

Optimal design and operations of plug & play photovoltaic-battery systems

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Thesis submitted for the degree of
Master of Science in
Electrical Engineering, option Power
Systems and Automation

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Published by Sean Nassen,
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Preface

This Master's thesis marks the completion of my Master of Electrical Engineering: Power Systems and Automation at KU Leuven. The work presented investigates the technical performance, operational behavior, and economic viability of plug & play battery systems, with a focus on real-world measurements and system-level analysis under Belgian conditions.

This topic was chosen in the context of rapidly evolving residential energy systems, driven by increasing photovoltaic adoption, electricity price volatility and the growing need for household energy flexibility. Plug & play batteries are a relatively recent development that lower the barrier to residential energy storage while introducing new technical and regulatory challenges. This combination of novelty and practical relevance made it a very interesting subject for in-depth investigation. In addition, the topic aligns well with a personal preference for hands-on work with real electronic systems and measurements, rather than focusing exclusively on simulations and purely theoretical analysis, allowing for a more direct understanding of system behavior in practice.

I would like to express my gratitude to my supervisor Dipl.-Phys. Jens Moschner for his guidance, feedback and constant availability throughout the course of this work. I am also grateful to my assistant-supervisor Dr. Georgi H. Yordanov for his valuable input, feedback and support during the measurement tests at EnergyVille. I would further like to thank my assistant-supervisor Ir. Fereshteh Poormohammadi for her feedback and suggestions.

In addition, I would like to thank everyone who supported the installation and monitoring of the residential battery system used in this study at EnergyVille, with special thanks to Gert Verbeek for his assistance. I also acknowledge the contribution of my assessors for their time and evaluation of this work.

Finally, I would like to thank my family and friends for their continuous support throughout my studies. In particular, I am grateful to my sister, with whom I could always discuss the challenges encountered during this work, which helped me clear my mind and find solutions. I would also like to thank the residents of the large household who allowed the installation of the batteries in their home, enabled the execution of experiments and provided access to their measured data.

Sean Nassen

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Abstract

The electrification of residential energy consumption has increased the adoption of technologies such as photovoltaic (PV) panels, electric vehicles, heat pumps and most importantly for this thesis: batteries. They are primarily used by households to reduce electricity costs, either by increasing self-consumption of locally generated PV energy or by storing electricity purchased during low-price periods for use when prices are higher. An additional benefit of increased self-consumption is that it reduces strain on the electricity grid, contributing to a more stable power system. In recent years, plug & play batteries have emerged as a new category of residential storage systems characterized by simplified installation and improved accessibility for households unable or unwilling to install conventional home battery systems.

This thesis evaluates the technical performance of plug & play batteries for residential use in Belgium, where these devices were officially approved on 17 April 2025. Compared with conventional home batteries, plug & play batteries can be installed directly by the owner without the need for a certified electrician, thereby avoiding installation costs and making them flexible and movable storage solutions.

Different plug & play battery types are characterized in this work through controlled laboratory and residential measurements to determine their performance across relevant metrics, including efficiency and functional limitations. Their profitability is subsequently assessed under residential operating conditions, taking into account battery pricing and electricity savings. Since these batteries commonly include a ten year warranty period, achieving a payback period (PBP) within this timeframe is considered the threshold for a financially attractive investment.

In addition to the comparative evaluation, potential improvements are identified on both the hardware and software side in order to further enhance the performance of plug & play batteries. By analyzing the specific strengths of different battery types and combining their most favorable existing design elements and control strategies, together with novel optimization concepts that extend beyond the features present in the currently tested battery systems, a theoretically optimized system is proposed.

The results show that plug & play batteries can achieve a PBP within ten years, demonstrating their financial viability under favorable conditions. Furthermore, the findings indicate that these systems are not limited to small households, but can also provide a competitive alternative to conventional home batteries in larger residential applications. The addition of DC connections for PV panels can further improve efficiencies, making plug & play batteries a promising and accessible contribution to the continued electrification and decentralization of household energy systems.

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List of Abbreviations and Symbols

Abbreviations

AC	Alternating Current
AREI	Algemeen Reglement op de Elektrische Installaties
BMS	Battery Management System
BVES	Bundesverband Energiespeicher Systeme e.V.
CT	Current Transformer
DC	Direct Current
DoD	Depth of Discharge
EMS	Energy Management System
EnFluRi	EnergieFlussRichtung (Direction of Energy Flow)
HTW	Hochschule für Technik und Wirtschaft
LFP	Lithium Iron Phosphate
MPPT	Maximum Power Point Tracking
NPV	Net Present Value
PBP	Payback Period
PerMod	Performance Simulation Model for PV-Battery Systems
PV	Photovoltaic
RfG	Requirements for Generators
RTE	Round-Trip Efficiency
SoC	State of Charge
SPI	System Performance Index

Symbols

$E_{ACcharge}$	AC energy used from the grid to fully charge the battery
$E_{ACdischarge}$	AC energy injected into the grid to fully discharge the battery
$E_{DCcharge}$	Internal DC energy which the battery stored to fully charge
$E_{DCdischarge}$	Internal DC energy which the battery supplied to fully discharge
E_{PV}	DC energy that PV panels need to produce to fully charge the battery
$\eta_{ACcharge}$	Efficiency of the battery when it charges using AC grid energy
$\eta_{ACdischarge}$	Efficiency of the battery when it discharges to the AC grid
$\eta_{DCcharge}$	Efficiency of the battery when it charges using DC energy generated by PV panels
$\eta_{battery}$	Efficiency of the battery that does conversions between electrical and chemical energy
$\eta_{inverter}$	Efficiency of the inverter that turns DC energy into AC energy

Chapter 1

Introduction

Residential energy systems are undergoing rapid transformation as households increasingly adopt technologies such as photovoltaic (PV) panels, electric vehicles, heat pumps and battery energy storage systems. These developments are driven by fluctuating electricity prices, decarbonization targets and the growing desire of households to reduce their dependence on the electricity grid. Among these technologies, residential battery systems have become increasingly relevant because they allow households to store electrical energy for later use, thereby increasing flexibility in energy consumption.

One of the primary motivations for households to invest in battery storage systems is the potential for financial savings. Batteries can reduce electricity costs by increasing the self-consumption of locally generated PV electricity and by storing electricity purchased during periods of lower market prices for use during more expensive periods. In addition to these direct financial benefits, greater self-consumption reduces both the consumption of electricity from the grid and the injection of surplus electricity into the distribution grid and can therefore contribute to a more stable and efficient electricity system.

Currently, several battery concepts for residential applications exist. The most established solution is the conventional home battery, which is permanently installed and commonly offers capacities in the range of 5 kWh to 15 kWh and powers in the range of 2.5 kW to 10 kW. A second and more recent category is the plug & play battery, which generally offers capacities in the range of 2 kWh to 5 kWh and power ratings between 0.8 kW and 2.5 kW. In addition, certain plug & play battery systems are stackable, allowing the total storage capacity to be increased by aggregating multiple battery units. For example, four individual 2 kWh battery modules can be aggregated to create an 8 kWh system. In these configurations, the stacked battery modules typically share the same power electronics and inverter system, meaning that the total storage capacity scales with the number of modules while the rated power remains unchanged. This approach can also mitigate expenditures, since only a single inverter is required for multiple battery modules. Due to their lower storage capacity, lower power rating, compact size and modular design, plug & play batteries are generally better suited for smaller households and smaller photovoltaic

(PV) installations. This is particularly the case for plug & play PV systems, which typically have installed capacities ranging from 0.8 kWp to 1.6 kWp. These systems achieve these higher installed capacities by connecting multiple PV panels (each rated at around 400 Wp) to a microinverter equipped with multiple maximum power point tracking (MPPT) inputs. A third concept is the use of electric vehicle batteries for household applications through bidirectional charging technologies. However, this technology remains under development and is therefore outside the scope of this thesis [2].

A literature review is first conducted to establish the necessary background for the evaluation of plug & play battery systems. This review examines the current state of residential battery technology, existing plug & play PV and battery systems and key performance indicators such as efficiency and self-consumption. In addition, previous research on the economics of residential battery systems, control strategies and system optimization is analyzed in order to identify existing knowledge gaps and to position the objectives of this thesis within the broader scientific literature. A more detailed overview of this literature review is provided in Chapter 2.

There exist two kinds of plug & play devices: plug & play PV systems and plug & play batteries. These devices differ from conventional PV panels and home batteries in two major ways. First, the installation of such devices is simple enough to be carried out by the customer, meaning that no certified electrician is required, which eliminates installation costs. In addition, these devices can easily be disconnected and moved to another residence if the user decides to relocate. Furthermore, compared to conventional PV panels or home batteries, plug & play devices are subject to less restrictive installation requirements in rented properties, where owners may be reluctant to approve major structural and electrical modifications to the building. Secondly, the majority of Western European countries have introduced regulations that limit the maximum output power of such devices to 0.8 kW, which is based on the "Requirements for Generators" (RfG) defined in [3], there is however one country which has not officially implemented this 0.8 kW regulation: Belgium.

Plug & play energy devices first gained commercial momentum in several Western European countries, including Germany and the Netherlands, around the year 2021. Their growing popularity subsequently increased interest in the Belgian market. On the 17th of April 2025, plug & play batteries were officially approved for residential use in Belgium through the introduction of the C10/26 regulatory framework for eligible devices listed by Synergrid on their homologation list [4]. This made plug & play batteries a particularly timely and relevant subject for academic investigation. More information regarding the regulatory framework of these plug & play devices such as the C10/26 and 0.8 kW regulations can be found in Chapter 3.

Despite their growing market presence, the technical capabilities and economic viability of plug & play batteries in Belgium remain insufficiently documented. Questions remain regarding their real-world efficiency, charging and discharging behavior, profitability under Belgian electricity tariffs and their competitiveness relative to conventional home batteries. In addition, the extent to which current systems can be further improved through hardware innovations and advanced control strategies

has not yet been fully explored.

This thesis therefore evaluates the technical performance of plug & play batteries for residential use in Belgium. Different commercially available battery systems are characterized through controlled laboratory measurements in order to assess relevant performance metrics such as efficiency, operational behavior and functional limitations. Based on these results, the profitability of plug & play batteries is analyzed under representative residential operating conditions. The elimination of installation costs, combined with the reduction in battery prices in recent years [5], may allow these systems to become financially profitable for a broader range of households. Since these systems commonly offer warranty periods of approximately ten years, achieving a payback period (PBP) within this timeframe is considered a key indicator of financial attractiveness. Another topic investigated in this thesis is the applicability of plug & play batteries in larger households compared with conventional home battery systems. This is evaluated through the installation of an actual plug & play battery in a large Belgian household by the author of this present work, allowing its cost effectiveness and technical performance to be compared with those of a conventional home battery. In addition, the interaction of these batteries with a smart meter through the P1 port is analyzed in this real-world household environment. The methodology used to conduct these measurements, the results of them and the economical calculations of these devices are further documented in Chapter 4.

In addition to the comparative evaluation of existing systems, this thesis investigates potential improvements mainly on the hardware side but also on the software side. By identifying the specific strengths of different battery types and combining their most favorable design elements and newly proposed optimization concepts, a theoretically improved plug & play battery system is formulated. All the information regarding these optimizations can be found in Chapter 5.

The findings of this work provide insight into the current state of plug & play battery technology and establish a technical foundation for future, more detailed economic analyses based on simulated household consumption profiles, advanced tariff modeling and long-term operational scenarios. An example of such an analysis is the KU Leuven Master’s thesis that will be released by the end of this year by Wannes Thierens, entitled “Costs, benefits and optimization strategy of plug & play PV-battery systems”.

Chapter 2

Literature Review

This chapter provides an overview of the existing literature relevant to residential battery energy storage systems and, more specifically, plug & play battery technologies. First, conventional home battery systems, their technical characteristics and their economic parameters are reviewed. Next, the current state of research on plug & play energy devices is introduced. Subsequently, standardized measurement methodologies for battery systems are discussed in order to justify the testing procedures used in this thesis. Finally, the identified research gaps that motivate the present work are presented.

2.1 Home Battery Energy Storage Systems

The average installed price of residential home battery systems is approximately 1000 €/kWh, including installation costs, shipping costs, value-added tax (VAT) and other associated expenses [6]. Although battery prices have decreased by approximately 54 % over the past five years, the total investment cost remains significant due to the additional costs associated with installation and grid integration [5].

Modern home battery systems typically achieve round-trip efficiencies (RTEs) greater than 90 %, meaning that for example more than 9 kWh of usable AC energy remains available after charging a battery with 10 kWh of electrical energy [7], [8]. In addition, these systems can increase the self-consumption ratio of households with PV systems to values between 50 % and 80 % [5]. A common method for determining the economically optimal size of a home battery is to analyze the average electricity consumption of a household between sunset and sunrise. For example, if a household consumes on average 10 kWh during this period, a battery with a similar usable capacity can significantly reduce the amount of electricity drawn from the grid. However, battery sizing is also influenced by several other important factors, including the local climate conditions, electricity tariff structure, PV production profile and household heating demand [5]. These technical and economic performance indicators provide an important reference framework for evaluating and comparing plug & play battery systems with home battery systems.

2.2 Plug & Play Energy Devices

Compared with conventional residential battery systems, the amount of available research concerning plug & play energy devices and plug & play batteries in particular remains limited. Most existing studies focus either on general residential energy management systems or on plug & play PV technologies rather than specifically on plug & play battery storage systems.

Several studies nevertheless address concepts that are closely related to plug & play batteries. For example, research has been conducted on home energy management systems with plug & play functionality that allow the integration of existing devices, such as smart meters, inverters, and batteries, without requiring major modifications to the residential electrical installation [9], [10]. Other studies investigate methods to improve the performance of plug & play PV systems through load alignment strategies and the integration of local energy storage [11].

The increasing commercial introduction of plug & play devices in Western European countries, such as Germany and the Netherlands, demonstrates growing market interest in low-threshold residential energy technologies. Their simplified installation procedure, lower installation costs and suitability for rented properties and apartments distinguish them from conventional home battery systems. Despite this growing market relevance, detailed technical and economic evaluations of plug & play battery systems remain scarce in the academic literature.

2.3 Measurement Guidelines on Batteries

In order to obtain reliable and universally comparable measurement results, standardized testing methodologies are required for battery energy storage systems. The measurements performed in this thesis are therefore based on the “Efficiency Guideline for PV Storage Systems” developed by the “Bundesverband Energiespeicher Systeme e.V.” (BVES) [12]. These guidelines define standardized procedures for evaluating battery efficiencies and operational performance under representative conditions.

Previous research performed in the same laboratory in EnergyVille on inverter efficiency characterization was used as a starting point for the development of a suitable measurement setup for plug & play batteries [13] [14]. By building upon earlier experimental work and using comparable measurement equipment, the accuracy and repeatability of the obtained results could be improved.

