Benchmarking of Hybrid Thermal and Electrical Storage for Renewable Energy Communities

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Abstract Renewable energy communities (RECs) facilitate the local synergy between different energy forms and offer an opportunity to couple electrical and thermal energy demands with local renewable energy sources and locally sited thermal and electrical storage. This application presents a complex integration setting for the assessment of hybrid energy storage, motivating the development of a new assessment and benchmarking framework. This chapter will revisit relevant electrical and thermal storage technologies suitable for REC integration and hybrid energy and storage systems. A benchmarking framework for application-level assessment of hybrid energy storage systems is proposed. Requirements and relevant KPIs for the REC application of a multi-domain hybrid storage system are identified. To demonstrate the benchmarking framework on the REC application, a complete reference implementation is presented, including configurable system inpucts, optimisation and simulation modules as well as a calculation module for performance indicators. A showcase of the reference benchmark is computed and analysed.

Keywords Electro-thermal hybrid · Application benchmark · Benchmarking pipeline · Open-source model · Renewable energy community (REC)

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1 Introduction and Motivation

Energy Storage Systems (ESS) have a key role in enhancing renewable energy sources' ability to contribute to grid stability, flexibility and resilience. In a fully renewable energy system, energy storage is required on several time scales to buffer and balance between intermittent and variable energy supply and the non-flexible energy demand. The integration of energy storage systems with renewable energy power plants in bulk energy systems has been extensively studied, with their benefits well-documented. Especially remote and island systems as well as microgrids, also called "electrical islands", depend on energy storage to complement the intermittent and variable nature of renewable energy sources (RES) for their operation in isolation from the bulk energy system. Since the fluctuations of RES availability appear both on short and longer time scales, the balancing energy from ESS must also be available on several scales. Hybrid Energy Storage Systems (HESS) offer the vision to combine different types of ESS to optimally match the balancing needs.

As part of a HESS, thermal energy storage systems often offer more cost-effective long-term energy storage than the often-dominant electrochemical ESS. The efficient combination of electrical with thermal storage further motivates investigation of potential thermal energy consumers in addition to purely electrical consumption, increasing the effective energy efficiency. The integration of production and consumption of both thermal and electrical energy domains is economically possible, e.g. under the regulatory paradigm of Renewable Energy Communities (RECs).[1]

As with any storage solution, the eventual benefits of hybrid energy storage must be assessed in such an application context. For any given storage technology, there are clear indicators of technological progress: efficiency, lifetime (cycle life), capacity cost (€/MWh), response time, which apply to a broad range of applications. For individual storage applications, a simple demand profile typically is sufficient to assess how key performance indicators quantified in the procurement of the appropriate technology. For *hybrid* storage solutions, however, the quantification is much less apparent: the indicators of several technologies would have to be combined, the decision on how the individual storage subsystems are used will depend on a control system with dispatch optimization considering application objectives, and the optimal integration also depends on application considerations, where complementarity and flexibility of demand, energy conversion technologies and energy transport infrastructure need to be taken into account.

The main question to be addressed in this book chapter is: *How can benefits and technology trade-offs of within hybrid energy storage solutions be benchmarked for applications where electrical and thermal loads are to be served as well as renewable energy production is available for local consumption?*

Hybrid energy storage can be beneficial when there is complementarity between several storage technologies, so that the most advantageous combinations can be expected to beat a single technology. However, since the technology parameters of

[1] RECs were first legally defined in the European Union Directive 2018/2001 on the promotion of the use of energy from renewable sources (Dec. 2018).

hybrid storage are not restricted by any specific storage technology, and the technologies used will interact in a given application context, it is not meaningful to assess competitiveness on a set of standard indicators that are quantified independent of the application. Instead, the idea would be to assess the technologies in an application context using benchmark systems that can accommodate a variety of storage technologies. Such benchmark systems should represent relevant applications and allow for tuning of all relevant parameters, enabling the investigation of combinations of various storage technologies.

This chapter presents the concept of this application-oriented assessment approach and illustrates it on a reference application of renewable energy communities. The renewable energy community application is a complex application model, involving thermal and electrical energy production, consumption and storage. Such applications are also expected to bring hybridization benefits in terms of the complementarity between thermal and electrical energy processes, e.g. by recovering and storing renewable or waste heat sources in addition to supplying renewable heat from electricity-based infrastructure.

As a benchmarking approach, the objective of the given framework is to enable a FAIR and open approach to benchmarking. The presented model and calculation pipeline is therefore aimed at an open-source approach, and the development of both models and calculation codes is well- documented.

1.1 A Benchmarking Framework for Hybrid Energy Storage Systems with Complex Application Integration

The proposed benchmarking and assessment framework addresses the suggested requirements, following a simple structure as illustrated in Fig. 1. The main purpose of the assessment framework is to integrate assessment of key performance indicators with a configurable benchmark system. The notion of "benchmark" comprises a reference application, including an application model, with a preselected set of key performance indicators (KPIs).

The framework supports the calculation and reporting of both static (fixed by technology choice) and dynamic (computed by a simulation model) performance indicators. Static KPI can be derived directly from the system structure definition,

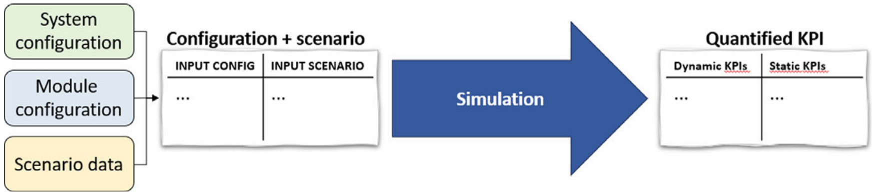

Fig. 1 Conceptual outline of assessment framework

such as the devices and materials used; static KPIs need to be updated when a user selects a different set of system parameters or replaces modules. Dynamic performance indicators require a dynamic simulation of the system's operation and can then be calculated based on system information and the time traces of the simulation.

The main idea of this approach is to harmonize the calculation principles and to deliver an integrated system view of all relevant KPIs for a hybrid energy storage application. For example, operating costs, lifetime and efficiency of a hybrid storage solution require a dynamic simulation, since the mix and contributions of each technology will vary on the operating demands and control strategies employed; the critical raw materials used to compose the respective storage solution, in contrast, are based on static look-up in respective databases. The focus of this chapter is to outline the benchmarking concept and to illustrate its configurable application to a renewable energy community case.

To perform reasonably in an application context, the hybrid energy storage or energy system also requires some form of dispatch optimization as well as logic for the real-time coordination of the respective storage systems. Such an application-oriented assessment method enables a technology-neutral approach to performance comparison. From a technology assessment point-of-view, we would require a larger set of such benchmark models, (at least) one for each of the applications considered. As renewable energy production as well as consumption profiles can vary widely depending on geographical conditions, the formulation of a benchmarking approach should eventually also consider this geographical dependency.

1.2 A Renewable Energy Community as Reference Case for Electro-Thermal Hybrid Energy Storage

A reference case was conceived to demonstrate the assessment of a complex hybrid energy storage system, integrating multiple electrical and thermal storage systems in one application. The application is considered as grid-connected Renewable Energy Community, in part because of the additional challenges of evaluating the performance of grid-connected systems as opposed to fully islanded energy system.

To construct a realistic system, the parameters of an existing electrical system were used and amended with suitable thermal consumption, energy harvesting, energy conversion, and thermal energy storage technologies. A schematic of a sample renewable energy community with hybrid electrical and thermal energy storage is illustrated in Fig. 2.

The electrical grid and resources for the reference case of an energy community is based on an existing electrical system available at the CEDER research facility in Soria, Spain. It is a micro-grid composed of a medium voltage ring (15 kV) with seven low-voltage substations. Each of these substations has combinations of renewable energy sources, energy storage systems, and consumption (electric load) connected. The complete microgrid is monitored and can be managed in real time.

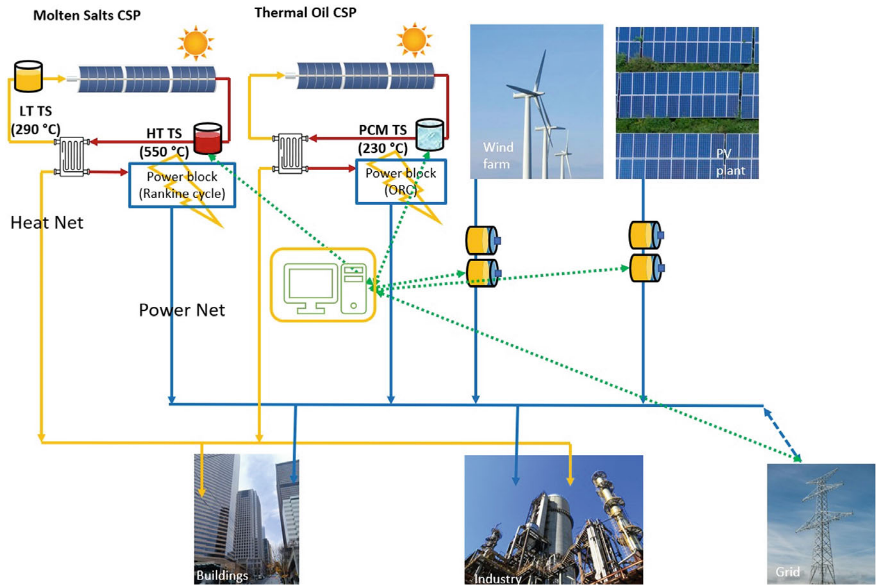

Fig. 2 Concept of a renewable energy community with hybrid electrical and thermal energy storage

To complete the CEDER-based system with a thermal network aspect, the given electrical systems is coupled with a fictional thermal network which includes two Concentrated Solar Power (CSP) plants at a different temperature level parametrised for the irradiance of the selected location, a thermochemical storage, a phase change material (PCM) storage, a boiler, a molten salt energy storage system integrated with, a Rankine cycle system for the electrical production. This system has a classic Rankine cycle using compressed steam superheated at 550 °C and an Organic Rankine cycle using an organic fluid to manage the lower temperature of the second CSP. Thermal and electrical loads include hospital, residential buildings, offices, hotels and some industrial facilities such as a pelletizer. Several of these thermal components are based on structures and research results associated with a research facility in Portici, Italy.

