the inverter. Bottom: energy capacity.

The generator clipping shown in Figure 4.13 measures the percentage of intervals in which the generator is stuck at 15 MW (max. power). Low values would indicate that power is not the bottleneck. In this case, if the actual percentage of the generator is still below the target, the limitation would be economic (REopt prioritises PV+BESS due to being cheaper in many hours). By contrast, if clipping values are high the limitation could be because of a lack of power at peaks and it would be recommended to increase the generator power or to shift the use of the generator to critical hours. In this case, clipping remains low even with high target shares, confirming that the 24% actual usage is due to a cost criteria.

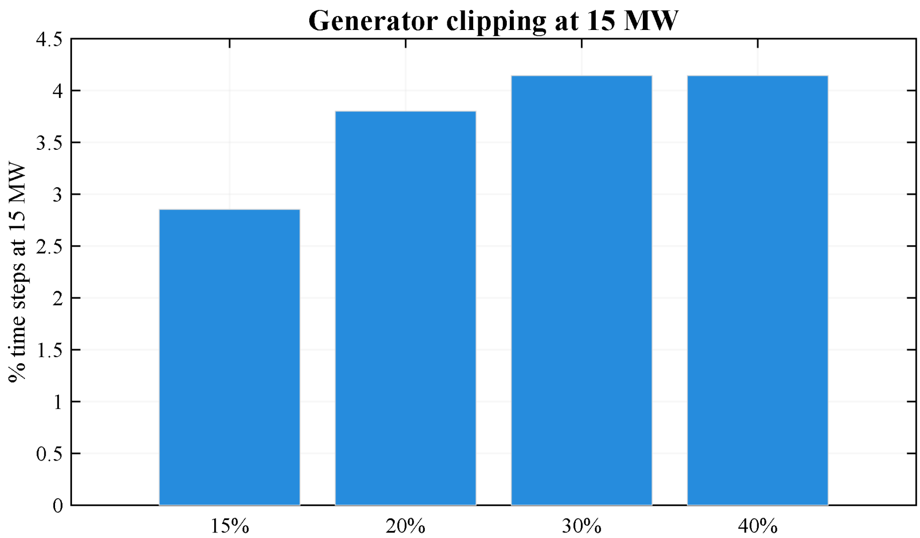

Figure 4.13: Generator clipping: percentage of intervals with the generator at nominal power (15 MW).

Implementing the generator significantly reduces BESS energy: from 17.6 GWh (0% of diesel generation) to 0.18 GWh (30-40%). In addition, BESS power drops from 41 MW to 27 MW, with a slight increase in some cases due to the ramps introduces by the generator. Furthermore, with a 15 MW generator the actual share obtained saturates at 24% when the target shares are 30-40%. Since the clipping is low (4%), this is a sign of economic limitation rather than power limitation.

5. Conclusion & Future Work

The purpose of this project was to propose a practical framework for sizing and operating a battery (BESS) within a hybrid system with PV (HES) in an island mode mine. In this type of operation, demand is usually variable and with considerable night-time consumption, so accurate battery sizing remains a challenge in order to ensure supply without relying on diesel generation

A reference HES with PV generation and a mine load profile with 15-minute resolution has been created over a year. The loads are classified into three groups (critical, deferrable and non-critical) to define priorities. These loads are then combined into a single profile for optimisation. PV production is calculated based on weather data (irradiance and 2-m air temperature) and datasheet parameters, and the battery is modelled by defining power, energy and SOC limits. Different scenarios are evaluated to observe how these behaviors vary with battery size.

Optimisation and Limitations:

To evaluate different battery sizes, an optimisation procedure based on REopt was followed. REopt is an optimiser that generates combinations of PV and BESS capacity and tests over one year of operation with 15-minute resolution. Each solution is validated by simulating the HES with its technological limits. Operational control during the simulation is simple and prioritised: first PV is used, then the battery to cover the aggregate demand. This provides power and SOC profiles, as well as metrics such as curtailment, which allow sizes to be compared and the most suitable one to be selected.

