Test Methodology for Residential Stationary Battery Energy Storage Systems

Master's thesis in Sustainable Electric Power Engineering and Electromobility

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Abstract

This thesis proposes a compressed test sequence designed to characterize and assess the annual performance of a stationary battery energy storage system integrated with a residential solar PV system, within a short testing duration. The approach followed consists of studying annual system profiles (load demand and irradiance profiles) obtained from historical measurements, through which four representative days that best reflect the system's annual operational patterns were systematically selected. The dimensioning aspect for the battery energy storage system, PV and power electronic converter systems, along with their relationship between the energy and power capacities of the battery, was studied through a market survey. The criteria utilized in the selection of the representative days assess the relative error between sums and averages values of the annual and representative day system profiles. These representative days serve as the basis for the compressed test sequence. To evaluate the performance of the system, the relevant performance metrics were evaluated. These include conversion efficiencies based on the energy flow path in the system, battery storage capacity, and round-trip efficiency. The results of the market survey indicated that a typical energy-to-power ratio ranging between 2–3.5 kWh/kWp, with an average battery size of around 5–10 kWh for SBESS coupled with a PV system in residential applications. The survey also highlighted that the size of the SBESS is influenced not only by the size of the PV system, but also by the power electronics converter (PEC) capacity and the system topology connection applied in the system. Using flow-duration curves, the results show how closely the selected representative days align with the annual system profiles. For load demand, the relative errors between the daily and annual averages and sums were 0.1% and 1.6%, respectively. The irradiance profile showed slightly higher deviations, with relative errors of 3.0% for averages and 4.7% for sums between daily and annual values, respectively. This highlights the impact of transitional boundaries between seasons, where the largest deviations in seasonal profiles are observed. The proposed test sequence followed a 4-day sequence, with two additional days reserved for reconditioning and rebalancing the battery's state of charge (SOC). The Battery Management System (BMS) of the SBESS regulates the battery energy flow on the basis of the selected representative day profiles. In this way, the test sequence allows the battery to be cycled according to the load demand and the PV throughput, following the self-consumption and self-sufficiency control strategy commonly used in residential applications.

Keywords: Stationary battery energy storage systems (SBESS), power electronics converters (PEC), PV system, Test sequence, converter efficiency, system performance matrices.

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Khentsane Mgiba, Gothenburg, Month 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating current
BMS	Battery Management System
DC	Direct Current
DOD	depth of discharge
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
PV	Photovoltaic
PEC	Power Electronic Converter
RTE	Round Trip Efficiency
SBESS	Stationary Battery Energy Storage System
SOC	State of Charge
SPM	System Performance Matrices
STC	Standard test Conditions
WST	Whole System Test

Nomenclature

Below is the nomenclature of indices that have been used throughout this thesis.

Variables

E_{BAT}	Energy capacity of the battery, [+] (E^{+}_{BAT}) for discharged (also referred to Usable Energy capacity) , [-] (E^{-}_{BAT}) for charged [Wh]
$E_{BAT(nom)}$	Nominal storage capacity of the battery (datasheet) [Wh]
$P_{INV,AC(in)}$	Nominal AC input power of the PV-storage bidirectional converter or Hybrid inverter at the AC point [W]
$P_{INV,AC(out)}$	Nominal AC output power delivered from the PV-storage bidirectional converter or Hybrid inverter at the AC point [W]
$P_{BAT,Max(chg)}$	Maximum charge DC power of battery [W]
$P_{BAT,Max(dschg)}$	Maximum discharge DC power of battery [W]
$P_{BAT,DC}$	Battery Power, [+] ($P^{+}_{BAT,DC}$) when discharging, [-] ($P^{-}_{BAT,DC}$) when charging [W]
$P_{BATINV,AC}$	Nominal continuous discharge AC power from the battery inverter, [+] ($P^{+}_{BATINV,AC}$) for discharging, [-] ($P^{-}_{BATINV,AC}$) for charging [W]
$P_{BAT,CONV,DC}$	Nominal continuous discharge DC power from the battery DC-Dc Converter, [+] ($P^{+}_{BAT,CONV,DC}$) for discharging, [-] ($P^{-}_{BAT,CONV,DC}$) for charging [W]
P_{GRID}	Power supplied from the grid, [+] (P^{+}_{GRID}) Power import from the grid (supply), [-] (P^{-}_{GRID}) Power Export to the grid (feed-in)[W]
$P_{INV,AC}$	Total 3-phase converter AC Power [W]
P_{LOAD}	Load power consumption [W]
$P_{PV,DC}$	Measured DC output power from the solar PV generator [W]
$P_{PVINV,AC}$	Measured AC output power from the PV-inverter [W]
U_{BAT}	Nominal voltage (DC) of the Battery [V]
$U_{BAT(min)}$	Lower voltage limit corresponding to SOC_{min} of the Battery [V]
$U_{BAT(max)}$	Upper voltage limit corresponding to SOC_{max} of the Battery [V]

$\eta_{BAT,RTE}$	Battery energy round-trip efficiency [%]
$\eta_{BAT,RTEC}$	Coulomb round-trip efficiency of battery
η_{BAT2AC}	Conversion path efficiency from battery system to consumer load and grid feed-in [%]
$\eta_{GRID2BAT}$	Conversion path efficiency from main grid to battery energy storage system [%]
η_{PV2AC}	Conversion path efficiency from PV system to consumer load and grid feed-in [%]
η_{PV2BAT}	Conversion path efficiency from PV system to battery energy storage system [%]

Contents

1
Introduction

Test sequences for stationary battery energy storage systems (SBESS) have recently received increased focus due to their potential to enable reliable and efficient performance evaluation under realistic operating conditions. As SBESS becomes increasingly important for complementing decentralized and renewable energy sources, understanding and verifying their performance becomes essential. Renewable energy sources such as solar and wind are variable, which can lead to mismatches between energy generation and load demand. SBESS serves as a complementary energy storage system, supporting the integration of renewable energy, improving grid stability, improving self-consumption, and strengthening the resilience of residential, industrial and distribution systems [1]. To ensure that these systems are effectively evaluated for their performance, test sequences offer a systematic approach to characterize key performance metrics such as conversion efficiency, storage capacity, and round-trip efficiency for the performance evaluation of the system. In this way, the use of test sequences allows an effective evaluation of system performance under various operating conditions. This can be observed in whole system dynamic test methods applied for thermal systems, which evaluate the performance of the heating system under transient operating conditions [2]. By replicating annual performance in a controlled and repeatable manner, such test sequences provide insight into the system's overall efficiency and thermal behavior. As a result, this helps to identify potential inefficiencies in the performance of the system under realistic conditions.

Compressed test sequences offer the advantages of reducing the time and resources that would be required for comprehensive testing. This approach not only optimizes testing duration but also facilitates the evaluation of various system configurations, which is crucial for the harmonization of test methods across different test facilities. Harmonization in test sequences ensures consistent and comparable results across various topologies of the system. Standardized testing protocols are essential for maintaining reliable and uniform system testing, enabling insightful comparisons between various system topologies. This work focuses on compressed test sequences and the evaluation of system performance metrics of stationary battery energy storage systems coupled to PV systems designed for residential applications.

1.1 Problem Background

Performance testing and assessment of stationary battery energy storage systems allows for the primary evaluation of their capacity to store and release energy following the pattern of the load demand and type of application. When coupled with a solar photovoltaic (PV) system, the performance of the battery energy storage system and the power flow through the power electronic converter (PEC) are influenced by the type of application and load demand. The different types of connections between the SBESS and the PV system commonly found in the market are AC-coupled, DC-coupled, and PV-generator-coupled systems. These different topologies influence the performance of the system as a whole. PV systems are significantly affected by variations in solar irradiance and efficiency of its system. The efficiency of the PEC system is influenced by the load it experiences, where during periods of low load, such as low solar irradiance, the converter is lightly loaded and operates with lower efficiency. The SBESS performance is influenced by the charging and discharging pattens of the system, which influences the storage capacity of the battery. Most often, the available technical information and performance indicators of battery energy storage systems consist of single values with unknown operating conditions and different test conditions, making it a challenge to compare them with other battery energy storage systems or other system topologies [3]. Using single values to describe the operation of the system is unreliable because the operating conditions corresponding to these single values are unknown. Varying operating conditions make it unrealistic to assess system performance using a single efficiency value.

With the growing market for battery energy storage systems and PV installations, a variety of product ranges and system configurations are available [4]. This diversity poses a challenge when comparing the performance of systems using a single efficiency value for a full year of operation. This complexity makes system comparisons challenging for consumers and non-experts. Test sequence supports better decision-making for consumers and system installers by providing reliable and standardized performance data. It helps consumers understand how SBESS will perform under realistic operating conditions and informs system installers about the operational requirements of the systems, ultimately fostering optimized utilization of SBESS. It has been identified that unified and compressed test methodologies for evaluating the performance of battery energy storage systems in the context of the entire system are still lacking [3]. The need for uniformity and compatibility means that the same test methodology can be utilized to analyze different system topologies and applications of stationary battery energy storage systems. Therefore, characterizing the performance of the entire system, considering daily and seasonal variations in terms of performance matrices, becomes crucial to investigate.

Performance matrices play a crucial role in defining the criteria for measuring, testing, and evaluating the system both technically and economically. They enable different stationary battery energy storage systems to be compared with each other in terms of their performance and cost considerations. These performance matrices include the assessment of losses influenced by the system sizing (converter, battery, and PV system), losses influenced by converter conversion paths, losses influenced by the battery energy storage system (usable storage capacity and depth of discharge), and losses related to the control and energy management system (standby losses, dead time, and settling time) [3]. The system sizing is determined by the power rating of the PV system and converter system. It is related to the size of the battery energy storage system and, additionally, the load demand. Conversion losses occur during the DC to AC and AC to DC conversion employed for the DC system, which consists of the PV and battery energy storage system. The control and energy management system losses are attributed to the energy consumed during the standby mode operation of the system and losses due to the time system response delays to changes in load demand [3]. This work focus on the system performance matrices based on the assessment of losses influenced by converter conversion paths, and the battery energy storage system (usable storage capacity and depth of discharge).

Standard test procedures, such as those provided by The National Renewable Energy Laboratory (NREL) [5], IEEE Std 1526-2020 [6], and the European Standard EN 50530-2010 [7], are based on functionality and operational testing under defined test conditions. Additionally, Efficiency Guidelines [8] outline that the system's power conversion efficiency can be tested for different power flows under static conditions. However, comprehensive information and comparisons under dynamic conditions (varying power levels and realistic operating conditions) are still lacking [4]. While other performance tests representing the annual operation with only a few representative days exist predominantly for testing the operation of thermal systems [9, 10, 11], there is a gap in their application to PV-battery storage systems. This work proposes a dynamic test sequence for PV and battery energy storage systems, utilizing the Whole System Test (WST) method. This proposal comprises the analysis of the power flow of a PV-battery storage system in terms of System Performance Matrices and Efficiency Guidelines [8]. The Efficiency Guidelines provide a standardized foundation for defining and assessing the system performance metrics such as conversion efficiencies and round-trip efficiency. By following these guidelines, the evaluation method is harmonized, enabling a unified interpretation of the results and supporting the comparison of different system topologies evaluated under similar test procedures.

1.2 Literature Review

From the findings of the literature review, performance-related data such as efficiency, specified in data sheets, are often based on maximum tested or achievable performance values. However, these specifications do not account for performance values during real operation. Round-trip efficiencies of the battery are typically presented as the same between charging and discharging cycles. However, in practice, there is a hysteresis between the charging and discharging cycles, resulting in different battery efficiencies [12]. Laboratory tests for these test sequences are usually extensive and costly, and simulation-based tests are complex, requiring expert interpretation and traceability. Furthermore, using common performance matrices allows for a similar interpretation and fair comparison to other related systems in different applications. This highlights the need to develop time-condensed test sequence for performance evaluation that are suitable for consumers and non-expert users of the system.

Standard test procedures are based on functionality and operational testing under defined testing conditions. In the test procedure from the National Renewable Energy Laboratory (NREL) [5] and the IEEE Std 1526™-2020 [6], a recommended practice for testing and evaluating the performance of standalone PV systems coupled with a battery energy storage system is presented. These standards include battery capacity tests, functionality tests to determine the sun hours required for a full charge, verification of the PV and battery energy storage system's operation relative to the load, and the recovery test to restore charge into the battery and evaluate the ability of the control system to regulate the battery energy storage system when the battery is fully charged. The standards-based test procedure verified the required operation of the PV and battery energy storage system in relation to the load and control system. However, these standards also highlight that with short-duration testing some dynamic behavior of the system may not be properly covered. The Pacific Northwest National Laboratory (PNNL) express measuring procedures for investigating the performance of energy storage systems [1]. In the measurement procedures, charge/discharge powers and SOC range are selected and tested for each duty cycle, covering a 24-hour window to determine the performance of the energy storage systems for applications such as PV-smoothing, peak shaving, frequency regulation, and island microgrid. The test procedures elaborated include a storage test, where the deliverable capacity from the energy storage system is measured for its round-trip efficiency. The test procedure also included a test routine for determining the stand-by and battery self-discharge losses, the ramp-rate test, and the response time tests. The test duration is designed to span 12 to 24 hours per application, which makes it a complex and long-duration test. Hund et al. [13], elaborated on a cycle test method to evaluate the performance of the battery in a standalone PV system. In this test sequence, the battery was subject to different cycle tests inclusive of sustaining cycles test for battery nominal charge and discharge cycles, the deficit cycles test for deep discharge of the battery, the recovery cycles test for battery charge recovery, and the final battery capacity test to obtain the remaining battery capacity. Operational profiles were simulated in cycles under controlled laboratory conditions that the battery experiences during operation when connected to a PV system. This type of test method sustains a high number of cycles (1001 cycles) and runs a span of 2.74 years, maintaining a long duration for the testing period. The test procedure and report of Real et al. [14], verifies if the lead-acid batteries are suitable for a Solar Home System (SHS) with the intention of system evaluation and certification of battery energy storage system, international standard adoption, and harmonizing test procedures of existing national test methods for the improved quality of SHS systems. The report expresses the importance of appropriate PV system, good battery sizing and loading management, and method of charge for improved performance of the lead-acid stationary battery energy storage system coupled to a PV system.

Considering thermal systems, short-term/compressed test methods have been explored to represent the annual operation of combisystem (renewable energy combined heating systems). The Macsheep project report [9], The International Energy Agency (IEA) in their SHC Task 26 reports [10, 11], and Haller et al.[15] presented Whole System Test methods (WST) and cycle-based test methods for testing renewable energy combined heating systems in thermal applications for space heating and domestic hot water supply. These test procedures utilize short test duration principles, with one method running for 6 days and the other for 12 days, for evaluating the functionality and performance of space heating and domestic hot water supply in thermal systems. These test procedures have the ability to run autonomously, emulating real full cycles experienced in household operations. These studies gave a recommendation to harmonize test methods and hence achieve a unified test method for evaluating the performance of these type of thermal systems for PV systems in household applications. These types of test sequences utilized in thermal applications give an example of test sequences aimed at evaluating the performance of the PV systems with an energy storage system, obtained for dynamic and real-time conditions for different seasonal simulations and completed within a short duration of time, with the systems annual analysis representative of days and different seasons of the year.

1.3 Purpose and Contribution

The purpose of this work is to propose a compressed test sequence designed to evaluate and characterize the performance of stationary battery storage system coupled to a PV system (PV-battery storage system) for residential applications. This test methodology focuses on system performance metrics, including conversion path efficiency, storage capacity, and round-trip efficiency, and aims to replicate the system's annual performance under realistic operating conditions.

1.3.1 Aim of the Thesis

The thesis aims to achieve the following:

- Present an analysis of a market survey that examines existing stationary battery energy storage systems (SBESS) within the residential market in Sweden. The analysis focuses on the design, dimensioning and sizing of SBESS for residential applications, highlighting key factors that influence the integration with PV system.
- Present and analyze the results of a literature review on existing test methods and control strategies that evaluate the functionality and performance of PV-battery storage systems. This review provides a foundation for understanding current test methodologies and identifying gaps in the performance evaluation of SBESS.
- Proposing a compressed test sequence for stationary battery energy storage systems:
    1. Investigate and explain the dynamic behavior of PV-battery storage systems, focusing on key performance metrics such as conversion path efficiency, storage capacity, and round-trip efficiency, all within a realistic residential setting.
    2. Develop a compressed test sequence that effectively evaluates the annual performance of SBESS. The proposed test sequence will reflect realistic system profiles, accounting for seasonal fluctuations and varying operational conditions.
    3. Propose ways to assess the performance of SBESS based on the system profiles derived from seasonal variations and operational conditions

throughout the year. The aim is to optimize the duration of testing while maintaining the accuracy and characteristics of annual operation for performance evaluation.

1.3.2 Contributions of the Thesis

The contributions of the thesis includes:

- **Presentation of the Performance Matrices:** This work elaborates on performance metrics, with a specific focus on conversion path efficiency, which plays a crucial role in assessing the performance of SBESS integrated with PV systems for residential applications.
- **Demonstration of Dynamic Operation (Power Flows)**: The work contributes to a deeper understanding of the dynamic operation of SBESS, specifically power flows in residential settings, which are influenced by factors such as seasonal variations in solar irradiance and load demand. This understanding is essential for the optimization and harmonization of system performance.
- **Development of a unified compressed Test Sequence:** The work presents a unified and compressed test sequence, designed to evaluate the performance of SBESS. This addresses the challenges of traditional longer-duration testing and provides consistency and comparability in performance evaluation across different systems topologies.

1.4 Thesis Outline

The remainder of the thesis is followed by a Market Survey in Chapter 2, which investigates available battery energy storage systems in the residential market of Sweden. The Theory chapter (Chapter 3) elaborates on the power flow and evaluations of the system performance matrices and control functionalities of the battery energy storage system. In Chapter 4, the measurements taken for testing stationary battery energy storage systems are expressed, and the section concludes with the proposal of the time condensed test procedure. Chapter 5 elaborates on the results obtained from the measurements, while Chapter 6 provides the discussion and conclusion of this work.