2 Electrical, Thermal and Hybrid Energy Storage for Renewable Energy Communities

With a growing share of discontinuous renewables on the electricity grid, such as wind and solar, needed to meet international decarbonization targets, it is becoming increasingly difficult to balance supply and demand, ensure grid stability and avoid distortions in electricity markets, so there is a need for increased research and development of energy storage and system flexibility. This section provides background on existing thermal and electrical storage technologies as well as the literature on integrating storage and hybrid storage in renewable energy systems applications, including the application of multi-domain renewable energy communities.

2.1 Thermal Energy Storage

Thermal storage, together with other forms of energy storage, can provide significant help, especially by integrating its various types of storage technologies.

Thermal Energy Storage and Coupling with Renewable Energy Production.

Thermal storage technologies are in most cases less expensive than electrical energy storage and, especially at high temperatures, they can power Rankine or Bryton cycles for the production of electrical energy and chemical processes for the production of synthetic fuels that represent a further efficient storage solution for the coupling not only of the electrical sector, but also of mobility.

The fields of application, considering different temperature levels, concern:

- Residential heating and cooling, including domestic hot water;
- Waste heat valorisation and continuity in the thermal and/or electrical supply of powered industrial processes;
- Coupling with CST/CSP (Concentrating solar thermal/power) plants, both to produce electrical energy and for the powering of industrial processes (SHIP);
- Carnot batteries (CB) include a set of multiple technologies having the common basic principle of converting electricity into thermal energy, storing it in thermal energy storage systems (TES) and reconverting the heat into electricity, when needed. In the charging phase, the electrical energy is used to heat a thermal storage medium. This task can be performed by a traditional heat pump (HP), an electric heater or any other technology, such as direct conversion by Joule effect (P2H: power to heat). Similarly, in the discharge phase, any heat engine technology can be used, using Rankine, Brayton, Stirling or other different thermodynamic cycles, such as thermoelectric, thermionic and thermo-photovoltaic systems. Pumped Thermal Energy Storage (PTES) is a type of Carnot battery.

The main types of thermal energy storage are:

- Sensible (SHTES): energy is stored or released through an increase or decrease in the temperature of the storage medium. Therefore, these systems use the heat capacity of the material to store energy, and this is always present in a single phase, usually solid or liquid. The most common example of a SHTES with a liquid medium is water, while a solid medium would be a rock-type one. Both have the advantage of being cheap storage materials. The specific heat capacity of water is about four times higher than the rock-type one. However, water needs high pressures to reach temperatures above 100 °C, while rock-type material can easily reach temperatures of 700 °C. For a SHTES system, the efficiency strongly depends on the effectiveness of the insulation provided against heat losses. Depending on this, a SHTES can achieve an efficiency included in the range between 50 and 90%. Generally, STHES systems have a low specific energy, in the range of 10–50 Wh/kg. This leads to very large storage tank sizes. The capital costs associated with a SHTES system are in the range of 3400–4500 $/kW, while the price per unit of stored energy is in the range of 0.1–10 $/kWh.

- Latent (LHTES): the materials used are called PCMs. The energy released or absorbed during the phase change is known as latent heat. These transitions occur at an approximately constant temperature, thus facilitating the stabilization of the temperature over which the heat transfer occurs. They have the advantage of having a high specific energy (50–150 Wh/kg) compared to SHTES systems. The capital costs required for LHTES are in the range of 6000–15,000 $/kW, and the price per unit of stored energy is in the range of 10–85 $/kWh, significantly higher than for SHTES systems.
- Thermochemical (TCES): these storage systems are based on the principle of feeding chemical reagents with thermal energy, resulting in their dissociation into other components that can be separated, allowing them to store the supplied thermal energy. When needed, these components are made to react with each other, to return the energy previously supplied. The capital cost required for a TCES system is the lowest of the three types of storage technologies, in the range of 1000–3000 $/kW, and, in addition, the energy density, of 120–250 Wh/kg, is the highest. However, the price per unit of stored energy is 8–100 $/kWh, making it the most expensive of the three storage technologies, because it has currently a low TRL, especially for the high temperature applications.

Benefits from Combination of Different Thermal Storage Technologies

An emerging method for an energy storage system combines latent and sensible thermal energy storage systems.

For instance, (Laing et al. 2012) developed a combined storage solution for direct steam generation in CSP plants with a concrete storage for superheating steam, and a LHTES for evaporating water. A 700 kWh prototype plant was built at Litoral of Endesa in Carboneras, Spain.

In Rome (Italy) a hybrid TES prototype is under construction including a module able to store 40 kWh of thermal energy by PCMs, followed by a concrete module of about 150 kWh and another 40 kWh PCM TES with a higher phase change temperature. The overall operating temperature range of the system is 290 ÷ 450 °C (Liberatore 2024).

The benefits of these kind of systems are expected in a positive effect both to facilitate the management of the system due to stabilization of the Heat Transfer Fluid outlet temperature for many hours and to provide high-quality heat to the user.

Novotny et al. (2022) highlighted the importance of utilizing excess electricity to drive a Power-to-Heat (P2H) system, generating a temperature difference (thermal exergy). This can involve both hot and cold storage. During discharge, this stored thermal exergy is reconverted into electricity through a Heat-to-Power (H2P) system.

Dumont et al. (2020) illustrated an emerging method for a large-scale energy storage system, along with a charging cycle involving an Organic Rankine Cycle (ORC) and a discharging cycle involving a heat pump. It combines latent and sensible thermal energy storage systems. The authors demonstrate the potential of this combination through a temperature-entropy graph.

Some authors have reported the coupling of low temperature heat sources also with PTES (Pumped Thermal Electricity Storage) (Rehman et al. 2015). Other hybridization methods for medium–high temperatures used to obtain more compact cement-based TES consist of adding a shape-stabilized amount of PCM to their mix-design, so as not to compromise their thermo-mechanical performance. Such a hybrid sensitive/latent storage medium has the advantages of low concrete cost combined with a higher energy density (Miliozzi et al. 2021).

2.2 Electrical Storage for Renewable Energy Systems

Electrical energy storage offers the capacity to convert available surplus electricity into a storage form and to retrieve it in form electricity again. Bulk mechanical electricity storage has been available in form hydroelectric or pumped storage (gravitational) or compressed air (thermodynamic), which both depend on geographical features. Electrical and electrochemical energy storage systems, such as batteries and supercapacitors, are more flexible in terms of geographic deployment.

Energy storage mechanisms depend on the chemical and physical properties of the materials involved. In these systems, energy is typically stored in chemical form within the electrode materials (batteries) or through charge accumulation at interfaces (supercapacitors).

Batteries

Batteries store energy through chemical processes, specifically faradaic reactions or redox reactions, which take place at the anode and cathode. These reactions involve the transfer of electrons during oxidation at the anode and reduction at the cathode, enabling the conversion between chemical and electrical energy.

Battery storage technologies come in various forms, each characterized by attributes like energy efficiency, specific energy, and cycle duration. Lead-acid batteries, one of the oldest and most widely used technologies, are favoured for bulk energy storage due to their low cost and reliability (Mustafizur et al. 2020). However, they suffer from limitations such as short lifetimes, low energy density, and a restricted depth of discharge (DOD), which impacts their efficiency and usability, and they face environmental challenges due to the toxic nature of lead. In contrast, lithium-ion batteries provide significantly higher energy efficiency (90–95%), longer lifespans, and superior power density, making them ideal for electric vehicles. These advantages come at a higher initial cost and with concerns around the sourcing of critical raw materials like lithium and cobalt (Mustafizur et al. 2020; Mitali et al. 2022). Flow batteries, on the other hand, stand out for their flexibility, allowing power and energy capacity to be scaled independently. This makes them well-suited for large-scale grid applications, though their lower energy density and larger physical footprint limit their use in space-limited applications, Additionally, the most widely used vanadium flow batteries entail higher costs compared to lithium-ion batteries (Poli et al. 2024). Finally, nickel–cadmium batteries offer high energy density, durability, and low maintenance requirements, performing well under extreme conditions. However, they face environmental challenges due to the toxic nature of cadmium, leading to a decline in usage as more sustainable alternatives, such as nickel-metal hydride and lithium-ion batteries, have become available. Each of these technologies presents trade-offs in cost, efficiency, and environmental impact, influencing their application in specific use cases (Mustafizur et al. 2020; Mitali et al. 2022).

According to the review article by (Mustafizur et al. 2020), electro-chemical battery storage systems rank third in installed capacity, with a total power of 2.03 GW. The most widely used utility-scale electro-chemical batteries are lead-acid, lithium-ion, sodium-sulphur, nickel–cadmium, and flow batteries. Among battery technologies, Li-ion holds the largest market share, with a power production capacity of 1.66 GW, followed by sodium-based batteries (204.32 MW) and flow batteries (71.94 MW).

Supercapacitors

Supercapacitors are considered a complementary technology to batteries due to their unique characteristics, including high power density and exceptional cyclability, although they exhibit low energy density. These devices store energy by separating negative and positive charges. This separation allows supercapacitors to store static electricity for later use, enabling rapid energy release when needed.

There are three main types of supercapacitors: electric double-layer capacitors (EDLCs), pseudo capacitors, and hybrid supercapacitors. EDLCs store energy through charge accumulation on both sides of the dielectric layer, a process that is highly reversible and provides high power density. However, their energy density is relatively low compared to batteries. Pseudo capacitors combine this mechanism with Faradaic redox reactions, enabling improved energy storage through features like a large contact area and short paths for electron and ion transport. Despite these advantages, their performance heavily depends on precise control of electrode properties such as morphology, structure, and composition. Deviations can lead to reduced electroactive surface area and diminished performance. Hybrid supercapacitors integrate both Faradaic and non-Faradaic processes in their electrodes. Even though some electrode materials like carbon and metal oxides may exhibit poor conductivity, hybrid supercapacitors achieve high cycling stability, power density, and energy density. This is often accomplished using advanced 3D mesoporous electrode structures, which enhance their performance and affordability. These features make supercapacitors an invaluable addition to energy storage systems, especially in applications requiring quick energy discharge and high durability (Zhang et al. 2023).