Based on the experience with REopt in this study, certain practical limitations have emerged. These are detailed below.

- **Pre-classification of loads**:
  The optimiser only supports an aggregate demand profile; it does not allow internal priorities between loads (critical, deferrable, and non-critical) to be defined or respected. Segmentation must be done beforehand.
- **Unmet demand in island mode and diesel use**:
  In islanded systems, unmet demand is not a useful operational setting in REopt: the solver tends to force total coverage and pushes for oversizing the battery. That is why a diesel generator is introduced acting as unmet demand to cover deficits when PV and BESS are insufficient.
- **API 'black box'**:
  The web API offers little traceability regarding the 'why' behind each solution. Running REopt locally (Julia version) can allow for more control over the solver and improve reproducibility.
- **Parameter sensitivity**:
  If the power/energy ranges, SOC limits, or penalties are poorly scaled, it is common that REopt finds no solution. It usually requires iterations to open ranges or relax constraints, which increases computational time.

- **Generic battery**:
  The model does not assume a specific technology by default. Behaviour depends on user-defined efficiencies, limits, and costs.

- **Challenging to impose exact operational policies**:
  Targets like "exactly X% diesel per year" or specific duty cycles are not directly enforced, the solver prioritizes global cost optimality.

Sizing Results and Scenario Analysis:

The results of the BESS optimisation carried out in this study are shown below, with the following contributions:

- **General Findings:**
  - Profiles with night-time load increase battery size. Profiles with high consumption during the night force the BESS to transfer large amounts of PV energy to after sunset, resulting in higher energy size.
  - Covering 100% of demand with PV and BESS alone leads to large batteries (energy capacity in GWh). BESS must both absorb midday PV surplus and store enough energy for long nights and winter deficits, increasing the size even when PV capacity is increased.
  - Sizing is dominated by energy rather than power peaks (at PV = 100 MW without curtailment: 245.66 GWh vs 103.51 MW). In the profiles obtained, the battery is defined primarily by the energy to be transferred from day to night/winter, rather than by instantaneous peaks.

- **Influence of PV size on BESS size:**
  - Allowing curtailment reduces the energy and power of the BESS. With the same PV power, the system needs to transfer much less energy and requires more moderate power levels. For example, at a 100 MW PV power with curtailment, the energy of the BESS drops by approximately 14 times (245.66 to 17.58 GWh) and the power by about 2.5 times (103.51 to 40.64 MW), with a curtailment of 11.97%.
  - Without curtailment, increasing the PV can lead to oversizing the BESS. Going from 50 MW to 100 MW without curtailment multiplies the annual energy managed by the BESS by 4 times and the power by about 4.5 times, because the battery must capture the midday surplus and supply long winter nights.
  - There is a practical 'sweet spot' around 75 MW with low curtailment. The 75 MW case (approximate curtailment of 1.77%) significantly reduces the required size of the BESS, cutting around 16 GWh of energy capacity and 45 MW of power, while keeping curtailment very low.
  - Beyond 90-100 MW, diminishing returns appear. BESS size continues to decrease only slightly while curtailment grows rapidly. Additional PV contributes little to further storage reduction but adds a lot of spilled energy. That said, it may be justified if curtailment expenses are acceptable and the aim is to reduce the BESS size.

- **Influence of BESS initial SOC on BESS size:**

- With curtailment enabled, BESS size is practically independent of the initial SOC. When there is curtailment, it is not necessary to reserve headroom in the battery from the start. Excess energy is discharged and the size is determined by seasonal displacement rather than SOC_0.
- Without curtailment, an optimum appears around $SOC_0 = 0.25$. Here, the minimum BESS size that satisfies the demand is observed (approx. 17.6 GWh and 63 MW). There is enough headroom to capture daytime surplus without forcing the battery to oversize. Starting with a low-moderate SOC (20–30%) is preferable to starting high.
- With high SOC_0 and curtailment disabled, the BESS tends to be oversized. At $SOC_0 = 0.95$, there is little margin to absorb daytime generation, and the model responds by increasing capacities (around 245.7 GWh and 103.5 MW).
- At $SOC_0 = 0.10$ and curtailment disabled, BESS power stays close to 63 MW, but the required energy increases to around 31 GWh to cover initial deficits. This adjustment implies steeper initial ramps and higher risk at the start under poor solar conditions. This risk could be mitigated by starting up during a window of good resources.