In addition to laboratory measurements, information and simulation methodologies from the “Hochschule für Technik und Wirtschaft Berlin” (HTW Berlin) were used to perform supplementary efficiency analyses through “Performance Simulation Model for PV-Battery Systems” (PerMod) simulations [1]. These simulations make it possible to evaluate the viability of battery systems under representative residential operating conditions and varying electricity consumption profiles.

2.4 Research Gaps

The literature review demonstrates that conventional residential battery systems have already been studied extensively from both technical and economic perspectives. Existing research provides significant insight into battery efficiencies, self-consumption optimization, energy management strategies and the economic impact of residential energy storage systems. However, considerably less research has focused specifically on plug & play battery technologies.

Most currently available studies concerning plug & play systems focus primarily on photovoltaic applications, smart energy management concepts or general integration strategies rather than on the direct characterization of plug & play battery systems themselves. As a result, limited publicly available data exist regarding the real-world performance, efficiency, charging and discharging behavior and economic viability of these battery systems.

In addition, the recent regulatory approval of plug & play batteries in Belgium means that very limited research is available concerning their operation under Belgian technical, economic and regulatory conditions. The absence of a general 0.8 kW discharge limitation in Belgium further distinguishes the Belgian market from many neighboring European countries and creates a unique case for evaluating the practical capabilities of higher-power plug & play battery systems.

Another important gap in the literature is the lack of studies combining detailed laboratory characterization with real-world residential implementation and economic feasibility analysis. Existing work rarely evaluates how plug & play batteries behave in practical household environments, how they interact with smart meters and household loads, or how their profitability compares with conventional home battery systems.

Furthermore, only a limited amount of research has investigated how the hardware and software architecture of plug & play batteries can be optimized by combining the strongest characteristics of different commercially available systems.

This thesis addresses these gaps by suggesting and evaluating a methodology to characterize commercially available plug & play batteries, evaluating their economic feasibility under Belgian residential conditions, analyzing their practical implementation in a real household environment and investigating potential hardware and software optimizations for future plug & play battery systems.

2.5 Conclusion

This chapter reviewed the existing literature concerning home battery energy storage systems, plug & play battery technologies, their economic parameters and the standardized methodologies used to evaluate battery systems. The review demonstrates that while conventional home batteries have been extensively studied, significantly less research has focused on plug & play battery systems, particularly under Belgian conditions. Furthermore, limited work has combined detailed laboratory characterization with economic feasibility analysis and real-world residential implementation.

2. LITERATURE REVIEW

Based on these identified research gaps, the following chapters evaluate commercially available plug & play batteries and investigate their technical and economic potential for residential applications in Belgium.

Chapter 3

Regulatory Framework

The market introduction of plug & play batteries has been accompanied by evolving technical standards and regulatory requirements across Europe. Because these systems are directly connected to household electrical circuits and can exchange power with the distribution grid, legislators and grid operators have introduced specific rules concerning safety, registration, and maximum output power. However, these requirements are not identical across countries, resulting in significant differences between national markets. Belgium provides a particularly relevant case, as its regulatory framework differs in an important aspect from that of many neighboring European countries.

3.1 European Output Power Limits

In many European countries, plug & play energy devices are subject to a maximum output power limit of 0.8 kW. This limit originates from the European legal framework concerning small-scale generators under the law (EU) 2016/631 "Requirements for Generators" (RfG) [3]. Article 5(2)(a) of this regulation classifies any generating unit connected to the low-voltage grid with a maximum capacity exceeding 0.8 kW as a Type A power-generating module. Consequently, such installations must comply with specific grid connection requirements, including mandatory registration procedures determined at the national level, as well as prescribed frequency response capabilities.

These requirements apply at the grid connection point, which in residential installations corresponds to the electricity meter. Therefore, the classification depends on the maximum power that can be injected into the grid rather than on the specific configuration of the equipment installed behind the meter. Generating units with a rated power below 0.8 kW are exempt from these additional requirements and can generally be installed as plug & play devices without the need for verification by a certified electrician.

As a result, many European Union member states adopted the 0.8 kW threshold when defining the regulatory framework for plug & play PV systems and plug & play battery systems.

For plug & play batteries, this commonly means that the input or charging power is not restricted by regulation and may occur at the maximum rate allowed by the battery’s technical design, whereas discharge power injected into the household installation or grid is limited to 0.8 kW. This creates a system that is generally safer and easier to integrate into residential electrical networks, although it also reduces flexibility and peak power capability compared with conventional home battery systems. The 0.8 kW threshold is generally considered conservative enough that the additional current remains within safe thermal limits, even for older residential wiring systems with lower safety margins. As a result, the risk of overheating, cable damage or fire is significantly reduced, including in uncommon overload scenarios.

One such overload scenario can occur when a household circuit protected by a 16 A circuit breaker at a nominal voltage of 230 V, such a breaker corresponds to 3.68 kW of allowed power before it trips. If for example two electric heaters of 3 kW each are connected to the same circuit, the total demand reaches 6 kW, causing excessive current through the breaker and leading it to trip in order to protect the wiring. However, if a 3 kW plug & play device simultaneously supplies part of this demand through the same circuit, the current flowing through the breaker will be reduced to 3 kW, preventing the breaker from tripping. Despite this, the wiring downstream of the connection point could still be exposed to a combined load of 6 kW, which is significantly above its intended rating. If such a condition persists for an extended period, overheating and fire risk may arise. This situation could have been prevented if the owner of the residence was aware of how the circuit breakers are wired in their household, but this is not commonly the case. Limiting plug & play discharge power to 0.8 kW thus reduces the likelihood and severity of such hidden overload conditions.

At present, no clearly defined regulations appear to prohibit households from installing multiple plug & play batteries in parallel. Consequently, users could increase the total available discharge power by combining several units. For example, three separate batteries each limited to 0.8 kW could theoretically provide a combined output power of 2.4 kW. This could also cause dangerous setups to be made in household since the general public is not aware of the implications of having multiple plug & play devices with large loads on the same circuit.

3.2 Belgian Regulatory Framework

Belgium has followed a different regulatory path from many neighboring countries. On the 17th of April 2025, plug & play batteries were officially approved for residential use through the implementation of the C10/26 regulatory framework. Under this framework, only devices included on the Synergrid homologation list are permitted for legal installation and operation. This marked the formal introduction of plug & play battery systems into the Belgian residential market.

Despite this approval, the initial Belgian framework still imposed an additional requirement that reduced the practical simplicity of these systems. All plug & play batteries were required to be equipped with an "EnergieFlussRichtung" (EnFluRi)

sensor installed by a certified electrician. As a result, these products could not yet be considered fully “plug & play”, since professional installation was still necessary. On the 15th of October 2025, this requirement was amended, after which the mandatory installation of these sensors was removed [15]. Instead, the battery can communicate with a P1 device connected to the P1 port of a smart meter. This device reads the real-time consumption and injection values measured by the smart meter and, unlike conventional measurement installations, does not require installation by a certified electrician. As a result, it can be installed directly by the user, preserving the plug & play nature of the system. Through this communication, the battery is continuously informed about the household load and grid injection levels, allowing it to respond accordingly by minimizing both grid consumption and injection or by reducing peak power demand through peak shaving strategies.

3.3 Belgian Power Limits and Registration Requirements

As of June 2026, approximately fourteen months after the official approval of plug & play batteries in Belgium, no laws or regulations require these systems to be limited to an output power of 0.8 kW. This distinguishes Belgium from many other European countries where such limits remain in force.

Instead, the main obligations for purchasers consist of administrative registration and compliance with household circuit limitations. If a plug & play device has a rated output power exceeding 0.8 kW, or if it is installed in a household that does not yet have a smart meter, the device must be registered through the Fluvius website [16]. In the latter case, when a plug & play battery is registered in a household without a smart meter, the utility (Fluvius in Flanders) is required to install a smart meter at the premises within three months of the registration. In addition, the socket group to which the device is connected must not exceed a total power of 2.6 kW. When these two requirements are fulfilled, no certified electrician is required to modify the electrical installation or to perform additional "Algemeen Reglement op de Elektrische Installaties" (AREI) inspections [17] [18].

In practical terms, this means that a consumer may install a plug & play battery capable of delivering 2.6 kW, provided that the device is properly registered and that it is the only electrical appliance connected to that socket group. In that case, the battery would also be the only device supplied through the corresponding circuit breaker.

3.4 Implications for the Belgian Market

The Belgian framework creates a unique market environment for plug & play batteries. The absence of a general 0.8 kW discharge limit allows higher-power systems to operate than in many neighboring countries, potentially improving the economic value of these batteries through greater peak shaving, load shifting, and self-

3. REGULATORY FRAMEWORK

consumption. At the same time, users must still comply with registration procedures and circuit-level safety constraints.

Because of these distinctive regulatory conditions, Belgium represents an especially valuable case study for evaluating the technical and economic potential of plug & play battery systems in residential applications.

Chapter 4

Measurements and Results

This chapter presents the experimental measurements, economic analysis, simulations, and real-world implementation results obtained during the evaluation of residential plug & play battery systems. The objective of these investigations is to characterize the technical behavior, operational performance and economic potential of commercially available plug & play batteries under representative Belgian residential conditions.

First, the laboratory measurement setup is introduced, including the tested battery systems, the different categories of plug & play batteries, and the measurement equipment used to characterize their operation. Controlled laboratory tests were performed to determine important technical parameters such as charging and discharging efficiencies, round-trip efficiency (RTE), standby losses, measurement deviations, smart meter interaction behavior and irregular operating phenomena that may affect practical performance.

Afterwards, a simplified economic analysis is performed for all tested battery systems in order to evaluate their financial viability under representative Belgian residential conditions. This analysis investigates whether the batteries are capable of recovering their initial investment within their typical ten-year warranty period. Representative household consumption profiles and PV production profiles are used to estimate the operational behavior of the batteries and to determine the resulting financial savings under current electricity tariffs.

Next, the technical performance of the investigated battery systems is analyzed in detail. Particular attention is given to the influence of operating power levels on efficiency and system behavior. The obtained results are then used as input parameters for PerMod simulations based on the BVES guidelines in order to evaluate the annual energy performance of the batteries under different residential operating conditions.

Finally, the practical implementation of a plug & play battery system in a large Belgian household is discussed. This section examines the installation procedure, regulatory registration process, interaction with smart meter devices and the real-world impact of the batteries on grid consumption, grid injection, and peak power demand. Additional measurements performed on the installed system are also pre-

sented to compare the practical behavior of the batteries with the previously obtained laboratory results.

4.1 Battery System Specifications

The experimental measurements performed at the EnergyVille laboratory focused on two commercially available plug & play battery systems: the Marstek Venus C 1.0 and the Anker SOLIX Solarbank 3 E2700 Pro. Throughout the remainder of this thesis, these systems will respectively be referred to as the Marstek C and the Anker. Before discussing the characteristics of these batteries, it is first necessary to distinguish between the three main categories of commercially available plug & play battery systems.

The first category consists of batteries that are connected exclusively through the AC grid. These systems can both charge and discharge only through the AC side of the household installation and will therefore be referred to as AC batteries.

The second category consists of systems that can both charge and discharge through the AC grid while also allowing PV panels to be connected directly to the battery through DC inputs. In this configuration, energy originating from the PV panels only undergoes a DC-to-DC conversion before charging the battery. These systems will be referred to as AC+DC batteries.

For AC batteries, charging from PV panels involves several conversion stages. First, the PV panels generate DC power, which is converted to AC power by a microinverter. Subsequently, the battery converts this AC power back to DC power in order to charge the battery cells internally. As a result, additional conversion losses are introduced compared with systems that support direct DC charging.

The final category consists of fully DC-coupled battery systems that do not have an AC connection. In these systems, the battery is placed between plug & play PV panels and the associated microinverter. Consequently, the battery can only be charged directly by the PV panels and cannot charge from the AC grid. These systems will be referred to as DC batteries.

Electrical diagrams illustrating the integration of these three battery types into a residential installation are shown in Figure 4.1. The green conversion blocks represent the internal power electronics of the battery system, while the yellow conversion blocks represent an external microinverter. The arrows indicate the possible directions of energy flow. For the AC battery diagram, both the battery system and the external microinverter consist of separate DC-to-DC and DC-to-AC conversion stages. However, this is not universally the case, as some microinverters and AC battery systems integrate these stages into a single DC-to-AC conversion unit.

Based on these classifications, the Marstek C is categorized as an AC battery, while the Anker is categorized as an AC+DC battery.

The most important characteristics of the Marstek C and the Anker are summarized in Table 4.1. The Marstek C has a maximum charging and discharging power on the AC grid of 2.5 kW, which is approximately twice the power capability of the Anker. This higher power capability makes the Marstek C more suitable for

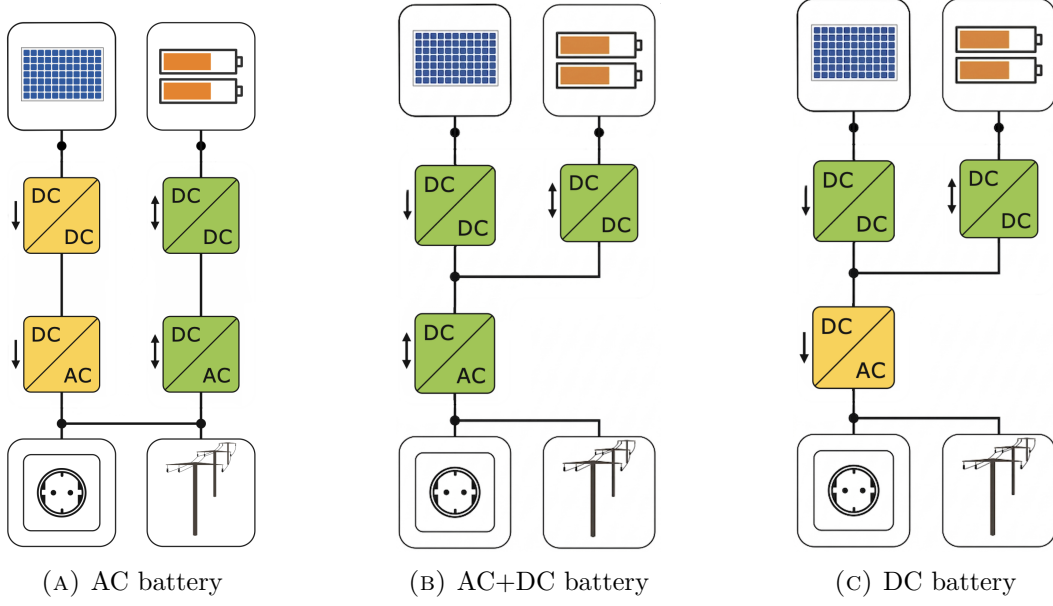


FIGURE 4.1: Electrical diagrams of the three main plug & play battery configurations [1].

compensating large household load peaks or handling larger PV installations that are connected to the AC grid. Since the Anker is an AC+DC battery it also has a maximum PV DC input power of 3.6 kW (four inputs with each being rated at 0.9 kW). Both systems have a similar storage capacity of approximately 2.5 kWh. However, the Anker is approximately 57 % more expensive than the Marstek C. In contrast, the Anker provides a higher depth of discharge (DoD). A higher DoD allows a larger fraction of the battery's nominal capacity to be utilized, thereby increasing the amount of energy available to the user. However, deeper charge-discharge cycles generally accelerate battery degradation and can reduce the overall lifetime of the battery. In addition, maintaining the battery at a very low SoC for extended periods, such as during winter months when PV production is limited and the battery may remain inactive for long durations, can further contribute to battery degradation and potentially cause irreversible damage to the cells. As a result, the selected DoD represents a trade-off between maximizing usable capacity and preserving long-term battery health. The chosen value therefore depends on whether the manufacturer prioritizes energy availability or battery longevity.