2
Market Survey

This section elaborates on the market survey conducted to examine the market for stationary battery energy storage systems (SBESS) within the residential sector of Sweden. The focus was on single-family and multi-family buildings. With many battery installations coupled to solar PV systems, the survey aimed to investigate systems with and without solar PV installations.

2.1 Market Surveying Method

The survey was conducted online via email, where companies supplying or installing solar PV and battery energy storage systems for residential applications were contacted. Reference was made to companies listed on the Svensk Solenergi website[1], known for incorporating battery energy storage systems into their solar PV installations. A range of offerings, highlighted through references and previous projects, as well as datasheets from Original Equipment Manufacturers (OEMs), were examined to study the sizes and diversity of available battery energy storage systems and converters offered in the residential market. The survey questionnaire document outlined the purpose of the survey and the type of information required. The required information focused on stationary battery energy storage systems and solar PV systems, including dimensioning parameters, battery energy and power capacities, cell technology, available control strategies, and typical PV sizes, as highlighted in the list below.

List of requested data from Market survey

- Dimensioning parameter(s)
- Energy capacity [kWh]
- Power capacity [kW]
- PV size in relation battery size [kWp/kWh]
- Cell technology (LFP, NMC, etc.)
- Available control strategies from the battery
- Battery Supplier or datasheet
- Comments/Additional information

[1] https://svensksolenergi.se/sok-medlemsforetag/

2.2 Market Survey Results and Discussion

2.2.1 Market Survey Based on Data Requested via Email

The results obtained from the online market survey conducted through email, based on the requested data listed in Section 2.1 using the survey questionnaire, are presented in Table 2.1. The Table 2.1 data is presented in Fig. 2.1 in a scatter plot.

Table 2.1: Received data for battery energy systems from the market survey

Offer no.	**Dimensioning parameter(s)**$^{(1)}$	**Energy (kWh)**	**Power (kW)**	**PV size (kWp)**$^{(2)}$	**Battery Supplier or datasheet**
1	Site for battery PV size	5	2.5	Max 15	Huawei (Huawei Luna)
2	Site for battery PV size	10	5	Max 15	Huawei (Huawei Luna)
3	Site for battery PV size	15	5	Max 15	Huawei (Huawei Luna)
4	Site for battery	10	4	Not relevant	PylonTech (+ Ferroamp)
5	Site for battery	14	4	Not relevant	PylonTech (+ Ferroamp)

1. Such as suitable PV, PEC sizes in relation to the battery size.
2. For example, maximize self-consumption (from PV), peak power shaving, market arbitrage, grid/off-grid connection, etc.

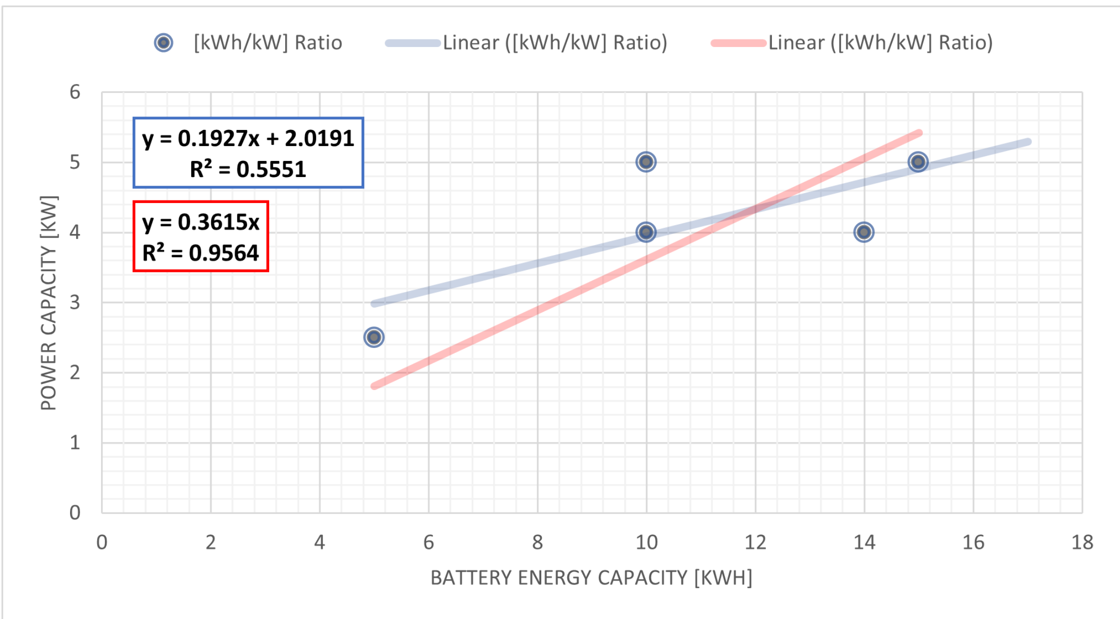

Figure 2.1: The relation between the energy capacity and power capacity.

It is observed that the majority of battery energy storage systems are integrated with solar PV systems, highlighting how these systems complement renewable energy supply systems. The predominant cell technology is Lithium-ion, chosen for its energy capacity, longevity, and competitive price [16]. The control strategy implemented in the market aims for increased self-consumption and peak-shaving, with the goal of reducing the energy drawn from the main grid and consequently lowering electricity prices. To provide an overview of the dimensioning parameters between power and energy capacity for the battery energy storage system. The size of the battery energy storage system in relation to the solar PV system is expressed using the kWh/kWp ratio, referred to as the Energy-to-Power ratio. According to storage inspections in Germany [17], the ratio of usable battery storage capacity to solar PV throughput is approximately 1 kWh of usable battery storage capacity per 1 kWp of solar PV throughput. When looking into the survey results in Fig. 2.1, the energy-to-power ratio is between 2–3.5 kWh/kWp, with the dominant battery size ranging around 10 kWh.

2.2.2 Market Survey Results from Supplier Previous Projects

In addition to information obtained from suppliers' feedback, offerings highlighted in references and previous projects of solar PV systems with battery energy storage were extracted and analyzed from websites for further insight. Table 2.2 presents the extracted data on references and previous projects and illustrating the relationship between solar PV kWp output and kWh of battery energy storage capacity.

Table 2.2: Extracted data from reference projects from the market survey

Project no.	**Solar PV output (kWp)**	**Battery energy capacity (kWh)**	**Residential type**
1	15.8	10.0	Single-Family/Villa
2	19.0	12.8	Single-Family/Villa
3	14.4	15.0	Single-Family/Villa
4	13.2	11.0	Single-Family/Villa
5	13.8 (1)	10.0	Single-Family/Villa
6	17.4 (1)	10.0	Single-Family/Villa
7	15.2	14.1	Single-Family/Villa
8	17.7	18.0	Single-Family/Villa
9	93.3 (1)(2)	26.0	Multi-Family/BFR
10	266.7 (1)(2)	81.0	Multi-Family/BFR
11	11.3	7.0	Single-Family/Villa
12	16.4	14.0	Single-Family/Villa
13	17.0	9.6	Single-Family/Villa

1.Values were presented in kWh per year production, a scale factor of 900 kWh/kWp is utilized.
2.Values not included in scatter plot (Multi-Family house application).

From the references and previous projects, it is observed that the majority of offerings are for single-family households compared to multi-family applications. This observation underscores the growing trend of self-generated electricity consumption. To have a better view on the dimensioning parameters and the relationship between solar PV power peak and the energy capacity of the battery energy storage system, the data from Table 2.2 is presented in Fig. 2.2 as a scatter plot.

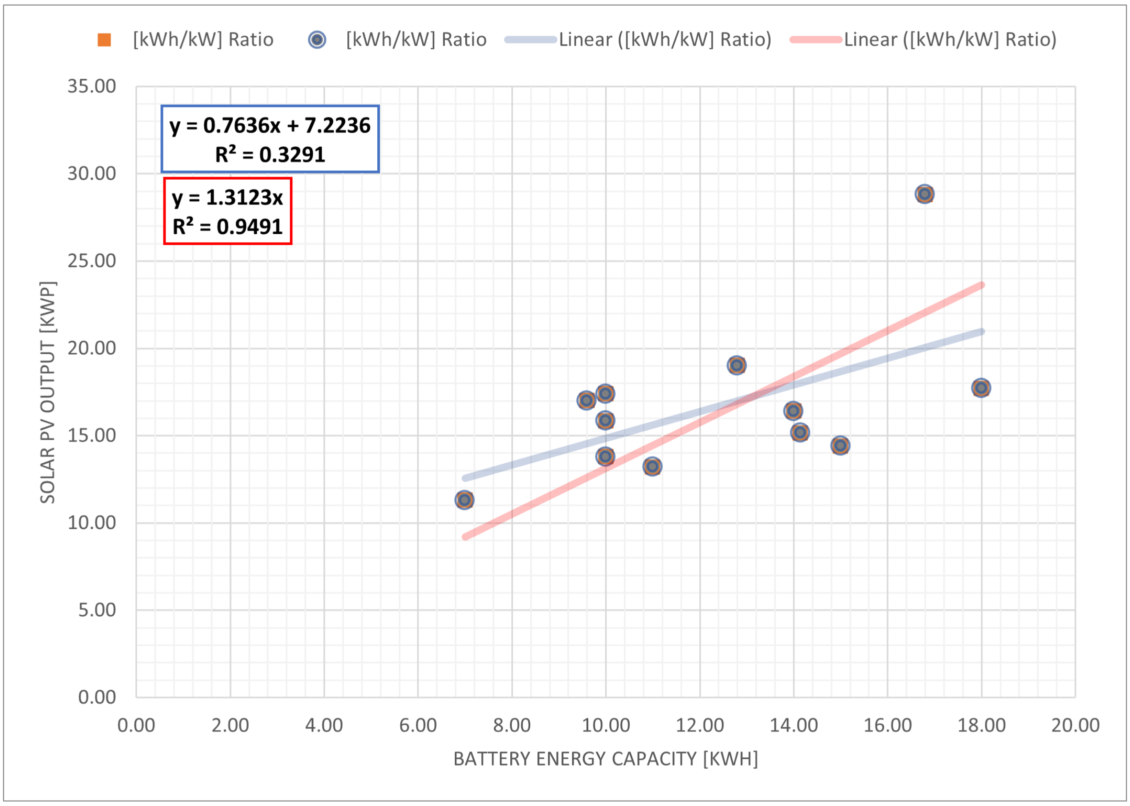

Figure 2.2: The relation between the solar PV peak power and battery energy storage

Based on the data obtained from references and previous projects on suppliers' websites, the majority of offers with integrated battery energy storage systems are intended for single-family households/villas. There are a few reference projects for multi-family/BRF with a mention of battery energy storage on the suppliers' websites. The survey highlighted that the integration of battery energy storage systems aims to extend and complement the self-generated electricity from solar PV installations, with a focus on increasing self-consumption control strategies. The results emphasized the relationship between the energy-to-power ratio and the size of the battery energy storage system in comparison to the size of the solar PV system. The energy-to-power ratio was found to range between 0.5–1 kWh/kWp. This differs from the results obtained in Section 2.2.1, indicating that the size of the SBESS is influenced not only by the size of the solar PV but also by other aspects, including the dimensions of the converter system and the type of topology connection system applied in the system. From the IEA PVPS report [16], it is highlighted that in AC-coupled systems, the size of the battery is influenced by the size of the converter system, and for DC-coupled systems, the size of the battery is determined based on the solar PV output production. In the survey, the size of the battery is in the range of 10–14 kWh with solar PV power peak of 15 kWp for single-family/villa household as seen in Fig. 2.2. For multi-family households, the energy-to-power ratio is around 0.3 kWh/kWp and battery size is between 26 kWh and 81 kWh with solar PV power peak of kWp of 93 kWp and 267 kWp, respectively.

2.2.3 Market Survey Results from Supplier/OEM Datasheets

In this part of the survey, the relationship between the maximum continuous charging power and battery usable capacity was investigated. Table 2.3 presents a summary of technical data obtained from OEM's datasheets, illustrating the correlation between the maximum continuous charging power and the battery's usable capacity for residential applications. By using the power required to charge the battery from the power electronic converter, the dimensioning relation of the battery energy storage system is observed. To have a better view on the dimensioning parameters in

Table 2.3: Extracted data from data-sheets of Original Equipment Manufactures (OEM) for the market survey

Reference Suppliers	**Maximum Cont. Charging Power (kW)**	**Battery Usable Capacity (kWh)**	**Operating Voltage range**
Supplier A.1	5.0	9.3	400–450 VDC
Supplier A.2	5.0	9.6	420–450 VDC
Supplier A.3	7.0	16.0	420–450 VDC
Supplier B	5.0	13.5	50 VDC
Supplier C.1	7.0	10.0	230 VAC
Supplier C.2	8.0	20.0	231 VAC
Supplier C.3	8.0	30.0(1)	232 VAC
Supplier C.4	8.0	40.0(1)	233 VAC
Supplier C.5	8.0	50.0(1)	234 VAC
Supplier C.6	5.0	10.0	160–230 VDC
Supplier D.1	4.0	6.3	174–216 VDC
Supplier D.2	6.0	9.5	261–324 VDC
Supplier D.3	7.8	12.7	384–432 VDC
Supplier E.1	6.6	9.6	150–219 VDC
Supplier E.2	8.8	12.8	200–292 VDC
Supplier E.3	11.0	16.0	250–365 VDC
Supplier E.4	13.1	19.2	300–438 VDC
Supplier E.5	15.3	22.4	350–511 VDC
Supplier E.6	17.5	25.6	400–584 VDC
Supplier F	3.3	5.2	100–131 VDC
Supplier G.1	11.5	11.5	720 VDC
Supplier G.2	17.2	17.2	720 VDC
Supplier G.3	23.0	23.0	720 VDC
Supplier G.4	28.8	28.8(1)	720 VDC

1.Values not included in scatter plot (Multi-Family house/Commercial application).

relation to data obtained from the suppliers datasheets, the correlation between the maximum continuous charging power and the battery usable capacity of the battery energy storage system from Table 2.3 is presented in Fig. 2.3 as a scatter plot.

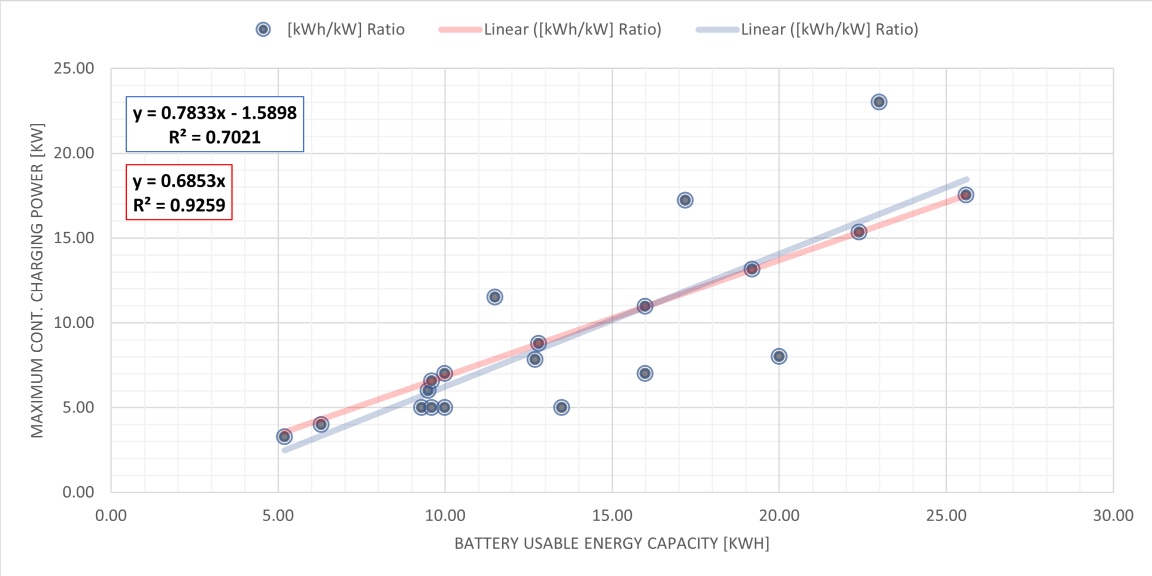

Figure 2.3: The relation between the maximum continuous charging power and usable capacity of battery energy storage system

The energy-to-power ratio presented in this section differs from that of Section 2.2.1 and Section 2.2.2 because it is directly linked to the power required from the converter to charge the battery. This ratio can also serve as an indicator of the battery charging rate, known as the C-rate, which refers to the rate at which the battery is charged or discharged. From survey, the kWh/kW ratio is between 1–2.2 kWh/kW range. A conclusion cannot be properly drawn as the type of topology connection (AC-coupled or DC-coupled) is missing from the data; however, the results provide an idea of the size of the battery in relation to the converter size, specifically in terms of how much power from the converter is needed to charge a certain size of a battery.