- **Influence of Diesel Generator Integration on BESS Size:**
  - Introducing the generator significantly reduces the energy of the BESS. By moving from 0% to targets of 30-40% diesel, the energy capacity of the BESS is reduced from 17.6 GWh to 0.18 GWh. The power also decreases (from 41 MW to 27 MW), with some occasional spikes due to the ramps introduced by the generator.
  - With low diesel target share, the BESS behaves as seasonal storage. With higher consumption, it shifts toward daily cycling. As diesel share rises, long seasonal deficits are covered by the generator and the battery cycles more day–night, reducing the energy required.
  - BESS power does not automatically decrease when diesel is added. Although the energy required decreases, the power can be kept high to follow peaks and ramps introduced by the generator.
  - The actual share of diesel is saturated due to economic criteria, not due to a lack of power. With a 15 MW generator, the effective share remains around 24% even though the target is 30-40%. Generator clipping is low (4%), a sign that the limitation comes from the relative cost compared to PV and BESS combined.
  - Seasonal strategy preferences. Diesel usage concentrates in winter to avoid deep discharges. The optimizer prefers diesel during critical weeks, keeping SOC higher and reducing long, stressful cycles.
  - Diesel reduces storage costs and mitigates seasonal demands, but introduces fuel costs and emissions. The optimum point depends on the price of diesel, the costs assigned to renewable autonomy and battery lifetime considerations.

This project has several shortcomings that reduce the accuracy of modelling and the obtained solutions. To address these, the following points for future work are required to improve the results.

Future Work:

- **Multi-year analysis for a greater robustness**:
  Analysing one single year can lead to innacurate conclusions if that year is not representative. Extending the analysis to multiple years of PV and demand data would increase

confidence in sizing. In addition, adding forecast for future years would allow for better simulation.

- **Alternative long-term storage technologies**:
Lithium-Ion battery is assumed to be the default solution for this type of configuration. Since the storage used is seasonal, a Li-ion battery may not be the optimal choice. Studying long-term storage technlogies allows the solution to be adjusted to the actual number of hours that need to be covered. Some suggestions may be:

  – Pumped hydro storage: It is utilized when many hours of energy need to be displaced (long nights/winter), long life-time or low energy costs per kWh are required. Feasibility depends on the site, resources and permits, as it requires elevation difference and space for reservoirs.[73]

  – Compressed air: This method is adequate for large amounts of energy and long durations. one disadvantage is that it requires caverns or tanks and a thermal complexity that can increase the operational costs [74]. In this case, the cavities resulting from mining could be converted into storage caverns.

  – Liquid air: Similar to compressed air, this method is also suitable for large amounts of energy over long periods of time. In this case, it requires cryogenic tanks that are costly, and its efficiency is moderate. [75]

  These technologies could be combined with a small Li-ion battery for fast response and better power quality.

- **Load profile with lower night-time demand**:
In the project the load profile that has been used has a high night-time demand, which forces the battery to cover more load during many consecutive hours. Testing a profile with a lower night-time demand could reduce the size of the BESS.

- **Own optimization/dispatching model (Python/MATLAB)**:
Relying on REopt as a 'blackbox' limits the decision traceability and the policy control (when to curtail, when to apply diesel ramps,etc...). A custom model could provide more transparency and greater capacity of experimentation.

- **Thermal management and extreme weather**:
The effect of temperature is not modelled on the HES system. This thermal management can be critical in hot (during the day) and cold (during the night) conditions in Australia. Implementing this would improve realism and operational safety.

- **Battery degradation**:
The actual model does not take into account an estimate of degradation linked to power and SOC profiles. Including this would allow to evaluate the lifetime by calculating equivalent cycles (rainflow), throughput, etc.