The actual usable battery capacity can therefore be determined by multiplying the nominal capacity by the corresponding DoD value. For example, for the Marstek C, only 88 % of the nominal 2.560 kWh capacity is usable, resulting in an effective battery capacity of 2.253 kWh.

	Marstek C	Anker
AC Grid Power Limit [kW]	2.5	1.2
DC PV Power Input Limit [kW]	/	3.6 (4 x 0.9)
Capacity [kWh]	2.560	2.688
Battery Type	AC	AC+DC
Price [€]	700	1100
Depth of Discharge (DoD) [%]	88	95
Usable Capacity [kWh]	2.253	2.554

TABLE 4.1: Characteristics of the plug & play batteries tested in the laboratory.

4.2 Laboratory Measurement Setup

Several additional devices were required to construct the laboratory measurement setup. The Yokogawa WT1806E Precision Power Analyzer [19] was used to measure all relevant electrical quantities with high precision. Due to its scaling capabilities, the device maintains high accuracy even at low power levels and provides consistent measurement performance across its operating range. The Yokogawa records the following measurements:

- DC voltage and current of the Regatron G5 Universal Regenerative DC Source Sink;
- DC voltage and current of the Regatron G5 Solar Array Simulator;
- DC voltage and current of the internal battery terminals (applicable only to the Anker setup, as discussed later in this section);
- AC voltage and current at the grid connection point of the plug & play battery system;
- AC voltage and current of the ZSACRV9826 load simulator.

The maximum measurement error of the Yokogawa as a function of power level is shown in Table 4.2. At higher power levels, the maximum measurement error stabilizes at approximately ± 0.4 %. It should also be noted that, for all measured efficiency values, the maximum relative measurement error doubles. This is because efficiencies are calculated as the ratio of two quantities measured with the same instrument, consequently, the relative uncertainties of both measurements contribute to the final result. However, this doubling of the maximum error represents a conservative overestimation, as any systematic errors cancel out in the ratio, and only random errors contribute to the propagated uncertainty. This uncertainty should therefore be taken into account when interpreting all efficiency results that were measured by the Yokogawa in this work.

The main sources of these measurement errors are the Yokogawa instrument itself, the LEM current transducers it employs and the precision resistors connected

Power [kW]	Maximum Measurement Error [%]
0.05	± 0.90
0.1	± 0.55
0.2	± 0.40
0.4	± 0.40
0.8	± 0.40
1.2	± 0.40
1.6	± 0.40
2	± 0.40
2.5	± 0.40

TABLE 4.2: Maximum measurement errors of the Yokogawa power analyzer as a function of measured power.

to these LEMs. The LEMs used in this power analyzer are Fluxgate-based sensors. They operate by driving the magnetic core into a controlled saturation state as part of their sensing principle, continuously forcing the core to remain near zero net magnetic flux during operation. This technology provides low offset, low offset drift and a superlinear response. It also enables excellent accuracy due to the near-zero offset behavior, which is particularly advantageous when measuring small currents, where offset errors have a relatively larger impact [20]. The LEMs are connected to precision resistors (shunt elements), which convert the sensed current into a measurable voltage signal for the Yokogawa instrument.

The Yokogawa is capable of acquiring up to 2 million samples per second (2 MHz). All measured quantities, such as voltage, current and power, are stored in 100 ms intervals by averaging 200 000 samples collected during each interval. However, the energy values reported for each 100 ms interval are not computed from these averaged values. Instead, they are calculated directly from the original high-resolution samples, thereby preserving the full measurement resolution and ensuring that no accuracy is lost due to averaging effects.

The Regatron G5 Universal Regenerative DC Source Sink [21] and the Regatron G5 Solar Array Simulator [22] were used to emulate the electrical behavior of PV panels. These PV simulators measure their output DC electrical quantities at a sampling frequency of 48 kHz and do not apply any averaging to the measured values.

Household load behavior was simulated using the Höcherl & Hackl ZSACRV9826 AC load [23]. To enable dynamic battery control based on household power flow, a Shelly Pro 3EM [24] was integrated into the setup. This device continuously measured the AC grid power and communicated these measurements to the battery system, allowing the battery to regulate its charging or discharging power in order to achieve a net household power exchange of approximately 0 W.

The Shelly device therefore performs a function similar to that of the P1 smart meter interface commonly used in residential installations. A key difference, however, lies in the measurement accuracy of the two devices. The Shelly Pro 3EM

has an accuracy class B rating, corresponding to a maximum measurement error of $\pm 1\%$, whereas Belgian smart meters have an accuracy class 0.5S rating with a maximum error of $\pm 0.5\%$ and are MID-certified. Consequently, Belgian smart meters are specified to be approximately twice as accurate as the Shelly Pro 3EM. One similarity between both devices is their temporal measurement resolution. Both operate with a sampling frequency of 1 Hz and don't apply any averaging to their measured values, meaning that any load change within the household is only reflected in the reported measurements after an average delay of approximately 0.5 s. This delay corresponds to the time required for the devices to capture and transmit updated measurement values to the battery system. The interaction between plug & play batteries and actual smart meters through the P1 interface is further investigated in the household implementation presented in Section 4.6. The Shelly device measures the voltage and current on the AC phase to which the battery system, the load simulator and the microinverter are connected.

The current transformers (LEMs) used with the Shelly Pro 3EM are split-core transformer-type current sensors. Compared to the previously described Fluxgate LEMs, these sensors are less accurate due to a larger offset in their measurements, which results in higher measurement errors [25].

A 2.4 GHz Wi-Fi network was also required for this setup, as both battery systems and the Shelly Pro 3EM rely on this frequency band for inter-device communication. These devices do not support 5 GHz networks, therefore, the existing 5 GHz Wi-Fi infrastructure at EnergyVille could not be used. Although each device supports Bluetooth connectivity through its respective application, this functionality was not allowed to be used to enable communication between the devices. Such interoperability would have been more convenient for this application.

The electrical configurations of the Marstek C and Anker laboratory setups are shown in Figure 4.2 and Figure 4.3, respectively. The electrical diagrams also show that four-wire measurements are used at each measurement point: two wires for voltage sensing and two wires connected to the terminals of the current sensor. For the electrical diagram of the Anker setup, only one PV input is shown. In practice, however, the first two PV inputs are used. Since both inputs rely on identical power electronics, only a single input is represented in the diagram for clarity and due to space limitations. A photograph of the physical implementation of the Anker setup is shown in Figure 4.4.

The two setups differ primarily in the method used to provide PV generation. For the Marstek C setup, simulated PV power generated by the Regatron system was supplied to an APSystems EZ1-M 0.8 kW microinverter, whose AC output was connected to the household AC grid. In contrast, the Anker setup additionally allowed the simulated PV power to be connected directly to the DC PV inputs of the battery.

A second important difference concerns the possibility of performing internal DC measurements. For the Anker battery, internal DC battery leads could be accessed safely by opening the enclosure through removable screws, allowing accurate internal DC measurements to be obtained directly. The Marstek C, however, was sealed using a glass panel bonded with silicone. Attempting to remove this panel could

4.2. Laboratory Measurement Setup

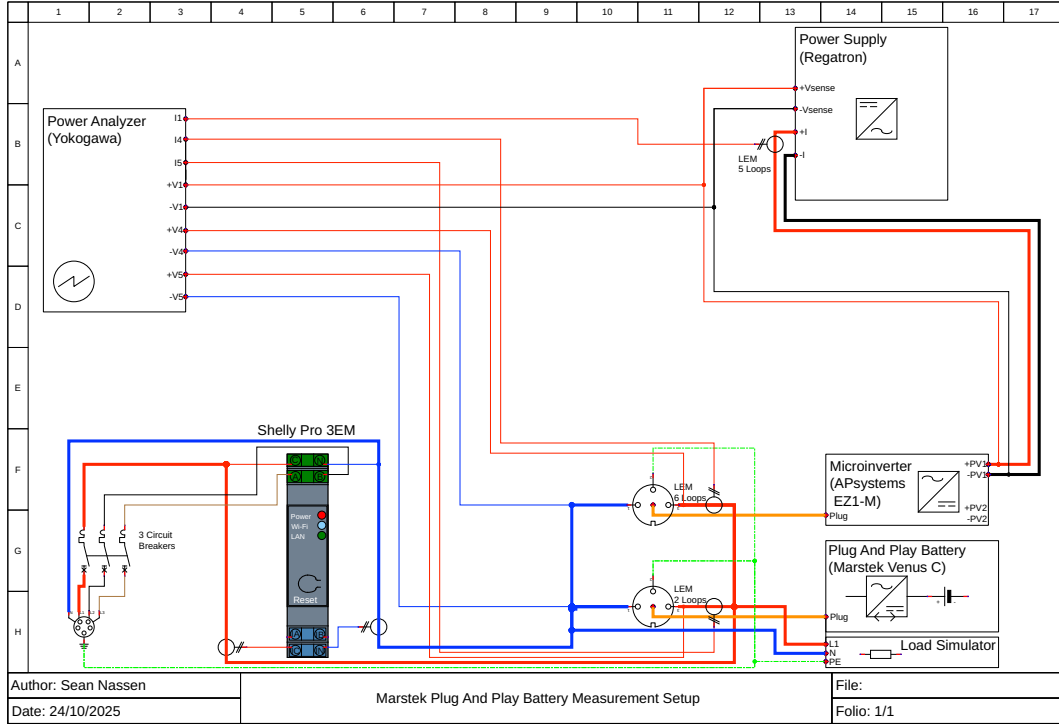


FIGURE 4.2: Electrical diagram of the laboratory setup for the Marstek C.

potentially damage the battery and create hazardous conditions in the laboratory environment. Consequently, no direct internal DC measurements could be performed on the Marstek C.

As a result, one assumption had to be made for the Marstek C, namely that the usable internal battery capacity corresponded exactly to the calculated value of 2.253 kWh. This assumption introduces a small uncertainty in the charging and discharging efficiency calculations discussed in Section 4.3.1. However, it does not affect the calculated RTE, since the RTE depends only on external energy measurements.

4. MEASUREMENTS AND RESULTS

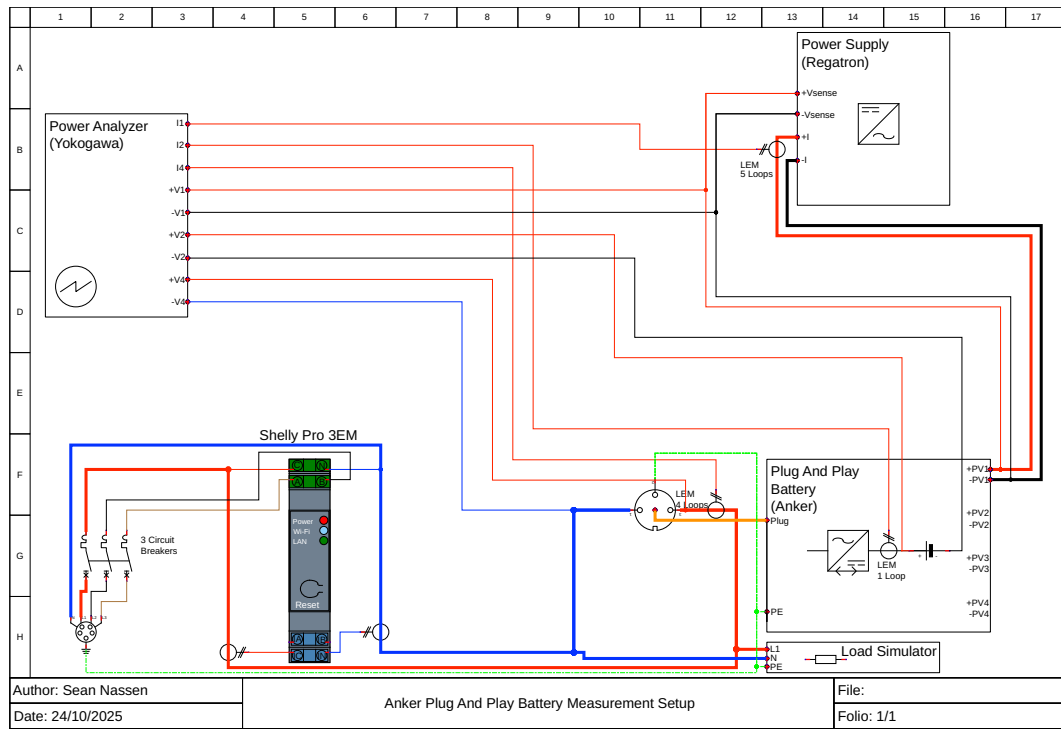


FIGURE 4.3: Electrical diagram of the laboratory setup for the Anker.



FIGURE 4.4: Physical implementation of the Anker laboratory setup.

4.3 Technical Performance

4.3.1 Efficiency

The efficiencies of the battery systems were determined by performing complete charging and discharging cycles at different power levels. This approach made it possible to evaluate the battery performance over the full operating range of the systems. The efficiencies were calculated by comparing the measured external AC or PV energy with the corresponding internal DC battery energy during each test cycle.

Example calculations are provided below to clarify the methodology. Equation 4.1 presents the efficiency calculations for a full 1.2 kW charging and discharging cycle of the Marstek C, together with the resulting RTE. Equation 4.2 similarly shows the calculations for a 1.2 kW discharge cycle and direct DC charging cycle of the Anker battery.

For the Marstek C and the AC charging configuration of the Anker, the calculated RTE values were additionally multiplied by 96.1 % to account for the efficiency losses of the inverter, which is a typical efficiency that inverters for PV panels have [14]. This correction ensures a fair comparison with the Anker DC charging configuration, since both systems then have the same starting point, namely DC energy generated by the PV panels, and the same end point, namely AC energy injected into the household installation. When the battery is charged directly from the AC grid instead of from PV panels, this correction factor is not required. Consequently, the definition of a round-trip cycle used in this work differs from the conventional approach, which typically considers energy starting from an AC input and ending at an AC output. Instead, the RTE is defined in a manner that also allows comparison with battery systems charged directly by PV generation, for which no AC input stage is present.

Since internal DC measurements were available for the Anker it was also possible to separately determine the efficiency of the battery itself at different power levels to see how much energy is lost due to conversions between electrical and chemical energy. For the Marstek C are the battery efficiencies already incorporated in the charge and discharge efficiencies themselves since the assumption $E_{DCcharge} = E_{DCdischarge} = 2.253 \text{ kWh}$ was made.