3
Theory

The performance evaluation of the stationary battery energy storage system (SBESS) considers the behavior of interconnected components and power flows within the entire system. For this work, the SBESS coupled with the PV system is referred to as the PV-battery storage system. The PV-battery storage system consists of a PV system made of solar photovoltaic modules, the power electronic converters (PECs), and a battery energy storage system. The purpose of the system is to operate relative to the grid to supply energy to the load. This section will elaborate on the performance matrices of the battery energy storage system integrated into a PV system. The objective of the performance matrices is to present evaluation criteria to assess the performance of the SBEES. The 'Efficiency Guideline for PV storage systems' published by the German Solar Industry Association (BSW) and the German Energy Storage Association (BVES), provides a guideline for assessing the performance of grid-connected stationary battery energy storage systems integrated with PV systems. It introduces System Performance Indicators (SPI) to evaluate power losses and overall system efficiency, enabling both technical and economic assessment based on operational performance [8]. The system performance indicators explored in this project are:

- Self-Consumption and Self-Sufficiency
- Sizing of PEC and SBESS
- Conversion path efficiency
- Round-trip efficiency (RTE)
- Usable and storage capacity and Depth of Discharge (DOD)

3.1 Self-Consumption and Self-Sufficiency

With the battery energy storage system that is intended for residential application, aimed for optimizing the use of self-generated solar power to increase self-consumption, its performance can be measured and characterized by evaluating the degree of self-consumption and self-sufficiency achieved in operation. The Self-Sufficiency Ratio (SSR) expresses the extent to which the production from the PV system output and battery energy storage system can meet the complete load demand of the household [18, 19]. The Self-Consumption ratio (SCR),

$$\text{SCR} = \Big[\frac{(P_{PV,DC} * \eta_{PV2AC} + P_{BAT,DC} * \eta_{BAT2AC}) - P^{+}_{GRID}}{P_{PV,DC}}\Big] * 100\% \tag{3.1}$$

$$\text{SSR} = \Big[\frac{(P_{PV,DC} * \eta_{PV2AC} + P_{BAT,DC} * \eta_{BAT2AC}) - P^{+}_{GRID}}{P_{LOAD}}\Big] * 100\% \tag{3.2}$$

expresses the proportion of PV produced and stored energy in the battery energy storage system that is directly self-consumed by the household load [18]. From the SSR of (3.2), how much a household (in this case with a PV-battery storage system) is independent from the main grid, can be observed, where a higher SSR indicates that the household is more independent from the grid supply [18]. The SCR of (3.1) expresses how much of the locally produced and stored energy (PV and battery energy storage) that is consumed by the household load, and higher SCR indicates that the majority of the locally produced energy from the PV and battery energy storage is consumed by the household load demand [18]. In the study from Widén et al. [20], the study indicated that as the size of the battery energy storage system increases, the rate at which self-consumption increases becomes less in relation to the size of the PV system, this is demonstrated in Fig. 3.1.

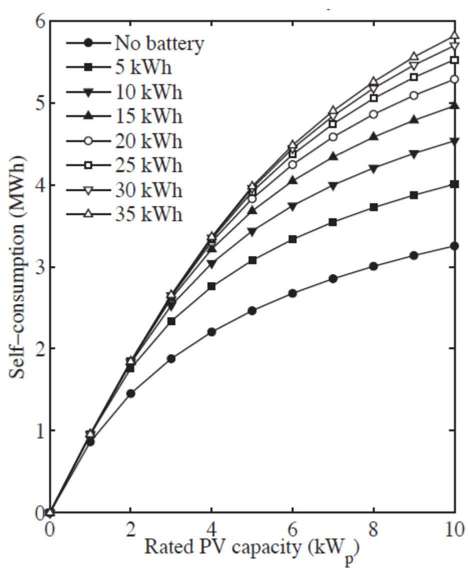

Figure 3.1: Self-consumption in relation to size of battery storage and PV system [20].

3.2 Sizing of Stationary Battery Energy Storage System (SBESS)

A typical battery energy storage system consists of rechargeable battery modules and a charge controller system. The modules are made up of interconnected battery cells designed to achieve the required output capacity [21]. Rechargeable batteries convert chemical energy to electric energy during discharge and vice versa during charging. Common types include lead-acid, nickel, and lithium-ion, with lithium-ion preferred for its lightness, high energy density, and long lifespan. Batteries operate within specific capacity and voltage limits, managed by the charge controller in the battery management system, which regulates charging and discharging rates, referred to as C-rates, to ensure safe operation and long life. When coupled with a PV system, the battery stores excess energy from the PV modules during the day and discharges it to supply loads at night or during low solar radiation. Batteries can also store grid energy during non-peak times and discharge during peak times.

The coupling of the battery influences how much energy that can be fed into the battery. For DC-coupled system, the size of the battery is influenced by the size of the PV throughput, and for AC-coupled systems, the battery converter will influence the power and voltage ratings of the battery [17]. When the converter power is lower than the battery charge power, the converter is the limiting factor. When the converter is larger than the battery charge power, the converter will operate with relatively high conversion losses, especially in the low power range. In this case, battery charge and discharge power affect the optimal operation of the PV-battery storage system. A low charging power results in the battery not optimally storing all excess energy generated by the PV system when solar irradiance is available. Conversely, low discharge power benefits applications with high energy capacity demand (low power, long duration) but may have a challenge to meet peak power demands, which require high power over a short period. Similarly applies to high charge power, which allows for faster battery charging, while high discharge power limits the amount of energy capacity that can be drawn from the battery [3].

3.3 Sizing of Power Electronics Converters (PEC)

Converters are one of the important components in a PV-battery storage system. The main purpose of a converter in a PV system is to efficiently convert the energy in DC-form from the PV modules production to AC current that can be utilized for household applications [22]. Solar converters are equipped with module optimizers such as Maximum Power Point Trackers (MPPT) that monitor and adjust the power output from the PV modules to ensure optimal performance. A battery energy storage system utilizes bidirectional converters, enabling both the charging and discharging of the battery. The Power Electronic Converter (PEC) control system, together with the Battery Management System (BMS), regulates parameters like battery voltage, current, and state of charge. When island operation is included, the converter can also control and monitor this mode. For the power flow conversion from DC to AC, the converter's ability to efficiently convert DC power to AC with minimal losses is an important performance indicators for the operation of PV and battery energy storage systems. Converter efficiency is significantly influenced by its loading conditions. As shown in Fig. 3.2, the converter performs more efficiently when operating near its rated or nominal load, particularly in relation to PV input [17]. Hence, whether connected to AC- or DC-coupled system, the rated power of the DC/AC and AC/DC converters directly influences the charge and discharge power of the battery energy storage system.

When the converter is lightly loaded, it operates at lower efficiency, thereby limiting the output power from the PV system due to higher conversion losses [23]. This relation impacts system sizing and operational efficiency, as undersized converters may limit energy throughput during peak PV production and high load demand periods, while oversized converters can lead to low operational efficiencies and hence, increased losses in the system. In Fig. 3.2, converter efficiency peaks at approximately 20% of the converter loading. Due to this, the converter is rated to be 10 to 30% lower in power rating in relation to the PV maximum output power, allowing it to operate closer to full capacity and within the high efficiency region [22, 23]. In this way the converter is operated with 10 to 30% under load in relation to the maximum power output from the PV system, meaning even when partially loaded, it can operate close to its high efficiency regions. When considering the battery energy storage system, if the charge power is low, meaning the battery converter is rated and sized small, the amount of PV power that can be stored in the battery will

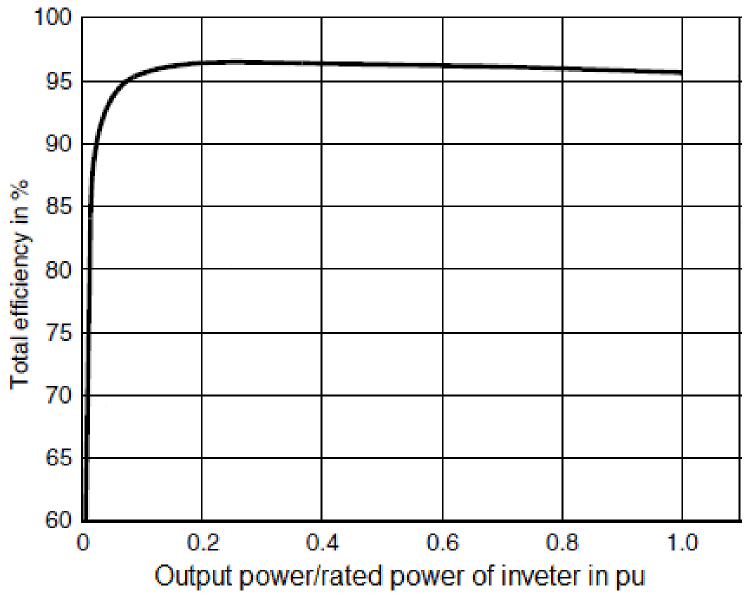

Figure 3.2: Converter efficiency curve [23].

be limited. This influence is observable when the PV system's maximum output exceeds the battery converter's charging power, limiting how much solar energy that can be stored in the battery. Conversely, oversizing the battery converter can lead to higher conversion losses at low loads. Therefore, optimal sizing of the power electronic converter in relation to both the PV system and SBESS is a crucial factor influencing the overall performance of the PV-battery storage system [3].

Figure 3.3 illustrates how conversion efficiency varies with converter loading during battery discharge [24]. Converter efficiency depends on power throughput from the DC

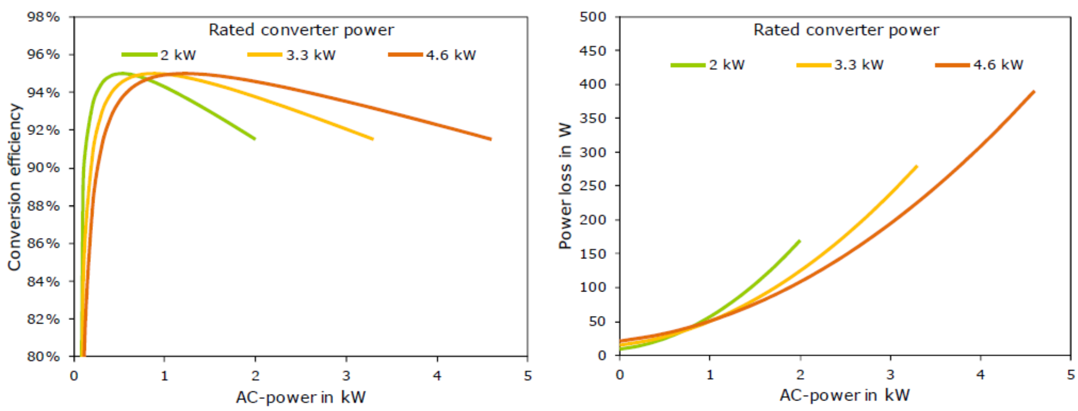

Figure 3.3: Efficiency curves for different converter power sizes [24].

side (PV and battery) to the AC side (load), and is affected by losses at different loading levels. At low power loading, the efficiency is influenced by power limitation losses where DC input is lower than AC output. When the converter loading reaches approximately 30% of its rated AC power, it reaches its peak efficiency. As power throughput increases further, approaching the converter's rated power, efficiency declines due to increased resistive losses in the system. Considering the sizing of the SBESS in relation to the the converter, the converter's charge/discharge power becomes a crucial factor in SBESS. The converter sizing ratio refers to the ratio between the nominal power of the converter and the usable capacity of the battery.

3.4 Conversion Path Efficiency in PV-Battery Storage Systems

Conversion losses include losses from the operation and switching of power electronics, as well as the converter connection topology (AC or DC). These losses impact the mean power flow between the PV system, converter, SBESS, grid, and load, and are influenced by the number of power electronics converters in the system. The charged and discharged battery energy capacity in Wh and current capacity in Ah are characterized as,

$$E^{-}_{BAT} = \int_0^t P^{-}_{BAT,DC}\, dt \tag{3.3}$$

$$C^{-}_{BAT} = \int_0^t I^{-}_{BAT}\, dt \tag{3.4}$$

$$E^{+}_{BAT} = \int_0^t P^{+}_{BAT,DC}\, dt \tag{3.5}$$

$$C^{+}_{BAT} = \int_0^t I^{+}_{BAT}\, dt \tag{3.6}$$

where $P^{-}_{BAT,DC}$ and $P^{+}_{BAT,DC}$ are the nominal continuous battery charge and discharge DC power from the battery side, and I^{-}_{BAT} and I^{+}_{BAT} are the measured charge and discharge currents of the battery [8]. The battery discharged energy capacity E^{+}_{BAT} is also referred to the usable energy capacity of the battery deliverable to the load until reaching the battery's lower voltage limit.

The power flow and losses in a PV and battery energy storage system are influenced by the number of conversion paths taken to and from the load and grid. Different topologies, namely AC-coupled, DC-coupled, and PV generator-coupled systems, represent various configurations of PV-battery storage systems [8, 17]. The conversion path efficiencies explored include the PV to AC path (PV2AC), PV to battery path (PV2BAT), battery to AC path (BAT2AC), and AC to battery path (AC2BAT), where the AC side includes the load and the grid. The PV2AC path refers to the power flow from the PV system to the AC side. To evaluate this conversion path accurately, the battery must remain inactive,neither charging nor discharging. This means that the battery's DC power flow, $P_{BAT,DC}$, should ideally be zero, ensuring that all power transferred from the DC side to the AC side is sorely supplied from the PV system. The PV2BAT path represents the charging path of the battery from the PV system. For this power flow, it is essential that no energy is exchanged with the AC side, meaning both $P_{INV,AC(in)}$ and $P_{INV,AC(out)}$ should ideally be zero. This ensures that all power generated by the PV system is directed exclusively to charge the battery. The BAT2AC path represents the conversion path for discharging the battery to the AC side, supplying both the load and the grid. In this power flow, it is crucial that no energy is generated or transferred from the PV system, meaning $P_{PV,DC}$ should ideally be zero. This ensures that all power delivered to the AC side comes exclusively from the battery. Additionally, it is important that the battery supply is prioritized over the grid supply when analyzing this conversion path. This means that the load must be supplied solely by the battery energy storage system. The AC2BAT represents a conversion path for charging the battery from the grid. In this power flow,it is essential that no power is transferred from the PV system to the battery, meaning $P_{PV,DC}$ should ideally be zero. This ensures that the battery is charged exclusively by the grid. Figure 3.4 – Fig. 3.6 illustrates the topological connections with their respective power flows and conversion paths (3.7 – 3.17), between PV system, converter system, and stationary battery energy storage system to load demand and grid.

3.4.1 AC-Coupled System

In the AC-coupled configuration shown in Fig. 3.4, the SBESS is charged by the PV system through the PV inverter and the hybrid inverter [17]. From the grid side (AC side), the battery charging and discharging path is through the hybrid inverter only. The grid and load share a common AC coupling point, where the GRID2LOAD path involves no power conversion stages. In the PV-to-load/grid (PV2AC) power flow path, the PV inverter

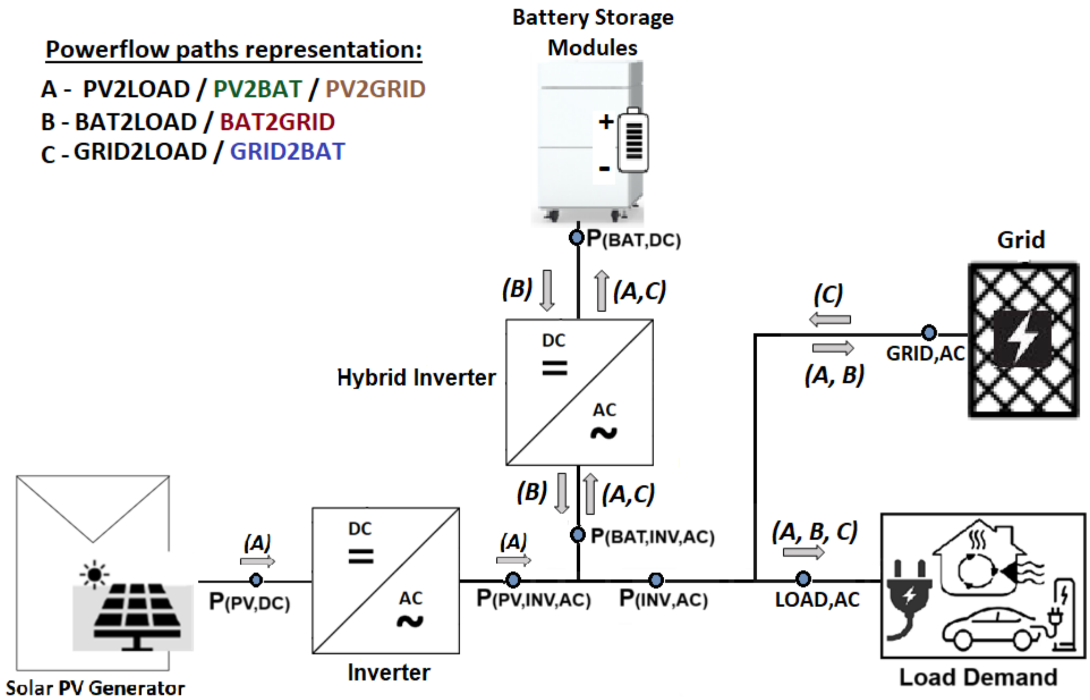

Figure 3.4: Power conversion paths for PV-battery storage system in a AC-coupled topology [8].

converts DC from the PV generator into AC, supplying both the load demand and feeding excess energy into the grid (grid feed-in),

$$\eta_{PV2AC,ac} = \frac{P_{PVINV,AC}}{P_{PV,DC}}. \tag{3.7}$$

As shown in (3.7), the conversion path efficiency is influenced by the DC power from the PV generator $P_{PV,DC}$ and the AC power from the PV inverter $P_{PVINV,AC}$ [8]. The battery, on the other hand, supplies the load and grid feed-in through the BAT2AC path, utilizing a bidirectional battery converter (hybrid inverter) for DC-to-AC conversion [8]. The battery-to-load/grid conversion path efficiency (BAT2AC) during discharge is influenced by the nominal continuous AC discharge power from the battery hybrid inverter, $P^{+}_{BATINV,AC}$, and the nominal continuous DC discharge power from the battery side, $P^{+}_{BAT,DC}$,

$$\eta_{BAT2AC,ac} = \frac{P^{+}_{BATINV,AC}}{P^{+}_{BAT,DC}}. \tag{3.8}$$

Considering battery charging cycle, the conversion path efficiencies for charging from the PV system (PV2BAT) and from the grid (GRID2BAT) are expressed as,

$$\eta_{GRID2BAT,ac} = \frac{P^{-}_{BAT,DC}}{P^{-}_{BATINV,AC}} \tag{3.9}$$

$$\eta_{PV2BAT,ac} = \eta_{PV2AC,ac} \cdot \eta_{GRID2BAT,ac} = \frac{P_{PVINV,AC}}{P_{PV,DC}} \cdot \frac{P^{-}_{BATINV,AC}}{P^{-}_{BAT,DC}}. \tag{3.10}$$

As seen from (3.9) and (3.10), the conversion path efficiency for charging the battery from the grid (GRID2BAT) is influenced by the nominal continuous AC charging power from the battery converter, $P^{-}_{BATINV,AC}$, and the nominal continuous DC charging power of the battery, $P^{-}_{BAT,DC}$ [8]. Similarly, the efficiency of the conversion path for charging the battery from the PV system (PV2BAT) is influenced by both the efficiencies of the PV-to-AC (PV2AC) and AC-to-battery (GRID2BAT) conversion paths [8].

