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Advancing the energy efficiency of home energy storage systems

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Advancing the energy efficiency of home energy storage systems

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Executive Summary

Home Energy Storage Systems (HESS) are batteries and associated electronics installed in residential buildings for the purpose of storing energy. This report explores the current status of HESS energy efficiency, identifies current standards available to test HESS energy efficiency performance, identifies current barriers to lifting the minimum energy efficiency of HESS, and makes recommendations to address these barriers.

Energy efficiency is an important performance metric for HESS because inefficient products entering the market now will have lasting impact on energy consumption for the next decade, as typical product lifetimes exceed 10 years. The International Energy Agency projects 200 GW of behind-the-meter (HESS) storage capacity globally by 2030 under a net zero scenario. Differences in HESS energy efficiency performance now could result in substantially more energy consumed by 2030 if minimum performance standards are not implemented.

Energy efficiency in home energy storage systems: current status

Desktop review focused on product websites, product datasheets, performance testing standards, independent testing studies, and emerging regulations to develop an overview of HESS energy efficiency performance, testing standards, and regulatory responses. Over 90 HESS units on the market are included in the detailed analysis of HESS performance data, representing a range of cell chemistries including lithium-ion or nickel manganese cobalt (NMC), lithium titanate, lithium iron phosphate (LFP), and lead-acid chemistries. An overview of findings is provided, explored in more detail in Section 2:

Round trip efficiency (RTE) is the principal performance metric used to evaluate and communicate the energy efficiency performance of HESS. RTE is a percentage score that represents the relationship between the amount of energy flowing into a battery (charge) and the amount of energy that flows out (discharge). The higher the percentage score, the less energy lost during the charge-discharge cycle, the better the energy efficiency.

Testing parameters are the conditions under which HESS RTE performance is tested. Testing parameters vary widely between standards. Those found to influence RTE performance include ambient temperature profiles and duty cycle testing such as solar photovoltaic (PV) time shift or seasonal profiles.

Product datasheets were often missing round-trip efficiency (RTE) performance information, accounting for approximately 25% of the HESS units analysed. When RTE performance data is provided there is a lack of information on which performance testing standard/s were used to test RTE performance.

A review of available HESS energy efficiency performance data, representing just under 70 HESS units, highlighted the following trends, explored in more detail in Section 2:

- HESS energy efficiency performance ranges between 80% and 98%,
- Lithium cell chemistries typically report energy efficiency performance at 90% or higher,
- Lead-acid chemistries are less studied with respect to energy efficiency but generally claim efficiency above 80% and have achieved energy efficiency ratings of 87% under independent performance testing,
- RTE performance was significantly influenced by the level of integration of inverters within HESS units. Alternating current (AC) coupled systems tend to incorporate inverters into the HESS units and reported RTE ratings slightly lower, at between 80% and 95%, than direct current (DC) coupled systems, at 87% to 98%.

A lack of policy or regulation globally, or regionally, to mandate a consistent approach to HESS energy efficiency performance testing is having a negative impact on the availability of adequate and equivalent HESS energy efficiency performance information. As a result, a combination of issues are emerging which include gaps in energy efficiency performance data provision across the market, a lack of clarity on the equivalency of data that is reported, and differences in RTE performance results between datasheets and independent testing. Clarity on a preferred standard and mandated requirements to test to the standard/s would reduce variations in data availability and increase performance data equivalency.

Performance testing standards and regulations

Three performance standards and one regulation were identified during desktop analysis. More detail is provided in Section 2.6, and includes a comparison of performance metrics, required testing parameters, and information on the status of implementation. The standards and regulations covered in this comparison are outlined below:

- **International Electrotechnical Commission 61427-2:2015+AMD1:2024** International standard. Current standard.
- **Australian Battery Performance Standard** Australian standard, currently in review by Standards Australia.
- **The Standard for Uniformly Measuring and Expressing the Performance of Electrical Energy Storage Systems** United States standard. Current standard.
- **European Battery Regulation: Article 10** European Union. Status: Energy efficiency performance documentation required for all products from Aug 2024. Electronic performance information via the Battery Passport required from Feb 2027. Minimum performance standards will be introduced by Feb 2026 and apply from Aug 2027

Across the three standards and one regulation, differences are observed in the required performance testing metrics relevant to RTE (such as DC RTE, AC RTE, RTE fade at 50% of lifecycle), the parameters specified for testing (such as temperature or humidity), and the required duty-cycles that batteries should be tested to.

Approaches to lifting minimum energy efficiency performance

Introducing minimum energy efficiency performance standards for HESS could reduce the risk of poor performing products entering the market. No mandated minimum performance standards were identified for HESS in the jurisdictions under study. However, this is likely to change in the near future with the European Union announcing minimum performance standards to be introduced by 2026.