The resulting efficiencies are summarized in Table 4.3 and Table 4.4, while a graphical comparison is shown in Figure 4.5. As discussed previously, all efficiency values reported in this section are subject to a maximum measurement error equal to twice the corresponding values listed in Table 4.2 for each power level.

When considering the weighted average efficiencies over the complete operating range, the Anker achieves an RTE that is 4.29 % higher than that of the Marstek C under equivalent AC charging and discharging conditions. This indicates that the Anker uses more efficient internal power electronics with lower conversion losses.

A further increase of 3.55 % in RTE is observed when comparing the Anker operating under direct DC charging conditions with the same system operating under AC charging conditions. This improvement can be explained by the reduced number of

power conversion stages. During DC charging and afterwards AC discharging, only a single DC-to-AC conversion occurs during battery discharge, whereas AC charging with AC discharging requires both an AC-to-DC conversion during charging and a DC-to-AC conversion during discharge. The additional conversion stage therefore introduces additional losses.

Another noteworthy observation is the low charging efficiency of the Marstek C at low power levels. At a charging power of 0.05 kW, the measured AC charging efficiency is at 0 %. This behavior occurs because the Marstek C requires a minimum input power before the internal AC-to-DC conversion process can operate correctly. A likely explanation is that the internal control circuitry and power conversion electronics first require a sufficient amount of input power to initialize and maintain stable operation. At very low charging powers, nearly all incoming AC energy is therefore consumed by these internal electronics rather than being transferred to the battery cells. This limitation is not observed during low-power discharging operation, since the battery can directly supply the additional required energy for the internal control electronics without first requiring an AC-to-DC conversion stage. Only from approximately 0.06 kW onward does measurable DC charging of the battery occur.

As a result, situations may arise in which low levels of excess PV production are entirely consumed by conversion losses instead of being stored in the battery. For example, when a household produces approximately 0.06 kW of surplus PV power, charging the Marstek C becomes energetically unfavorable. In such cases, directly injecting the excess power into the grid may be more beneficial, since compensation for injected energy can still be received from the electricity supplier. Possible optimizations for this behavior are discussed further in Chapter 5.

One additional efficiency parameter that is important to evaluate is the inverter efficiency of the Anker system. Since the Anker supports direct PV connections, PV power can bypass the battery cells and be directly converted to AC power whenever the battery is fully charged or when PV production simultaneously supplies household loads. In this operating mode, the incoming PV energy bypasses the battery cells entirely and is directly converted and supplied to the AC grid through the internal inverter.

To determine the inverter efficiency, the ratio between the AC power output and the DC power input was measured at different power levels. The resulting efficiencies are shown in Table 4.5. When comparing these values with the AC discharge efficiencies of the Anker, it can be observed that almost all inverter efficiencies are consistently lower at all operating powers, with differences reaching up to an absolute value of 8.37 %. This difference is caused by the additional DC-DC conversion stage required for incoming PV energy before the inverter converts the power to AC. During battery discharge, this DC-DC conversion stage is not required, thereby avoiding the associated conversion losses.

It can also be observed that the inverter efficiency decreases significantly at higher PV power levels. This behavior is related to the limited maximum AC output power of 1.2 kW, while the applied PV input power during the measurements can reach up to 1.8 kW. In practical operation, the system can even receive up to

3.6 kW when all four PV inputs are used, resulting in calculated efficiencies as low as 33.56 %.

However, it is important to note that this low value does not reflect a reduction in the inverter’s intrinsic conversion efficiency (defined as the ratio of AC output power to DC input power at the inverter terminals). Instead, the apparent efficiency decrease is caused by system-level power curtailment. Under these conditions, the battery system no longer operates the PV modules at their maximum power point. The operating point of the PV panels is deliberately shifted away from the maximum power point in order to limit the available DC power to the inverter’s maximum AC output capability of 1.2 kW. As a result, the reduced ratio between measured AC output power and total available PV power leads to a lower apparent efficiency, without implying an actual degradation of the inverter’s conversion performance. The inverter itself continues to operate at its maximum power of 1.2 kW, where it achieves a conversion efficiency of 93.84 %.

The availability of up to 3.6 kW of PV input power is, however, advantageous when the battery is not fully charged. In such operating conditions, the system can utilize the full available PV power to charge the battery instead of curtailing generation. This enables flexible power allocation, for example by charging the battery at 3.6 kW when no grid export is required or by charging at 2.4 kW while simultaneously exporting the remaining 1.2 kW as AC power to the grid. This capability ensures that excess PV generation is still effectively utilized, either for storage or for grid injection, when the battery is not yet fully charged.

Another phenomenon observed during this bypass operating mode was the presence of small periodic discharge spikes originating from the battery itself. The measured behavior of these discharge spikes is shown in Figure 4.6. During the normal charging phase, no irregular behavior was observed. However, once the battery reached full charge, periodic discharge peaks with a duration of approximately three seconds occurred every four seconds on both the internal DC battery leads and AC output, with peak discharge powers of approximately 19 W. Since these power peaks are also observed at the AC output of the battery system, it indicates that they are not related to the internal consumption of the device’s electronics.

As a result of these repeated discharge pulses, the battery SoC eventually decreased to 99 %, after which the battery resumed charging from PV power until full charge was reached again. This process then continuously repeated itself. The average discharged power associated with this irregular behavior was measured to be 6.18 W.

Although the magnitude of these discharge peaks is relatively small, this behavior introduces additional energy losses and may contribute to unnecessary battery cycling during extended periods of high PV generation.

Power [kW]	Marstek C		
	$\eta_{ACcharge}$ [%]	$\eta_{ACdischarge}$ [%]	RTE [%]
0.05	0	67.06	0
0.1	35.72	79.76	27.38
0.2	70.58	84.56	57.36
0.4	81.93	89.78	70.69
0.8	86.91	91.81	76.68
1.2	87.67	91.97	77.48
1.6	88.01	91.26	77.18
2	88.70	89.93	76.66
2.5	86.49	88.67	73.70
Average	81.77	88.64	70.93

TABLE 4.3: Measured efficiencies of the Marstek C.

1.2 kW Marstek C Efficiencies

$$\begin{cases} \eta_{ACcharge} = \frac{E_{DCcharge}}{E_{ACcharge}} = \frac{2.253 \text{ kWh}}{2.570 \text{ kWh}} = 87.67 \% \\ \eta_{ACdischarge} = \frac{E_{ACdischarge}}{E_{DCdischarge}} = \frac{2.072 \text{ kWh}}{2.253 \text{ kWh}} = 91.97 \% \\ RTE = \eta_{ACcharge} \cdot \eta_{ACdischarge} \cdot \eta_{inverter} = 77.48 \% \end{cases} \quad (4.1)$$

1.2 kW Anker Efficiencies (DC charge)

$$\begin{cases} \eta_{DCcharge} = \frac{E_{DCcharge}}{E_{PV}} = \frac{2.634 \text{ kWh}}{2.719 \text{ kWh}} = 96.86 \% \\ \eta_{ACdischarge} = \frac{E_{ACdischarge}}{E_{DCdischarge}} = \frac{2.284 \text{ kWh}}{2.458 \text{ kWh}} = 92.92 \% \\ \eta_{battery} = \frac{E_{DCdischarge}}{E_{DCcharge}} = \frac{2.458 \text{ kWh}}{2.634 \text{ kWh}} = 93.32 \% \\ RTE = \eta_{DCcharge} \cdot \eta_{ACdischarge} \cdot \eta_{battery} = 84.00 \% \end{cases} \quad (4.2)$$

Power [kW]	Anker					
	$\eta_{DCcharge}$ [%]	$\eta_{ACcharge}$ [%]	$\eta_{ACdischarge}$ [%]	$\eta_{battery}$ [%]	RTE_{DC} [%]	RTE_{AC} [%]
0.05	72.15	57.91	70.97	96.80	49.56	38.23
0.1	80.05	72.98	84.91	96.77	65.79	57.64
0.2	85.02	83.37	92.08	96.74	75.74	71.37
0.4	89.02	90.94	96.96	95.59	82.50	80.99
0.8	91.11	92.98	99.08	94.72	85.50	83.86
1.2	96.86	92.87	92.92	93.33	84.00	77.40
1.6	96.70	/	/	/	/	/
1.8	96.61	/	/	/	/	/
Average	90.52	86.60	92.53	93.20	78.77	75.22

TABLE 4.4: Measured efficiencies of the Anker.

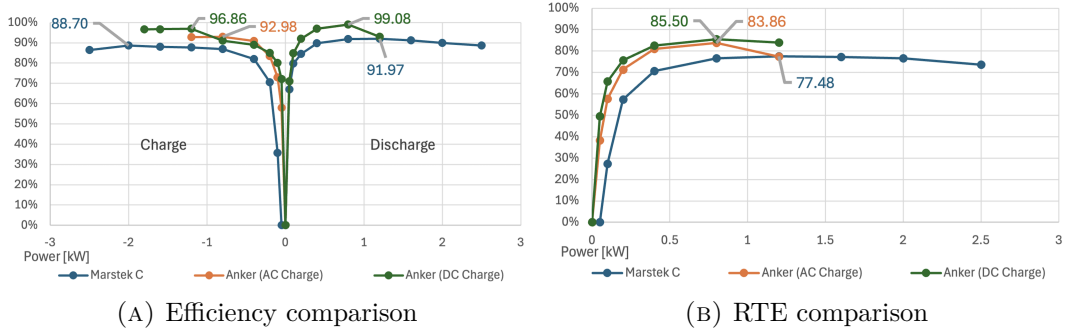


FIGURE 4.5: Efficiency and round-trip efficiency comparison between the Marstek C and Anker battery systems with all peak values labeled.

Power [kW]	$\eta_{inverter}$ [%]
0.05	62.60
0.1	76.87
0.2	85.02
0.4	91.18
0.8	93.64
1.2	93.84
1.6	75.52
1.8	67.14
Average	85.20

TABLE 4.5: Measured efficiencies of the Anker inverter.

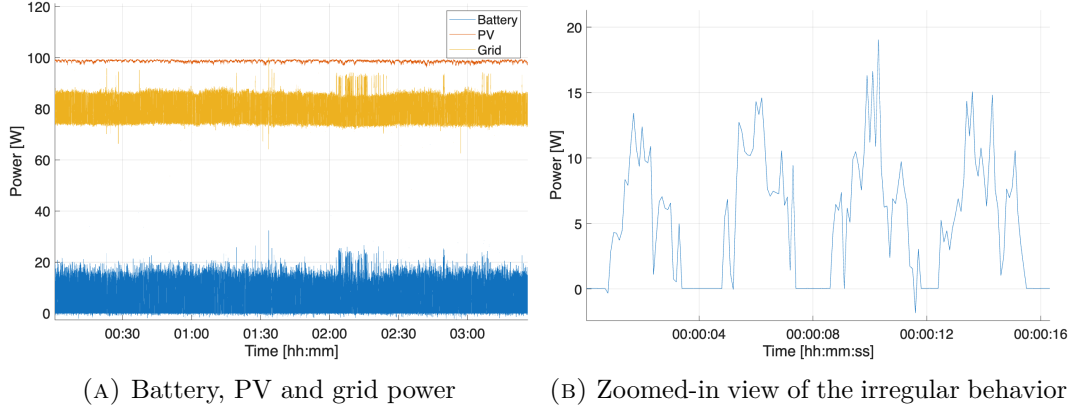


FIGURE 4.6: Measured irregular discharge behavior of the Anker battery when 0.1 kW of PV power is being converted.

4.3.2 Usable AC Energy

Using the measured efficiencies, the actual amount of usable AC energy that can be delivered to household appliances can also be determined. This usable AC energy is calculated by multiplying the usable battery capacity shown in Table 4.1 by the weighted average AC discharge efficiency.

Based on this calculation, the Marstek C provides 1.997 kWh of usable AC energy, while the Anker provides 2.363 kWh. Consequently, the actual usable energy available to the household depends not only on the nominal battery capacity, but also on the DoD and the discharge efficiency of the battery system.

4.3.3 Standby Loss

Another important characteristic of residential battery systems is their standby power consumption. To determine these standby losses, both batteries were monitored during periods in which no charging or discharging operations were performed. The average power consumption measured during these idle conditions was then used to determine the standby loss of each system.

The measured standby loss of the Marstek C is 6.01 W, while the standby loss of the Anker is 8.82 W. Although these power levels are relatively small, standby losses continuously occur throughout the day and can therefore have a noticeable impact on the long-term energy efficiency and economic profitability of the battery system.

4.3.4 Measurement Deviation

The measurement accuracy of the Yokogawa, Shelly and battery monitoring systems was compared in order to evaluate the deviation of each device relative to the Yokogawa WT1806E precision power analyzer, which has maximum measurement errors that are stated in Table 4.2.

Since the Shelly and the battery systems only measure AC-side power, their measurements were compared directly with the AC power measured by the Yokogawa. The accuracy of these measurements is particularly important because the battery control system attempts to regulate the household power exchange with the grid toward an ideal value of 0 kW. Measurement deviations therefore directly influence how accurately the battery can compensate for household consumption or PV generation.

The deviation percentages at different power levels are shown on the logarithmic scale in Figure 4.7. The Shelly exhibits an average deviation of 0.16 %, whereas the Marstek C shows a larger average deviation of 1.83 %. And for the Anker the average deviation for its AC measurements is 0.82 %.

It can also be observed that the deviation increases at lower power levels. This is primarily due to the fact that the Shelly device and battery device operate with fixed measurement ranges, which leads to reduced accuracy at low signal levels because of end-of-scale effects, digitization errors and potential amplifier bias. In contrast, the Yokogawa power analyzer employs automatic range scaling, which helps maintain higher accuracy across a wider measurement range and mitigates these low-power errors. The Shelly and internal battery measurement systems do not offer this same level of adaptive scaling, resulting in larger relative deviations in the low-power operating region.