In a HESS, supercapacitors are effectively utilized to mitigate short-term voltage and frequency fluctuations in the grid. Their high-power density and rapid charge–discharge capability make them well-suited for handling transient disturbances. When integrated with larger energy storage systems, such as batteries, supercapacitors act as a complementary component (Zhang et al. 2023).

Bocklisch (2015) highlights the advantages of combining storage technologies, emphasizing how hybrid systems can enhance overall efficiency. This approach is particularly valuable in mitigating the drawbacks or damages associated with reliance on a single technology, offering a more balanced and resilient energy storage solution.

2.3 Hybrid Electrical and Thermal Energy Storage in Energy Systems Applications

The European Union Renewable Energy Directive (RED II), part of the Clean Energy for All Europeans Package, defines "Renewable Energy Communities" (RECs), establishes a governance framework for them, and enables energy sharing within these communities. RECs are citizen-driven projects designed to advance the clean energy transition through various forms of consumer co-ownership. These initiatives empower local communities to engage in renewable energy production and consumption, fostering resilience, enhancing energy efficiency, and supporting decentralized renewable energy generation.

Storage systems are considered vital components of RECs. These systems play a crucial role by storing variable energy and deploying it as dispatchable generation during periods of high demand within the electrical grid (Lowitzsch et al. 2020). This raises the question of hybridizing these storage systems: can combining different forms of electrical and thermal energy storage provide enhanced benefits compared to using them individually?

Whereas electrical and thermal energy forms are relevant to quite different applications and require different infrastructure. Hybridization of electrical and thermal energy storage solutions is typically only relevant in applications where both forms of energy are eventually required by an end user. From a physical perspective, thermal storage at lower temperatures has lower quality, since it cannot be converted to electricity. Depending on the infrastructure involved and the system boundary, the services required, and the applicable legal and commercial conditions, the performance criteria and applicable solution concepts vary widely, also in terminology and technological maturity.

Storage System Integration with Renewable Energy in Applications

A report from the National Renewable Energy Laboratory (NREL) (Reilly et al. 2022) examines state-of-the-art wind-storage configurations and system controls, along with the techno-economic sizing of wind-battery hybrid systems for different grid types. Extensive research has been conducted on the design, regulation, and management of energy within storage systems, with a strong emphasis on optimization algorithms for sizing individual components. In their review article, Nkwanyana et al. (2023). Examine the optimization techniques used in the design, configuration, and deployment of various RESs and different storage systems.

Future economic feasibility studies have explored the impact of configuration-location combinations in HES hybrid systems. Schleifer et al. (2023) demonstrated that smaller batteries can achieve similar economic performance to larger ones when paired with complementary PV-wind systems. They also analysed how the energy and capacity values of PV-wind-battery hybrid systems might evolve over time across locations with differing levels of solar and wind complementarity. Aykut Fatih Guven et al. (2024) take a nuanced approach by exploring a range of scenarios involving load demand and generation fluctuations due to the variability of RESs. By utilizing real-world data on load, wind speed, and solar irradiance, alongside multiple storage options, they examine various algorithms for convergence and optimize the system to identify the most efficient configuration. As can be seen, a lot of these studies focused on specific storage technologies and their optimal integration into a RES system.

Sector Coupling in Hybrid Energy Systems

Sector coupling refers to the exploitation of flexibility options and associated benefits (e.g. increased renewable energy adoption) across energy usage sectors, such as electricity and heating or electricity and transportation.

The studies mentioned above do not include sector coupling. Sector coupling between electricity and thermal systems is recognized as a crucial strategy for maximizing the full potential of RESs and supporting the achievement of green energy transition goals6. This approach enables excess renewable energy to be stored and converted into heat using boilers or heat pumps, which can then be stored in thermal energy storage systems, such as pumped thermal energy storage (PTES), for later use (Steinmann et al. 2019).

Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) technologies have been proposed as innovative solutions to support decarbonization efforts. The core concept involves utilizing the batteries (Lithium-ion) of electric vehicles (EVs) to store energy during periods of low demand and discharge it during peak hours to assist with peak shaving. To evaluate their feasibility and effectiveness, various techno-economic models have been developed. Feasibility studies have also been conducted on integrating HRES into renewable energy hybrid microgrids and vehicle-to-grid/home systems. García-Vázquez et al. (2022) studied the feasibility of a hybrid renewable energy system with an energy storage system for a house, where the vehicle-to-home (V2H) option is considered as a backup/support system and focused on the sizing of PV panels and storage devices. The widespread adoption of these technologies by the public remains to be seen in the future. A study conducted in Norway—one of the countries with the highest EV adoption rates—highlighted key strategies to encourage uptake. These include providing financial incentives such as tax credits, launching educational campaigns to emphasize the benefits of EVs with V2G capabilities, expanding EV charging infrastructure, and fostering the development of a robust public–private V2G ecosystem (Mehdizadeh et al. 2024).

Goyal et al. (2024) propose a design for a sector-coupled microgrid that integrates the electric, thermal, hydrogen, and transport sectors. Their design incorporates battery storage for electricity and hydrogen storage tanks for hydrogen. The study evaluates the techno-economic impacts and total emissions, indicating that a decarbonized sector-coupled microgrid is both feasible and effective in advancing sustainability goals.

Electro-Thermal Hybrid Storage Energy Systems Applications

Sihvonen et al. (2024). investigated an electrical-thermal hybrid storage system, involving an underground pumped hydro storage (PHS) system and a sand-based high-temperature thermal energy storage (HTTES), an electrical thermal energy storage, which is coupled with power-to-heat and discharged into district heating (DH) in an island energy system. Their findings highlight a clear need for storage capacity from diverse sources. However, this study did not consider electrical storage components, such as batteries and supercapacitors, revealing a gap in comprehensive research on integrating both thermal and electrical storage systems into RESs grids, particularly when coupled with power-to-heat technologies.

Geographical Variability Effects on Hybrid Energy Storage Applicability

Most studies investigate the application of hybrid energy systems assessments for a specific given geographic location or area. Zhu et al. (2024) conducted a comprehensive review of the findings and limitations associated with various REss and storage solutions implemented at different sites worldwide.

Our review identified several studies that address different types of consumption data and load profiles based on seasonality. Enrique Rosales-Asensio et al. (2024) examined two distinct use cases of buildings in different locations—New York and California—using REopt to determine the optimal sizing of storage systems for minimal costs and emissions. The study revealed a high level of complexity, with outcomes heavily influenced by factors such as solar irradiance, load profiles, and the energy tariffs applied. Kobashi et al. (2022) investigated the integration of EVs in commercial and residential districts across cities in Japan. Their study concluded that such strategies could play a significant role in advancing urban decarbonization efforts. Lysenko et al. (2023) modelled the variable nature of RES and consumption as a random process in their study of hybrid power systems with storage. This approach was used to analyse and optimize the sizing of the storage battery system, accounting for the stochastic behaviour of energy generation and demand. Mazzeo et al. (2020) investigated the worldwide techno-economic mapping and optimization of standalone and grid connected PV-wind HRES to supply the electrical demand of an office building district. These studies, however, neither account for sector coupling nor offer a comprehensive framework for analysing alternative use cases.

3 Benchmarking Framework for Hybrid Energy Storage

Hybrid energy storage technology performance is characterized by three aspects that are each influenced by the application they operate under: (a) storage technology performance, (b) interaction and integration of multiple storage technologies, and (c) the control and coordination strategies. To assess the potential impact of variations in material, device, integration and control system parameters at an application level, it is of interest to offer a benchmarking approach that accounts fully for the relevant constraints and performance criteria for the given application.

Since modelling and simulation of energy storage in energy systems applications is critical for planning and technical assessment of potential energy solutions, there exists a wealth of planning and technical design tools and models in the field, each aimed at different purposes. However, benchmarking contrasts with the requirements planning and technical design, which typically include a case-by-case adaptation of model and analysis approach: the performance estimation via a benchmark instead requires a stable but configurable and easily adaptable benchmark model.

Another dimension of interest would then be to consider adaptation to the geographic and associated environmental conditions which induce a systematic and consistent variation of input parameters that would substantially affect outcomes, given different demand and resource availability. In this section, we will outline a benchmarking framework that supports the above-listed requirements.

3.1 Requirements for Application-Level Performance Assessment for Hybrid Energy Storage

To develop a framework for benchmarking for hybrid energy storage at application-level, we shall consider the key ingredients of the benchmark model: an appropriate system application model (system boundary and dynamics), associated modelling tools (potential modularization and configurability), assessment scenarios (ensuring consistent input data), and the identification of relevant performance assessment criteria.

3.1.1 Functional Aspects of an Application-level Benchmark

An effective benchmark case should consider and represent the following aspects:

Dynamic Simulations Covering the Full Application Range Including Partial Charge Performance

Storage systems must be able to respond quickly to verify the flexibility to be provided to users and grid services needed for RES integration, including the time scale. For thermal systems, partial charge studies quantify how much performance can degrade when operating temperatures are dynamically varied as compared to the thermodynamic design.

Application-Level Cross-Domain Integration of Storage with Non-Storage Sub-Systems

Hybrid thermal/electrical integrated systems should have significant advantages in terms of reducing energy losses. Such application-level benefits cannot be assessed at the level of storage technology.

Multi-Model Capability

Hybrid energy storage applications, accrue benefits from operating over a wide range of timescales and behaviours relevant to application-level performance. A single model cannot capture the full range of these application-aspects. A benchmark requires a set of jointly configurable models.

Control Strategies

Control strategies determine the system behaviour and performance in view of a control objective, concerning, for example, power/capacity range, fluctuations in electricity prices, electricity demand, power production and any waste heat integration as well as produce a clear environmental benefit especially for lower greenhouse gas emissions. Several control strategies may be combined to cover several time scales.