An approach to introducing minimum standards will need to balance a range of important performance parameters within an emerging market to avoid inhibiting technology development and innovation. Policy intervention could take the form of a rating system to differentiate performance within technology classes initially, with firmer minimum energy performance standards introduced as the home energy storage market matures. This approach would focus more on achieving standardisation in testing and information provision, an important first step towards better energy efficiency performance.

Recommendations

Mandate energy efficiency performance testing for HESS

Identifying and mandating a benchmark performance standard should be a goal over the long term, a common or harmonised standard could incorporate regional variability where necessary. Standards development often trends towards proliferation in the early stages, before eventually working towards consolidation. As the HESS industry and performance testing standards are still developing, identifying a globally harmonised standard now will reduce the burden associated with testing to multiple standards and provide certainty on performance expectations.

Mandatory testing will also provide transparent and reliable performance data for HESS performance comparison. RTE needs to be transparent, comparable across products, clearly identify the methodology used to evaluate performance, and differentiate efficiency relevant to the system scope (e.g., DC RTE, AC RTE).

Important testing parameters and testing to representative use cases must be incorporated into mandatory standards. Testing parameters that have been shown to influence RTE include ambient temperature and duty cycle testing. The only type of duty cycle testing identified during this study relates to solar PV connected HESS (e.g., solar PV time shift and seasonal profiles). Additional duty cycles should be integrated to assess the influence of other use cases on HESS energy efficiency performance, such as when HESS are used more intensely in the example of virtual power plants.

Establish a HESS performance rating system

Implement a HESS performance rating system like the System Performance Index developed in Germany. HESS could be rated on their performance by an independent testing body or manufacturers could be required to test to a mandatory standard. A performance testing and rating system would enable HESS manufacturers to achieve future product performance enhancements, particularly for batteries with inherent technical differences that may limit energy efficiency performance, before minimum standards are introduced. Firmer energy performance standards could be introduced as the HESS market matures.

Minimum energy efficiency performance requirements

The introduction of minimum energy efficiency performance requirements will reduce the risk of poor performing products entering the market. HESS energy efficiency is an important performance metric because inefficient products entering the market now will have an impact on energy consumption for the next decade, with typical product lifetimes in excess of 10 years. The International Energy Agency projects 200 GW of behind-the-meter (HESS) storage capacity globally by 2030 under a net zero scenario. Inefficient HESS entering the market now could result in substantially more energy consumed by 2030 if minimum performance standards are not implemented.

Contents

1. Overview

1.1 Problem definition

The home energy storage system (HESS) market is a rapidly evolving space. The battery market is experiencing major innovations in chemistries and technical capabilities, resulting in new models being released annually.

The typical range of HESS energy efficiency performance is not well understood. The HESS market is engaging inconsistently with performance testing and the provision of performance data. There is currently no standardised policy or regulation globally to manage the energy efficiency of HESS entering the market across the globe[1]. Nor is there a universally standardised approach to test and report energy efficiency performance for HESS [1].

Energy efficiency is an important performance metric for HESS because inefficient products entering the market now will have lasting impact on energy consumption for at least the next decade, with typical product lifetimes exceeding 10 years. The International Energy Agency projects growth of almost 200 GW of additional behind-the-meter (HESS) storage capacity globally by 2030 under a net zero scenario [2]. Differences in HESS energy efficiency performance now could result in substantially more energy consumed by 2030 if minimum performance standards are not implemented.

This research seeks to provide an overview of HESS energy efficiency performance and identifies current options available for future policy responses.

1.2 Approach to research

4E Technology Collaboration Programme of the International Energy Agency commissioned the Institute for Sustainable Futures to research the status of HESS energy efficiency. A series of questions were developed to guide the research, outlined below:

1. What are the typical energy efficiencies across HESS?
2. Are there inherent HESS product variations that result in differences in energy efficiency?
3. How are jurisdictions studying or regulating this product with regard to energy efficiency?
4. Are electrochemical home energy storage devices a suitable target for energy efficiency policy?