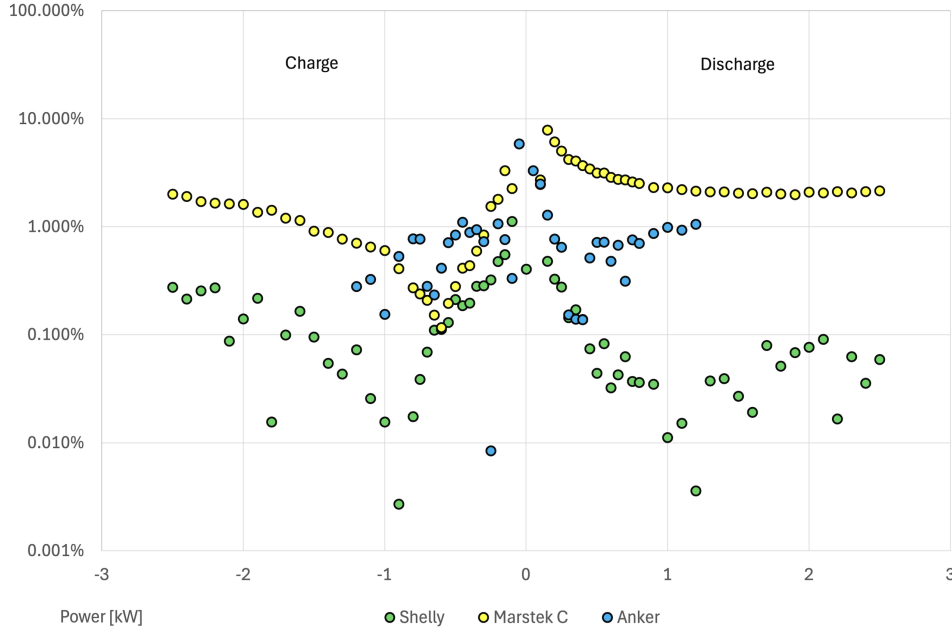


FIGURE 4.7: Measurement deviations of the Shelly and battery systems relative to the Yokogawa precision power analyzer.

4.3.5 Smart Meter Interaction

The interaction between the battery systems and the smart meter measurements plays an important role in determining how effectively the batteries can minimize the household power exchange with the grid. To evaluate this behavior, several tests were performed in which either the simulated PV production or the simulated household load was changed abruptly between different power levels. These experiments allowed the response speed and control accuracy of the battery systems to be evaluated.

The charging behavior of the Marstek C under varying PV generation conditions is shown in Figure 4.8. At low charging powers, the battery system exhibits unstable operating behavior, which is consistent with the previously observed low charging efficiencies at low power levels. Significant fluctuations in charging power can be observed in this operating region. For example, when the microinverter produces approximately 63 W, the Marstek C alternates between charging powers of 61 W, 93 W, and 121 W at a frequency of approximately 3.33 Hz.

At higher charging powers, the behavior of the Marstek C becomes more stable. When the simulated PV production changes, the total household power initially deviates from the target value, but the battery adjusts its charging power within approximately three seconds to restore the net power exchange close to 0 W.

Over the complete charging test, the average total power measured at the grid connection point was -2.63 W, indicating that the battery charged slightly more power than required. Nevertheless, the overall control performance remains acceptable as long as the battery does not operate predominantly below 100 W charging power.

During discharge operation, the Marstek C was able to track the household load accurately, even at lower power levels. The response time remained approximately 3 s, which includes the 0.5 s that is on average needed for the Shelly Pro 3EM to measure and transmit its data. While the average total power during the discharge test was 6.22 W, indicating a slight over-discharge relative to the actual household demand.

The same AC charging and discharging behavior tests were also performed for the Anker battery system. During these tests, the Anker was able to accurately track both changes in household load consumption and variations in PV production. The average response time required for the battery to reach the expected operating power was approximately 2.5 s, with the Shelly delay also included here.

For the charging behavior test, in which the PV production level was varied and the Anker adjusted its charging power accordingly, the average measured grid power was 10.57 W. This indicates that the battery charged slightly less than required to maintain the ideal net grid power of 0 W.

For the discharging behavior test, where the household load consumption was varied and the battery adjusted its discharge power, the average measured grid power was -7.43 W. This indicates that the battery discharged slightly less power than necessary, resulting in a small remaining power draw from the grid.

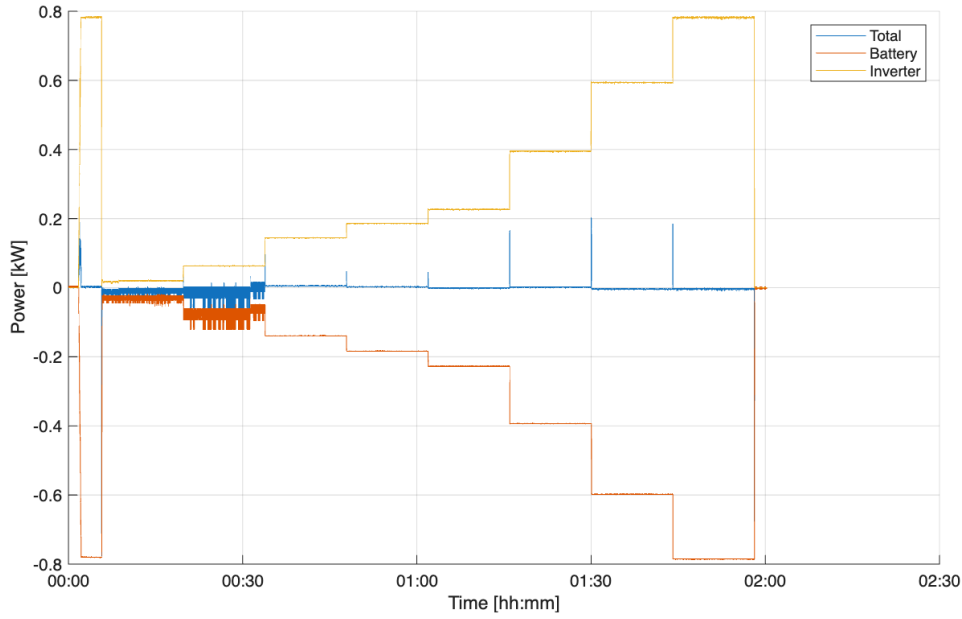


FIGURE 4.8: Charging behavior of the Marstek C under varying simulated PV generation levels.

4.4 PerMod Simulation

PerMod simulations were performed to evaluate the energy efficiency and overall system performance of the plug & play battery systems under realistic residential operating conditions. The simulations calculate a “System Performance Index” (SPI), which represents the performance of a realistic battery system relative to an ideal battery system operating under identical conditions.

To determine the SPI, the battery systems were first simulated using the experimentally determined parameters obtained from the laboratory measurements and following the BVES guidelines. These parameters include efficiencies, standby losses, response times, and other operational characteristics. Using these values, a one-year simulation with a temporal resolution of one second was performed in order to determine the power flows between the PV installation, household load, battery system, and electrical grid for a representative Belgian household. From these simulations, the total annual energy exchanged in each power flow could be determined.

Subsequently, the same simulation was repeated using an idealized battery system with perfect operating characteristics, namely 100 % efficiency and thus with no losses. By comparing the annual energy flows of the realistic battery system with those of the ideal battery system, the SPI can be calculated.

Compared with a simple weighted average of the measured RTEs, the SPI provides a more representative measure of real-world battery performance, as it inherently accounts for the distribution of operating power levels over the course of a year. As a result, operating conditions that occur more frequently have a pro-

portionally larger influence on the final performance metric. In addition, the SPI captures system-level effects that are not fully reflected in basic efficiency averages, including sizing losses, conversion losses, control-related losses and standby losses.

This distinction is particularly important for systems such as the Marstek C, which exhibit significantly lower efficiencies at low charging powers. For example, when the Marstek C is combined with a relatively small PV installation, low charging powers occur more frequently, resulting in a lower SPI value. In contrast, a weighted average RTE assumes that all operating power levels occur equally often and therefore does not fully represent realistic operating behavior.

Both a PV production profile and a residential load profile are required to perform the PerMod simulations.

For the PV generation profiles, measured PV production data from the year 2023 was used. The data originated from physically present 0.8 kWp PV installations located on the roof of EnergyVille 2 in Genk, Belgium. The PV modules were mounted vertically at a tilt angle of 90 ° and the measurements were recorded with a temporal resolution of one second.

Three different PV orientations were considered: east-facing, south-facing, and west-facing. This allows the influence of PV orientation on the performance of the battery systems to be evaluated.

The measured PV data was used to represent two different installation sizes: 0.8 kWp and 1.6 kWp. For the 0.8 kWp configuration, the measured data was used directly without modification. For the 1.6 kWp configuration, all measured power values were multiplied by a factor of two, thereby simulating two identical 0.8 kWp PV installations operating simultaneously under the same irradiance conditions. For both PV system configurations, the DC power generated by the PV panels is converted to AC power using an inverter with an assumed efficiency of 96.1 %.

For the residential load profile, a generalized household consumption model provided within the PerMod simulation environment was used. This load profile has a temporal resolution of one second and is based on an open dataset containing synthetically generated residential electricity demand profiles (profile no.31 in [26]).

The selected profile has a base annual electricity consumption of 5010 kWh/a. To represent households of different sizes, the profile was scaled such that an annual electricity consumption of 1000 kWh is assumed per household resident. Consequently, a household consisting of three residents corresponds to an annual electricity consumption of 3000 kWh, while a two-person household corresponds to an annual consumption of 2000 kWh.

The resulting SPI values for the different simulation scenarios are shown in Table 4.6. In total, twelve unique operating conditions were evaluated for each battery system. These scenarios were created by varying three parameters: the number of household residents, the installed PV capacity, and the orientation of the PV installation.

For the Marstek C, the results indicate that the average operating power level is the dominant factor influencing the SPI. Since lower charging and discharging powers are associated with lower efficiencies, scenarios with higher average power flows generally result in improved SPI values. Increasing the number of residents

PV Orientation	Marstek C			Anker		
	East	South	West	East	South	West
1 Person, 0.8 kWp PV	51.0	52.8	46.0	56.0	59.4	49.3
2 People, 0.8 kWp PV	54.0	56.9	51.2	56.5	60.3	51.6
1 Person, 1.6 kWp PV	67.1	70.8	63.2	71.6	75.1	67.8
2 People, 1.6 kWp PV	67.9	69.4	64.3	71.1	72.8	66.5

TABLE 4.6: SPI values [%] of the two battery systems for different residential operating scenarios.

increases the average household consumption, which in turn increases the average battery discharge power. Similarly, increasing the PV installation size results in higher average charging powers.

However, the influence of these parameters is not always straightforward. For example, increasing the number of residents from one to two in a household with a 1.6 kWp PV installation does not result in a substantial change in SPI. Although the larger household consumption increases the average discharge power, it simultaneously reduces the amount of excess PV generation available for charging the battery, thereby decreasing the average charging power. These two effects partially compensate each other.

For the Anker system, the SPI was calculated under the same operating conditions as the Marstek C, namely AC charging and AC discharging. The operating mode in which the Anker is charged directly from PV power was not considered, as this configuration is not adequately supported by the simulation software and therefore cannot be represented accurately in the reference case. Consequently, an SPI value for the DC-charged Anker configuration could not be determined.

The SPI trends observed for the Anker are similar to those of the Marstek C, indicating that the average operating power level is also a dominant factor influencing system performance. Scenarios with higher average charging and discharging powers generally result in higher SPI values due to the improved efficiencies achieved at these operating points. Due to the higher RTE of the Anker, the system consistently achieves SPI values that are approximately 4 % higher than those of the Marstek C under comparable conditions. This demonstrates that the better conversion efficiency of the Anker translates directly into improved annual system performance.

4.5 Cost Effectiveness

The simulations presented in the previous section also provide detailed information on the energy flows occurring throughout the one-year simulation period. From these results, the reduction in grid electricity consumption, the decrease in PV energy injection into the grid and the change in average monthly peak power can be determined. These quantities form the basis for evaluating the economic performance of the tested battery systems.

The economic analysis is performed for the scenarios with south-facing PV panels, as this orientation yielded the highest SPI values for the considered households. Based on the calculated annual savings, the net present value (NPV) and PBP are determined to assess whether the battery systems are capable of recovering their initial investment within the ten-year warranty period.

For the NPV calculation, standard Belgian baseline assumptions are adopted, namely a discount rate of $r = 3 \%$ and an inflation rate of $e = 2 \%$. The electricity prices used in the analysis are based on a fixed electricity contract from Eneco. These prices are equal to 0.287 €/kWh for daytime consumption, 0.257 €/kWh for nighttime and weekend consumption, and -0.038 €/kWh for both daytime and nighttime/weekend grid injection. These values include all variable electricity-related costs, such as energy costs, distribution tariffs and taxes. Fixed subscription fees and data management costs are excluded, as they are independent of the amount of electricity consumed. The capacity tariff is assumed to be 51.99 €/kW per year.

The daytime and nighttime consumption tariffs are averaged when calculating the cost savings associated with reduced grid consumption. An example of the annual savings and NPV calculation is provided in Equation 4.3 for the Anker battery in the scenario consisting of a one-person household with a 1.6 kWp PV installation. The resulting NPV and PBP values for all simulated scenarios are summarized in Table 4.7.

$$Consumption = \frac{0.287 \text{ €/kWh} + 0.257 \text{ €/kWh}}{2} \cdot 338 \text{ kWh} = 91.93 \text{ €}$$

$$Injection = -0.038 \text{ €/kWh} \cdot 642 \text{ kWh} = -24.40 \text{ €}$$

$$PeakPower = 51.99 \text{ €/kW} \cdot (1.941 \text{ kW} - 1.650 \text{ kW}) = 0 \text{ €} \text{ (below } 2.5 \text{ kW)}$$

$$Savings = Consumption + Injection + PeakPower = 91.93 \text{ €} - 24.40 \text{ €} + 0 \text{ €} = 67.53 \text{ €}$$

$$NPV = -Cost + \sum_{t=1}^{10} \frac{Savings \cdot (1+e)^t}{(1+r)^t} = -1100 \text{ €} + \sum_{t=1}^{10} \frac{67.53 \text{ €} \cdot 1.02^t}{1.03^t} = -458.98 \text{ €} \quad (4.3)$$

None of the investigated small-household scenarios achieve an PBP below ten years, indicating that the tested battery systems are not yet economically attractive since their software and hardware are not yet optimized for these applications under the assumed conditions. The lowest PBP is obtained by the Anker battery in the two-person household with a 1.6 kWp PV installation, resulting in an PBP of 11.73 years.

The simulation results do, however, illustrate an important trend that can significantly improve the economic viability of these plug & play battery systems. If both the household electricity consumption and size of the PV installation increase then

the PBP will decrease. This trend is consistent with the SPI results discussed previously, where higher average operating powers generally resulted in better system performance.

A further reason why the PBP improves in larger households is the higher utilization of the battery system. Larger PV installations increase the likelihood that the battery reaches full charge before sunset, meaning that the battery can operate at its full usable capacity on a greater number of days throughout the year. This results in a larger reduction in grid electricity consumption and therefore higher annual savings.

In addition, the higher electricity demand of larger households increases the probability that the battery will be fully discharged before the next sunrise. As a result, a larger fraction of the available storage capacity is effectively utilized, improving the economic return on the battery investment.

Finally, larger households are more likely to experience monthly peak power demands above the Belgian capacity tariff threshold of 2.5 kW. In these situations, the battery can provide additional financial benefits through peak shaving by reducing the household's peak power demand. For smaller households, where monthly peak powers often remain below 2.5 kW, reducing these peaks does not generate additional savings because the minimum billable capacity tariff is already applied at the 2.5 kW level. Consequently, the economic value of peak shaving is significantly greater in larger households.