Performance Indicators and Cost Estimates

A benchmark is defined by its ability to summarize performance of a specific technology in reference to specific performance indicators. Such indicators should cover the full range of relevant technological, economic and sustainability indicators, consistent across sub-modules. E.g. cost reduction should be comparable sustainability trade-offs in the use of critical raw materials.

Assessment Reference Scenarios and Geographical Adaptation

Benchmark-style assessment requires a reference set of input operating scenario data. In RES based systems, the geographical location used as reference has significant effects toward the evaluation of a given system design. In principle it is possible to relocate a given model to a distinct geographical location by altering the environmental variables and associated input time series.

3.1.2 Limitations of Existing Modeling Tools in View of Benchmarking Requirements

Modelling tools used for performance assessment are not designed to meet all of the above listed requirements for benchmarking. Distinguished by the modelling purpose, we can revisit typical capabilities of energy system planning/optimisation tools and technical design and analysis tools.

Modelling and Planning Tools for Hybrid Energy Systems and Assessment Criteria

Since both renewable energy and demand tend to be fluctuating, uncertain and uncontrollable, the performance of a storage solution needs to be assessed in context of its application, e.g. to balance energy supply and demand, or provide the minimum cost of energy, given electricity market prices and varying tariffs, and possibly also to offer flexibility back to the energy system/electricity grid. Planning tools contain models of storage technologies and consider the expected behaviour over time of renewable energy supply and energy demand, a planning tool typically offers to optimize a system (configuration, sizing) for a given performance indicator (e.g. revenues, total system cost, CO_2 emissions). A challenge for most planning tools is, however, that electricity storage operates across time and across time scales, that revenues from multiple sources can be stacked, but also that the resource allocation at different time scales interact. An additional challenge in the planning of hybrid storage solutions is that there is an interaction between storage types, depending on the optimal forward-looking allocation as well as on the real-time reactive control algorithms, operating on a timescale of microseconds to minutes. It is therefore challenging to determine an appropriate problem reduction without too many (over-)simplifying assumptions.

There is a wide range of energy planning and modelling tools available that are capable of modelling hybrid energy systems, both as open source, free software (e.g. EnergyPlan[2]) and commercial software (e.g. Plexos,[3] Homer Pro[4]). These software packages are widely used for sizing, simulating operational scenarios, and optimizing multi-domain energy systems—covering thermal and electrical components—while integrating hybrid renewable and conventional energy sources, as well as multiple storage technologies. However, given that some of these tools come with limitations. For example, Plexos and Homer Pro are not free to use and typically require paid licenses, which can be a barrier for many users. While EnergyPlan is a free software for modelling smart energy systems, its hard-coded heuristics make it difficult to alter performance objectives, assess technology variants or to integrate it in a pipeline with other tools. A common challenge with the adoption of commercial planning tools is the lock-in situation since the models are typically not transferrable or open to modifications, and the performance objectives are built into the system. Limited configurability and openness become a barrier when more complex adaptations are required, as in the case of hybrid energy storage for grid-connected renewable energy communities.

Alternative to commercial planning tools are open-source energy system models. There is a wide range of open software models (https://wiki.openmod-initiative.org/wiki/Open_Models), each with a specific modelling, planning or assessment scope. Most models are built around an economic optimization capability, enabling optimization over time scales of days to decades.

Assessment of Non-Stationary Behaviour and Dynamic Technical Performance

In contrast with the energy systems modelling tools, a separate category of technical modelling software aims to represent the detailed dynamic (transient) behaviour of the technical system, typically in time scales from hours to microseconds, depending on the domain relevant physical phenomena and technology investigated. Here the use of commercial modelling software is dominant (e.g. MATLAB/Simulink, TRNSYS, Dymola, PSS/e), but also open-source platforms exist (e.g. Octave, Modelica/OpenModelica). Here, modelling tools can be divided in all-purpose (e.g. Simulink, Modelica) and domain-specific tools (e.g. PSS/e for Power systems, TRNSYS for Thermal applications).

[2] https://energyplan.eu/

[3] https://www.energyexemplar.com/plexos

[4] https://homerenergy.com/products/pro/index.html

System Boundaries and Their Effect on Model Detail and Assessment Criteria

Depending on the size, geographical extent, or electrical grid connection type, hybrid energy systems vary widely in the applicable technologies as well as the relevant services to be accounted for. Practical planning tools typically abstract the technologies and simplify the application service to allow for a general tool implementation, foregoing technology details for the benefit of a generic and simple planning tool. Detailed technical models increase time-resolution and thus enable the investigation of non-stationary physical phenomena that can affect the integration technologies and performance of the integrated system. Such detailed models limit the system boundary and accuracy of representation to the relevant time scale and relevant transient interactions.

The system boundary also affects the objectives, incentive structures and technical operating parameters of an energy system design. For example, an isolated (island) energy system is simpler to model in a planning tool (e.g. EnergyPlan), but the tool faces limitations when applied to scenarios where the system is connected to the grid and influenced by e.g. dynamic market prices and external grid interactions.

Geographical Adaptation of Assessments

Data sources like SECURES-Met (Europe) and TRNSYS (World) offer precise meteorological information, such as radiation and wind speed, which are vital for estimating solar and wind energy production. Similarly, electricity prices and associated tariffs and taxes vary significantly across regions; as most electricity networks in Europe are fully transparent on electricity prices, so such data can be located and integrated for several world regions.[5] Finally, consumption data, which also varies geographically and seasonally, is equally essential for developing a comprehensive assessment tool. Comprehensive, geographically organized and aggregated data on electricity, heat and fuel consumption is available, e.g. via (Hidalgo and Uihlein 2023). However, for assessing storage performance, detailed and disaggregated time-series are required, based on the modelling assumptions and time resolution; this aspect is difficult to achieve based on geographical databases alone. Here representative time series may be chosen from public databases,[6] considering an approximate match of e.g. climate, culture and business operating hours, but also synthetic load profile generation should be considered as a valid approach to represent characteristic load behaviour.

[5] An overview of useful data sources for electricity prices is listed here: https://wiki.openmod-initiative.org/wiki/File:Electricity_prices

[6] https://wiki.openmod-initiative.org/wiki/Data

Challenges with Existing KPIs and Performance Assessments

Key performance indicators (KPIs) are intended to enable technology-neutral assessment to differentiate technologies by performance for the same application. It is often desired to identify optimal performance or a performance trade-off between alternative technologies. Optimization methods may use a cost function to represent the performance indicators directly—generating an optimal design for the considered "cost". Above-mentioned planning tools will optimize typically by minimizing the total system cost (investment and operational), considering other technical criteria in the form of constraints (e.g. reduce/eliminate exchange with the power grid). For planning, where a wide range of alternatives need to be considered and traded off, such simple criteria are useful.

The suitability of a design, however, can in most applications not be reduced to a single straightforward cost (function) or constraint. The need to reduce complexity for optimization purposes also implies that the model details cannot completely capture the full range of criteria, so detailed dynamic models may be required to extend the assessment. It is therefore meaningful to formulate additional performance criteria that may be derived from the available application models.

3.2 The Proposed Application-Level Assessment Framework

This work focuses on developing a technology-neutral, open-source framework to quantify the application-oriented KPIs of configurable HESS, including electro-thermal storage. The framework is intended to be adaptable to alternative geographic locations, enabling seamless integration of generation and consumption data to facilitate comprehensive analysis based on the application-level system performance. Figure 3 outlines the main components and interactions in the proposed application-level assessment framework. Notably, the framework imposes a fixed benchmark theme, which then determines the content of the configuration (light blue), model (red) and KPI calculation (green) modules. Following the principle of benchmarking, a user interacts with the configuration, not the models or the KPI selection.

Application Benchmark Definition and Models

For a given application, the benchmark defines a specific application with a reference system configuration, relevant performance indicators and a complete reference implementation of the required models. Baseline scenarios and valid KPI ranges are identified for the given application. Static computations and data are available for configuration-driven calculations of static KPIs. The computational modules that perform the calculations for the associated KPIs are also included to avoid interpretation issues in text-based definitions of performance indicators. The model is documented fully so that a user can interpret and interact with the system and

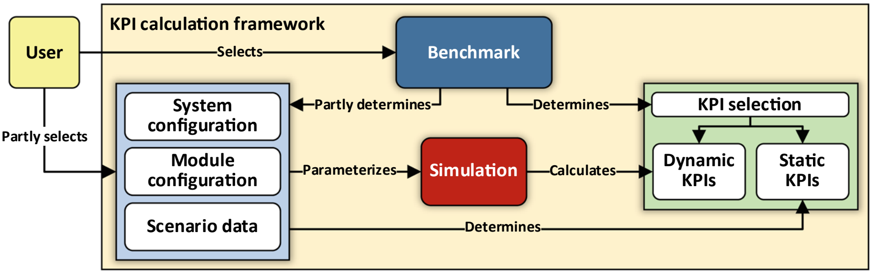

Fig. 3 Schematic of assessment framework with benchmark context

scenarios configuration. An application benchmark typically comprises several sub-models, such as for example a scheduling model and a dynamic operational model in order to represent relevant dynamics in all timescales associated with the quantified performance indicators.

System and Scenario Configuration

For the benchmark model, it is essential that the calculations are harmonized and any modifications to the benchmark parameters are traceable. It is therefore paramount to enable a file-based parametric configuration of the benchmark model, enabling to document and trace parameter changes to observed effects and to enable comparison of results across the literature. The user interface of the benchmark is therefore mainly in the specification of system configuration and scenario parameters, enabling the otherwise consistent and automated assessment of a given benchmark across several sub-models. Examples of adjustable parameters is the selection of size or numbers and types of storage modules of different types of storage included in the benchmark. Users may be able to investigate alternative efficiency among the technologies. An extreme case of configurability would be the possibility to alter the geo-location of the application, as this would result in the need to automatically update the location-associated time series and parameters, as discussed above.