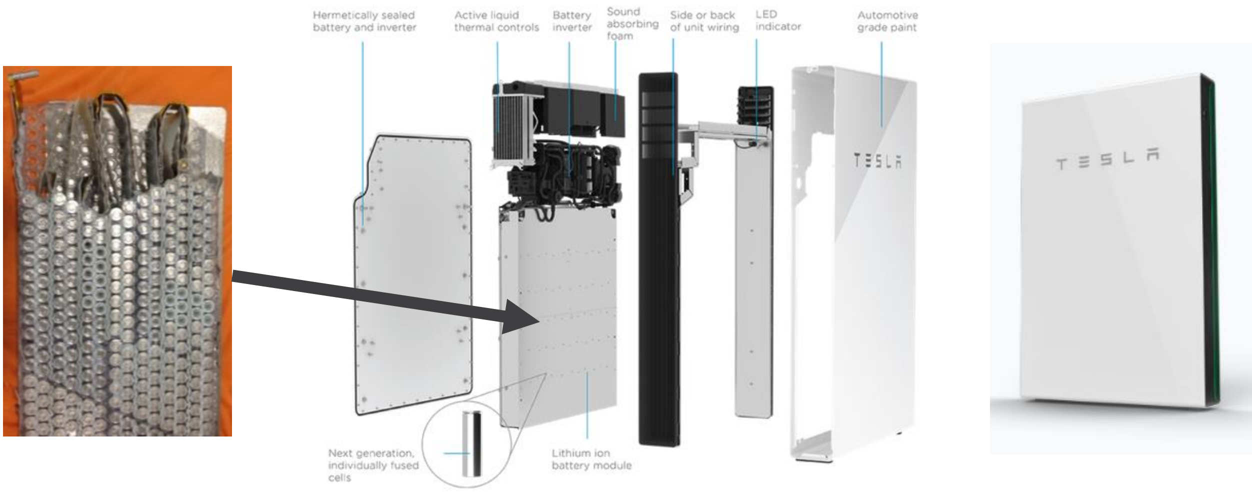
Desktop research collected data from product websites, product datasheets, performance testing standards, independent testing studies, and emerging regulations. Data was collated to develop insights on product specifications, system configurations, performance testing standards, and energy efficiency testing results. The results of this research are organised into four sections.

The first section provides an overview of the topic, explaining the system components included in HESS, discusses technical differences and describes typical applications. The second section presents data collected from the literature on energy efficiency performance and outlines available testing standards and regulations relevant for the purposes of testing HESS energy efficiency performance. The third section discusses research findings. Lastly, section four provides a series of recommendations for future policy responses.

1.3 Home Energy Storage Systems (HESS)

HESS are batteries and associated electronics installed in residential buildings for the purpose of storing energy. HESS falls under the broader category of stationary energy storage which encompasses grid scale batteries, community batteries, residential batteries, industrial batteries and batteries in recreational applications such as caravans, camping and mobile homes. Common terminology used to describe the broader ecosystem of stationary battery applications includes Battery Energy Storage Systems (BESS) and Stationary Energy Storage Systems (SES). This study focuses on energy storage systems for the residential markets, hence home energy storage systems (HESS).

An example of a HESS product, the Tesla Powerwall, is presented in Figure 1 below[1]. System components are discussed further in Section 1.4.



Inside the Tesla battery module are hundreds of cylindrical cells

The Tesla system incorporates an inverter and liquid cooling but not all HESS have these components.

Figure 1 Tesla Powerwall, adapted from Nexus Solar.

1.4 HESS components and system inclusions

HESS currently available on the market feature a range of component inclusions and capabilities. Some products are designed as a stand-alone, all in one unit, with an integrated inverter and WIFI connectivity. Other models provide the battery pack only and are designed to be built into a system, along with relevant supporting electronics. Additional electronic components integrated into the design of a HESS product have the potential to increase system energy consumption during normal operation and therefore reduce energy efficiency. With this in mind, it is important to know which components can be included in a HESS so that different systems can be compared on an equivalent basis when it comes to energy efficiency performance. This section highlights the key components that may be included within a HESS. Section 2.4 discusses the potential energy efficiency implications of including or not including certain components.

Battery pack and associated electronics

Battery packs and associated electronics comprise cells and modules, the battery management system (BMS), the thermal management system (TMS) and the energy management system (EMS). These individual components, along with batteries cells, modules and electronics are described in more detail here.

Battery cells, modules, and electronics

All HESS will include battery cells or packs, which come in different shapes, sizes and chemistries. Cells or packs are connected to each other in series or parallel to create battery modules. Battery modules are managed via a module management system (MMS) which monitors and controls the voltage, current and temperature of each individual cell within the battery module.

Battery management system (BMS)

[1] https://nexussolar.net/everything-you-need-to-know-about-the-tesla-powerwall-2/

Some battery packs and/or modules require a battery management system (BMS). Lithium chemistries require a BMS while lead acid batteries typically do not. As lead acid technologies have evolved, some products are starting to incorporate BMS's. The BMS monitors and controls the voltage, current and temperature across all battery packs or modules, communicating with the module management systems (MMS).

Thermal management system (TMS)

The TMS can be active or passive and are used to regulate the HESS temperature during charging and discharging. Active TMS's integrate liquid cooling or fans to keep the temperature regulated. Passive systems incorporate vents into the HESS design to promote airflow to regulate the temperature but do not require power.

Energy management system (EMS)

The EMS coordinates across all electronics and management systems within the HESS. EMS's sometimes integrate cloud connectivity for more sophisticated energy management and offer the potential to integrate with other home energy system devices and appliances within the home. WIFI enabled EMS's can facilitate connection to other HESS's on the electricity grid to create virtual power plants, as demonstrated in Sonnen's virtual power plant technology, SonnenCommunity[2].