To investigate this effect further, two additional large-household scenarios were simulated. The first scenario uses the original PerMod residential load profile, corresponding to an annual electricity consumption of 5010 kWh/a, combined with a 5 kWp PV installation. The second scenario uses an alternative load profile included in the PerMod database, representing a large household equipped with both an electric vehicle and a heat pump. This profile has an annual electricity consumption of 9363 kWh/a and a temporal resolution of one second [27]. A 10 kWp PV installation is assumed for this household.

The resulting SPI, NPV and PBP values for both the Marstek C and the Anker battery systems are presented in Table 4.8. In contrast to the smaller household scenarios, all large-household configurations achieve a PBP below ten years, indicating that the batteries are capable of recovering their initial investment within the warranty period. The most favorable result is obtained for the Anker battery in the household with an annual consumption of 9363 kWh/a and a 10 kWp PV installation, where the PBP decreases to 7.59 years.

Another way to achieve a lower PBP is through the adoption of newer generations of plug & play batteries. In the short period since the Marstek C and Anker systems were purchased, several new products have entered the market that offer comparable storage capacities at significantly lower prices. This rapid decline in battery prices has the potential to substantially improve the economic viability of plug & play battery systems.

Taking Marstek as an example, because it currently offers one of the largest product portfolios in the plug & play battery market, two recently introduced bat-

tery systems with capacities around 2.5 kWh can be identified: the Venus D and the B2500-D. The main characteristics of these systems are summarized in Table 4.9.

The Venus D is conceptually similar to the Anker, as both are AC+DC batteries with integrated support for direct PV connections. However, the Venus D is available at half the purchase price of the Anker while offering a comparable usable storage capacity. This significant reduction in investment cost can considerably shorten the PBP, even if the technical performance remains similar.

The B2500-D follows a different design philosophy since it is a DC plug & play battery. Unlike AC-coupled systems, it does not contain an integrated microinverter and therefore does not perform any DC-to-AC power conversion internally. Instead, it is intended to operate together with plug & play PV panels and an external microinverter. As a result, the battery itself only performs battery-related power conversion functions, reducing component costs and avoiding part of the conversion losses associated with integrated inverter systems. Consequently, DC batteries generally offer both lower purchase prices and potentially higher system efficiencies than comparable AC-coupled alternatives.

The availability of these newer battery systems demonstrates that the economic attractiveness of plug & play batteries is improving rapidly. Although the tested Marstek C and Anker systems do not achieve an PBP below ten years in the considered small-household scenarios with their current configurations, their economic performance is already approaching this threshold. Continued reductions in battery prices, combined with further hardware and software optimizations such as those discussed in Chapter 5, are expected to further improve both the technical performance and economic viability of these systems. As a result, future generations of plug & play batteries may become financially attractive even for households with relatively low electricity consumption and modest PV installations.

As mentioned previously, the Master's thesis that will be conducted by Wannes Thierens will investigate the economic performance of plug & play battery systems in greater detail. That work will evaluate advanced control strategies and will employ more comprehensive and accurate simulation models to determine the achievable PBP under a wider range of operating conditions.

The economic analysis presented in this thesis is therefore intended as a preliminary assessment. Its objective is to determine whether currently available plug & play batteries can achieve an PBP below ten years when operated using relatively simple control strategies and without the implementation of additional optimization techniques. This provides an initial indication of their economic viability and establishes a baseline against which future optimization approaches can be evaluated.

4.6. Hands-on Implementation in a Large Household

	Marstek C		Anker	
	NPV [€]	PBP [a]	NPV [€]	PBP [a]
1 Person, 0.8 kWp PV	-849.64	53.81	-693.15	29.67
2 People, 0.8 kWp PV	-869.88	60.23	-725.53	32.69
1 Person, 1.6 kWp PV	-600.76	23.49	-458.98	17.81
2 People, 1.6 kWp PV	-441.90	17.31	-154.58	11.73

TABLE 4.7: NPV and PBP results of the tested battery systems in small households.

	Marstek C			Anker		
	SPI [%]	NPV [€]	PBP [a]	SPI [%]	NPV [€]	PBP [a]
5010 kWh/a, 5 kWp PV	83.4	38.06	9.65	83.9	204.18	8.37
9363 kWh/a, 10 kWp PV	87.9	257.55	8.03	88.1	332.15	7.59

TABLE 4.8: SPI, NPV and PBP results of the tested battery systems in large households.

	Venus D	B2500-D
AC Grid Power Limit [kW]	2.5	0.8 (2 x 0.4)
DC PV Power Input Limit [kW]	4 (4 x 1)	1.6 (2 x 0.8)
Capacity [kWh]	2.560	2.240
Battery Type	AC+DC	DC
Price [€]	550	360
Depth of Discharge (DoD) [%]	90	90
Usable Capacity [kWh]	2.304	2.016

TABLE 4.9: Characteristics of the newer plug & play batteries from the brand Marstek.

4.6 Hands-on Implementation in a Large Household

4.6.1 Installation and Registration

During the making of this thesis, an opportunity arose at the end of March to implement a battery system in a large Belgian household. The residence consists of seven occupants, is connected to a three-phase AC installation and is equipped with a 10 kWp PV installation and an 8 kW non-hybrid inverter. The primary objective of the household was to increase self-consumption by storing excess PV generation in a battery system with a sufficiently low investment cost to achieve a PBP in less than ten years.

An analysis of the smart meter data from the previous year indicated that a battery system with approximately 10 kWh of storage capacity and 5 kW of power capability would provide a suitable balance between storage capacity and house-

4. MEASUREMENTS AND RESULTS

Product	Price per Product [€]	Amount	Total Price [€]
Marstek Venus E	1137.5	2	2275
10 m BC01 Cable	40.5	2	81
P1 Splitter	9	1	9
Total			2365

TABLE 4.10: Price breakdown of the plug & play battery installation for the large household.

hold demand. This sizing was based on the observation that the average electricity consumption between sunset and sunrise during the spring, summer and autumn seasons was approximately 10 kWh. In addition, the highest measured power peaks were around 5 kW.

A battery system with these characteristics would therefore be capable of supplying most of the overnight electricity demand while also significantly reducing peak power consumption. A 5 kW battery can reduce the household peak demand to below the 2.5 kW capacity tariff threshold during many peak events while simultaneously offsetting nearly all nighttime electricity consumption during periods with sufficient stored energy.

For further clarification, the total electricity exchanged by the household over the past year before any batteries were installed consisted of 1720 kWh of daytime consumption and 2664 kWh of night/weekend consumption. The amount of energy the household exported was 5944 kWh during the day and 2317 kWh during night/weekend periods. And the average monthly peak power was 4.97 kW.

After evaluating several conventional home battery systems and plug & play battery systems, the selected solution consisted of two Marstek Venus E 3.0 batteries, hereafter referred to as the Marstek E. Similar to the previously tested Marstek Venus C 1.0, the Marstek E is an AC-coupled plug & play battery system, although it represents a newer generation with improved efficiencies and enhanced software functionality. The physical outdoor installation of the batteries is shown in Figure 4.9. The batteries were installed in a corner against the north-facing wall of the building, ensuring that they are never exposed to direct sunlight. Although the maximum allowed operating temperature of these batteries is 55°C, direct solar exposure would in principle not cause operational issues. However, it could lead to increased internal temperatures and consequently a reduction in overall efficiency.

Each battery has a nominal capacity of 5.12 kWh, corresponding to an effective usable capacity of 4.506 kWh when accounting for the 88 % DoD and a rated power of 2.5 kW. The complete installation therefore provides a total usable capacity of 9.012 kWh and a combined power capability of 5 kW.

The total investment cost of the installation, including VAT and shipping costs, amounted to 2365 € (231 €/kWh). A detailed price breakdown is provided in Table 4.10. The additional cables were purchased to allow outdoor placement of the batteries.



FIGURE 4.9: Physical implementation of the two Marstek E batteries installed outside the household.

Product	Price per Product [€]	Amount	Total Price [€]
Growatt APX10.0P Battery	2336	1	2336
Growatt SYN-50-XH-10 Inverter	172	1	172
Installation Costs	1000	1	1000
AREI Registration	200	1	200
Total			3708

TABLE 4.11: Example price breakdown of a conventional home battery installation for a large household.

Two main factors motivated the selection of a plug & play battery system instead of a conventional home battery installation. First, the overall investment cost was substantially lower. A conventional home battery installation would have required either replacement of the existing non-hybrid inverter with a hybrid variant or installation of an additional battery inverter. Furthermore, plug & play batteries do not require installation by a certified electrician or mandatory AREI inspection costs, resulting in an additional cost reduction of approximately 1000 €. An example cost estimation for a comparable conventional battery installation is shown in Table 4.11.

The estimated cost of the conventional installation amounts to 3708 € (370.8 €/kWh),

which is significantly lower than the previously reported average value of approximately 1000 €/kWh in [6]. This further illustrates the substantial decrease in battery prices in recent years. Nevertheless, the conventional solution remains approximately 60 % more expensive than the plug & play alternative, primarily due to installation-related costs. As a consequence, achieving a PBP within the typical ten-year warranty period becomes considerably more difficult for conventional battery systems, despite their generally higher efficiencies.

The second major advantage of the plug & play solution is the regulatory flexibility regarding multiple battery installations. Belgian regulations currently permit the installation of multiple 2.5 kW plug & play batteries within the same household, provided that each battery is connected to a separate electrical circuit to remain below the 2.6 kW limit per socket group, that the devices are registered through the Fluvius platform for systems above 0.8 kW and that the batteries are included on the Synergrid homologation list.

The legality of this installation was further confirmed by the official Fluvius approval process. Following online registration and an administrative waiting period of approximately 1.5 months, the installation was fully approved without requiring additional inspections or modifications by a certified electrician. The batteries could already be operated during this waiting period. Figure 4.10 shows the approved registration of the installation together with the battery specifications listed on the Fluvius platform, demonstrating that Fluvius was fully aware of the installed battery capacities and power ratings during the approval process.

4.6. Hands-on Implementation in a Large Household

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☐	Installation	Installation number	Power	Date of commissioning	Competence	
☐	 Plug-and-play (in the socket) [Redacted]	[Redacted]	5 kVA	29/03/2026	Owner	Details
● Active						
☐	 Solar energy [Redacted]	[Redacted]	8 kVA	23/12/2020	Owner	Details
● Active						

(A) Confirmed registration of the plug & play batteries

 **Plug-and-play (in the socket)**
Installation number [Redacted]

General **Technical data** Users

Battery	
Total capacity	10,24 kWh
< >	
Date of commissioning	29/03/2026
Make	Marstek
Model	Venus E 3.0
Capacity	5,12 kWh

Inverters	
Total power	5,00 kVA
< >	
Make	MARSTEK
Model	MST-BIE5-2500
Power	2,50 kVA
Hybrid	No

(B) Characteristics of the plug & play batteries

FIGURE 4.10: Fluvius registration platform showing the approved plug & play battery installation together with the registered battery characteristics (black boxes added for privacy).

4.6.2 Behavior and Performance

After installation of the batteries, initial tests were performed using a HomeWizard P1 device to communicate smart meter information to the battery systems. However, after several hours of operation, undesirable behavior was observed. In situations where the household load was 1 kW, one battery discharged at 2 kW while the second battery simultaneously charged at 1 kW. Although the net power measured by the smart meter remained close to 0 kW, this operating mode introduced unnecessary conversion losses. This behavior occurred even when the batteries were connected to separate phases.

To resolve this issue, the HomeWizard P1 device was replaced with the Marstek P1 device supplied with the batteries. Following this simple modification, the undesired charging and discharging interactions were no longer observed during the subsequent two months of operation. The results therefore suggest that the manufacturer-provided P1 device should preferably be used to ensure correct battery coordination and control behavior. To retain the monitoring functionality of the HomeWizard application, a P1 splitter was installed so that both the Marstek and HomeWizard devices could simultaneously access the smart meter data.

To evaluate the practical impact of the battery system, smart meter data from the same date in 2025 and 2026 were compared, as shown in Figure 4.11. The comparison demonstrates that grid consumption (purple values) was almost entirely eliminated due to the batteries storing sufficient energy during the daytime to supply the household throughout the night. A small residual grid consumption of approximately 0.2 kWh to 0.4 kWh remained due to imperfect tracking of household load and PV injection.

The final two subfigures in Figure 4.11 illustrate the operating behavior of both batteries throughout the day. In most operating conditions, the batteries shared the charging and discharging power that was needed for the household. At low power levels (below approximately 0.2 kW), however, only a single battery remained active while the second battery stayed idle. This operating strategy is beneficial because battery efficiencies at very low power levels are reduced, as demonstrated previously. Operating one battery at for example 0.1 kW is therefore more efficient than operating two batteries simultaneously at 0.05 kW each.

The batteries remained operational throughout April and May, allowing a direct comparison between the smart meter data of these months and the corresponding months from the previous year. As shown in Table 4.12, grid consumption decreased substantially due to the increased self-consumption enabled by the batteries. Grid injection was also reduced because part of the excess PV energy was stored locally instead of being exported to the grid. In addition, the peak power demand decreased because the batteries supplied part of the household demand during peak load periods.

The household operates under a fixed electricity contract with Eneco. This means that the same electricity prices used in section 4.5 can also be applied here. So these electricity prices amounted to 0.287 €/kWh for daytime consumption, 0.257 €/kWh for nighttime consumption, -0.038 €/kWh for both daytime and

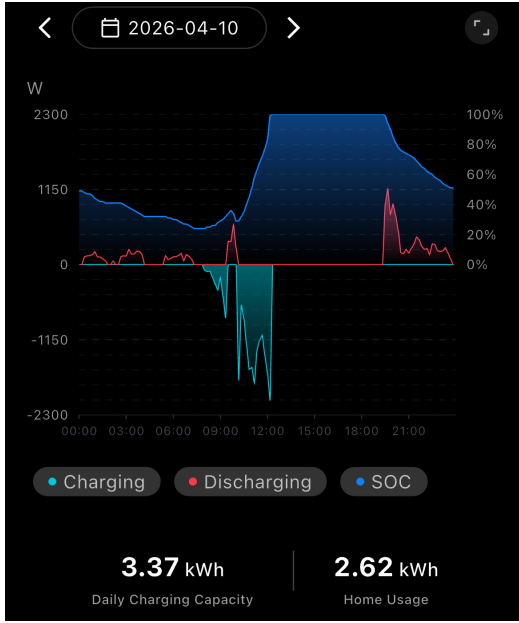
4.6. Hands-on Implementation in a Large Household



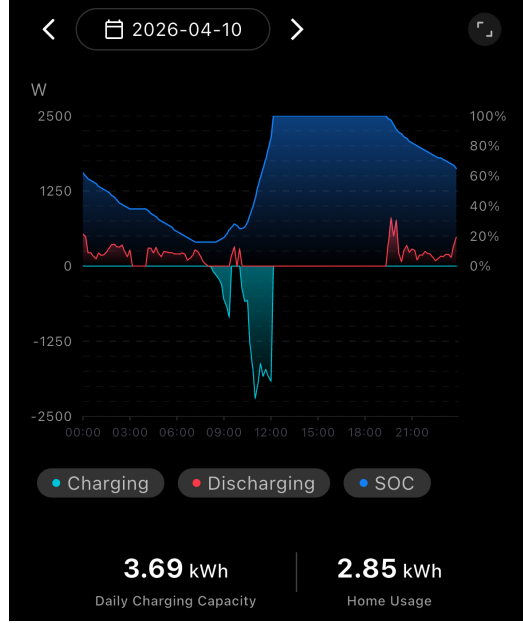
(A) Consumption profile on 10 April 2025



(B) Consumption profile on 10 April 2026



(C) Operating power and SoC of the first battery



(D) Operating power and SoC of the second battery

FIGURE 4.11: Consumption profiles (purple = grid consumption, green = grid injection) on 10 April 2025 (without batteries) and 10 April 2026 (with batteries), together with the operating statistics of both batteries.