The AC-coupled system enables the PV system and the battery energy storage system to be connected and operated independently. In this configuration, the battery size is primarily influenced by the size of the bidirectional converter (hybrid inverter) and is less dependent on the size of the PV system [18, 25]. With high number of converters in this topology, AC-coupled systems may incur increased conversion losses and component costs [25].

3.4.2 DC-Coupled System

Considering the DC-coupled system illustrated in Fig. 3.5, the conversion path efficiency for delivering power to the load and grid feed-in from the PV system (PV2AC) is expressed in (3.11). This conversion path efficiency is influenced by the nominal AC output power from the combined PV-battery storage system at the AC point $P_{INV,AC(out)}$, the DC power from the PV generator $P_{PV,DC}$, the nominal continuous battery charge DC power $P^{-}_{BAT,DC}$, and the nominal continuous battery discharge DC power $P^{+}_{BAT,DC}$,

$$\eta_{PV2AC,dc} = \frac{P_{INV,AC(out)}}{P_{PV,DC} - P^{-}_{BAT,DC} + P^{+}_{BAT,DC}}. \tag{3.11}$$

The battery supplies the load and grid feed-in through a conversion path (BAT2AC). The conversion path efficiency influenced by the nominal AC output power delivered from the PV-battery storage converter (hybrid inverter) at the AC point $P_{INV,AC(out)}$ and the nominal continuous battery discharge DC power from the battery side $P^{+}_{BAT,DC}$,

$$\eta_{BAT2AC,dc} = \frac{P_{INV,AC(out)}}{P^{+}_{BAT,DC}}. \tag{3.12}$$

$$\eta_{GRID2BAT,dc} = \frac{P^{-}_{BAT,DC}}{P_{INV,AC(in)}} \tag{3.13}$$

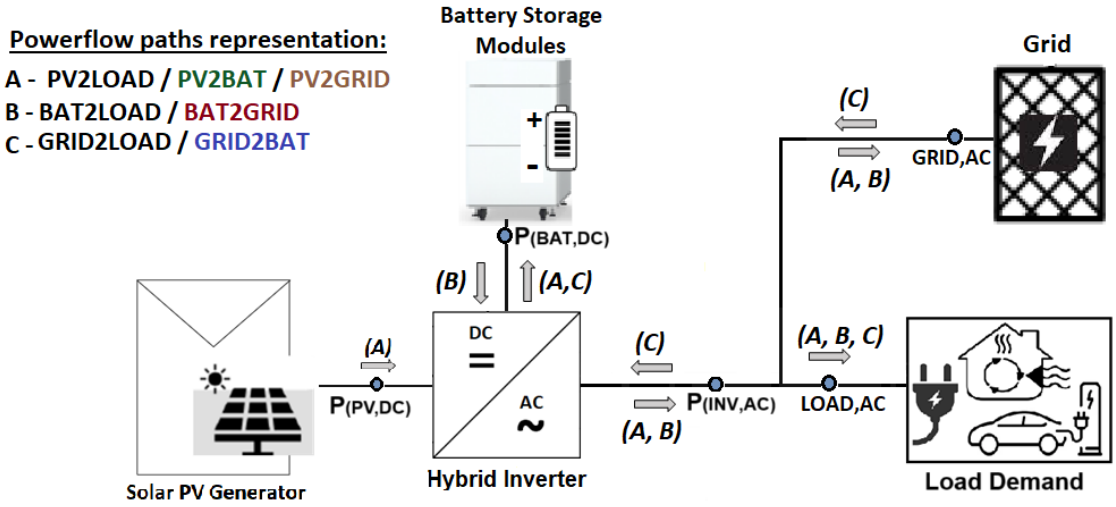

Figure 3.5: Power conversion paths for PV-battery storage system in a DC coupled topology [8].

$$\eta_{PV2BAT,dc} = \frac{P^{-}_{BAT,DC}}{P_{PV,DC} + P_{INV,AC(in)} - P_{INV,AC(out)}}. \tag{3.14}$$

In the DC-coupled system, the conversion path efficiencies for charging the battery from the grid (AC2BAT) and from the PV (PV2BAT) are defined in (3.13) and (3.14), respectively. In these expressions, $P_{INV,AC(in)}$ and $P_{INV,AC(out)}$ represent the nominal AC input and output powers of the PV-battery storage converter at the AC connection point [8]. The DC-coupled system allows the PV system and SBESS to be connected through a hybrid inverter that enables bidirectional power flow for the battery, while maintaining unidirectional power flow for the PV system. In this topology, the size of the PV system directly influences the size of the battery energy storage system [25].

3.4.3 PV Generator-Coupled Systems

The PV generator-coupled topology, as shown in Fig. 3.6, represents another configuration within the DC-coupled arrangement. The conversion path efficiency to supply power to the load and grid feed-in from the PV system (PV2AC) is expressed in (3.15). This conversion path efficiency is influenced by the nominal AC output power from the PV-battery storage system at the AC point, $P_{INV,AC(out)}$, the DC power from the PV generator, $P_{PV,DC}$, the nominal continuous battery charge DC power, $P^{-}_{BAT,DC}$, and the nominal continuous battery discharge DC power, $P^{+}_{BAT,DC}$,

$$\eta_{PV2AC,pvgen} = \frac{P_{INV,AC(out)}}{P_{PV,DC} - P^{-}_{BAT,DC} + P^{+}_{BAT,DC}}. \tag{3.15}$$

The battery to AC conversion path efficiency,$\eta_{BAT2AC,pvgen}$, is influenced by the nominal AC output power from the PV-battery storage converter at the AC point $P_{INV,AC(out)}$, as well as the nominal battery discharge DC power from the battery converter $P^{+}_{BAT,DC}$,

$$\eta_{BAT2AC,pvgen} = \frac{P^{+}_{BAT,CONV,DC}}{P^{+}_{BAT,DC}} \cdot \frac{P_{INV,AC(out)}}{P^{+}_{BAT,CONV,DC}} = \frac{P_{INV,AC(out)}}{P^{+}_{BAT,DC}} \tag{3.16}$$

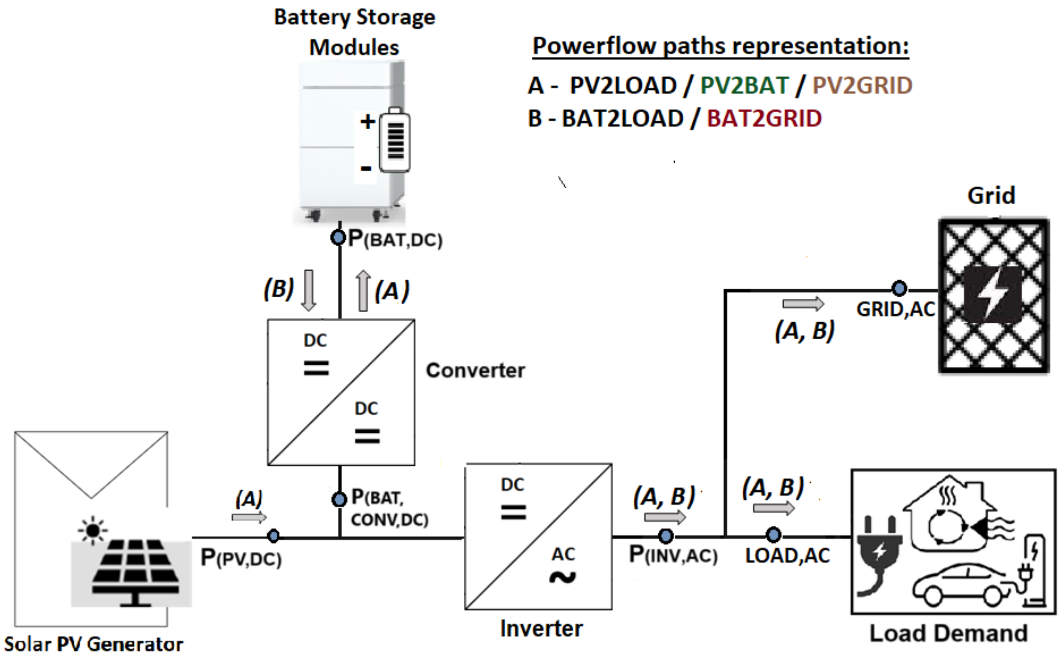

Figure 3.6: Power conversion paths for PV-battery storage system in a PV generator-coupled topology [8].

$$\eta_{PV2BAT,pvgen} = \frac{P^{-}_{BAT,DC}}{P_{PV,DC}}. \tag{3.17}$$

The conversion path efficiency to charge the battery from the PV system (PV2BAT) in the PV generator-coupled system is given by (3.17), where $P_{PV,DC}$ represents the DC power from the PV generator [8]. In the PV generator-coupled topology, a DC-DC converter is connected in parallel to the PV system on the DC side. In this configuration, AC2BAT charging is not permitted due to the direct coupling between the PV system and SBESS. Consequently, the inverter allows only DC-to-AC power flow. This topology enables efficient operation between the DC-DC converter and the PV-battery storage inverter [4].

3.5 Round-Trip Efficiency of the SBEE

A round-trip forming a complete cycle between charging and discharging of the battery will accumulate voltage hysteresis losses due to the electrochemical processes of the cells of the battery. The charge path of the electrochemical cell of the battery is not the same as that of the discharge path, shown by a voltage difference referred to as voltage hysteresis (ΔE) and this leads to energy being lost due to the difference in voltages between charging and discharging [12]. Figure 3.7 demonstrates the charge and discharge of the battery forming a voltage hysteresis which results in energy losses.

In this way, the energy released from the battery after a round-trip is less than the amount of energy store, hence indicating the efficiency of the battery energy storage system in terms of the corresponding losses accumulated through the round-trip [17, 12]. Bidirectional converters enable both charging and discharging power flow paths for the

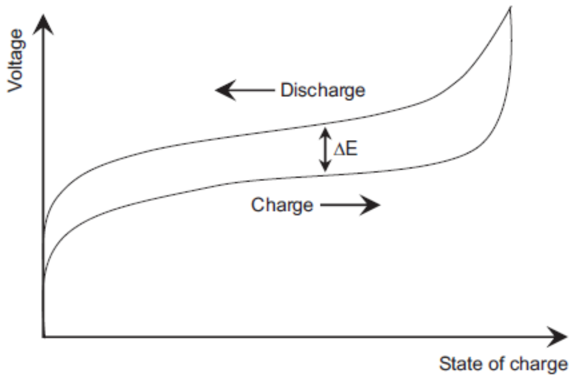

Figure 3.7: Voltage hysteresis between charge and discharge path [12].

battery energy storage system. However, due to round-trip losses, the conversion path losses increase, contributing to the reduction in the overall efficiency of the SBESS [17].

$$\eta_{BAT,RTE} = \frac{\int_0^t P^{+}_{BAT,DC}\, dt}{\int_0^t P^{-}_{BAT,DC}\, dt} \tag{3.18}$$

$$\eta_{BAT,RTEC} = \frac{\int_0^t I^{+}_{BAT}\, dt}{\int_0^t I^{-}_{BAT}\, dt} \tag{3.19}$$

Equations (3.18) and (3.19) describe the battery energy round-trip efficiency and Coulomb round-trip efficiency, respectively, where $P^{-}_{BAT,DC}$ and $P^{+}_{BAT,DC}$ are the nominal continuous battery charge and discharge DC powers from the battery side, and I^{-}_{BAT} and I^{+}_{BAT} are the charge and discharge currents of the battery [8]. The powers and currents are integrated for a time period (t) to obtain the respective energies and capacities of the variables. The battery energy round-trip efficiency expresses the energy charged and energy discharged to and from the battery, and the coulomb round-trip efficiency expresses the capacity charged and the capacity discharged from the battery [8].

3.6 European Efficiency

The efficiencies from (3.7) – (3.18) can be evaluated in comparison to aggregated efficiency, specifically the European efficiency, which is used to quantify the performance of the power conversion system in PV and battery energy storage applications. The European efficiency is calculated by considering individual conversion path efficiencies across the system and applying scaling factors based on the system configuration and conditions. Niedermeyer et al. [25], presented equations and table with the scaling factor to represent the corresponding European efficiency in relation to the conversion path efficiencies for different connection topologies,

$$\eta_{EURO,ac} = \eta_{PV2AC,ac} \times \eta_{BAT2AC,ac} \times \eta_{GRID2BAT,ac} \times \eta_{BAT,RTE} \tag{3.20}$$

$$\eta_{EURO,dc} = \eta_{BAT2AC,dc} \times \eta_{PV2BAT,dc} \times \eta_{BAT,RTE}. \tag{3.21}$$

3.7 Influence of Control System Losses

The losses on the control side represent the losses due to power consumed by the control system of the PV-battery storage system. These are inclusive of the self-discharge of battery on standby, Maximum Power Point Tracker (MPPT) losses, and time delays on the control system. The standby power consumption entails the power losses incurred when the control systems such as Maximum Power Point Tracker (MPPT), Battery management System (BMS), converter control system and grid PCC meters are in idle or standby mode [17]. The MPPT losses are due to inaccurate measurements which lead to delay or rapid adjustments in the tracking of the maximum power point, resulting in reduced throughput from the PV system [17].

3.8 Usable Storage Capacity and Depth of Discharge on the Performance of SBESS

The usable storage capacity of the battery is different from its nominal rated capacity, and it represents the deliverable capacity to load when the battery is discharged [17]. The usable and storage capacities are important key figures to consider for the performance of the battery energy storage system. The storage capacity is influenced by the load and the rating of the PV system. The usable capacity describes the amount of energy obtainable from the battery when it's discharged. The usable capacity is affected by the electrochemical losses inside the battery due to side reactions.

The battery capacity is, in operation, limited by the lower and upper limit of the state of charge (SOC), which when reached can put stress on the battery leading to reduced battery operational lifetime [18]. To ensure that the battery is not discharged beyond these limits and hence accelerating aging, the depth of discharge (DOD) should be constantly monitored. The depth of discharge is represented by the ratio of the usable capacity (E^{+}_{BAT}) to the nominal (nameplate) storage capacity ($E_{BAT(nom)}$) of the battery as expressed as [17, 18].

$$DOD = \frac{E^{+}_{BAT}}{E_{BAT(nom)}} * 100\% = SOC(t_{start}) - SOC(t_{end}). \tag{3.22}$$

As seen in (3.22), higher DOD gives increased usable capacity, which indicates the extent to which the battery has been discharged, which may result in increased higher cyclic aging of the battery [17, 26]. Cyclic aging is the aging of the battery influenced by its charge/discharge cycles. A DOD of 100% indicates that the battery is fully discharged and has a risk of reaching the lower SOC limits [18]. Manufacturers' specifications typically include the recommended Depth of Discharge (DOD) in their battery datasheets to maintain battery health, ensuring that the battery is not discharged beyond the specified DOD limit.

4

Methods

This section describes a systematic approach for developing the compressed test sequence to evaluate the annual performance of SBESS integrated with PV systems. It elaborates on the steps taken to select representative days that reflect the annual operational profiles of the system. As illustrated in Fig. 4.1, the process begins with analyzing the annual system profiles, including irradiance and load demand, to identify seasonal variations and define specific criteria for selecting representative days. The annual profiles were then categorized by season to ensure that the selected days accurately reflect the distinct operational characteristics of each season throughout the year. Based on this classification, selection criteria were defined, considering key performance indicators that influence the system's behavior throughout the year.

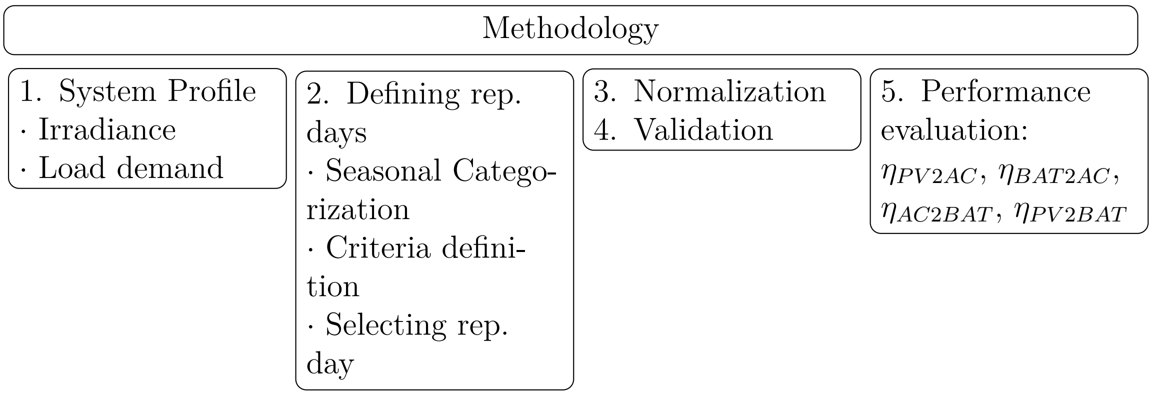

Figure 4.1: Illustration of the methodology steps for selecting representative days

With the defined criteria, the days that best match these conditions were selected as representative days. To maintain consistency, these selected days were normalized to proportionally reflect the total energy production and consumption observed in the annual operation. The selected representative days were then validated against the complete annual system data. This step confirms that they effectively capture the overall operational pattern of the system, including seasonal fluctuations in both PV generation and load demand. This structured approach ensures that the compressed test sequence remains an accurate and reliable representation of the annual behavior of the system under realistic operating conditions.