Power conversion / inverters

Power conversion is required to transform DC energy to AC and vice versa. Conversion is also required to a lesser extent to manage differences in voltage between solar PV systems and HESS.

Some, but not all HESS's incorporate inverters for power conversion into their products which has resulted in significant variations in the reported efficiency ratings across products. Inverters are increasingly built-in to AC coupled and hybrid systems to optimise conversion efficiency, save space, and create energy back-up independent of the grid. The efficiency performance of inverters and other HESS equipment is explored further in Section 2.4. Variations in HESS scopes are explored in more detail below; this overview is adapted from Orth et al., 2023 [3]:

- DC coupled systems do not incorporate inverters within the HESS. The battery pack or unit is stand alone. The inverter component is considered outside the scope of the HESS and sold as a separate component.
- AC coupled HESS usually incorporate an inverter within the HESS. If an AC coupled system is connected to solar PV the energy for the system is converted twice. Once from the PV system to the grid or load and then a second time from the grid to the battery. This introduces inefficiencies which are explored further in Section 2.
- Hybrid HESS also incorporate an inverter, similar to AC coupled systems, but hybrid systems integrate both the AC connection for the grid and load and the DC connection for solar PV.

Figure 2 demonstrates typical HESS product designs on the market. It should be noted that AC coupled systems may or may not be integrated with a solar PV system, indicated by the dotted line in Figure 2. An AC coupled HESS could be installed as a stand-alone system.

[2] https://sonnengroup.com/sonnencommunity/

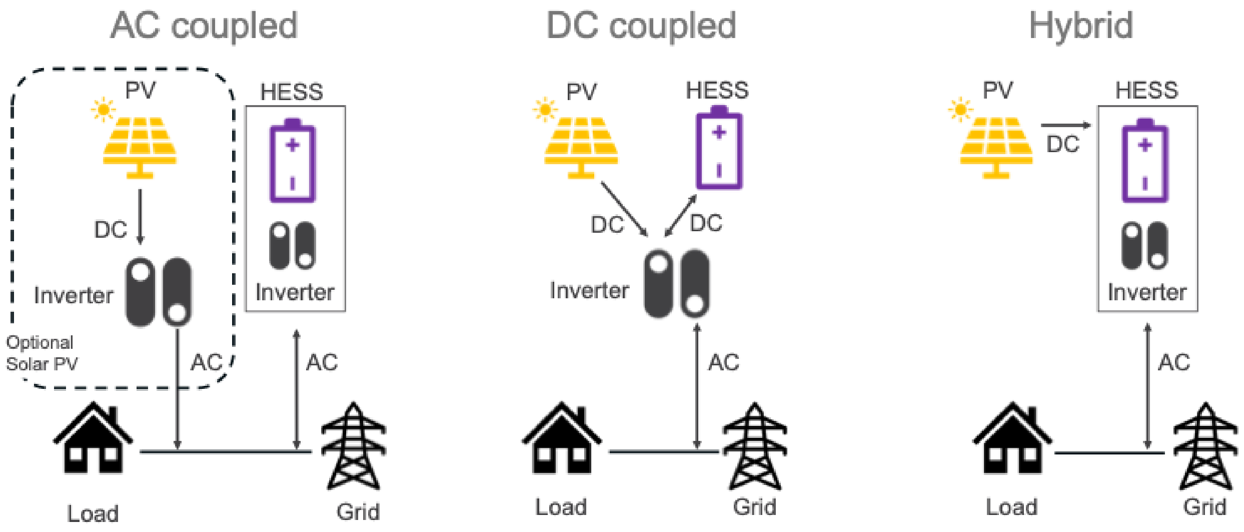


Figure 2 Typical HESS product configurations. Adapted from Orth et al., 2023 [3]

2. Energy efficiency performance

This section describes the principal metric used to describe energy efficiency in HESS, provides an overview of performances observed across the HESS market, and compares relevant testing standards and regulations. Performance data was collected from product manufacturer datasheets, comparison assessments, and manufacturer websites, as well as reports and papers published by independent performance testing studies. Just over 90 different HESS units were reviewed to provide this overview of HESS performance. A range of cell chemistries are represented, including lithium-ion or nickel manganese cobalt (NMC), lithium titanate, lithium iron phosphate (LFP), and lead-acid chemistries.

2.1 Communication of HESS energy efficiency performance

Round trip efficiency (RTE) is the principal performance metric used to evaluate and communicate the energy efficiency performance of HESS. RTE is a percentage score that represents the relationship between the amount of energy flowing into a battery (charge) and the amount of energy that flows out (discharge). The higher the percentage score, the less energy lost during the charge-discharge cycle, the better the energy efficiency. RTE is tested under certain conditions, referred to in this report as testing parameters. Testing parameters vary widely between standards. Testing parameters can include standard and extreme ambient temperature profiles, humidity, elevation, solar PV or seasonal time of charge and use profiles. A seemly simple concept can become complicated when comparing the range of testing standards available (see Performance testing standards) as well as the HESS technological inclusions and capabilities.