Module Configuration and Model Adaptation

The application benchmark should ideally be formulated in such a way that it includes and is enabled to operate with a wide range of storage technologies, which may or may not be activated. An intended but more comprehensive adaptation of the benchmark could be performed to integrate and alternative storage technology. The benchmark application model would have to be updated with a drop-in replacement of the respective model components in all the required sub-models.

Assessment Pipeline Automation

An implementation of this proposed benchmarking framework would be greatly facilitated by means of a configuration-driven software pipeline, where the input parameters, simulation model results and resulting performance indicators are calculated based on an automated and parallelizable process. This approach will facilitate the integration of the proposed framework in automated assessment pipelines.

Consideration of Geographically Adaptive Benchmarking

Since datasets for renewable energy production are available based on geo-location, the complexities in the geographical adaptation are more present in the representation of the consumption profiles. Another feature in a benchmarking approach would be flexibility on integration options that match the local build environment, regulatory requirements and so on. These complexities cannot be addressed all at once. However, a framework that facilitates the geographical adaptation of the benchmark in a computational sense (i.e. by parameterization of the relevant variables) would greatly facilitate the future adaptation of the given benchmark case to various local conditions. The suggested approach is therefore a clustered adaptation to specific design-geolocations, where the complete dataset is available and the benchmark has a meaningful representation for the given application.

3.3 Considerations on Performance Indicators

Key performance indicators are the main device of comparison stipulated by a benchmark. A benchmark setup should in principle include many pre-defined performance indicators to ensure consistency of comparisons. On the other hand, the prioritization of a small number of "key" performance indicators facilitates the discourse.

From Performance Indicators to Application-Oriented KPIs

In view of designing a valid application-oriented benchmark system for hybrid energy storage, it is important to consider a selection of key performance indicators that are relevant to be quantified by means of the application-oriented benchmark model. There are technical considerations on the requirements for computing aggregate, dynamic KPIs for a hybrid storage application, there are criteria to select and prioritize KPIs.

On Computation Requirements for KPI Calculation and Aggregation

A recent analysis of performance indicators for hybrid energy storage systems in Heussen et al. (2025a) and Scipioni (2025) suggests a classification of by several characteristics, that are important to establish a basis for comparison of hybrid to non-hybrid energy storage solutions. The two main considerations for a given KPI are (a) the relevant method of aggregation of KPIs from single-technology KPIs to KPIs representing the HESS performance, and (b) the variability subject to dynamic behaviour of the storage in operation.

Assessing overall system performance is to *aggregate* the KPIs using different methods:

- **Weighted Average KPIs:** These are KPIs calculated based on the proportional contributions of each component in the hybrid system.
- **Cumulative KPIs:** KPIs representing the total contributions of all components, reflecting the overall system performance.
- **Dominant- or Limiting- Technology Influenced KPIs**: These are KPIs that are influenced by either the strongest or the weakest technology in the system.
- **Application-level KPI**: KPI to benchmark the performance (enhancement) of an integrated system design, for a given application (requires a benchmark system implementation)

The second distinction can be made between dynamic and static KPIs. **Static KPIs** are primarily determined by the inherent material or device properties of the system components. In contrast, **dynamic KPIs** require evaluation of time-dependent behaviour in an application; for hybrid energy storage, this behaviour is also influenced by the interactions among storage technologies. These dynamic metrics require a representation of the controlled system behaviour under representative operating conditions.

A further distinction relevant to computation of KPIs is whether the indicator can be computed independently of (**absolute KPI**) or with reference to a baseline value (**relative KPI**). In application-based benchmarks Dimensioning-based vs. Fixed-sizing-based KPI: KPIs that consider system sizing based on operational dimensions versus fixed-sizing approaches.

On the Formulation of Key Performance Indicators for Application-Level Assessment

Firstly, performance indicators should reflect a sufficiently holistic view on technology performance so that important trade-offs are directly apparent from an analysis. For example, if economic improvements come at the cost of sustainability performance this should become immediately evident. Thus, a relevant set of performance indicators should include at least one indicator from each "technical", "economic" and "sustainability" categories. Secondly, the importance of performance indicators should be weighed by the interest of relevant stakeholders in those indicators. Finally, the prioritization of KPI is driven by the considered application and its associated technology-neutral service requirements. To select effective KPI the authors therefore suggest the following criteria for the formulation and selection of KPIs: quantitative, technology-agnostic, reproducible, mathematically robust, and well-defined across the system's entire operating range. Additionally, they must effectively capture key objectives.

In summary, we suggest the following criteria for discussing and selecting KPIs:

- *Quantitative and Comparable*: KPIs that are measurable and can be compared across different systems or technologies.
- *Replicable/Reproducible*: KPIs that can be consistently replicated across various scenarios or studies.
- *Feasible to quantify with the given benchmark*: KPIs that can be effectively quantified using the established benchmark.

- *Mathematically Sound*/Well-defined: KPIs that are defined clearly and are supported by sound mathematical principles.
- *Relevant to the Application*: KPIs that directly apply to and reflect the objectives of the specific system use cases, motivated by.
- *Absolute, if possible*: Give preference to KPI defined in absolute terms instead of relative to a reference scenario since citation of reference baselines weakens the general interpretability outside the application context.

The proposed criteria assisted in the below reported KPI selection process.

4 Technology Neutral System Requirements for REC

In this section performance indicators and functional requirements for a REC are outlined.

4.1 Storage Services in a REC Application

The foundation for RECs is the "Community" setting and its identification with a renewable energy supply. Renewable energy production (bio, thermal, electrical) is volatile and does not meet consumption needs for thermal, chemical or electrical energy in time. Storage can shift this energy in time and thus may enable a fully autonomous energy supply if the community were entirely based on an islanded or isolated energy system. However, the REC concept also applies to grid-connected communities, where at least the electricity exchange with the environment is possible.

Regarding the non-functional requirements for the integration of multi-domain hybrid energy storage systems in a Renewable Energy Community, three main groups of services can be facilitated: a) cross-domain energy balancing services, b) slow response grid services, and c) fast response grid services.

The first set of services is associated with optimizing energy efficiency, energy cost and minimizing CO_2 emissions and operates over timescales of hours to days. Here the thermal storage systems and cross-domain energy conversion units come to bear. The second and third group of services are focused on the balancing of the electricity flows. In case of exchange with the electricity grid it would be concerned with electricity prices and ancillary grid services, or, in case of a fully islanded/isolated system, it would be the local frequency and power balancing.

Slow-response grid services ramp in the range of tens of seconds to minutes, for a step equal to nominal power) and last in the range of one or several hours at nominal power. Examples of objectives in this group of services are minimizing consumption from the grid, reducing the curtailment of renewables, or participation in the electricity market for maximizing profit. Fast response grid services operate in the range of hundreds of milliseconds to a few seconds and last in the range of minutes at nominal power, such as participation in ancillary services (frequency regulation) or other fast response grid services (angle stability, reactive, etc.) current or future.

4.2 Performance Indicators for a Renewable Energy Community

Performance indicators should enable the assessment of hybrid energy storage contributions in an 'open' energy system application, i.e. a REC may exchange energy with its surrounding infrastructure. This section reports on the KPI selection for RECs, considering the criteria introduced in Sect. 3.3.

Relevant Performance Indicators for RECs

To quantify the benefits of hybridizing various energy storage technologies in a technology-neutral manner, the application-level performance should measure the effectiveness of the HESS in supporting the above listed services. If we further consider the stakeholders setting expectations to the REC, additional KPIs may emerge:

- End Users: Both residential, municipal, and industrial (SME) end users, who have evolved from passive participants to active contributors in the energy chain due to liberalization.
- Transmission and Distributed System Operator (TSO/DSO): Responsible for managing the high, medium and low voltage networks, ensuring the security and reliability of the energy system.
- Regulatory Authorities and Institutions: These stakeholders establish the rules and regulatory frameworks, ensuring that all parties adhere to the appropriate guidelines. They are also responsible for transposing EU regulations into national laws.
- Other Market Operators: This category includes electricity producers, aggregators, suppliers, Energy Service Companies (ESCOs), DR aggregators, and prosumers

It is self-evident that the services listed above are dynamic in nature and only a dynamic representation of the REC can offer the information needed to quantify them. Therefore, dynamic KPIs are required to evaluate system performance.

From a literature review on KPIs in energy system management (Scipioni 2025) three categories of relevant KPIs emerged: technical, economic, and sustainability indicators. Indicators within each category often overlap in scope and not all are relevant to the REC application.

Selected KPIs for This Case Study

In Table 1, a list of selected KPIs is presented to evaluate the REC from different aspects. The selection of KPIs for assessing RECs is driven by the need to evaluate their sustainability, economic, and operational performance. System Energy Efficiency ensures optimal use of renewable resources, reflecting energy waste. Meanwhile, System Operational CO_2 Emissions quantify the sustainability aspect, highlighting decarbonization efforts. The Flexibility Factor measures the system's ability to adjust consumption, generation, or ESS based on market/system status.

Economic assessment is a crucial aspect of REC development, highlighting Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) as essential

Table 1 List of KPI for this case study

Name	Description	Expected range for REC from literature	Classification
System energy efficiency	The ratio of consumed energy to the total generated energy. *This KPI is mainly relevant to regulatory authorities*	85–95% (Manso-Burgos et al. 2022; M et al. 2023)	Dynamic, absolute, application-level, technical
System operational CO_2 emission	The sustainability performance of an energy system by comparing its carbon emissions to a baseline scenario	0.08–0.2 $kgCO_2/kW^{*1}$ (Bianco et al. 2021; Manso-Burgos et al. 2022; M et al. 2023; Angelakoglou et al. 2020)	Dynamic, relative, application-level, sustainability, SH: all
Flexibility factor	Quantifies the technical capability of the system to adjust consumption, generation, or energy storage systems to import energy at the lowest price and export energy at the highest price within the overall trade market. *Relevant to consumer & DSO*	–^{*2}	Dynamic, absolute, application-level, technical
Capital expenditure (CAPEX)	Initial investment costs required to set up renewable energy infrastructure and related assets, defined here as Initial installation cost per kilowatt of installed capacity	1500–2000 €/kW *3	Static, absolute, application-level, economic
Operational expenditure (OPEX)	Costs associated with operation and maintenance after the initial setup	– €/KWh	Static, absolute, application-level, economic
Levelized cost of electricity (LCOE)	The total discounted costs incurred over the lifetime of a power generating system—including CAPEX and OPEX—by the total electricity generated during its lifespan	0.15–0.40 €/KWh *3	Static, absolute, application-level, economic

Table Notes: *(1) Range estimated for "fully self-supplied"—"fully grid-supplied"; *(2) New KPI definition; *(3) Ref. Chap. 6

KPIs. CAPEX represents the initial investment required for energy generation, storage, and infrastructure, while OPEX covers ongoing costs such as maintenance and management. These costs help in evaluating financial decision-making. Additionally, Levelized Cost of Energy (LCOE) provides standardized metrics for quantifying costs of electrical energy, considering instalment, operation, and management costs over the lifetime of the system. Together, these metrics provide a comprehensive assessment framework, supporting various key aspects of the system.