4.1 System Profiles

The test sequence should examine the annual operational performance of the PV-battery storage system while being time-condensed. To accomplish this, it is essential to examine the full-year profiles of the system. The system profiles under consideration include the irradiance profile and the consumer load profile representative of a single-family residential load. This section examines the profiles to understand their behavior throughout the year. This approach enables the definition of the criteria for selecting the representative days for the test sequence. Figure 4.2 presents the system profiles under study, obtained from full-year measurements with a temporal resolution of 1 minute from a region of the west coast of Sweden. The measurements were taken from June 1, 2022, to May 31, 2023. The load demand represents a heat pump used in a single-family household and the solar irradiance experienced in the region. The seasons in the region under study are ordered as follows: Summer spans June, July, and August; Autumn includes September, October, and November; Winter covers December, January, and February; and Spring comprises March, April, and May.

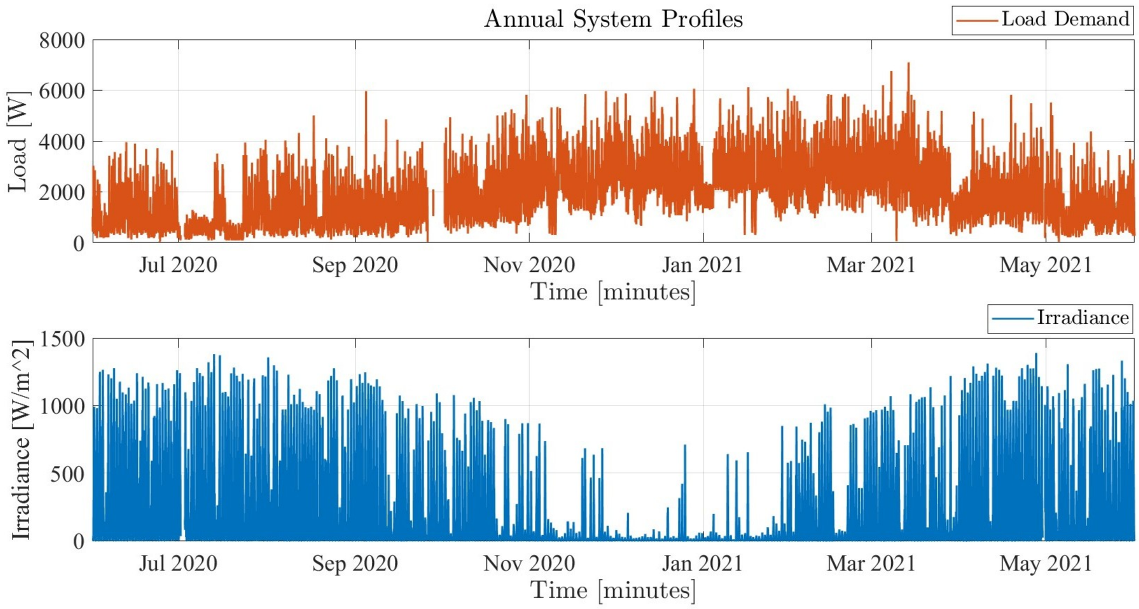

Figure 4.2: Load demand (top) and irradiance (bottom) profiles for full year operation taken from a west coast region in Sweden

The load demand varies throughout the year, as shown in Fig. 4.2, influenced by climate conditions and household energy usage patterns. Seasonal variations are significant in shaping the load demand profile, with energy consumption varying depending on the seasonal patterns and heating requirements. Higher energy demand occurs during the winter due to heating needs, with electric heaters and heat pumps contributing to higher demand. Conversely, the spring and autumn tend to exhibit intermediate load demand due to milder temperatures. For the system profiles under study, load demand is moderate during the spring and autumn seasons, higher in winter, and lower in the summer.

Throughout the year, solar irradiance varies as shown in Fig. 4.2. This variation can be influenced by several factors, such as the time of day, weather conditions, and seasonal changes. During the day, irradiance increases from sunrise and reaches its peak at noontime and decreases until sunset. Weather conditions, such as cloud cover and air pollution (e.g., dust), can affect the amount of solar irradiance received. Seasonal variations are characterized by the length of the day where longer and brighter days in summer result in higher irradiance, while shorter days in winter result in lower irradiance.

4.2 Defining the representative days

An essential requirement for the compressed test sequence is to identify representative days that accurately reflect the annual profile. The sequence of these days must align with the chronological order of the annual seasons, following the pattern of the system's yearly operation [2]. In this way, the natural progression of the system's behavior is captured, preserving the seasonal dependencies of load demand and solar irradiance. This ensures that the compressed test sequence reflects performance variations and serves as a reliable approach for assessing the system's performance characteristics and metrics in a realistic operating setting. In Section 4.1, system profiles were analyzed to identify patterns and variations across different seasons and to observe the relationship between load demand and irradiance throughout the year. This analysis forms the foundation for defining and characterizing the representative days used in the test sequence. A crucial criterion for selecting these representative days is ensuring consistency across all profiles. This means that the load demand and irradiance profiles for a specific season are taken from the same day and time. The test sequence must follow a systematic and uniform approach, enabling a fair comparison of SBESS performance across different systems and configurations. An essential requirement for the compressed test sequence is identifying representative days that accurately reflect the annual profile. The sequence of these days must align with the chronological order of the annual seasons, following the pattern of the system's yearly operation [2]. In this way, the natural progression of the system's behavior is captured, preserving the seasonal dependencies of load demand and solar irradiance. This ensures that the compressed test sequence serves as a practical approach for assessing the system's performance characteristics and metrics under realistic operating conditions. In Section 4.1, system profiles were analyzed to identify patterns and variations across different seasons and to observe the relationship between load demand and irradiance throughout the year. This analysis forms the foundation for defining and characterizing representative days. A crucial criterion for selecting the representative days is ensuring consistency across all profiles. This means that the load demand and irradiance profiles for a specific season are taken from the same day and time. The test sequence must follow a systematic and uniform approach to enable a fair comparison of SBESS performance across systems and configurations.

4.2.1 Data Processing and Assumptions

To simplify the management of the system profile data, data processing was first performed. The full-year data of the system profiles were resampled by clustering the data points. This was done by averaging the 1-minute temporal resolution data to hourly means. This approach reduced the number of data points while maintaining a good representation of the annual characteristics. While the 1-minute data resolution is ideal for capturing the detailed characteristics and patterns, it becomes dense and overly complex to handle due to the large size of the dataset.

To accurately characterize the seasons, it is essential to include the complete system profile, considering the correlation between irradiance and load demand across seasonal variations. As illustrated in Table 4.1, the largest seasonal deviations typically occurs at the transitional boundaries between seasons. For instance, in the spring season, a moderate load demand is expected. However, the maximum load demand observed in spring is 7100 W, which is higher than the maximum load demand in winter, recorded at 6120 W in January. In this way, it might seem reasonable to define the seasonal criteria by

Table 4.1: Seasonal Minimum, Maximum, and Average values of Load Demand and Irradiance Profiles

Seasons	Months	Load demand (W)	Irradiance (W/m^2)
Summer	Jun-2020	Min: 30	Min: 0
	Jul-2020	Avg: 1007	Avg: 197
	Aug-2020	Max: 4049	Max: 1380
Autumn	Sep-2020	Min: 30	Min: 0
	Oct-2020	Avg: 1831	Avg: 77
	Nov-2020	Max: 5970	Max: 1245
Winter	Dec-2020	Min: 300	Min: 0
	Jan-2021	Avg: 2831	Avg: 35
	Feb-2021	Max: 6120	Max:1009
Spring	Mar-2021	Min: 30	Min: 0
	Apr-2021	Avg: 1910	Avg: 173
	May-2021	Max: 7100	Max: 1389

excluding outliers or boundary values. However, doing so could exclude the true characteristics experienced throughout the year. This could result in a high deviation between the compressed test sequence profiles and the annual operation profiles. In this case, another criterion considered for this analysis is the sum of values for each season. When examining the sums of values for each season, it is observed that winter has a higher load demand, while the irradiance sum is lower. Utilizing the sums of these values, it becomes easier to distinguish the characteristics of each season. In this work, in addition to considering the typical order of the seasons and their corresponding months, the sums of the values for each season are also taken into account to ensure a more accurate representation.

4.2.2 Seasonal Characterization of the System Profiles

The first step in defining the representative days that will comprise the compressed test sequence is to categorize the annual system profiles into their respective seasons. In this way, allowing for a detailed study of the characteristics and patterns of each profile within each season. This will assist to define categories for each profile that best represent the characteristics of each season. The days with profiles that best fit the criteria defined within these categories will be selected as representative days for the test sequence. In Table 4.1, the System profiles are evaluated using monthly averages. In this way, the relationships between load demand and irradiance will be examined.

To define the representative days for the compressed test-sequence, specific criteria were established based on the analysis of the minimum, maximum, and average values of irradiance and load demand for each season. These criteria ensure that the test-sequence reflects the full range of conditions encountered throughout the year. For clarity, the system profile data were averaged on a monthly basis, with the respective minimum and maximum values for each season identified. By analyzing these parameters, the days that best capture the seasonal characteristics and behavior of the PV system and load demand can be selected.

4.2.3 Defining the Criteria for Selection of the Representative Days

This section focuses on defining the selection criteria for representative days. The seasonal characteristics outlined in Section 4.2.2, which incorporate the minimum, maximum, and average values of irradiance and load demand within each season, will be applied alongside the criteria presented in this section to identify specific days that best reflect the seasonal characteristics. By using these criteria, the most representative day for each season is selected, ensuring that its operational profile aligns with the seasonal trends. These selected representative days collectively form the test sequence system profiles. Figure 4.3 illustrates the flowchart outlining the steps taken in selecting the representative days based on these two criteria, the averages and sums of values.

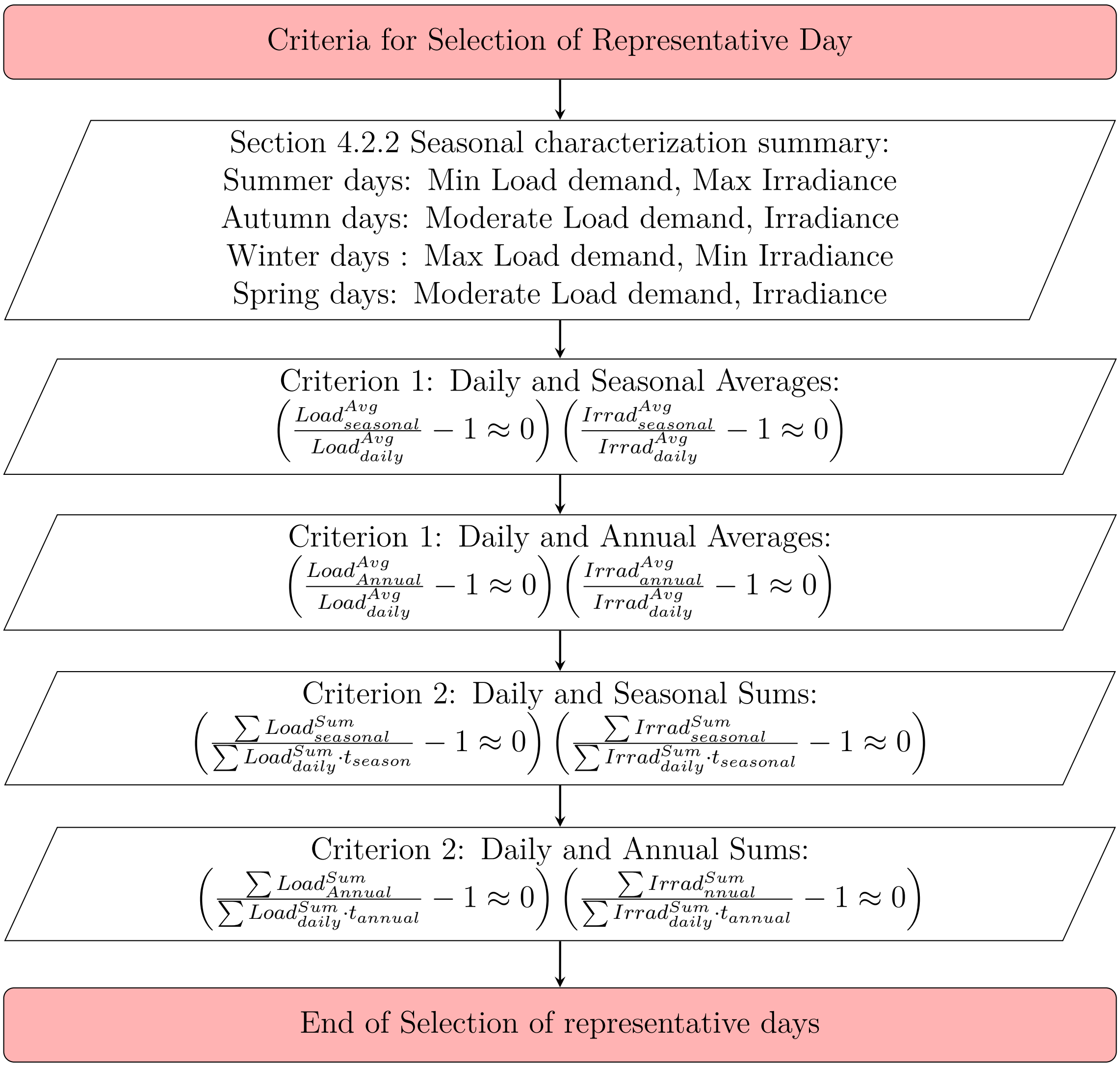

Figure 4.3: Selection of representative days flowchart

In this section, the averages and sums of values are considered as the criteria for selecting the representative days. From the resampled data in Section 4.2.1, daily averages and sums are calculated for each season. The seasonal averages and sums are then obtained, along with the annual averages and total sums. For the criterion based on averages, the daily averages are compared to the seasonal averages, and the relative error between them is determined. Furthermore, the seasonal averages are also compared to the annual averages. The goal is to obtain the total lowest relative error, as this ensures that the selected representative days align with and accurately reflect the seasonal characteristics. A low relative error in averages indicates that the selected days correspond well with the expected seasonal behavior, minimizing deviations that could impact performance evaluation.

$$\frac{Load^{Avg}_{seasonal}}{Load^{Avg}_{daily}} - 1 \approx 0 \tag{4.1}$$

$$\frac{Irrad^{Avg}_{seasonal}}{Irrad^{Avg}_{daily}} - 1 \approx 0. \tag{4.2}$$

Similarly, the representative days in comparison to the annual averages,

$$\frac{Load^{Avg}_{annual}}{Load^{Avg}_{daily}} - 1 \approx 0 \tag{4.3}$$

$$\frac{Irrad^{Avg}_{annual}}{Irrad^{Avg}_{daily}} - 1 \approx 0 \tag{4.4}$$

where $Load^{Avg}_{seasonal}$ and $Irrad^{Avg}_{seasonal}$ are the seasonal averages, and $Load^{Avg}_{annual}$ and $Irrad^{Avg}_{annual}$ are the annual averages for the load demand and irradiance profiles. The daily averages are represented by $Load^{Avg}_{daily}$ and $Irrad^{Avg}_{daily}$ for the load demand and irradiance profiles, respectively. As shown in (4.1) and (4.2), the days with daily averages that most closely align with the seasonal averages, as well as the daily averages that best match the annual averages in (4.3) and (4.4), and thus minimize relative error, are considered in this first criterion for selecting the representative days. In the same manner, the daily sums are compared to the seasonal sums, and the relative error between them is analyzed. The daily sums are normalized over the season (one test day per season) and the year (four test days per year). While averages capture typical daily behavior, the sums reflect the total irradiance and load consumption over the season. A low relative error in sums ensures that the selected representative days proportionally represent the seasonal and annual characteristics when scaled to the entire year. This is crucial for system performance assessments that depend on cumulative energy patterns, such as for energy storage utilization, grid dependency, and overall efficiency evaluations. The daily sums comparison to the seasonal sums are expressed as,

$$\frac{\sum Load^{Sum}_{seasonal}}{\sum Load^{Sum}_{daily} \cdot t_{season}} - 1 \approx 0 \tag{4.5}$$

$$\frac{\sum Irrad^{Sum}_{seasonal}}{\sum Irrad^{Sum}_{daily} \cdot t_{seasonal}} - 1 \approx 0. \tag{4.6}$$

For the representative days in comparison the annual sums,

$$\frac{\sum Load^{Sum}_{annual}}{\sum Load^{Sum}_{daily} \cdot t_{annual}} - 1 \approx 0 \tag{4.7}$$

$$\frac{\sum Irrad^{Sum}_{nnual}}{\sum Irrad^{Sum}_{daily} \cdot t_{annual}} - 1 \approx 0 \tag{4.8}$$

where $Load^{Sum}_{seasonal}$ and $Irrad^{Sum}_{seasonal}$ are the seasonal sums, and $Load^{Sum}_{annual}$ and $Irrad^{Sum}_{annual}$ are the annual sums for the load demand and irradiance profiles. The daily sums are represented by $Load^{Sum}_{daily}$ and $Irrad^{Sum}_{daily}$ while t_{season} and t_{annual} presents the duration of the season and the entire year, respectively. As shown in (4.5), (4.6), (4.7), and (4.8), the days with the lowest relative error, indicating the closest alignment with the seasonal and annual sums, are selected as the representative days for the test sequence.

4.2.4 Normalisation of the Representative Days into Annual Operation

To match the amplitude and totals of the 4-day data profile and ensure it is proportional to the annual profile for each season, the 4-day data profile is scaled against the annual system profile data. This is done by calculating the ratio of the sum of the annual system profile data to the sum of the 4-day representative profile. For the irradiance profile, the sum of the 4-day representative irradiance profile is scaled proportionally to the sum of the annual irradiance profile giving,

$$Irrad_{ScaleFactor} = \frac{\sum Irrad_{Annual}}{\sum Irrad_{rep-days}}. \tag{4.9}$$

The same approach is applied to the load demand, where the sum of the 4-day representative load profile is scaled proportionally to the sum of the annual load profile rendering in,

$$Load_{ScaleFactor} = \frac{\sum Load_{Annual}}{\sum Load_{rep-days}}. \tag{4.10}$$

Normalization of the data allows for scaling the representative days to match the annual system data, regardless of the time resolution format of the annual system data, whether it is in seconds, minutes, hours or days. The representative days are scaled to align with the size of the annual system data.