Energy efficiency of HESS should be understood with respect to the components included within the scope of a system, which can have an influence on overall energy efficiency ratings. Performance has also been found to be influenced by the cell chemistry. The next sections provide an overview of HESS RTE across the market, differentiating RTE performance by technical capability, system scope, and cell chemistry. This is followed by a detailed examination of efficiency losses by component.

2.2 HESS energy efficiency across the market

Fast-moving HESS product innovations have resulted in a flurry of approaches to communicating product performance specifications, with varying degrees of engagement with energy efficiency performance testing and claims. Differences in approaches to testing and communicating performance has ultimately resulted in a lack of clarity around product performance that can be expected across the market.

Studies have reported issues with products entering the market without sufficient performance testing and manufacturers have gone into administration soon after product release [4] resulting in the potential for poor product performance, a lack of appropriate product support, and a stranded product when issues emerge.

Product datasheets, where HESS performance information is found, lack comprehensiveness and standardisation. Findings indicate a lack of round-trip efficiency (RTE) performance information on some product datasheets, accounting for approximately 25% of the HESS units analysed in this desktop review. Additionally, when RTE performance is reported there is a lack of information on which performance testing standard/s were used to derive RTE. Variations in performance data provision has a significant impact on effective product comparison [1]. Consumers, system designers, and installers are left to make important purchase decisions whilst relying on inadequate product information [4]. This information gap is creating a high risk of poor performing products entering the energy market. The implications for energy efficiency across the whole energy system is significant, given the rapid growth expected in HESS adoption.

An overview of HESS energy efficiency performance, based on available performance data and representing just under 70 HESS units, is provided in Table 1. HESS energy efficiency performance data was collected directly from manufacturer datasheets [5] and independent testing studies [3,6,7]. Energy efficiency performance for DC coupled HESS has been reported as high as 98%, ranging from around 87% RTE. AC coupled and hybrid systems range in efficiency between 80% and 95%.

Table 1 Typical energy efficiency achieved across HESS on the market, relative to system scope.

AC coupled and Hybrid HESS		DC coupled HESS	
~80%	~95%	~87%	~98%

Differences observed between product datasheets and independent testing results

A difference in RTE performance was observed when comparing HESS data sheets with independent product testing results. Several reasons could cause the discrepancy between RTE reported on product datasheets and RTE performance observed in independent testing, including:

- Variations in testing methods or standards used,
- Variations in testing equipment,
- Observed RTE fade. One independent study performed testing over the anticipated HESS lifecycle and provided the average RTE performance over this time. It is possible that this average has picked up on fade in RTE performance over time, however, this study did not report performance fade as an output [6].
- RTE performance scope not specified. For example, several product datasheets for AC coupled or hybrid systems did not specify whether the performance reported was AC RTE or DC RTE,

Testing and reporting RTE performance according to AC RTE and DC RTE is critical to ensuring testing results are equivalent and comparable. This is because AC RTE will typically include an inverter within the scope of system testing, which can result in reduced RTE performance. The efficiency implications of different HESS components are explored in more detail in Section 2.4.

2.3 HESS energy efficiency by cell chemistry

Lithium cell chemistries typically achieve a higher energy efficiency compared to lead-acid chemistries, notwithstanding technical differences mentioned in Section 1.4. This is because the internal resistance during charging and discharging is lower for lithium chemistries compared to lead acid. Lower efficiencies are particularly pronounced during high charge and discharge rates – also referred to as cycle rate or C-rate.

HESS containing lithium battery packs typically use lithium iron phosphate (LFP) or nickel manganese cobalt (NMC) cell chemistries, but new chemistries are continually emerging. Lithium chemistry variations feature higher energy efficiency ratings than lead acid chemistries. Flow chemistries are now more typically used in grid or larger scale applications and less common in residential applications, however one study in Australia tested a flow battery that was on the market for a short period and so the results have been included here.

- Lithium chemistries typically report >90% efficiency [3–5,8].
- Lead-acid chemistries are less studied with respect to energy efficiency but generally claim efficiency above 80% and have achieved energy efficiency ratings of 87% under independent performance testing [4].
- Flow chemistries are now predominantly servicing the grid scale market, but one example previously on the residential product market in Australia achieved 75% RTE under independent testing [4].

2.4 HESS energy efficiency by component

If certain components, such as power conversion equipment (inverters), are included within the scope of the HESS this can significantly influence the overall RTE performance. A study by Munzke et al., 2021 [8], describes the potential for efficiency losses across individual HESS components. The study tested 12 different lithium-ion HESS systems according to an average annual consumption of 4200kWh with seasonal PV time shift testing for a region located in Germany. This is the only study identified during desktop review that provides a detailed breakdown of efficiency losses by individual HESS components. The insights provided are important for understanding why some HESS perform better than others, but the results also highlight where there may be opportunities to improve HESS energy efficiency performance.