4.3 Functional Requirements for Hybrid Energy Storage Integration

To enable the services and integration of hybrid energy storage across electrical and thermal domains, we can establish a set of functionalities that need to be established and available for a REC to actively manage and benefit from the integration of electrical and thermal energy storage into a multi-domain hybrid energy storage system.

Power Grid

In terms of voltage levels, a wide range of voltages would be valid, from low voltage to medium voltage. Presumably it will be low voltage (400 V) for small RECs but could have an accessible medium voltage connection point. For larger RECs it is possible to have medium voltage distribution (e.g. 15 kV). Regarding power, the maximum rated power (determined by the rated power of the connection transformer) could be sufficient with the sizing already done with the renewable generation systems for cases oriented to consumption management and generation maximization, however, for an operation in the electricity markets to maximize profit, it may be necessary to have a contracted power equal to the power of the renewables plus the installed ESS.

Storage systems could be connected in a distributed manner along the grid, or at the point of connection of the REC to the grid, depending on the service to be provided. For example, a large ESS plant connected at the REC PCC could provide electricity market operation services, while a distributed system could provide voltage stability services within the RES distribution grid.

Communication for monitoring and control

The communications network interconnects each device with the overall REC energy management system. This network must be capable, in terms of hardware, of being able to interconnect all the devices in a robust way and be able to manage the frequency of the commands and the variables to be monitored. It is possible to use a dedicated grid such as an Ethernet network or to wire an RS485 type communication network, or to integrate into the electrical distribution network by means of PLC (Power Line Communication) type systems. The storage systems should be able to be integrated into the REC's communication grid.

Control and monitoring system

The overall REC energy management control system would be responsible for sending power commands to each system so that the objectives/services to be implemented are fulfilled. Through the communications grid, it would communicate via an internal communications protocol, presumably a field bus (e.g. MODBUS) with each of the generation systems, storage, and—if any—manageable loads. Depending on the size of the power grid, this system could have an additional distributed monitoring system, so that in addition to monitoring information from each of the generation and storage devices, monitoring is available with dedicated devices at different points in the internal REC network.

Electric power generation

These are the elements that inject electrical power into the grid and can be conventional generation directly connected to the grid—synchronous power generating module (e.g. hydroelectric plants, diesel generators) or connected through electronic converters—power park module (e.g. wind generators). In the following, this section describes converters as a type of equipment or system.

The generation systems should be able to be controlled by the overall energy management system, so that they share the same communications protocol, and exchange the required setpoints and monitoring signals.

Electrical energy consumption

Electrical energy consumption can be manageable or unmanageable. The unmanageable ones will be desirable to be monitored, and the manageable ones can be connected to the grid through electronic converters (e.g. an electric vehicle charger) or not (such as an industrial process that can be interrupted, like a pelletizer). Similar to generation, certain types of loads could be associated with storage systems for various purposes, such as ensuring uninterrupted power supply to such loads.

Electronic converters

Power electronics devices are responsible for interconnecting the internal AC distribution grid of the REC with, and forming part of, storage systems, renewable generation systems, and—if any—manageable loads. These power electronics systems are usually connected at low voltage (e.g. 400 V) but it would be possible to connect them at medium voltage (either using multilevel configurations or by means of transformers integrated in the systems).

The converters usually integrate the power management control of each individual device, which must integrate appropriate communication protocols to integrate into the overall power management system. The amount of data and its frequency may depend on the service in question to be provided by the REC, for example, participating in the electricity market (one day-ahead) may involve fortnightly setpoints, while participating in secondary frequency regulation may involve setpoints every 4 s. These requirements may define the necessary communications protocol, with the most common being the use of how buses (e.g. MODBUS, CANOPEN, etc.).

4.3.1 Heat Networks

Heat networks deliver heat from one or several central sources through insulated pipes to buildings for space and water heating. This heat often comes from cogeneration plants powered by fossil fuels or biomass. However, heat-only boilers, geothermal energy, heat pumps, solar thermal, industrial waste heat, and even nuclear power plants can also be used. District heating plants are generally more efficient and have better pollution control than individual boilers. If combined with heat and power they can be an effective way to reduce carbon emissions.

Control and monitoring of the thermal system

Control and monitoring of thermal systems includes the optimized management of heat production (using different energy sources efficiently), the distribution network (reducing heat losses and ensuring an adequate heat supply to all users), and demand (monitoring consumption and encouraging efficient energy use). Various technologies, such as sensors (namely thermocouples), valves, control units, management software, and communication systems, are used to achieve these goals.

Heat generators

Heat generators are essential components in various applications, from heating residential buildings to powering industrial processes. The most important ones could be summarized in the following categories: combustion-based, such as furnaces, boilers, and water heaters; electric-based, which use electricity to generate heat; solar thermal, that can capture solar energy and convert it into heat, like solar water heaters, solar air heaters or for higher temperatures: concentrated solar heat plants. Besides, geothermal generators are a useful way to adopt the Earth's natural heat to produce thermal renewable energy.

Thermal power generators

Thermal power generators are devices that convert heat energy into electricity, so they function as sector coupling devices. Typical technologies are Rankine cycle (steam) or using heated compressed air in case of Bryton cycle.

Thermal energy storage

A thermal energy storage t is a component that allows heat or cold to be stored for later use in a variety of applications, such as heating and cooling buildings, generating electricity, and powering industrial processes. Its application is essential for ensuring supply continuity for users of renewable energy, particularly solar. These components can operate for different durations: short (hours), medium (days), or long (seasons). Depending on the application, they can utilize sensible, latent, or thermochemical heat.

Heat Exchangers

They are devices designed to transfer heat between two or more fluids, used in a wide range of applications, from heating and cooling buildings to industrial processes. These devices can be realized in various configurations, including shell and tube (with plain or finned tubes), plate, spiral, and coil. Heat exchangers are essential components in many engineering systems, and their proper design and operation are crucial for ensuring efficiency and safety.

5 How Hybrid Energy Storage Meets Identified Needs and Its Expected Benefits

The requirements for the case of a renewable energy community have been outlined in the previous section. This section provides the specific application and model where the suitable hybrid energy storage configuration is defined.

5.1 the Renewable Energy Community with Hybrid Energy Storage

This case study of a renewable energy community with multi-domain hybrid energy storage solution is based on the physical characteristics of an existing microgrid facility, complemented with a virtual thermal power setup. The reference system for this complex renewable energy community is illustrated in Fig. 4. The energy storage solutions are added as modules that can be scaled to fit.

Electrical Subsystem

The given electrical system is an experimental facility of CIEMAT dedicated to develop and test renewable energy systems, located at Soria (Spain). This facility is a micro-grid composed of a medium voltage ring (15 kV) with 7 substations for low voltage transformation as shown in Fig. 4.

Electric power generation, energy storage and electricity consumption are distributed among the substations.

In particular, the given microgrid has the following power generations systems:

- 5 wind turbines with a total installed capacity of 150 kW
- 1 photovoltaic power plant and photovoltaic panels installed on the roofs of the offices with total installed capacity of 360 kW
- A diesel generator (for emergency events) with an installed capacity of 100 kW

The electrical consumers of this microgrid are the following:

- 3 different office buildings

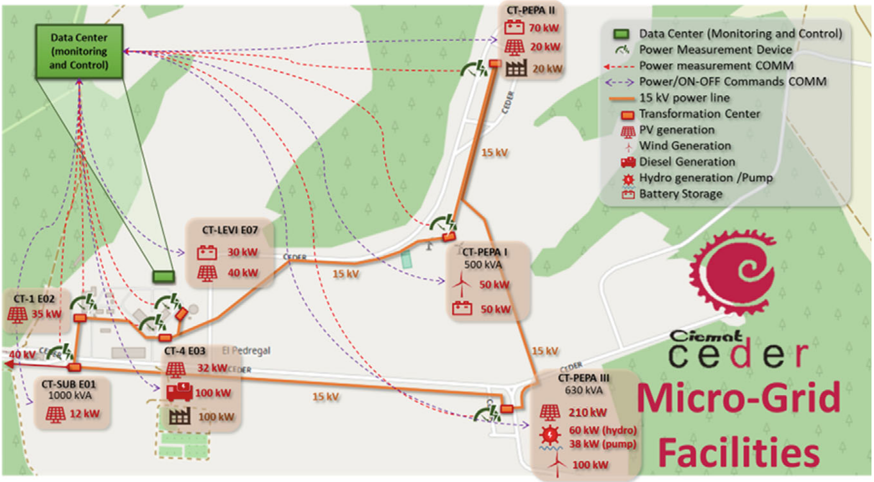

Fig. 4 Scheme of the CEDER facility microgrid

- 1 pelletizer facility (linked with a biomass power plant under commissioning), capacity of 100 kW electric.
- 8 electric vehicle chargers.

The microgrid has two relevant energy management systems, i.e. a complete DC grid to manage DC loads and battery-based storage systems, and a grid decoupling system to manage power within the power ring and emulate specific power frequency behaviours (not part of this model).

Thermal Subsystem

In addition to the physically present electrical system, the model includes a complementary fictional thermal network, based on components available in another lab facility.