4.2.5 Representative Days Validation

To validate and compare the annual data with the representative days, the flow-duration curve is used as an analytical tool. This approach provides a clear visualization of the data, making it easier to compare the representative days with the annual dataset. This comparison is crucial for assessing how accurately the selected representative days reflect the system's operational profile for the entire year. By overlaying the duration curves of the representative days onto the annual duration curve, any deviations or mismatches can be identified.

4.3 Schematic Representation of System Layout and Measurement Points

To best represent the system performance parameters, a schematic layout representative of a realistic PV-battery storage system is illustrated in Fig. 4.4. The layout consists of a SBESS, represented by battery storage modules, which is DC-coupled to a PV system (solar PV generator) through a bidirectional converter (hybrid inverter). This system supplies power to a single-family household load (load demand). Alternatively, the consumer load can be supplied through the grid when needed.

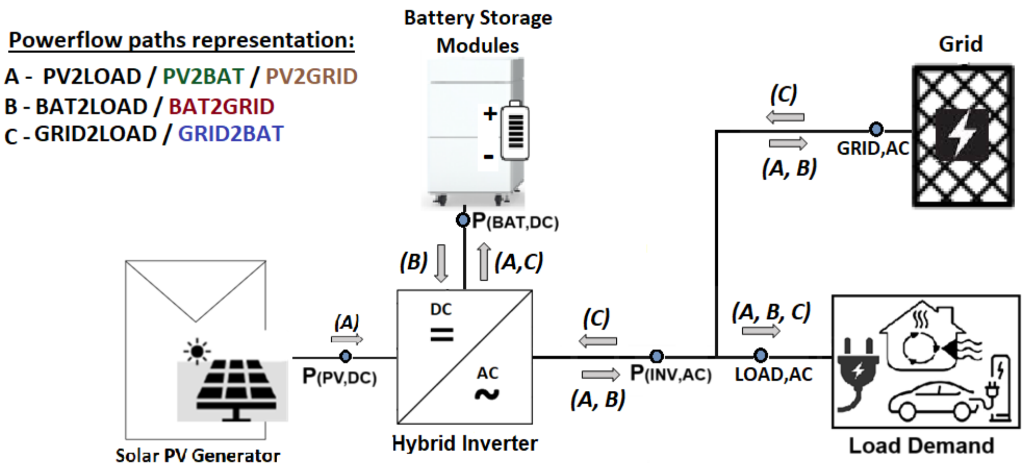

Figure 4.4: System schematic layout and power flow of the PV-battery storage system [8].

The schematic in Fig. 4.4 illustrates the measurement points, marked with dots, indicating where measurements are recorded. These points are positioned on either the AC or DC side of the system. In this schematic:

- The power generated by the PV system ($P_{PV,DC}$) is measured at location (PV,DC), with the power flow from the PV generator denoted by (A).
- Location (BAT,DC) measures the battery power for charging ($P^{-}_{BAT,DC}$) and discharging ($P^{+}_{BAT,DC}$), with the power flow to the battery indicated by (A, C) and the power flow from the battery represented by (B).
- At location (INV,AC), the AC power from the hybrid inverter ($P_{INV,AC}$) is measured. The power flow includes the power to the load (P_{LOAD}), denoted by (A,B, and C), and the power to and from the grid (P_{GRID}), denoted by (A,B) and (C), respectively.

The power flow directions within the system are represented by arrows, with their respective descriptions indicated by letters A, B, and C in Fig. 4.4. The polarities of the power flow are represented with positive (+) and negative (−) signs. In this context, the positive sign (+) indicates power flow when the battery is discharging ($P^{+}_{BAT,DC}$) and when the grid is supplying power to the load (P^{+}_{GRID}). Conversely, the negative sign (−) indicates power flow when the battery is charging ($P^{-}_{BAT,DC}$) and when power is being fed into the grid (P^{-}_{GRID}). A summary of the measured parameters and their descriptions is provided in Table 4.2. In Table 4.2, the measured parameters are correlated to their respective reference locations, which are marked in the schematic of Fig. 4.4 to indicate their positions within the system. The System Performance Matrices (SPM) that will be evaluated through the test sequence are expressed in Section3.4, where the performance matrices that evaluates the performance of the SBESS integrated to PV system are elaborated.

For the characterization of the efficiency to charge the battery from the solar PV system (PV2BAT), (3.14) is used. In this power flow from the PV system to the battery energy storage, a key condition is that no power flows to or from the AC side. This means $P_{INV,AC(in)}$ and $P_{INV,AC(out)}$ should ideally be zero. This ensures that all the power generated by the solar PV system is directed solely to the battery. For the characterization

Table 4.2: Measured parameters

Measured Parameter and Reference points as per Fig.4.4	**Description**
$P_{PV,DC}$ (W)	Generated power from solar PV generator
$P_{BAT,DC}$ (W)	Battery power, discharging [+], charging [-]
U_{BAT} (V)	Voltage of the Battery
$P_{INV,AC}$ (W)	Total 3-phase Converter AC Power, output from DC side [+], input from AC side [-]
P_{LOAD} (W)	Household load power consumption
P_{GRID} (W)	Power import from the grid (supply) [+], and Power Export to the grid (Feed-in) [-]

of the efficiency to discharge the battery to the AC side of the load and grid (BAT2AC), (3.12) is used. In this power flow from the battery energy storage system to the AC side of the load and grid, an important condition is that no power is generated or transferred from the PV system to the AC side. This means $P_{PV,DC}$ should ideally be zero, ensuring that all power transferred from the DC side comes exclusively from the battery. Additionally, the load should be supplied solely by the battery energy storage system.

For the characterization of the efficiency for charging the battery from the grid (AC2BATdc), (3.13) is used. In this power flow from the grid to the battery energy storage system, a key requirement is that no power is transferred to the DC side from the solar PV system, meaning $P_{PV,DC}$ should ideally be zero. This condition ensures that the battery is charged solely by the grid.

5

Results

This thesis proposes a test sequence designed to evaluate the performance of a stationary battery energy storage system (SBESS) integrated with a PV system (PV-battery storage system) in a residential application. The test sequence must be time-compressed while accurately capturing the system's operational characteristics under realistic conditions across various days of the year. This approach enables consumers to assess the annual performance of the PV-battery storage system within a shorter time frame compared to a full-year assessment. The system performance parameters evaluated through the test sequence include conversion path efficiency, usable storage capacity, self-consumption, depth of discharge, and round-trip efficiency. A detailed assessment of system profiles was performed, including load demand and irradiance, to identify patterns and variations that characterize the annual operating profile of the system. The annual system profiles were classified based on the minimum, maximum, average, and total values of irradiance and load demand for each season. Representative days that best matched these criteria were selected for use in the test sequence.

The system analyzed is based on the system of Fig. 4.4 presented in Section 4.3 of the methodology.

5.1 Validation of the Representative Days

To accurately assess how well the selected representative days align with the annual operating profiles, the flow duration curves were analyzed. This approach evaluates how well the representative days reflect the system's overall annual operational profile. By analyzing the duration curves of the representative days in comparison to the full-year data, deviations can be identified, providing insights into how the representative days deviated from the annual data and validating the selection process. To maintain consistency in the analysis, the 4-days data was normalized against the annual data to preserve proportionality with the total energy production and consumption throughout the year.

Figure 5.1 – Fig. 5.4 present the duration curves for each selected representative day, corresponding to each season of the year. Presenting the duration curves for each selected representative day allows for a more detailed examination of how each season's unique characteristics, such as differences in load demand and generation patterns, deviate from or match the system's annual profile. In this way, seasonal specific patterns and deviations can be observed to determine which representative day best reflects its corresponding season. This approach provides a better understanding of the operational behavior of the system, ensuring that all seasonal dynamics are properly considered when combined into a representative annual profile.

In examining the duration curves of the selected representative days, it can be observed that the summer and autumn seasons (Fig. 5.1 and Fig. 5.2), align more closely with the system's seasonal operating profiles, compared to the winter and spring profiles (Fig. 5.3 and Fig. 5.4).

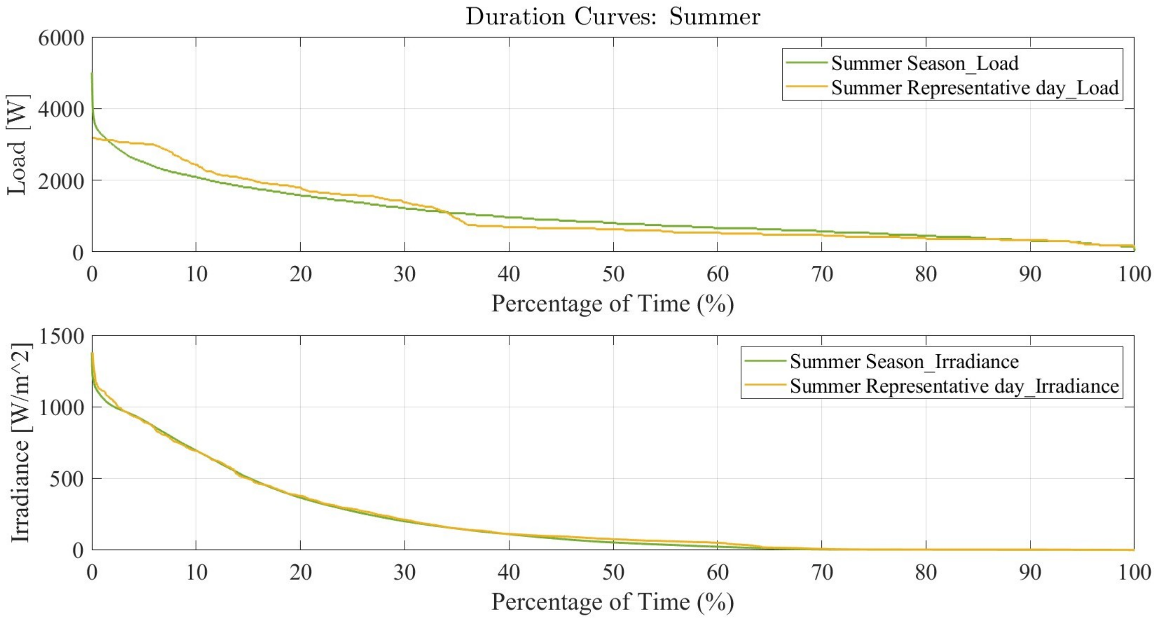

Figure 5.1: Duration Curves for summer season (top) vs representative day (bottom) system profiles, comprising load demand and irradiance profiles

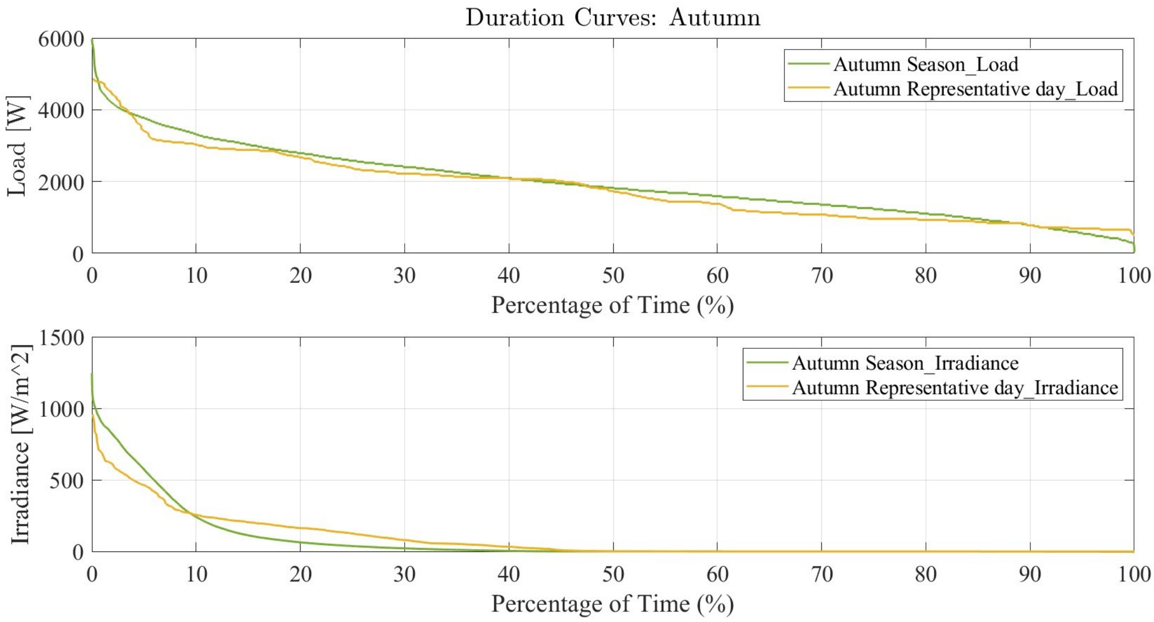

Figure 5.2: Duration Curves for autumn season (top) vs representative day (bottom) system profiles, comprising load demand and irradiance profiles

When examining the profiles themselves, the winter season shows greater deviations in both the load demand and irradiance profiles compared to the seasonal profile. However,

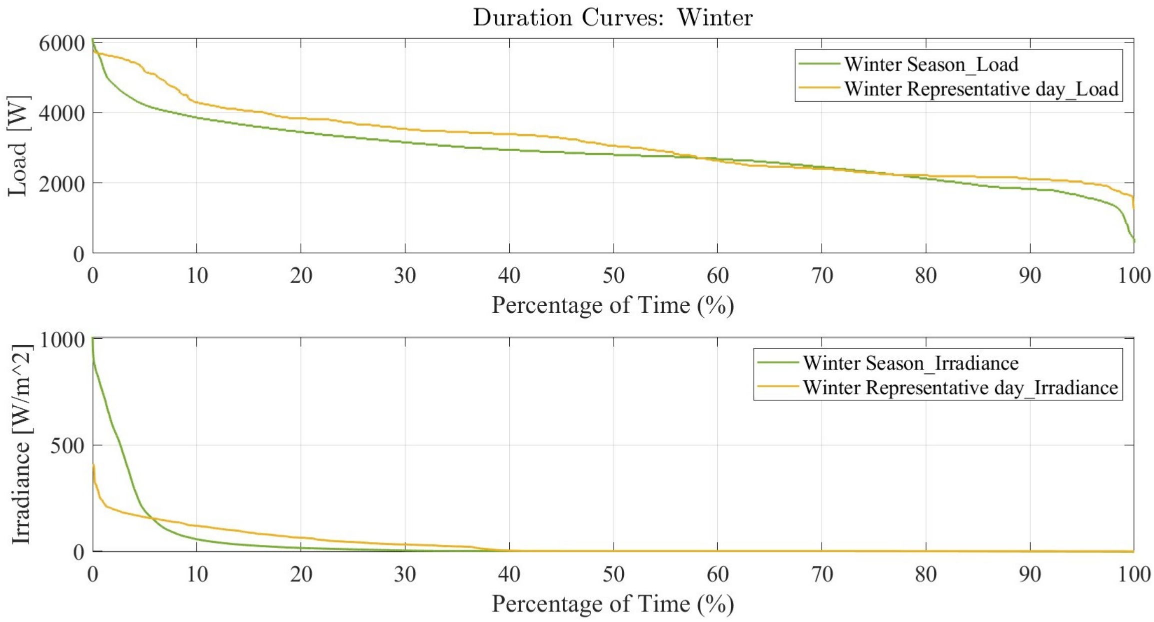

Figure 5.3: Duration Curves for winter season (top) vs representative day (bottom) system profiles, comprising load demand and irradiance profiles

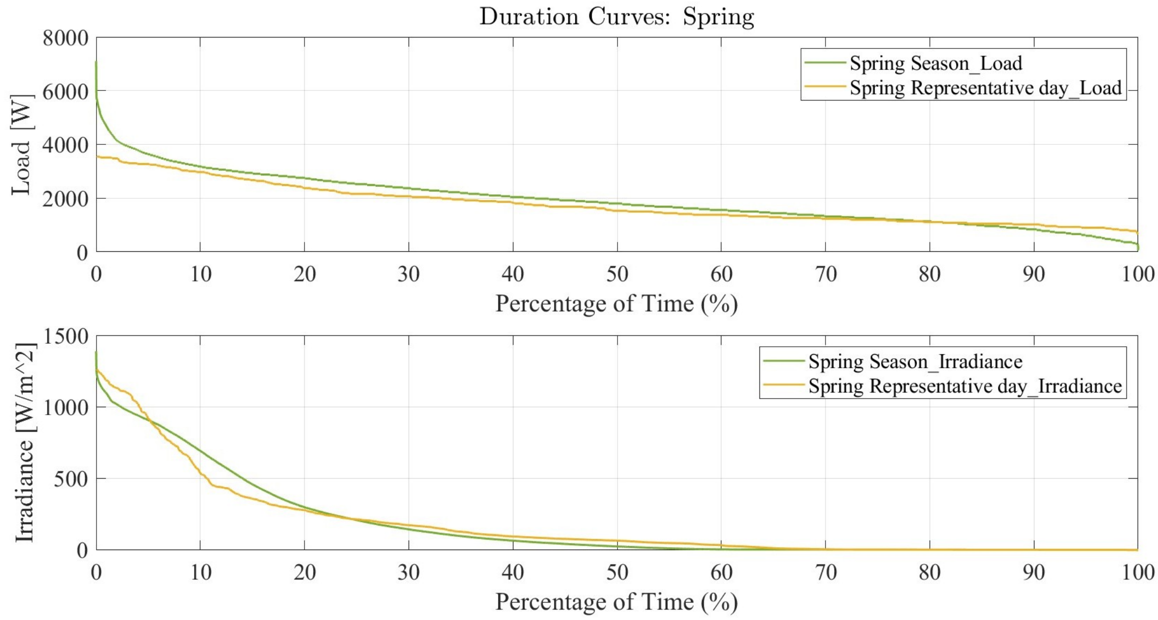

Figure 5.4: Duration Curves for spring season (top) vs representative day (bottom) system profiles, comprising load demand and irradiance profiles

for the other seasons, the deviations are more evenly distributed between the load demand and irradiance profiles relative to the annual profile. When analyzing the combined duration curve that represents the annual system profile against the combined four-day representative day profile in Fig. 5.5, it can be observed that the selected representative days closely align with the seasonal operating profiles for load demand, though some deviations are noted. A more significant deviation appears in the irradiance profile, particularly at data points below 20% of the time, where it deviates more from the annual system profile. This suggests that deviations are more pronounced during periods of high irradiance rather than low irradiance. For load demand, deviations occur at data points below 5% of the time, primarily during periods of higher load demand. These deviations are more noticeable in the winter and spring duration curves, as shown in Fig.5.3 and Fig.5.4. Figure 5.5 presents the duration curve for the overall four representative days in comparison to the annual data profile.