Battery pack and electronics

The battery pack and associated electronics were found to contribute between 0.2% and 1.8% of energy efficiency losses [8]. Losses occur during charging and discharging of individual cells and via electronic systems such as the module management system (MMS), battery management system (BMS) and thermal management system (TMS) which contribute to the control of voltage, current and temperature.

Auxiliary loads and standby

HESS AC and DC stand-by or auxiliary consumption was found to contribute between 0.05% and 1.3% of energy efficiency losses [8]. Electronic equipment will consume energy even if the battery is not charging or discharging as optimal HESS parameters are monitored and managed. Energy is also consumed through LED displays, if they are integrated into the HESS.

Power conversion equipment

Power conversion equipment, also referred to as inverters, were found to contribute between just over 4% and just under 16% of energy efficiency losses [8].

Some, but not all HESS's incorporate inverters for power conversion into their products which has resulted in significant variations in the reported efficiency ratings across products. A summary of the impacts of including power conversion equipment is provided below:

- **DC coupled HESS typically report higher energy efficiency performance** as they do not include an inverter in their assessment of RTE. Inverters sit as a separate component to the battery system. Energy efficiency ratings of DC coupled HESS typically only consider DC connected components, technically referred to as DC Round trip efficiency.
- **AC coupled HESS typically report lower energy efficiency performance during testing.** An AC coupled HESS will typically achieve a lower efficiency rating than a DC coupled HESS because the inverter will be included in the efficiency assessment, unless DC RTE has been specified. AC coupled systems are also particularly inefficient when integrated with a solar PV system because both the solar array and the HESS will incorporate an inverter and therefore energy is converted twice across the home energy system. To effectively compare AC coupled HESS with DC coupled HESS, RTE should be tested and recorded as both AC RTE and DC RTE. However, testing studies have reported difficulties in isolating DC components in an AC couple system for the purpose of testing DC RTE [6].
- **Hybrid HESS are typically more efficient than AC coupled systems**. A hybrid HESS integrates an inverter and connection for both the solar PV and the grid, reducing the double conversion and inefficiencies of the AC coupled system. This design can have a positive impact on energy efficiency if the system is appropriately designed and sized for the use case. However, to effectively compare the performance of hybrid HESS with other systems, RTE should be tested and recorded as both AC RTE and DC RTE. Isolation of DC components may prove challenging, as testing studies have reported difficulties in isolating DC components in AC compatible systems for the purpose of testing DC RTE [6]

Additionally, test results produced by Munzke et al [8], indicate that partial load during battery discharge is an important determinant of power conversion inefficiency and recommends that batteries designed for home storage applications should be optimised for efficiency at partial load. During the study it was shown that a large proportion of household loads fall under 1kW, therefore HESS should be optimised for efficiency under 1kW energy load. Additionally home energy management systems could optimise charge and discharge to avoid partial loads where feasible.

Peripheral equipment

Cloud-based energy management is emerging as an innovative feature to manage the charge cycle of HESS and other energy producing, consuming, and storage products in the home. It was determined in the study by Munzke et al., 2021 that 'peripheral equipment', which includes cloud-based features, account for between 0.3% and 3.4% of efficiency losses [8].

2.5 Emerging HESS capabilities

Most HESS that offer cloud or remote energy management and monitoring will allow the user to monitor energy flowing in from the solar PV system, energy being stored in the HESS, and energy used in the home. Energy use is usually characterised as one load without the ability to differentiate between different energy using appliances.

Smart energy management capabilities are increasing. However, energy management functionality is usually enabled through aftermarket energy monitoring hardware and apps that can control energy across the home, including appliance management.

HESS are increasingly integrating energy management functionality within the scope of the product, with examples of advancements outlined below:

1. Basic state of health monitoring which incorporates either an app or access to a webpage that gives information on battery state of health information such as voltage, temperature and current. An example of this type of cloud-based energy management is featured with the PowerPlus brand's PowerLink module[3].
2. A more advanced HESS monitoring system integrates with the solar array or grid to provide usage information. An example of this functionality is the Tesla App for Energy[4]. The Tesla Powerwall also features a storm watch function which automatically charges the battery in the case of a storm warning to provide backup energy in case of an outage.
3. Apps and features are emerging that enable connection with other HESS's across a regional network to create a virtual power plant. This technology is available in Sonnen products, called the SonnenCommunity[5].