- **Economic evaluation**:
Currently, there is no comparison cost-related between diferent options in order to quantify them. Introducing Net Present Value (NPV), ROI or other economic matrices would help to make a more informed decision.

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A. Appendix: Constants Modelling

This appendix covers values used in modelling and some of the reasons for choosing them.

Photovoltaic

The values used to calculate PV electricity production can be viewed in Table A.1.

Constant	**Symbol**	**Value**	**Units**	**Source**
Derating Factor	f_{pv}	95	[%]	[76]
Rated Power Output	$P_{pv.r}$	30.8	[MW]	[76]
Solar Irradiation under Standard Test Condition	G_{STC}	1000	[W/m^2]	[76]
PV Power Temperature Coefficient	α_T	-0.26	[%/°C]	[76]
Standard Test Condition Temperature	T_{STC}	25	[°C]	[76]
Nominal Operating Cell Temperature	$NOCT$	44	[°C]	[76]

Table A.1: Data used for modelling the PV production.

BESS

The values used to parameterize the battery model are shown in Table A.2.

Constant	**Symbol**	**Value**	**Units**	**Source**
Battery Energy Capacity	E_{bess}	Optimized	[MWh]	Model input/REopt
Max Charge Power	$P_{bess}^{ch,\max}$	Optimized	[MW]	Model input/REopt
Max Discharge Power	$P_{bess}^{dis,\max}$	Optimized	[MW]	Model input/REopt
Minimum State of Charge	SOC_{min}	0	[%]	Model input
Maximum State of Charge	SOC_{max}	100	[%]	Study assumption
Initial State of Charge	SOC_{init}	Optimized	[%]	Model input
Battery Internal Efficiency (per path)	η_{int}	95	[-]	Model input
Inverter Efficiency (discharge, AC/DC)	η_{inv}	99	[-]	Model input
Rectifier Efficiency (charge, DC/AC)	η_{rec}	99	[-]	Model input
Round-Trip Efficiency (incl. converters)	η_{rt}	$\approx$ 92.2	[-]	Derived $(0.95 \cdot 0.99^2)$
Continuous C-rate	$C\text{-}rate$	–	[h^{-1}]	Study assumption
Time Step	Δt	15	[min]	Model input
Ambient Temperature (nominal)	T_{amb}	–	[°C]	Site condition

Table A.2: Data used for modelling the BESS. “Optimized” indicates variables left free for REopt sizing.

B. REopt Data

In this appendix, there are tables relevant of the REopt opmitization method, as well as results.

Table B.1 shows the Main REopt payload keys and expected data types.

Table B.1: Main REopt payload keys and expected data types (as used in the script).

Block	Key	Description
Settings	`time_steps_per_hour`	Integer; here 4 (15-minute resolution).
	`off_grid_flag`	Boolean; `true` for islanded mode.
Site	`latitude`, `longitude`	Real numbers; site coordinates.
	`name`	String; optional identifier for traceability.
ElectricLoad	`loads_kw`	Vector of load values in kW (read from CSV).
	`year`	Integer; calendar year associated with the time series.
	`critical_load_fraction`	Real in [0,1]; set to 1.0 for islanded operation.
PV	`min_kw`, `max_kw`	Real; PV capacity bounds to be optimized [kW].
	`production_factor_series`	Vector (dimensionless) of PV production factors.
	`dc_ac_ratio`, `inv_eff`	Real; DC/AC ratio and inverter efficiency.
ElectricStorage	`min_kw`, `max_kw`	Real; BESS power bounds [kW].
	`min_kwh`, `max_kwh`	Real; BESS energy bounds [kWh].
	`soc_min_fraction`, `soc_init_fraction`	Real in [0,1]; minimum and initial SOC.
	`internal_efficiency_pct`	Percentage; BESS internal efficiency.
	`inverter_efficiency_pct`	Percentage; battery-side inverter efficiency.
	`rectifier_efficiency_pct`	Percentage; rectifier efficiency for charging.