The thermal power will be generated from renewable sources such as:

- A concentrated solar power plant (CSP) with an internal ESS based on molten salts. The output power of the CSP + ESS system has been evaluated for the irradiance of CEDER locations to maximize efficiency and power production.
- The CSP has the particularity that has a Rankine Cycle to allow heat conversion to electricity a part of the generated thermal power. This element permits to link both grids, electric and thermal, and it is considered essential in the energy management of the complete system.

The thermal consumption has been generated from real data and from standard consumptions of open databases. The available power consumption profiles to be considered has been hospitals, offices, residential buildings, hotels, and industrial loads. The consumptions have been scaled to the same scale as the real electric grid.

Hybrid Energy Storage System

The electrical ESSs considered in the reference model are based on real systems available in CEDER facilities. All ESS considered are connected to low AC voltage (400 V) by means of individual power electronic converters that allow managing the power delivered or stored by each subsystem. The analysis considers, in order to size the energy storage in the system, define the number of stacks or systems based on the following consideration of basic stack of each ESS type:

- A pumped hydro storage system with 50 kW of installed capacity and 2000 m^3 of deposit.
- The considered electrochemical energy storage system is modelled based on a stack of $LiFePO_4$ with 82 kW and 82 kWh of rated power and energy, respectively.
- A 150 kW fast energy storage system based on supercapacitors and a flywheel has been modelled, supporting grid stability analysis; however, this example study uses only a 1 h time resolution, it is not active.

In the thermal grid, molten salt-based systems are already integrated into the CSP and TSP and are governed as integrated part of the power plants themselves. An additional ESS based on PCM is integrated as pure thermal storage module to actively contribute to energy management.

The complete complex multidomain system will be controlled by a single energy management system to optimize performance metrics, as described further in Heussen et al. (2025a).

5.2 *Expected Benefits from Hybridization*

This section explains how energy storage contributes to benefits in the REC and how it is expected to enhance KPIs.

Expected Areas of Benefits

Benefits from the hybrid energy storage in the Renewable Energy Community application arise in two fundamental ways. Firstly, the introduced thermal energy storage systems *enable and facilitate* the integration of thermal renewable energy into the REC, thereby replacing fossil sources of energy, such as a combined heat and power plant or direct oil burners. Secondly, the cross-domain hybrid energy storage system *optimizes* the operation of the available energy storage systems with respect to efficiency and grid-oriented flexibility, which adds financial benefits.

To quantify this range of benefits, a set of four KPIs is proposed. The benefit of enabling solar energy in meeting thermal energy demands massively offsets carbon emissions, measured in terms of a relative KPI, the *Operational* CO_2 *emissions*, since the carbon offset is relative to a reference technology. The optimization benefit is associated with reducing energy losses (KPI: *System Energy Efficiency*), reducing cost of grid-procured electricity (KPI: *Operating cost*) and creating additional revenues by means of flexible operation with respect to the electricity grid (KPI: *Flexibility Factor*). With reference to the criteria outline in Sect. 3, these KPI cover technical, economic and sustainability criteria.

Quantification of Benefits Using Selected KPI

As outlined in Sect. 4.2, a set of KPIs has been identified to quantify the benefits of hybrid storage systems in the REC: system energy efficiency, system operational CO_2 emissions, and the flexibility factors. These KPIs have been selected to provide a comprehensive assessment of sustainability, technical and economic performance of hybrid storage systems. This subsection provides specific definitions and explanations of these KPIs.

In evaluating hybrid storage systems, it is essential to not only quantify performance improvements but also conduct a trade-off analysis to understand potential compromises, which further motivates the need for these KPIs. In this regard, system energy efficiency highlights how effectively the system minimizes energy losses during conversion and storage processes. System operational CO_2 emissions provide insight into sustainability performance, emphasizing the reduction in carbon emissions relative to a baseline scenario. Meanwhile, the flexibility factor and its variations help evaluate both technical and economic trade-offs, such as the system's ability to technically shift energy imports and exports during favourable price periods to reduce costs and economically maximize revenues.

Considering these KPIs, we can assess the system performance and quantify trade-offs like cost reductions and potential energy losses, that lead to an informed decision-making in the configuration of hybrid storage systems.

System Energy Efficiency

This metric measures how effectively an energy system utilizes the energy it generates. In essence, it is the ratio of the energy that is consumed to the total energy produced. The energy efficiency can be calculated for any types of energy in a hybrid power system as follows:

$$\begin{aligned} Efficiency =& (Consumed\ energy \\ & + Energy\ exported)/(Total\ generated\ energy \\ & +\ Energy\ imported) \end{aligned}$$

For a hybrid system with thermal and electrical subsystems, thermal and electrical efficiency can be calculated as follows, respectively:

$$\begin{aligned} Efficiency\_th =& (Consumed\ thermal\ energy \\ & + Thermal\ energy\ converted\ to\ electricity) \\ & /(Total\ generated\ thermal\ energy \\ & + Thermal\ energy\ converted\ from\ electricity) \end{aligned}$$

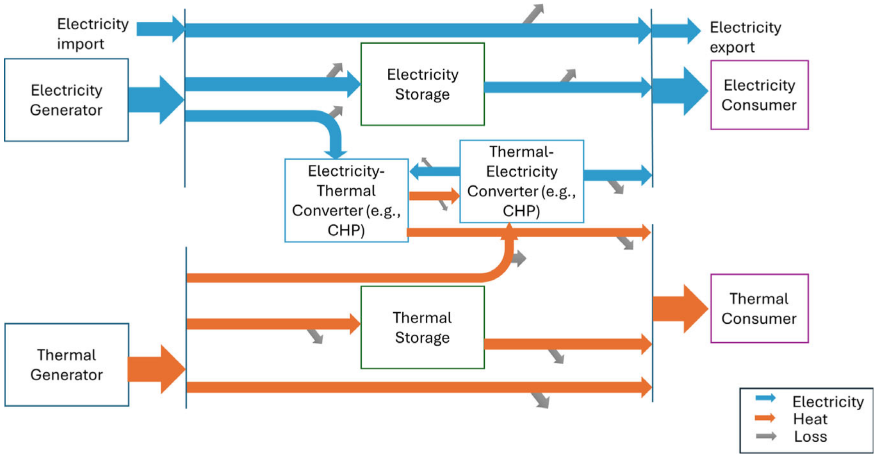

Fig. 5 Thermal and electrical energy flows in a hybrid energy system

$$\begin{aligned} Efficiency\_el = &(Consumed\ electricity + Exported\ electricity \\ &+ Electricity\ converted\ to\ heat) \\ &/(Total\ generated\ electricity + Imported\ electricity \\ &+ Electricity\ converted\ from\ heat) \end{aligned}$$

Figure 5 illustrates the interaction between different components of a thermal-electrical energy system, emphasizing how these interactions influence overall system energy efficiency. Energy efficiency in this context refers to how well the system minimizes energy losses and maximizes the use of both electricity and heat throughout the energy conversion, storage, and consumption processes.

System Operational CO_2 Emissions

This indicator quantifies the sustainability performance of an energy system by comparing its carbon emissions to a baseline scenario (Bianco et al. 2021). The baseline is defined as a situation in which all energy demands are met using traditional energy sources, such as fossil fuels. The metric expresses the reduction ratio in CO_2 emissions achieved by employing cleaner or more efficient technologies. The formulation is as follows:

$$ECO_2 = \frac{(Baseline\ \mathrm{CO_2}\ emission - Actual\ \mathrm{CO_2}\ emission)}{Baseline\ \mathrm{CO_2} emission}$$

A higher value reflects a more significant reduction in the system's carbon footprint.

Flexibility Factor

Inspired by established flexibility KPIs outlined in review paper (Clauß- et al. 2017), an enhanced flexibility factors has been devised in this section to comprehensively address the dynamics of energy systems. In this chapter, we just calculate the following flexibility factor and refer to the documentation for more factors (Heussen et al. 2025a).

The proposed Flexibility Factor represents the combined significance of imported energy at the lowest price time slots (LPT) and exported energy at the highest price time slots (HPT) within the overall trade market. It quantifies the system's technical ability to import energy during LPT and export energy during HPT. Thus, it is formulated as follows:

$$\begin{aligned} FF = &(Energy\ imported\ during\ LPT \\ &+ Energy\ exported\ during\ HPT) \\ &/(Total\ energy\ imported + Total\ energyexported) \end{aligned}$$

In this study, price slots are categorized based on the median price: prices above the median are classified as high-price time slots, while prices below the median are classified as low-price time slots. It is worth noting that the factor depends on import/export volumes and price variability. Besides, the calculation assumes that the total amounts of energy import/export remain constant. Special cases include fixed pricing or when transactions are absent during asymmetrical pricing. For simplicity, we have not delved into further details. The detailed formula and other flexibility factors can be found in Heussen et al. (2025a).

Cost Analysis: CAPEX, OPEX, and LCOE

This section presents key economic indicators for evaluating the financial viability of an energy system. These indicators include capital expenditure (CAPEX), operational expenditure (OPEX), and levelized cost of energy (LCOE). The CAPEX, OPEX, and LCOE are calculated as shown in the following.

- **Capital Expenditure (CAPEX)** accounts for the total investment required to establish an energy system, including the costs of equipment and installation.
- **Operational Expenditure (OPEX)** represents the fixed annual costs incurred in maintaining system operations. These costs are assumed to remain constant throughout the project's lifetime.
- **Levelized Cost of Energy (LCOE)** quantifies the cost of generating energy over the project lifetime, incorporating investment, operational, and fuel costs. It is calculated using the following formula:

$$LCOE = \sum_{t=1}^{n} \left[C_t + O_t + F_t)/(1+r)^t \right] / \sum_{t=1}^{n} \left[E_t/(1+r)^t \right]$$

where C_t represents the capital expenditure in year t, O_t denotes the operational expenditure in year t, F_t accounts for fuel costs in year t, and E_t represents the energy generated in year t. r is the discount rate, and n is the project lifetime in years. Key assumptions include a plant lifetime of 25 years, which is standard for this type of facility, and an annual discount rate of 3.41% (Mongird et al. 2019). A lower LCOE indicates improved cost-efficiency in energy generation. The metric provides a comparative basis for evaluating different energy systems under varying economic and operational conditions.