Month	Grid Consumption [kWh]	Grid Injection [kWh]	Peak Power [kW]
April 2025	237.771	1122.783	5.022
May 2025	245.201	1434.203	5.075
April 2026	24.907	989.141	3.330
May 2026	49.489	909.466	2.555

TABLE 4.12: Grid consumption, grid injection, and peak power during April and May in 2025 (without batteries) and 2026 (with batteries).

nighttime injection and 51.99 €/kW annually for the capacity tariff for peak power consumption.

Using these tariffs together with the smart meter measurements from April and May, the total financial savings achieved by the battery system can be calculated as shown in Equation 4.4. The resulting calculations indicate that the battery installation generated total savings of approximately 104.36 € during these two months.

$$\begin{aligned} Consumption &= 0.272 \text{ €/kWh} \cdot (237.771 \text{ kWh} + 245.201 \text{ kWh} - 24.907 \text{ kWh} - 49.489 \text{ kWh}) \\ &= 111.13 \text{ €} \end{aligned}$$

$$\begin{aligned} Injection &= -0.038 \text{ €/kWh} \cdot (1122.783 \text{ kWh} + 1434.203 \text{ kWh} - 989.141 \text{ kWh} - 909.466 \text{ kWh}) \\ &= -25.02 \text{ €} \end{aligned}$$

$$\begin{aligned} PeakPower &= \frac{51.99 \text{ €/kW}}{12} \cdot (5.022 \text{ kW} + 5.075 \text{ kW} - 3.330 \text{ kW} - 2.555 \text{ kW}) \\ &= 18.25 \text{ €} \end{aligned}$$

$$\begin{aligned} Savings &= Consumption + Injection + PeakPower = 111.13 \text{ €} - 25.02 \text{ €} + 18.25 \text{ €} \\ &= 104.36 \text{ €} \end{aligned} \tag{4.4}$$

To estimate the NPV and PBP of the battery installation, smart meter data from April 2025 to March 2026, corresponding to the full year before the battery systems were installed, was analyzed. For each day, both the grid energy consumption and the excess PV energy injected into the grid were evaluated to determine the potential utilization of the battery systems.

The daily grid energy consumption was divided by 8.250 kWh, corresponding to the usable AC energy that the batteries can deliver after accounting for discharge losses. This yields the fraction of a full battery discharge cycle that could have been utilized on that day. Similarly, the daily excess PV energy injection was divided by 10.178 kWh, representing the AC energy required to fully charge the batteries when charging losses are taken into account. This yields the fraction of a full battery charge cycle that could have been achieved on that day. Since it is assumed that the batteries can perform at most one full charge and one full discharge per day, these values should be interpreted as the achievable fraction of a full cycle.

The lower of these two values was then selected, as it determines the actual battery utilization for that day. Example days illustrating the calculation of the corresponding battery utilization are provided below:

- Day 1: 5 kWh consumption, 15 kWh injection → 61 % discharge, 100 % charge → limited consumption causes batteries to be only used for 61 %.

- Day 2: 15 kWh consumption, 5 kWh injection → 100 % discharge, 49 % charge → Limited PV production causes batteries to be only used for 49 %.
- Day 3: 15 kWh consumption, 15 kWh injection → 100 % discharge, 100 % charge → Batteries are fully utilized on this day.

Applying this procedure to all 365 days of smart meter data yields a cumulative battery utilization equivalent to 259 full cycles over the course of a year. This corresponds to an average daily utilization of approximately 71 % of the usable battery capacity. Since the battery systems are assumed to perform at most one charge-discharge cycle per day, this result can be interpreted as the batteries being fully utilized for 259 days per year, while remaining effectively unused for the remaining 106 days.

This corresponds to approximately 8.63 months of full utilization annually. To obtain a more conservative estimate in the economic analysis, however, only 8 months of full battery utilization per year are assumed.

With these findings, the annual savings amount to $104.36 \text{ €} \cdot 4 = 417.44 \text{ €}$. Applying the same NPV and PBP formulations as presented in Section 4.5, with the same discount rate of $r = 3 \%$ and inflation rate of $e = 2 \%$, results in $NPV = 1592.86 \text{ €}$ and $PBP = 5.86 \text{ a}$. These results demonstrate that this battery installation achieves a PBP of less than ten years.

Measurement Tests

Three additional measurement tests were performed on the installed Marstek E batteries. The first test evaluated the deviation between the AC power values measured by the Marstek E and the household smart meter. The resulting deviations are shown in Figure 4.12. The largest deviations occurred at low power levels, where the error approached approximately 3 %. The weighted average deviation over the tested operating range was approximately 0.7 %.

A second test focused on the standby losses of the battery system. A single Marstek E battery exhibited a baseline standby consumption of 9 W. However, the battery software allows several non-essential features, such as Bluetooth communication and status LEDs, to be disabled. By disabling these features, the standby consumption decreased to 7 W.

The final test investigated the conversion efficiencies of the Marstek E. Unlike the previously tested batteries, the Marstek E provides internal DC measurements directly from the battery terminals. This enables the simultaneous monitoring of AC-side and DC-side power values, allowing approximate efficiency calculations to be performed continuously. However, these calculations require an assumed value for η_{battery} . In this work, a value of 93.20 % was used, corresponding to the weighted average battery efficiency measured for the Anker. The accuracy of the internal DC measurements is unknown, and therefore the obtained efficiencies should be interpreted as indicative rather than fully validated values.

The resulting efficiencies are summarized in Table 4.13, with the RTE of the Marstek C included alongside for easier comparison between the two devices. How-

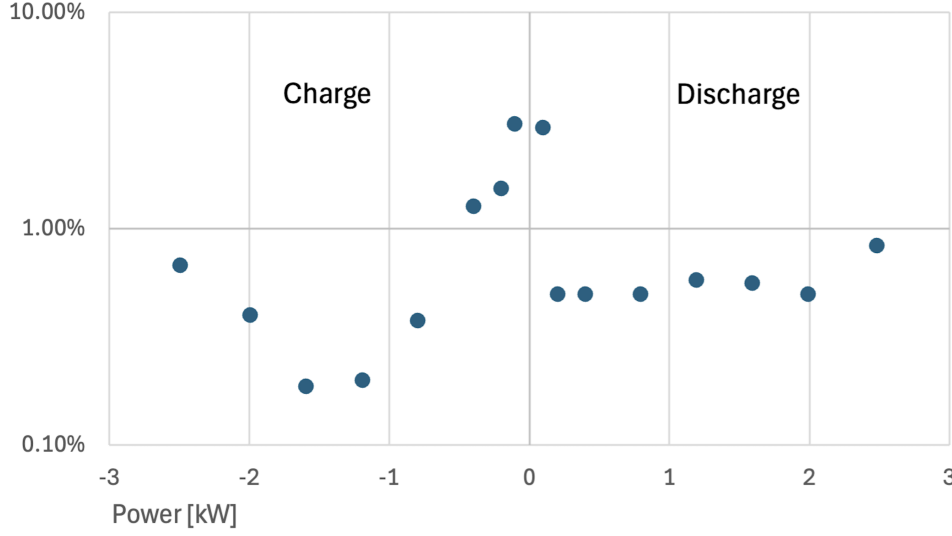


FIGURE 4.12: Measurement deviations of the Marstek E relative to the smart meter.

ever, it should be noted that the two systems were measured using different instruments, and therefore their respective maximum measurement errors are not identical. Figure 4.13 compares the values of the Marstek E with those of the previously tested plug & play battery systems. The Marstek E achieves a weighted average RTE of 73.88 %, representing an improvement of approximately 2.95 % compared to the Marstek C. Under identical operating conditions (AC charging and AC discharging), its efficiencies are 1.34 % lower than those of the Anker system. These results indicate that the newer generation Marstek E incorporates slightly more efficient internal power electronics with reduced conversion losses, giving it a performance that is almost similar to that of the Anker system, which also uses a more optimized power conversion architecture.

The low charging efficiencies at very low power levels that were previously observed for the Marstek C are however still present in the Marstek E. Charging powers below approximately 0.06 kW again resulted in 0 % charging efficiency, meaning that very small excess PV powers are entirely dissipated as conversion losses. In practice, however, this limitation is less problematic in the investigated household because the large 10 kWp PV installation generally produces sufficiently high excess power levels. Furthermore, at low excess powers only one battery remains active while the second battery stays idle, thereby reducing the impact of low-power inefficiencies. Only once the excess PV power exceeds approximately 0.2 kW is the charging power distributed between both batteries.

Power [kW]	Marstek E			Marstek C
	$\eta_{ACcharge}$ [%]	$\eta_{ACdischarge}$ [%]	RTE [%]	RTE [%]
0.05	0	67.57	0	0
0.1	68.32	81.97	50.15	27.38
0.2	79.90	87.28	62.46	57.36
0.4	88.44	91.72	72.66	70.69
0.8	92.60	93.88	77.86	76.68
1.2	93.72	94.17	79.05	77.48
1.6	94.10	94.38	79.55	77.18
2	93.83	94.06	79.04	76.66
2.5	93.50	93.72	78.49	73.70
Average	88.54	91.54	73.88	70.93

TABLE 4.13: Measured efficiencies of the Marstek E and Marstek C batteries.

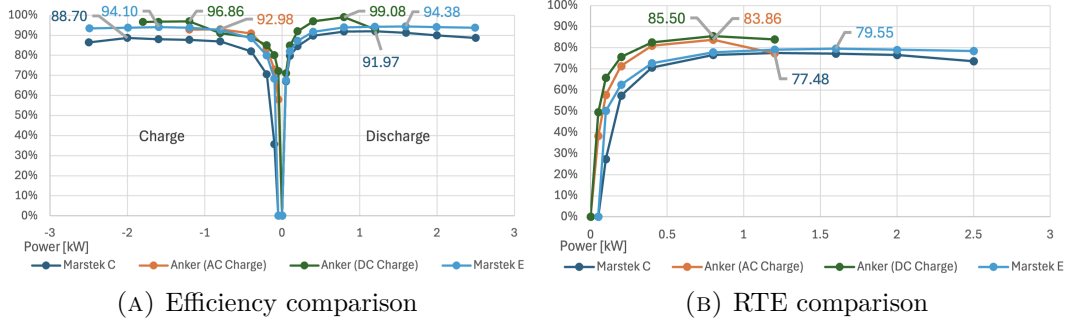


FIGURE 4.13: Efficiency and round-trip efficiency comparison between the Marstek E and the previously tested battery systems with all peak values labeled.

4.7 Conclusion

This chapter presented the laboratory characterization, cost effectiveness calculations, simulation analysis and real-world implementation results of residential plug & play battery systems. The performed measurements demonstrated that the investigated batteries are capable of significantly increasing residential self-consumption while reducing grid consumption, grid injection, and peak power demand.

The laboratory measurements showed that the efficiencies of plug & play batteries strongly depend on their internal architecture and operating power levels. The AC+DC coupled Anker system achieved higher round-trip efficiencies than the AC-coupled Marstek systems due to the reduced number of energy conversion stages and use of more efficient electronics. In contrast, the AC-only battery systems experienced noticeably lower efficiencies at low charging powers because of conversion startup losses. The measurements also highlighted the importance of standby consumption, measurement accuracy and control response time, as these factors directly influence the practical performance of the battery systems in residential operation.

The cost effectiveness analysis shows that plug & play battery systems can already deliver measurable economic benefits under typical Belgian residential conditions by reducing grid consumption, limiting PV injection and lowering peak power demand. However, the results also indicate that, under the assumed electricity prices, load profiles and control strategies, none of the tested small-household configurations achieve a payback period within the ten-year warranty period. Economic performance is strongly dependent on the average operating power level, with higher consumption and larger PV installations significantly improving profitability due to more favorable utilization of the battery capacity. For larger household scenarios, the systems do reach an PBP below ten years, demonstrating that these technologies become increasingly viable as energy demand and PV capacity increase. In addition, the analysis highlights that continued reductions in battery costs and further improvements in control strategies are likely to be decisive factors for achieving widespread economic viability in smaller residential applications.

The PerMod simulations demonstrated that the effective performance of plug & play batteries depends not only on their measured efficiencies, but also on the interaction between household consumption, PV production profiles and battery operating behavior. Higher average operating powers generally resulted in improved SPI values because low-power operating conditions, which are associated with lower efficiencies, occurred less frequently.

The real-world implementation in a large Belgian household further confirmed the practical viability of plug & play battery systems and proves that they are not only useful for small households. The installed Marstek E batteries substantially reduced electricity consumption from the grid and lowered peak power demand while achieving these results at a significantly lower investment cost compared to conventional home battery systems. The installation also demonstrated that current Belgian regulations allow relatively large plug & play battery capacities to be deployed without requiring major electrical modifications, provided that the applicable registration and installation conditions are respected.

Overall, the results indicate that plug & play batteries already provide a technically feasible and economically promising solution for increasing residential self-consumption in Belgium, particularly because they eliminate installation costs and because of the rapidly decreasing prices of battery systems. At the same time, the measurements identified several technical limitations and optimization opportunities related to conversion efficiencies, low-power operation, control behavior and software functionality. These findings form the basis for the optimization strategies and economic analyses discussed in the following chapter.

Chapter 5

Optimal Design and Operations

This chapter investigates how plug & play battery systems can be further improved beyond their current commercial implementations by analyzing both hardware architectures and software control strategies. While previous chapters focused on measured performance and real-world behavior of existing systems, this chapter shifts the focus toward optimization potential and design choices that influence efficiency, flexibility and economic performance.

The first part of this chapter addresses hardware-related optimization, including the role of DC coupling, inverter constraints, system architecture and also introduces new concepts such as residential low-voltage DC microgrids. Different plug & play battery topologies are compared in terms of efficiency, cost implications and operational limitations, with particular attention to how power electronics and energy conversion stages influence overall system performance.

The second part focuses on software and control strategies. Existing operating modes such as self-consumption optimization, dynamic tariff operation and hybrid “smart” modes are evaluated, followed by a discussion of additional control improvements that are not typically implemented in manufacturer software. These include minimum power thresholds, peak shaving strategies and the potential role of external energy management platforms in extending system functionality. Together, these aspects provide a structured overview of how both hardware and software choices can significantly affect the real-world performance of plug & play battery systems.