HESS energy efficiency performance could be enhanced through better integration with home energy management system (HEMS) products. The efficiency benefits could include:

- Energy efficiency optimisation via better energy management between HESS and other energy using appliances in the home such as hot water systems, pumps and electric vehicles.
- Product lifetime extension through monitoring and management of both energy system and weather events that push HESS outside of their optimum operating parameters. For example, HESS perform sub-optimally at rates of discharge under 1kW or when temperatures are extreme.
- Monitoring, reporting and optimisation of HESS state of health parameters like RTE, characterisation of RTE fade based on current usage, and user suggestions on how to positively influence future state of health.

The type of functionality identified in the points above require separate components to those incorporated in the HESS, including power monitors, controllers and a separate app to those integrated in HESS. Capabilities are emerging in products like the Schneider Electric Pulse Smart Panel and associated energy management app available in the US[6].

2.6 HESS performance testing standards, regulations and ratings systems

An overview of HESS performance testing standards and relevant regulations is provided in this section. A review of available standards was performed with a regional focus on Europe, Australia, and the United States. An international standard was identified during the desktop review, also included below.

Performance testing standards

There are different regional approaches emerging regarding energy efficiency performance testing for HESS. Standards working groups globally have made significant progress in the development of testing and performance evaluation procedures for the purpose of communicating the energy efficiency performance of

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[3] https://www.powerplus-energy.com.au/wp-content/uploads/2022/05/V2.0_powerlink_specifications_powerplusenergy.web_.pdf
[4] https://www.tesla.com/en_au/support/energy/powerwall/mobile-app/tesla-app-for-energy
[5] https://sonnengroup.com/sonnencommunity/
[6] https://shop.se.com/design-your-system/undefined/schneiderhome/pulse-smart-electrical-panel

HESS [3,4,6,8–15]. Extensive work has culminated in the development of three performance testing standards and one regulation (minimum performance standards yet to be released). International and regional approaches to energy efficiency performance testing and reporting are outlined in Table 2, including information on the status of implementation.

Table 2 Performance testing standards and regulations for HESS

	Performance standard or regulation	Round trip efficiency metrics	Testing parameters	Additional testing specifications
International	International Electrotechnical Commission 61427-2:2015+AMD1:2024 [9] *Status: published standard*	RTE (without Power Conditioning Equipment) %	Standard temp. 25C Min and max temp: manufacturer specified	Endurance test for PV time-shift
Australia	Australian Battery Performance Standard [10] *Status: currently being considered for publication by Standards Australia*.	1.DC RTE (without Power Conversion Equipment) % 2. DC Coulombic RTE (without Power Conversion Equipment) % 3.AC RTE (with Power Conversion Equipment) %	Standard temp. profile: 25C Extreme temp. profile: -12C to 41C Seasonal temp. profile: (solar shift) Humidity	DC and AC RTE across 4 seasonal and 4 regional profiles.
European Union	European Battery Regulation – Article 10 [15] *Status: energy efficiency performance documentation required for all products from Aug 2024* *Electronic performance information via the Battery Passport required from Feb 2027* *Minimum performance standards will be introduced by Feb 2026 and apply from Aug 2027*	Initial RTE and its fade at 50% of cycle life, as a %	Ambient temperature requirements may be specified with release of minimum performance standards.	State of Health information Remaining RTE
United states	The Standard for Uniformly Measuring and Expressing the Performance of Electrical Energy Storage Systems [14] *Status: published standard*	RTE over one duty cycle under normal operating conditions, %	Manufacturer specified operating temperature range.	Standby Energy Loss Rate Self-Discharge Rate
Comment	Performance testing standards and regulations presented above are at various stages of implementation, as noted in status information.	Round-Trip Efficiency is the key performance metric across performance testing standards, however, testing procedures to derive round trip efficiency differ slightly. E.g., The Australian Battery Performance Standard stipulates the testing and reporting of DC and AC round trip efficiency. While other standards do not.	Ambient temperatures, particularly extreme temperatures, during testing have a significant influence on average round trip efficiency performance. Ambient temperature and humidity testing profiles should be specified as part of any regionally specific performance testing standard.	If HESS are integrated with solar PV then duty cycle testing (e.g., Solar PV time-shift, or seasonal load profile) will give a more accurate picture of average round trip efficiency over seasonal temperature and solar availability variation. Including a requirement for state of health information could eliminate the need for an independent testing regime to verify RTE performance.

Duty cycle testing

Duty cycle testing describes testing the performance of a battery relative to the role that battery is designed to perform. In the residential market there are several functions that HESS may be required to perform, including but not limited to back up power generation in power shortages, solar energy storage, price responsive storage, and virtual power plants. Testing standards and regulations featured mature duty cycle testing protocols for HESS integrated with solar PV, referred to as solar PV time-shift testing or seasonal load profile testing. Testing protocols that represent other duty cycles were not specified within the standards.

Performance Rating Systems

The System Performance Index, is an example of a performance testing and rating system, developed by the Solar Storage Systems Research Group in Germany [16]. This performance index rating system tests the performance of HESS according to a representative duty cycle and ranks them within performance classes from A to G, where class A scores higher than or equal to 94.5% (10kW systems). The lowest performance class, class G, scores lower than 82.5% RTE (5kW systems). No other performance ranking or rating systems were identified.