6 Technical–Economic and Sustainability Analysis of REC—Proof of Concept Study

A system model of the fully integrated renewable energy community with hybrid electro-thermal energy storage and conversion has been developed in parallel by using MATLAB Simulink as modelling environment, and an optimization module in the CPLEX environment. MATLAB Simulink was chosen to enable the potential investigation of faster time scales relevant to the electrical system integration and operation and due to the availability of models suitable for investigating this timescale. The optimization module is used for sizing optimization of components in the system and performing daily economic energy dispatch among HESSs and other dispatchable components. Simulink and optimization models are presented in detail in Heussen et al. (2025a), and the source code is available for evaluation at Heussen et al. (2025b).

For basic usage of the benchmark system, the following parameters are intended for adjustment by users:

- Day—Represents the simulated day of the year (0–365).
- P nominal—Defines power profiles for production and consumption, measured in peak kWs.
- Type of ESS—Specifies the type of electrical storage unit, selectable from options 1 to 3.
- Ness—Sets the number of parallel storage stacks (0–500).
- SoCi—Determines the initial state of charge for storage systems on a scale from 0 to 1.
- Location—Identifies the system's geographical placement, such as Soria or Portici.
- Profile Case—Defines the type of electric vehicles, building consumption, and pelletizer processes (see documentation for details).

Due to the modularity of the provided benchmark and the modelling framework, additional changes are straightforward to implement for advanced users, such as:

- Extension of the benchmark to other input data profiles and other locations
- The addition of alternative consumption profiles

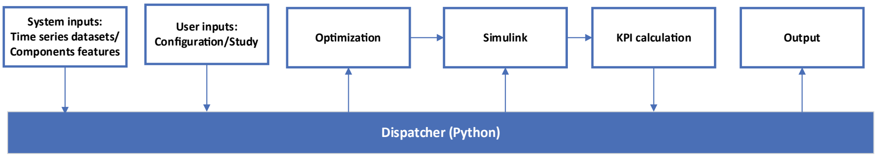

Fig. 6 Pipeline dispatcher and different modules of the system

The modular design of the system also facilitates the alteration of the system to serve more advanced study goals:

– Alternative electrical storage models (via drop-in replacement of existing storage models)
– Extension of simulation models to investigate performance criteria at faster time scales.

The calculation pipeline orchestrates the execution of a given study maintaining consistent parameters and configurations across optimization and simulation modules, ensuring traceable documentation of the process. The Dispatcher, as shown in Fig. 6 and as the core coordination module, manages the flow of data and computations across different components of the framework using Python.

The pipeline consists of the following key stages:

System Inputs: This stage includes time series datasets and component features, providing the foundational data required for simulations and analyses.
User Inputs: Users define the study configuration, specifying parameters and settings to tailor the simulation according to specific research or design objectives.
Optimization: This module processes input parameters and performs optimization computations, improving system performance based on predefined constraints and objectives.
Simulink: The framework interfaces with Simulink to execute dynamic simulations, validating and refining system behaviour through time-domain analysis.
KPI Calculator: KPIs are calculated based on simulation results, offering quantitative insights into system performance and efficiency.
Output: The results, including optimized parameters, simulation outputs, and performance metrics, are documented and stored for further analysis.

The Dispatcher integrates these components, ensuring seamless data exchange and execution order. This structured approach enables the automatic documentation of input data, parameters, and results, facilitating reproducibility and traceability. Additionally, it supports integration into larger data pipelines, such as impact assessments of design parameters or statistical design of experiments, making it a robust tool for complex system analyses.

The source code and data for the REC Benchmark are available in the public dataset (Heussen et al. 2025b), and further use cases as well as the user interface are documented in Heussen et al. (2025a).

Baseline Configuration Design

A basic system design was chosen based on heuristics that enable the REC to operate in a fully self-sufficient mode. This is an extreme case for a grid-connected REC and leads to high system costs but aligns well with the remote off-grid cases studied in previous book chapters.

To evaluate the performance of the hybrid storage system in various conditions, first, four representative days were selected through analysis, with one day chosen from each quarter of the year. The selection was performed using the k-medoids clustering method (Kaufman and Rousseeuw 1990), leading to the selected days for design: 20 February 2022, 23 May 2022, 28 July 2022 and 16 December 2022.

After selecting days, a basic dispatch is run through a simple rule-based approach used to allocate energy resources for each day, ensuring that energy storage is available for the next day. It consists of a thermal dispatch, where the Rankine Cycle system converts excess thermal energy into electricity for peak-saving, and the PCM system manages the remaining thermal energy. The electric dispatch prioritizes maximizing grid power delivery while minimizing grid power intake, using pumped hydro storage to reduce power exchange and batteries to manage residual energy. Shiftable loads such as EVs are not considered.

The dispatch process results in specific daily storage requirements, evaluated in three key metrics:

- Power-based requirement: Storage capacity needed to meet power constraints.
- Energy-based requirement: Storage capacity required to satisfy energy demands.
- Final storage requirement: The maximum of the power-based and energy-based requirements, ensuring system feasibility.

The results give the storage units' requirements for each day presented in Table 2.

Based on the analysis, the baseline storage capacities for the hybrid system are determined as average value of final storage requirement of the four main representative days as follows:

- 83 units of Battery Stacks
- 9 units of Hydro-Pump systems
- 28 units of PCM storage systems

Table 2 The storage units' requirements for each representative day

nDay	dateDay	nBAT			nHyP			nPCM		
51	20-Feb-2022	4	94	94	7	9	9	14	26	26
143	23-May-2022	3	77	77	7	11	11	13	26	26
209	28-Jul-2022	4	107	107	7	11	11	19	31	31
350	16-Dec-2022	4	53	53	7	5	7	13	27	27

Although one unit of Supercapacitor Energy Storage appears in the results, it is not utilized, so it has been removed from the study. The features of the ESSs are illustrated in Table 3 (values represent one unit/module).

Scenario Definition

To evaluate the impact of hybrid storage system variations on the REC, three different scenarios are considered, listed in Table 4, where variations between PCM and Battery storage module numbers were considered for approximately equal investment and maintenance cost. The idea of this scenario choice is to investigate trade-offs between electrical and thermal storage options in the REC application. Each scenario is investigated twice, using a self-sufficiency objective function, and an economic objective function. The economic scenario means that we minimize the total energy costs, while the self-sufficiency scenario means that we minimize the energy drawn from the grid.

Scenario Assessment Results

To assess the economic KPIs, CAPEX LCOE, and OPEX are listed in Table 5, calculated for the baseline configuration showing the initial capital cost of €757.65/kWh, which reflects the investment needed for full self-sufficiency in energy supply. Besides, the LCOE is 0.097€/kWh, and operational cost is obtained €1.54/kW, supporting the economic viability of the system.

For the performance evaluation, two days 51 and 143 were selected from the four original k-medoids-clustered design days to represent a range of seasonal and operational conditions. Table 6 compares system performance under self-sufficiency and economic objectives. The KPIs shown in the table reflect the average values calculated from these two days.

Table 3 Features of the storage systems

Features	Pumped-hydro energy storage	Battery	PCM
Maximum output power (kW)	450	6806	1400
Efficiency	75%	95%	90%
Capacity (kWh)	2575	6806	5740
Operation and maintenance cost (c£/kWh)	0.002	0.005	0.003

Table 4 Scenarios for hybrid storage system configurations and capital costs

Scenarios	Number of battery stacks	Number of PCM modules	Total capital cost of storages
Scenario 1	83	28	3,373,545
Scenario 2	88	20	3,380,925
Scenario 3	78	36	3,366,165

Table 5 Economic indicators of hybrid storage systems, including CAPEX, LCOE, and OPEX

KPIs	Value
Initial capital cost (CAPEX)	757.6476 €/kWh
Levelized cost of electricity (LCOE)	0.097€/kWh
OPEX	1.54€/kW

Across all scenarios, the flexibility factor remains relatively stable, ranging between 0.58 and 0.62, indicating that flexibility is not a major differentiator in this comparison. The more significant variations are observed in efficiency and CO_2 emission reduction.

It is observed that Scenario 1 offers strong overall performance, with high efficiency (0.93–0.94) and the greatest CO_2 emission reduction[7] under the economic objective (0.45 kg/kWh). Besides, Scenario 3 (economic) achieves the highest efficiency (0.98) while maintaining moderate emissions reduction (0.35 kg/kWh), making it suitable for performance-driven applications. In contrast, Scenario 2 (economic) shows the lowest efficiency (0.86) and minimal emissions reduction (0.02 kg/kWh), suggesting it is the least favourable configuration among the three.

Finally, the LCOE remains constant at 0.097–0.098€/kWh across all scenarios, suggesting that this difference in battery and PCM module configurations does not significantly affect the overall cost of electricity generation.

[7] The reduction in CO_2 emissions in our system—comparable to a fully renewable setup—can only be evaluated based on the energy exchanged between thermal and electrical systems. This assessment relies on the emission factors of the electrical and thermal grids. The emissive factor represents the greenhouse gas emissions (primarily CO_2) associated with the production and distribution of electrical and thermal energy. The emissive factors used in this study are 0.354 $kgCO_2$/kWh for the electrical grid and 0.202 $kgCO_2$/kWh for natural gas.

Table 6 Performance comparison of hybrid storage scenarios under self-sufficiency and economic objectives

KPIs	Scenario 1 (self-sufficiency)	Scenario 1 (economic)	Scenario 2 (self-sufficiency)	Scenario 2 (economic)	Scenario 3 (self-sufficiency)	Scenario 3 (economic)
Flexibility factor	0.62	0.62	0.60	0.60	0.58	0.58
Efficiency day	0.93	0.94	0.93	0.86	0.93	0.98
CO_2 Emission/kWh reduction	0.33	0.45	0.17	0.02	0.27	0.35
LCOE	0.097	0.097	0.097	0.097	0.097	0.098

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