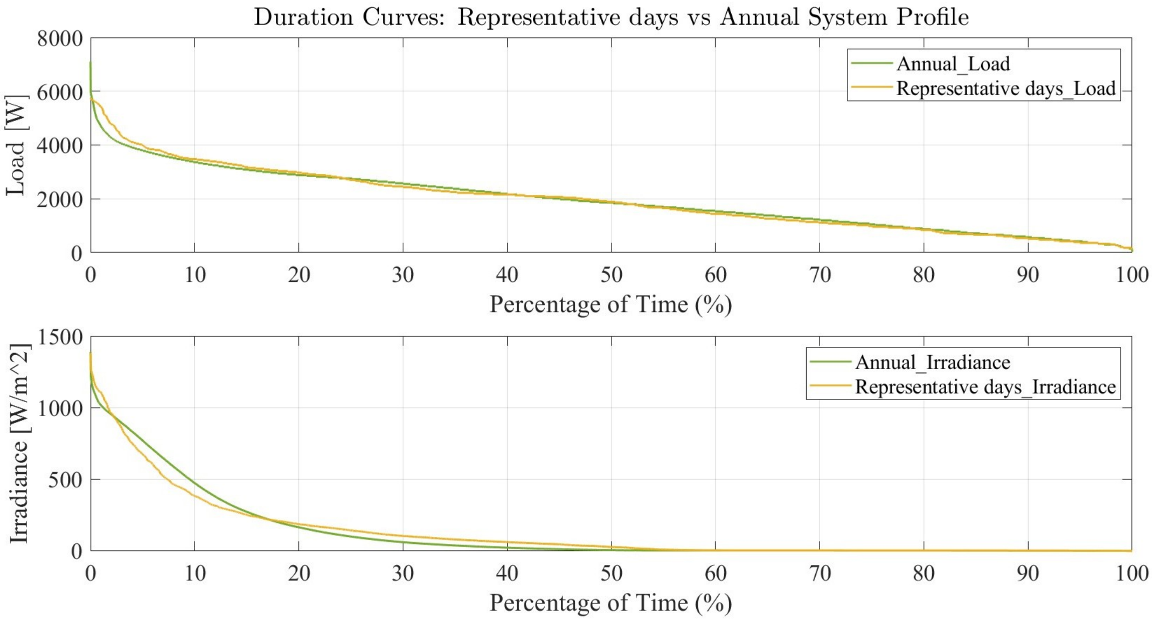

Figure 5.5: Duration Curves for annual data (top) vs 4-day representative days (bottom) system profiles, comprising load demand and irradiance profiles

Using (4.1) to (4.6), the relative error between annual and representative days profiles based on average and sums of values has been determined as presented in Table 5.1.

Table 5.1: Relative error between annual and representative days

Relative error (%)	**Rep.day "day 1" (Summer)**	**Rep.day "day 2" (Autumn)**	**Rep.day "day 3" (Winter)**	**Rep.day "day 4" (Spring)**
Load Demand:				
Daily vs Seasonal Averages (4.1)	0.36	7.4	9.55	9.69
Daily vs Seasonal Sums (4.5)	2.03	3.82	9.51	8.23
Daily vs Annual Averages (4.1)	0.10			
Daily vs Annual sums (4.5)	1.64			
Irradiance				
Daily vs Seasonal Averages (4.2)	3.56	11.33	7.88	1.17
Daily vs Seasonal sums (4.6)	5.86	14.29	7.92	2.49
Daily vs Annual Averages (4.2)	3.02			
Daily vs Annual sums (4.6)	4.71			

Looking at the daily analysis representative of the seasons, it can be observed that the load demand for the summer season has the lowest relative error between the averages and sums of values, with 0.36% and 2.03%, respectively. The representative day with the highest relative error is the autumn season irradiance profile in terms of the sum of values, showing a relative error of 14.26%, which is the highest among all representative days. The winter representative day showed relative errors close to 9% for irradiance and 10% for load demand profiles. The aim is to achieve the lowest possible relative error for 100% of the time, as this would indicate that the data points consistently align with the annual system profiles throughout the test period. For the overall comparison of representative days versus the annual system profiles, as shown in the flow-duration curves in Fig. 5.5, the analysis shows that the load demand closely aligns with the averages and sums of the annual data, whereas the irradiance profile exhibits a higher deviation error of 3.02% for the averages and 4.71% for the sums compared to the load demand profile, which achieves a relative error below 2% for both averages and sums. The flow-duration curve plot shown in Fig. 5.5, shows that the selected representative days profiles closely align the annual system profiles. Normalization ensured that the energy profiles of the representative days reflected the seasonal and annual proportions accurately. The duration curves demonstrated that the representative days effectively captured the key operational characteristics of the system, validating the selection process and confirming the suitability of the compressed test sequence for performance evaluation.

5.2 Results of Selected Representative Days

The selected representative days, determined based on the defined criteria, are presented in the following section. Figure 5.6 illustrates the system profiles of the selected representative days with minutely indexed time resolution, illustrating the overall operating pattern throughout the year. Each day captures the characteristics of its respective season and

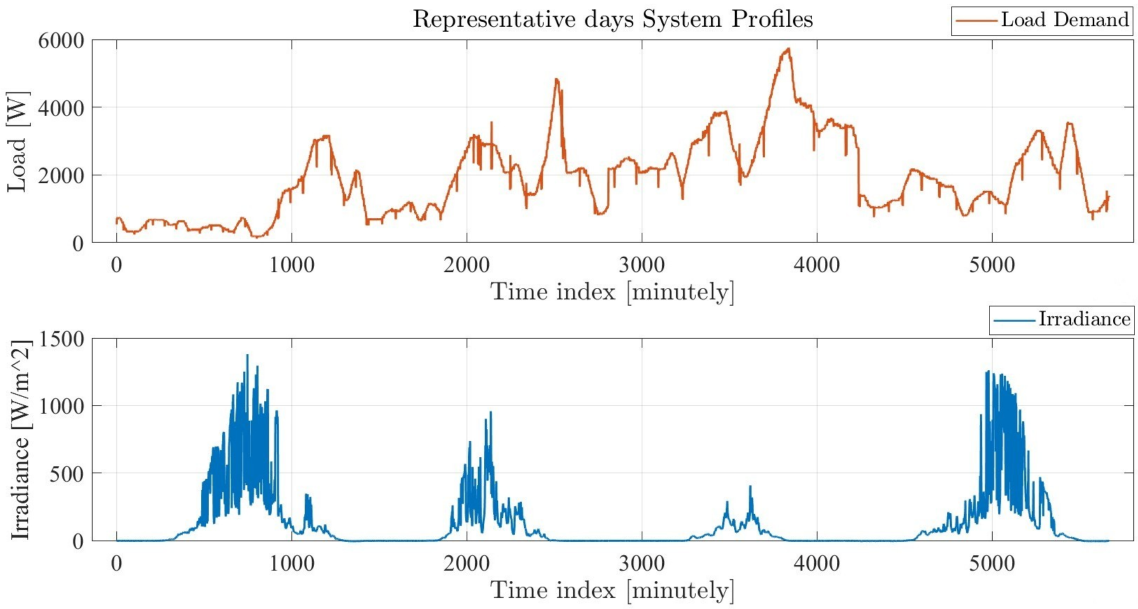

Figure 5.6: Representative days system profiles, comprising load demand and irradiance profiles, representing the annual operating profile for a west coast region in Sweden

together these days provide a comprehensive representation of the annual operational profile of the system. Four representative days were chosen, each corresponding to a specific season. As shown in Fig. 5.6, the summer season is characterized by a low load demand, observed from 0 to 1440 minutes (day 1), whereas winter exhibits high load demand, observed between 2880 and 4320 minutes (day 3). In contrast, autumn and spring (day 2 and day 4) exhibit balanced load demand patterns, reflecting the transitional nature of these seasons, where load demand and irradiance remain at intermediate levels without extreme fluctuations.

The results emphasize the seasonal variation in load demand, aligning with typical residential energy consumption trends influenced by seasonal factors. For instance, the low load demand observed in summer corresponds to extended daylight hours and reduced heating requirements, whereas the high winter load reflects increased heating needs and shorter daylight durations. The moderate load demand in autumn and spring represents a balance between heating and cooling demands.

5.3 Proposed 4-day Test-Sequence

The objective of the test sequence is to assess the annual performance metrics of the SBESS connected to the PV system within a shorter duration. Throughout the year, the performance of the BESS is influenced by seasonal variations, which in turn affect the battery's output. Studying these variations is crucial for evaluating the ability of the system to reliably store and supply energy under different seasonal conditions. An accurate assessment of annual performance ensures that the SBESS can effectively meet load demand throughout the year. Additionally, this evaluation provides insights into efficiency, and potential system improvements, contributing to the optimization of energy management strategies and the long-term sustainability of the system.

The test sequence adopts a 4-day Whole System Test (WST) method, with each day representing a specific season of the year as expressed in Section 5.2. The battery will undergo charge and discharge cycles based on the variability of PV generation and load consumption. The power flow within the system is critical as it defines the conversion paths, directly influencing the overall efficiency of the battery energy storage system and determining its performance across different seasons.

5.3.1 Test Conditions

The following test conditions are considered for the test sequence:

- **Control strategy:** Internal control strategy to maximize self-consumption and self-Sufficiency.
- **Boundary conditions:** The power supply to the load are from the battery, PV generation and main grid. The battery is supplied from the PV system.
- **Time resolution:** The self-consumption control strategy consists of storing the battery power over a longer period, resulting in a high total energy demand from the battery to meet the load demand. Therefore, a high time resolution, such as one minute, is recommended to capture the operational conditions of the system and the change in load demand [25].
- **Battery SOC condition:** The sequence begins in the summer season, with low load demand. By the start of the next day, the battery is expected to be partially

discharged, assuming there is no heavy load demand during summer. As a result, the SOC is set to 50% at the start of each seasonal day, reflecting both the current state and the characteristics of the previous season. The battery voltage limits are defined by $U_{BAT(max)}$ at full charge and $U_{BAT(min)}$ at full discharge. When the SOC is at 50%, the battery terminal voltage is expected to correspond to the nominal voltage level $U_{BAT(nom)}$.

- **System profiles:** Typical residential household load and supply from a PV-battery storage system are based on the load demand and irradiance profiles outlined in Section 4.1.
- **Test conditioning phases:** The test sequence comprises two phases: the "reconditioning phase" and the "re-balancing phase" which occur at the beginning and end of the test sequence, respectively. The "reconditioning phase" is a preparation day where the load demand and irradiance profiles are reconditioned and loaded into the test and control systems. Additionally, the battery is reconditioned to a partially discharged state, setting the state of charge to approximately 50% ($SOC_{50\%}$) before the test sequence begins. The "re-balancing Phase" is where the battery will be cycled to obtained ($SOC_{50\%}$), angling with the state of charge to that reconditioning phase state of charge.
- **Data record and test sequence duration:** Data recording will be continuous throughout the test sequence, with an additional day for setup and the reconditioning phase. The battery cycling phase starts after the 4-day system profile duration. Measurements begin at the beginning of the system profiles. Each seasonal day measurement spans 24 hours, covering a full day cycle to ensure the complete load consumption characteristics are captured for an accurate assessment of the system performance metrics.

5.3.2 Test sequence

- **Recondition phase "day 0":** The test sequence starts with the "reconditioning phase," where the control system is configured for self-consumption. The 4-day system profiles, representing the annual operation across different seasons, are loaded into the test system. To determine the value of the energies required for evaluating usable capacity, round-trip efficiency (RTE), and depth of discharge (DOD), the battery is first cycled. It is first charged to a full state of charge ($SOC_{100\%}$), then discharged to a fully depleted state ($SOC_{0\%}$) following the methods of Section 3.8. After each phase of the charging and discharging cycle, the battery is required to reach a steady state (rest), for the battery to stabilize before measuring the charged and discharged capacities. The rest phase ensures that the battery to stabilize to ensure more accurate measurement battery capacity.

  For the test sequence start, the battery's state of charge (SOC) is reconditioned to $SOC_{50\%}$, corresponding to $U_{BAT(nom)}$, indicating that the battery is in a partially discharged state. Once the battery is reconditioned to $SOC_{50\%}$, the test sequence will commence, signaling the "start of measurement" and the initiation of the test sequence duration.
- **Test Day 1:** The representative day 1 represents summer season with high solar radiation and low load demand. The battery discharges at night to meet the load

demand, starting from a partially charged state, and recharges in the morning when the solar generation exceeds the load demand.

- **Test Day 2:** Day 2 represents autumn season with moderate solar radiation with partly cloudy conditions, resulting in a balanced PV system throughput. The load demand fluctuates between low and high, reflecting typical autumn consumption patterns. The test sequence continues from day 1, which may differ from the initial test sequence SOC.

- **Test Day 3:** Day 3 represents the winter season with lower solar radiation and cloudy conditions, leading to reduced solar PV system output. The load profile reflects higher energy demand compared to summer and autumn seasons. The test sequence continues from day 2.

- **Test Day 4:** Day 4 represents the spring season with moderate solar radiation and partly cloudy conditions, similar to autumn. The solar PV system throughput is moderate compared to "summer" or "winter" season. The load profile reflects moderate demand, fluctuating between low and high. The test sequence continues from day 3, with the test running for the full day.

- **Re-balancing Phase:** At the end of the 24-hour duration of day 4, the battery's state of charge (SOC) is reconditioned to $SOC_{50\%}$, corresponding to $U_{BAT(nom)}$, indicating that the battery is in a partially discharged state. This ensures that the battery's state of energy remains balanced between the beginning and end of the test sequence, meaning the energy generated corresponds to the energy consumed throughout the sequence. Once the battery is reconditioned to $SOC_{50\%}$, the test sequence is stopped, signaling the "end of measurement" and the end of the test sequence duration.

Figure 5.7 shows the time series of the test sequence over the four selected test days, with each day representing a different season. This figure captures the chronological distribution of load demand and irradiance profiles change throughout each day, effectively reflecting the seasonal variations in system behavior over the year.

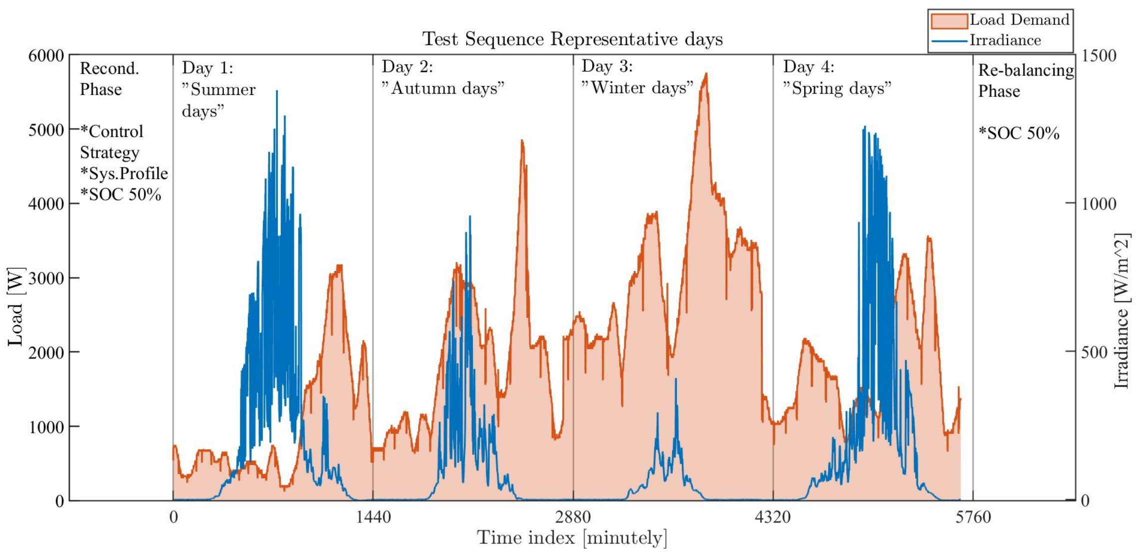

Figure 5.7: The four days test sequence time series

The test sequences expressed, is summarized and presented in flowchart in Fig. 5.8.