5.1 Hardware

A key aspect in the optimization of plug & play battery system hardware is the use of DC connections. In the Anker system, for example, the availability of PV input ports increases the weighted average RTE by 3.55 % compared to its equivalent AC-only charging configuration. This improvement is mainly explained by the avoidance of multiple conversion stages: without DC inputs, PV energy would first be converted from DC to AC by the microinverter and subsequently converted back to DC for

battery charging. Direct DC coupling eliminates these intermediate conversion steps and therefore reduces conversion losses.

However, AC+DC hybrid systems can also introduce a fundamental limitation related to power matching between PV input and AC output capability. In the case of the Anker, the maximum AC output power is 1.2 kW, while up to 3.6 kW of PV input levels are possible. When the household load exceeds the inverter’s AC output limit, the system cannot fully exploit the available PV generation. For instance, in a scenario where both PV generation and household demand are 2.4 kW, a separate 2.4 kW PV inverter would be able to fully supply the load, whereas the Anker system can only provide up to 1.2 kW of AC power. As a result, the PV operating point is shifted away from its maximum power point, meaning that MPPT is partially lost and the remaining potential PV production is effectively curtailed. A similar effect occurs when the battery is fully charged and PV production exceeds the 1.2 kW inverter limit, leading to clipped energy that could otherwise contribute to grid injection compensation.

A second architecture is the DC plug & play battery. In this configuration, the battery is connected directly to plug & play PV panels on the input side and to an external microinverter on the output side. The battery itself performs no DC-to-AC conversion, which shifts this function entirely to the external inverter. In principle, this configuration yields the highest efficiency of the three plug & play architectures, since both internal conversion stages and associated losses are minimized. However, the overall system efficiency becomes dependent on the efficiency of the external microinverter. The same power mismatch limitations described above also apply in this configuration. An additional limitation is the inability of these systems to charge directly from the AC grid, which prevents their use in applications involving dynamic electricity pricing (e.g. charging during low-price periods and discharging during high-price periods). In return, DC systems are typically expected to have lower hardware complexity and therefore lower cost.

From a system design perspective, AC plug & play batteries are most suitable in situations where no plug & play PV panels are used, for example when a household already has a dedicated PV installation with its own inverter, or when the battery is exclusively used for dynamic electricity tariffs. In contrast, DC batteries are most suitable when plug & play PV panels and a microinverter are already part of the system or are intended to be bought, provided that dynamic tariff operation is not required. For households that want flexibility between plug & play PV integration and tariff-based energy shifting, AC+DC hybrid systems remain the most versatile solution.

A more fundamental hardware-level optimization concept is the introduction of low-voltage DC microgrids within residential environments. In such a concept, both batteries and major household appliances would be equipped with standardized DC interfaces (e.g. 48 V DC). Appliances such as heat pumps, refrigerators, air conditioners and electric vehicle chargers could then be supplied directly from DC, reducing the need for repeated AC/DC conversion stages. This would improve overall system efficiency not only at the battery level but also at the appliance level, thereby reducing total household energy consumption. When battery capacity is



FIGURE 5.1: Example of a power station supporting DC output ports.

insufficient, the system could seamlessly revert to conventional AC supply.

Some modern power stations already implement DC output functionality using standardized connectors such as 5525, XT60 or USB PD, with adjustable DC voltage levels depending on the connected load. An example of such a system is the Pecron F5000LFP, which provides dedicated DC output ports as shown in Figure 5.1.

If, in the future, regulations allow the implementation of such low-voltage DC microgrids in residential buildings and household appliances are equipped with standardized DC input interfaces, direct energy transfer between batteries and end-use devices could become possible. In such a setup, users would simply connect the battery to the appliance using a standardized DC cable. Because the system operates at a low voltage level (e.g. 48 V DC), it is considered safe for residential use and thus still maintains a plug & play character, provided that appropriate safety standards and protections are implemented.

Finally, a straightforward but important hardware optimization is the use of higher-quality internal power electronics. This is clearly demonstrated by the difference in measured performance between systems: the Anker achieves an 4.29 % higher RTE than the Marstek C under identical operating conditions. This highlights that, beyond architectural choices, the quality and efficiency of internal conversion hardware remain a critical factor in overall system performance.

5.2 Software

The tested battery systems offer several control modes with different optimization objectives. A commonly used mode is self-consumption mode, which aims to keep the power measured at the smart meter close to 0 kW. In this mode, the battery charges when there is excess PV production (grid injection) and discharges when household demand is drawn from the grid. Another available mode focuses on dynamic electricity pricing, in which the battery charges during periods of low electricity prices and discharges during high-price periods to reduce electricity costs. These price signals can be obtained from external market data sources such as Nord

Pool. A third mode, often referred to as smart mode, combines both strategies by dynamically switching between self-consumption optimization and price-based optimization depending on the operating conditions. For example, during winter periods with limited PV production, the system primarily operates in dynamic pricing mode, whereas during periods with sufficient PV generation it prioritizes self-consumption.

Despite the availability of these control strategies, two relevant optimizations are not explicitly implemented in the default software of the tested systems. The first is the introduction of minimum power thresholds. As shown in Section 4.3.1, battery efficiency decreases significantly at low power levels, with the Marstek C reaching 0 % efficiency below approximately 0.06 kW. By enforcing a minimum charging threshold (e.g. 0.1 kW), the system can avoid operating in inefficient regions. In practice, small PV surpluses below this threshold (e.g. 0.05 kW) would otherwise be dissipated through inefficient battery operation, whereas exporting this energy to the grid would still yield financial compensation. A similar minimum threshold could also be applied for discharging, although this may reduce the ability of the battery to compensate small household loads.

The second optimization relates to peak power limitation, also known as peak shaving. Electricity tariffs in Belgium include a capacity component based on the monthly peak power demand. Maintaining a reserve state of charge allows the battery to supply short-term high loads and thereby reduce these peaks. Even a reduction of 1 kW in the monthly peak power corresponds to a yearly saving of 51.99 € under the considered tariff structure. In the simulations presented in Section 4.5, it was frequently observed that batteries were fully depleted before the occurrence of the highest monthly peak, indicating that a reserved energy buffer could further improve cost performance, provided that peak events exceed the 2.5 kW threshold.

Although these optimizations are not always included in manufacturer-provided software, they can be implemented using third-party energy management systems such as Home Assistant. This platform can be deployed locally on hardware such as a dedicated computer or a Raspberry Pi and provides full user control over connected energy devices. Multiple user-friendly guides are available, making the system accessible to most users. Several community-developed integrations exist that enable advanced battery control strategies, including minimum charge and discharge power constraints, SoC prioritization and peak shaving functionality for both Marstek and Anker systems [28] [29] [30].

The use of such open-source solutions enables continuous improvement of battery control strategies. If more advanced optimization algorithms become available in the future, users can update their configurations accordingly, ensuring that the system can always operate using the most effective available control logic. This flexibility significantly increases the long-term adaptability and performance potential of plug & play battery systems.

5.3 Conclusion

This chapter has shown that both hardware architecture and software control strategies play a decisive role in the performance of plug & play battery systems. On the hardware side, DC coupling can significantly reduce conversion losses, while hybrid AC+DC systems introduce flexibility at the cost of potential power mismatch limitations. Fully DC-based systems offer high theoretical efficiency and lower cost potential but are constrained by their limited tariff flexibility. Newly introduced concepts such as residential DC microgrids represent a longer-term pathway toward further efficiency gains by reducing conversion losses across both storage systems and end-use devices.

On the software side, it was demonstrated that current manufacturer control strategies already provide functional operation for self-consumption and tariff optimization, but still leave room for improvement. In particular, minimum power thresholds and peak shaving strategies can meaningfully improve efficiency and economic performance under realistic operating conditions. The ability to implement such strategies through open-source platforms such as Home Assistant further expands the optimization potential beyond factory settings.

Overall, the results of this chapter indicate that significant performance gains are still achievable without changes to the core battery technology itself, but rather through improved system integration and smarter control strategies. This highlights that future advancements in plug & play battery systems will likely depend as much on software intelligence and system-level design as on improvements in battery hardware alone.

Chapter 6

Conclusion

This thesis has shown that plug & play battery systems are already a technically viable and practically relevant solution for residential energy storage in Belgium. The laboratory measurements demonstrated that battery performance depends strongly on the internal architecture of the system and on the operating power level. In particular, the AC+DC Anker system achieved a higher round-trip efficiency than the AC Marstek systems because it avoids one of the conversion stages associated with AC charging, while the Marstek C exhibited very poor efficiency at very low charging powers. These measurements also highlighted the importance of standby losses, measurement accuracy, response time and inverter behavior, all of which affect the real-world usability of the systems.

The simulation and economic analyses further showed that the profitability of plug & play batteries is strongly dependent on the household load profile, PV size and average operating power. Higher operating powers lead to better system performance because low-power regions, where efficiency is lower, occur less frequently and the battery is able to be utilized more. For the considered small-household scenarios, none of the tested systems achieved a payback period within ten years, although the results were already close to that threshold in the most favorable cases. In contrast, the large-household implementation confirmed that plug & play batteries can recover their investment within the warranty period when the system is appropriately sized. The real-world installation in a Belgian household also demonstrated a substantial reduction in grid consumption and peak power demand at a significantly lower investment cost than a conventional home battery system.

From a design perspective, the thesis identified several clear directions for future improvement. On the hardware side, DC coupling, higher-quality power electronics and in the longer term, low-voltage DC microgrids can further reduce conversion losses and improve system efficiency. On the software side, minimum power thresholds, peak shaving and more advanced control logic can improve both efficiency and economic performance. These improvements are particularly relevant for industrial development, because they show that future plug & play battery products do not necessarily need to become much more complex to become more attractive, in many cases can smarter control and more suitable sizing already be enough.

Looking ahead, several promising directions for future research can be identified. A more comprehensive economic analysis using representative household consumption profiles will be conducted by the end of this year by Wannes Thierens and will demonstrate that even smaller households can achieve an PBP of less than ten years when appropriate control strategies are applied. In addition, larger plug & play battery systems in the 5 kWh range merit further investigation, as they may deliver improved economic performance in medium-sized and larger households as was shown in the large household implementation. However, evaluating the characteristics of larger systems also requires more time and resources. Consequently, for a Master's thesis focusing on this battery size, it may be more appropriate to limit the analysis to a single system, in contrast to this work, which was only able to evaluate two smaller batteries. Another particularly interesting area of research is the development of residential low-voltage DC microgrids, in which both battery systems and major household appliances are equipped with standardized DC interfaces. Such developments could significantly expand the applicability of plug & play energy storage beyond small households and increase its attractiveness across a much broader segment of the residential market.

Overall, plug & play batteries represent a promising technology for supporting the electrification, decentralization and flexibility of residential energy systems. As battery prices continue to decrease and control strategies become more advanced, their technical and economic attractiveness is expected to improve even further in the coming years.

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For literature search	<i>Google Scholar Labs</i>	This use is comparable to e.g. a Google Scholar search. You do not have to refer to such kind of GenAI use; you only have to refer to the literature references you have checked and used (without such references you would be committing plagiarism and thus committing an irregularity). However, be careful: • Be aware that the search output is restricted to the database the GenAI tool is built on. After this initial search, look for scientific sources and conduct your own analysis of the source documents. Interpret, analyse and process the information you obtained; verify it and do not just copy-paste it as you should understand and critically process everything you are writing. • Be aware that some GenAI tools may output no or wrong references. As a student you are responsible for further checking and verifying the absence or correctness of references; do not just copy-paste it.
For generating programming code	<i>Claude</i>	Use of GenAI for coding is allowed except when it is prohibited by the teacher or the program of study. If used for coding, correctly mention the use of GenAI assistance in accordance with the instructions on the page on being transparent about the use of GenAI.

For new ideas	generating (research)	/	This use of GenAI is allowed except when it is prohibited by the teacher or the program of study. Correctly mention the use of GenAI assistance in accordance with the instructions on the page on being transparent about the use of GenAI. Be careful: • Further verify in this case whether the idea is novel or not. It is likely that it is related to existing work. If so, that existing work should be correctly referenced in the text (without such reference you would be committing plagiarism and thus committing an irregularity).
For synthetic data	generating	/	Use of GenAI for generating synthetic data is allowed, provided that it is methodologically and ethically justifiable, except when it is prohibited by the teacher or the program of study. Always correctly mention the use of GenAI assistance in accordance with the instructions on the page on being transparent about the use of GenAI. Be careful: • Always carefully evaluate the generated synthetic data for quality and possible bias since the output is highly dependent on the quality of the data on which the models are trained.

For generating blocks of text (other than the allowed use without referencing mentioned above)	/	According to Article 84 of the Regulations on Education and Examinations your text should allow to correctly and properly assess your own knowledge, understanding and skills. Therefore, inserting blocks of text without quotes and a reference to GenAI assistance in your work is not allowed. Be careful: • If it is really needed to insert a block of text from a GenAI tool, for instance because of the nature of your assignment, mention it as a citation by using quotes and correctly mention the use of GenAI assistance in accordance with the instructions page on being transparent about the use of GenAI. • However, in general, such GenAI use should be kept to an absolute minimum; you should always check the original sources.
For generating visuals, video or audio	/	Use of GenAI for generating visuals, audio or video is allowed except when it is prohibited by the teacher or the program of study. Be careful: • If used, refer to GenAI for visuals according to the usual referencing style, following the instructions on the page on referencing GenAI. • If you work with existing visuals, audio or video, that existing work should be correctly referenced in the text (without such reference you would be committing plagiarism and thus an irregularity). • Explain the usage in the methods section (if there is one) and optionally attach (or link to) the prompts with the full output (or history).

Other use (specify here; this may also include a combination of types of use mentioned above):	/	To make sure other use of GenAI is allowed within the course or thesis, and if so, the conditions that may apply, contact the teaching staff of the course or the supervisor of the thesis beforehand and explain the intended GenAI use. Also inform the programme director. Motivate how you would comply with Article 84 of the exam regulations. Explain the use and the added value of the AI tool you consider to use and how it is in accordance with the assignment or thesis and the KU Leuven guidelines on responsible use of Generative AI tools. Depending on the kind of GenAI use, it may be needed to properly reference it in the text, in accordance with the instructions page on being transparent about the use of GenAI.
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ChatGPT was used to refine and improve text that was written by myself. All generated suggestions were carefully reviewed to ensure that no factual content was altered or introduced, maintaining a critical and scientific approach throughout the editing process. In addition, this GenAI tool was used to quickly summarize scientific papers in order to assess their relevance to the research. If a paper was deemed relevant, the corresponding sections were subsequently read and evaluated in detail.

Google Scholar Labs was used to find relevant scientific literature on plug & play battery systems for the literature review, as was advised by my assistant-supervisor.

Claude was used as a support tool for understanding and generating programming code, particularly for data management of measurement results and for understanding and developing control scripts for the load simulators.