B.1 REopt function

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```
#!/usr/bin/env python3
```

```python
# -*- coding: utf-8 -*-

import os, requests, json, time
from math import isfinite

HOST = "https://developer.nrel.gov/api/reopt/stable"
JOB_URL = f"{HOST}/job"
API_KEY = os.getenv("NREL_API_KEY")      # <-- set in environment

# --- Dials (study) ---
TARGET_SHARE = 0.40                      # 40% of annual demand served by the generator
PV_MW = 75.0
GEN_FIXED_MW = 10.0
GEN_VCOST_USD_PER_KWH = 0.25
ELEC_EFF_AVG = 0.35
DIESEL_LHV_KWH_PER_GAL = 36

def post_job(payload):
    hdr = {"Content-Type": "application/json", "x-api-key": API_KEY}
    r = requests.post(JOB_URL, headers=hdr, params={"api_key": API_KEY},
                      data=json.dumps(payload))
    r.raise_for_status()
    return r.json()["run_uuid"]

def poll_results(uuid, poll_s=15):
    url = f"{JOB_URL}/{uuid}/results"
    while True:
        res = requests.get(url, params={"api_key": API_KEY}, timeout=60)
        if res.status_code == 200:
            out = res.json()
            st = (out.get("status","") or "").lower()
            if st in ("optimal","finished","complete"):
                return out
            if st in ("error","failed","timedout"):
                raise RuntimeError(json.dumps(out, indent=2))
        time.sleep(poll_s)

def main():
    MW = 1000.0
    analysis_year = 2024

    # Load series (35,040 steps @ 15 min). No scaling applied.
    loads_kw = [MW*json.loads(l) for l in open("data/load_newkW.csv","r",encoding="utf-8-sig")]
    pf = [json.loads(l) for l in open("data/pv_pf_new.csv","r",encoding="utf-8-sig")]
    assert len(loads_kw) == len(pf) == 35040

    dt_h = 0.25
    total_load_kwh = sum(loads_kw)*dt_h
    kwh_per_gal = ELEC_EFF_AVG*DIESEL_LHV_KWH_PER_GAL
    assert isfinite(kwh_per_gal) and kwh_per_gal > 0
    fuel_cap_gal = (TARGET_SHARE*total_load_kwh)/kwh_per_gal

    payload = {
      "Settings": {"time_steps_per_hour": 4, "off_grid_flag": True},
```

```python
        "Site": {"latitude": -33.8, "longitude": 116.05, "name": "GLM"},
        "ElectricLoad": {"loads_kw": loads_kw, "year": analysis_year, "critical_load_fraction": 1},
        "PV": {
          "min_kw": PV_MW*MW, "max_kw": PV_MW*MW,
          "production_factor_series": pf, "dc_ac_ratio": 1.2,
          "inv_eff": 0.96, "can_curtail": True
        },
        "ElectricStorage": {
          "min_kw": 5*MW, "max_kw": 100000*MW,
          "min_kwh": 10*MW, "max_kwh": 100000*MW,
          "soc_min_fraction": 0.20,
          "soc_init_fraction": 0.50,
          "internal_efficiency_pct": 95,
          "inverter_efficiency_pct": 99,
          "rectifier_efficiency_pct": 99
        },
        "Generator": {
          "only_runs_during_grid_outage": False,
          "min_kw": GEN_FIXED_MW*MW, "max_kw": GEN_FIXED_MW*MW,  # fixed 20 MW
          "om_cost_per_kwh": GEN_VCOST_USD_PER_KWH,
          "fuel_avail_gal": fuel_cap_gal,
          "min_turn_down_fraction": 0.0
        }
    }

    uuid = post_job(payload)
    out = poll_results(uuid)
    with open("reopt_results.json","w",encoding="utf-8") as f:
        json.dump(out, f, indent=2, ensure_ascii=False)

if __name__ == "__main__":
    main()
```

Listing B.1: Minimal python REopt job used to call the API to generate results.