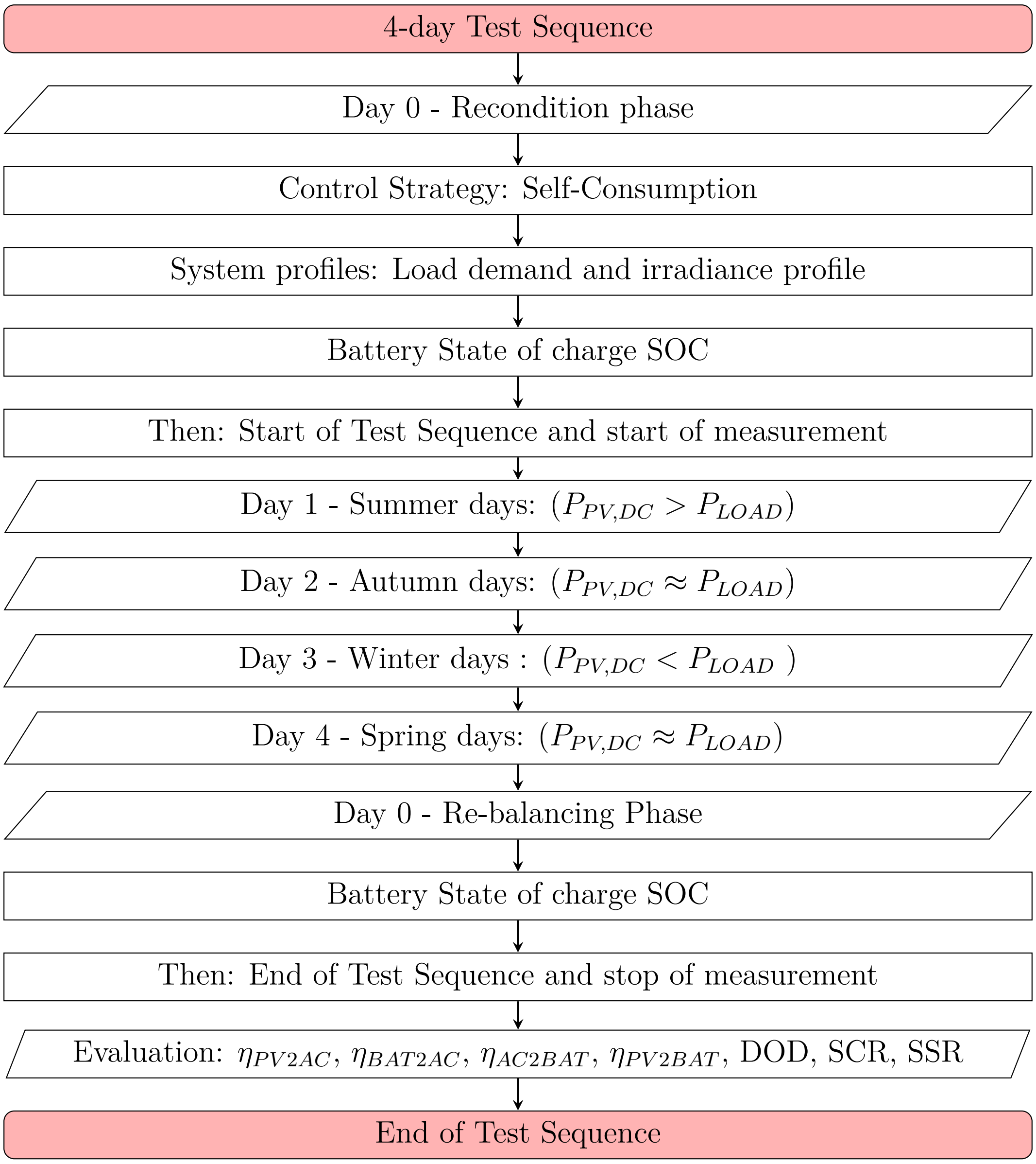

Figure 5.8: A 4-day Test sequence flowchart summary

5.3.3 Test Sequence Results Evaluation

In an ideal system, the total energy produced by the solar PV system and the deliverable energy from the battery energy storage system would be fully received by the consumer load. However, in a practical system, losses occur, resulting in some energy being lost in the process, with some of the generated energy consumed by the load and some consumed by system losses. Therefore, the efficiency of the PV-Battery storage system is one crucial performance factor for the operation. The purpose of the evaluation method is to investigate the performance and functionality considering the available energy from the battery and PV, and how efficiently the converter system operates to deliver energy from the solar

PV system and battery to the load demand, with the aim to reduce the energy drawn from the main grid.

For the evaluation of the data obtainable from the system profiles of the 4-day test sequence, the method of evaluation includes assessing the power flow, performance, and comparing the results with technical data from datasheets. The data points are based on Table 4.2 and system representation of Fig. 4.4. The data plots comprise power flow graphs illustrating various aspects of the system, including load demand, the solar PV production throughput for charging the battery, supplying the load, and power feed-in to the main grid. It also shows power flows for battery charging and discharging with the corresponding SOC, and the main grid power flow to feed the load. The performance graphs include the efficiency plots describing the relationship between converter efficiency and loading. The calculations involve the determination of self-consumption and self-sufficiency (3.1)–(3.2), and the conversion path efficiencies using equations (3.11)–(3.17) can tabulated in Table 5.2. Table 5.2 summarizes the expected results in evaluating the system performance metrics outlined from Section 3.1 to Section 3.8.

Table 5.2: Evaluation of the system performance matrices outlined in section of the system

	System performance matrices evaluation
Test Sequence Performance matrices evaluation	η_{BAT2AC} (3.12) η_{PV2BAT} (3.14) η_{PV2AC} (3.11) η_{AC2BAT} (3.13) SCR and SSR

The battery energy storage charge and discharge energies can be determined by computing the usable battery capacity, Depth of Discharge (3.22), and round-trip efficiency (3.18), as outlined from Section 3.5 to Section 3.8. The results are presented in Table 5.3. For a more accurate evaluation of the battery usable capacity, Depth of Discharge, and

Table 5.3: Battery usable capacity measurement

Parameters Charge cycle	**Parameters Discharge cycle**
Charge cycle test duration Start End	Discharge cycle duration Start End
$U_{BAT(min)}$ SOC_{min}	$U_{BAT(max)}$ SOC_{max}
$P_{BAT,Max(chg)}$ $U_{BAT(max)}$ SOC_{max}	$P_{BAT,Max(dschg)}$ $U_{BAT(min)}$ SOC_{min}
Battery charge energy capacity E^{-}_{BAT} (3.3)	Battery discharge (usable) capacity E^{+}_{BAT} (3.5)
$\eta_{BAT,RTE}$ (3.18)	
DOD (3.22)	

round-trip efficiency, they should be assessed throughout the entire charging and discharging cycle, and within the same cycles of charge and discharge. This is essentially done to take into consideration the effect of battery hysteresis, which varies in each cycle. Hence, this emphasizes why the direct use of a battery capacity in the test is recommended.

6

Discussion and Conclusion

6.1 Discussion

The thesis proposed a compressed test sequence that assesses the annual functional performance of the stationary battery energy storage system by evaluating its performance metrics. This test sequence is designed to represent and characterize the annual performance of the system in a time-condensed manner. The thesis focused on the behavior of the stationary battery energy storage system (SBESS) within a complete residential solar PV system under realistic operating conditions across different days of the year. From the study of system profiles, a day from each season with characteristics most closely aligned with the seasonal operating patterns was selected as a representative day for that season. These representative days were then combined to form a condensed set of days representing the system's annual operation. The selected days were validated using duration curves to evaluate how accurately they reflected the system's annual performance and operational dynamics. The validation through duration curves, also provided insights into their standard deviation from the annual data. To ensure consistency, the data was normalized, maintaining proportionality with the total energy production and consumption of the annual operation.

6.1.1 Market Survey

From the survey conducted in Section 2, battery energy storage systems installed both with and without coupling to solar PV systems were investigated, along with the relationship between the sizing of the PV system, the battery energy storage system, and the associated power electronic converter.

The results from the market survey are outlined in Section 2.2.1 to Section 2.2.3. The analysis of supplier references and past projects provide valuable insights into typical system configurations for residential PV-battery storage installations. Most offerings target single-family households, reflecting a rising trend in self-consumption control strategies. This indicates a strong relation between system sizing and intended use but also highlights that battery sizing depends on additional factors beyond PV system size, such as converter dimensions and system topology (AC, DC, or PV-generator coupled). The survey showed that the average battery size for residential applications is approximately 10 kWh, coupled with an average PV system size of about 15 kWp. These findings reinforce the importance of sizing analysis for system performance assessment.

Conducting the market survey, there were challenges experienced, that resulted in obtaining less survey information than anticipated. One of the aspects that limited the collection of data was the method of surveying, which was based on email communication. The majority of suppliers and installers contacted via email did not provide feedback, impacting the quantity of information received. While examining offerings from reference and previous projects, the majority of suppliers focused on the solar PV system, its size, rating, and the annual energy production achievable from the system. However, there was limited information mentioning about battery energy storage installation or inclusion. With very few references and technical details about battery energy storage systems, obtaining additional in-depth information about dimensioning parameters, available control strategies, cell technology, and the amount of installed battery capacity in the market proved to be a challenge.

A mitigation strategy would be to additionally organize virtual meetings and/or office meetings to facilitate proper discussions and gather feedback from the suppliers and installers. In addition, initiating the survey at earlier stages would provide an optimal time frame for proper feedback, analysis, and presentation of the survey results.

6.1.2 Test Sequence

With the selected representative days, the test sequence begins with a reconditioning phase, where the SOC level of the SBESS is adjusted to the required leve, in this case 50%. The $SOC_{50\%}$ is selected to closely align with the start of the first representative day profile, where Day 1 begins at midnight. This allows for a more practical and realistic start to the test sequence. The test sequence runs for four days, with each day representing a different season of the year. This allows the annual system characteristics to be studied through seasonal patterns, which influences the load demand and irradiance profiles. It is noted from previous studies and this work that as the number of test days increases, the relative error between the annual and representative days decreases [25], [2]. This highlights the need to have a balance between the test sequence duration and the number of representative days selected while maintaining the key characteristics of the annual system profiles. The next step involved the assessment of system performance metrics, which will be evaluated through the test sequence. These include the sizing of the power electronic converters (PEC) and the SBESS in relation to the load demand and PV throughput, conversion path efficiencies, battery round-trip efficiency, and depth of discharge.

With sizing analysis, at low loading, the converter's efficiency is significantly reduced due to internal losses such as conduction and switching losses. In these conditions, much of the energy from the PV system or battery is consumed by these losses, leading to a lower overall efficiency. During high load conditions, converter efficiency is higher. This does not indicate a reduction in the total amount of internal losses of the converter, but indicates that their contribution is low in comparison to the higher energy coming from the PV system and battery. Assessing these converter path efficiencies, allows consumers to first understand how the system behaves under real operating conditions. Second, it enables them to observe the converter's loading conditions and make informed decisions about when and how to load the converter to ensure operation in high-efficiency regions. This ensures that the self-generated electricity is consumed more efficiently, resulting in less electricity drawn from the grid. With information on battery capacity and round-trip efficiency, consumers can gain a comprehensive understanding of the annual performance of the battery energy storage system. Through the assessment of self-consumption and self-sufficiency, consumers obtain crucial insights into the actual utilization of their self-generated electricity. This information becomes a key factor influencing decisions when investing in a PV-Battery storage system.

Additionally, the test sequence demonstrated that the system profiles could be adapted to various topologies, not only providing insight into the annual performance of a typical SBESS but also offering a unified approach to evaluating different system topologies. This ensures that various configurations can be tested using the same test sequence, making it versatile and adaptable for different system setups. This flexibility makes the test sequence a valuable tool for system designers, engineers, and manufacturers, offering a universal testing method to assess system performance, regardless of specific system configurations or geographical condition.

6.2 Sustainability Perspective

During the operation of the solar PV and battery energy storage system, for efficient usage of materials and effective management, it is crucial to have the PV-battery storage system to operate with minimal losses and an extended lifetime. This approach minimizes losses and prolongs the lifespan of the system's materials. In this case, proper maintenance plans become important to keep track of the health of equipment, and to follow proper life-cycle, decommissioning, recycling, and reuse schedules for the equipment and components from PV storage system installations. With a household installation of a solar PV system and an energy storage system, an increase in energy awareness is established for consumers. In this scenario, consumers can constantly monitor and alter their power usage, thereby using energy more efficiently. Coupled with a renewable energy supply, such as solar PV installation, battery energy storage systems extend the availability and use of self-generated electricity from renewable energy sources. Batteries are also beneficial for maintaining grid stability, managing load demand through peak shaving, and relieving the grid from overload and costly expansion.

The end-of-life processes for materials should be in place to ensure that the materials from PV-battery storage systems are disposed of, recycled, and reused (when possible) in a well-managed manner. It is essential to implement effective strategies to account for and track materials and components, especially cell modules, converters, and batteries, ensuring correct waste classifications. An alternative solution for battery end-of-life and recycling involves the use of decommissioned batteries that have reached their operational end of life in stationary storage systems [27]. Stationary battery energy storage systems offer limited dynamic operation of the battery for high-energy and high-power applications. Therefore, the use of decommissioned batteries provides a way to reuse and give the battery a second life. This approach contributes to sustainable consumption, reduces the ecological footprint of battery storage systems, and minimizes the extraction of new materials.

6.3 Ethics Perspective

- **Data Collection and Privacy:** The data used for the market survey was obtained from publicly available sources, such as supplier websites and previous projects. For the survey conducted online via email, a survey questionnaire document was shared which outlined the purpose of the survey and the type of information required.

- **Transparency and Integrity:** The thesis provides a transparent disclosure of all data, results, and methodologies used throughout the study. The measurement data used is part of the authorized information, specifically granted for utilization in the research and analysis in this thesis.

- **Sustainability and Social Impact:** In reference to the results from the National Survey report, the SOM Institute's annual survey outlined that 80% of randomly selected respondents supported the increase in investments for residential PV solar installations in Sweden [16]. With solar PV installations for single-family households, the challenge of land excavation is replaced with rooftop installations, which have a less negative impact on the environment. This indicates the positive economic gains associated with PV solar installations. Furthermore, transitioning society to more sustainable renewable electricity sources has a positive impact on the environment. Battery energy storage systems, while offering similar benefits to solar PV systems, present a challenge in terms of space allocation for installation. This can be considered as an environmental impact, but it does not directly affect the well-being of society, making it a viable option. The use of PV-battery storage systems and participation in smart control initiatives give consumers the responsibility to be active rather than passive in terms of electricity usage and consumption. This leads advantageously to benefits in the environmental aspect of electricity production, savings, reduced losses, and increased use of sustainable renewable energy.

6.4 Future Work

The next step in this work involves testing the PV-battery storage system through the proposed test sequence and evaluating its performance using the defined perfoamcne metrics such as conversion path efficiency, round-trip efficiency, battery depth of discharge, and usable storage capacity. This evaluation will focus on assessing the system's effectiveness under various operating conditions, including system topology and representative system profiles. Additionally, the evaluation will examine how the duration of the test sequence influences the integrity and representation of the system's realistic annual operation.

- **Practical Testing:** For the applicability and reliability of the 4-day Test Sequence in real operation, it is crucial to validate the effectiveness of the compressed test sequence by evaluating it in a practical setting and comparing its results with those obtained from longer-duration test sequences.

- **System profiles:** One of the important steps in the thesis is the implementation of the system profiles (solar PV and load profiles) in a practical system. These profiles influence and validate the applicability of the test sequence and also determine how the battery is cycled.

6.5 Conclusion

This thesis proposes a four-day test sequence aimed at assessing the performance of a stationary battery energy storage system (SBESS) coupled with a PV system. To achieve this, four representative days were selected that closely align with the annual system profiles. The selected days were evaluated using flow-duration curves, as shown in Fig.5.5, and their relative errors presented in Tab.5.1. The results showed that the load demand closely aligns with the annual data, with a relative error of 0.1% for averages and 1.64% for the sums of values. In contrast, the irradiance profile exhibits higher deviation errors of 3.02% for averages and 4.71% for sums of values. The aim is to achieve the lowest possible relative error for 100% of the time, indicating that the representative days profiles consistently align with the annual system profiles throughout the test period. These results of the relative errors are indicative of the impact of utilizing reduced number of days in the compressed test sequence, as well as the influence of transitional boundaries between seasons. These were observed in the annual system profiles and summarized in Table 4.1, where extreme maximum and minimum values typically occur at these seasonal boundaries. For instance, the spring season exhibited a higher maximum load demand of 7100 W compared to the winter season, which had a maximum of 6120 W, highlighting the seasonal pattern deviations. However, the seasonal average values still maintained the expected characteristics of load demand and irradiance for each respective season. These outlier values or boundary data points have not been excluded in the analysis of the representative days, with the aim to preserve the true characteristics experienced throughout the year. However, they contribute to the higher deviation observed between the compressed test sequence profiles and the annual operational profiles.

Considering the sizing aspect of SBESS coupled with PV systems, a market survey was conducted to assess the relationship between the sizing of the stationary battery energy storage system, the PV system, and the associated power electronic converter. The survey highlighted the importance of proper sizing in product selection. The market survey results indicated a typical energy-to-power ratio ranging between 2–3.5 kWh/kWp, with the average battery size observed to be around 5–10 kWh. The survey also highlighted that the size of the SBESS is influenced not only by the PV system size but also by other factors, such as the power converter capacity and the type of system topology connection used in the system. Although sufficient data regarding sizing in relation to the power electronics converter system was lacking from the survey, the correlation between the maximum continuous charging power and the battery usable capacity of the battery energy storage system provided an idea of how the size of the converter can look like, offering insights into its dimensioning aspects. Further observations from references and previous projects in the survey, indicate that the majority of offerings for single-family households is for self-consumption and self-sufficiency, leaning into the market of self-generated electricity.

The 4-day compressed test sequence allows consumers to receive an overview and technical information about the annual operation of the SBESS in a short span of time. This approach enables the observation of power flow experienced by the battery and the benefits of including the SBESS can be quickly recognized. This test sequence is flexible and adaptable, meaning, it can be applied to various system topologies. The uniformity and compatibility of test sequences make them applicable for analyzing various system topologies and applications of stationary battery energy storage systems. What is observed is that performance matrices provide valuable insights into the performance of the PV-Battery storage system. Overall, the compressed test sequence adds value to the system by efficiently assessing its performance matrices and summarizing the annual operation in a short duration of time. This assists in the decision-making process when investing in stationary battery energy storage systems.

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