Table 3 HESS System Performance Index rating system developed in Germany

Class	SPI (5 kW)	SPI (10 kW)
A	≥ 92.5 %	≥ 94.5 %
B	≥ 90.5 %	≥ 93.5 %
C	≥ 88.5 %	≥ 92.5 %
D	≥ 86.5 %	≥ 91.5 %
E	≥ 84.5 %	≥ 90.5 %
F	≥ 82.5 %	≥ 89.5 %
G	< 82.5 %	< 89.5 %

3. Discussion

Energy efficiency performance

HESS energy efficiency is an important performance metric because inefficient products entering the market now will have a lasting impact on energy consumption for the next decade, as product lifetimes are typically over 10 years. The International Energy Agency projects 200 GW of behind-the-meter (HESS) storage capacity globally by 2030 under a net zero scenario. HESS energy efficiency performance is highly variable across the market, with RTE ranging between 80% and 98%. Inefficient HESS entering the market now could result in substantially more energy consumed by 2030 if energy efficiency performance is not managed.

Performance testing

Performance testing and disclosure of performance information is still substantially voluntary, influencing the degree of engagement with HESS performance testing. This is evidenced by the uneven provision of performance information on HESS datasheets and a lack of information about testing standards used when efficiency performance is reported, as noted in Section 2.2. Good quality, reliable, and comparable data on energy efficiency performance is essential for HESS comparison and energy efficient system design.

Variations were observed in the reported HESS RTE performance between independent performance testing studies and manufacturer product datasheets. Potential reasons for these differences include variations in testing methodologies, testing equipment, or testing over different timeframes (see Section 2.2). These issues could be addressed with a compulsory requirement to test HESS performance to a common testing standard, incorporating regional variations where necessary. Testing could be performed or overseen by an independent body to ensure that variations in testing equipment and methods are minimised.

A range of testing parameters or conditions have been shown to influence RTE performance. Performance testing standards should incorporate performance testing parameters that have been shown to influence RTE, such as ambient temperatures (particularly extreme temperatures) and system technical capabilities (AC or DC coupled). Incorporating testing parameters that simulate real operating conditions give a more comprehensive picture of RTE performance under different environmental conditions, especially important in the context of rising temperatures caused by global warming. Humidity and elevation profiles have been specified in some testing standards, indicating that these parameters could have an influence on HESS performance. Investigation, via further testing studies, should be performed to determine the influence of these parameters on HESS performance.

In addition to environmental testing parameters mentioned above, duty cycle testing provides confidence that a HESS will perform well under certain conditions of use. Several standards identified specify duty cycle testing relevant to solar PV integrated HESS, for example in the Australian Battery Performance Standard [10] and the IEC standard [9]. However, there was a lack of specifications for testing to other duty cycles that may simulate more intensive usage patterns, such as in the case of virtual power plants. Duty cycle testing standards could be extended to incorporate testing a range of use cases such as price responsive storage systems and virtual power plants to assess the performance of HESS under these alternative operating conditions.

As HESS performance testing standards continue to develop, it is likely that additional regionalised approaches will emerge. As much as possible, regional variations should be incorporated into a harmonised or common standard that could be applied across regions. A common standard applied across regions could reduce performance data equivalency issues and aid performance comparison across the market.

4. Recommendations

There are three major policy options that could be considered to improve HESS energy efficiency, including performance testing, HESS ratings and labelling, and minimum energy performance standards for HESS. In practice, a minimum energy performance standard would require both performance testing standards and ratings to be established before they could be implemented. A discussion of HESS energy efficiency performance testing and data provision issues are discussed in this section followed by a list of policy options.

Three policy options for improving HESS energy efficiency are outlined below.

Policy option 1: Mandate energy efficiency performance testing for HESS
Description A benchmark standard/s should be identified, which could incorporate regional differences where necessary, to provide a single, globally harmonised, approach to energy efficiency performance testing. HESS manufacturers or an identified representative body should be required to test HESS to the identified standard/s before the product enters the market. Performance testing should include a consistent list of key performance testing metrics and parameters commonly found in available standards, such as: • DC RTE • AC RTE • Standard temperature profile testing • Extreme temperature profile testing • Humidity and elevation profile testing • Duty-cycle testing which incorporates different use cases. Standards are already incorporating PV time shift testing. Other duty-cycle use-case testing should be established where necessary, for example when HESS are being used more intensely as in the case of a virtual power plant. • RTE performance information could be monitored over the product lifetime by energy management systems and incorporated into product state of health data. **Reasoning** Standards development often trends towards proliferation in the early stages, before eventually working towards consolidation. As the HESS industry, and associated performance testing standards are still developing, identifying a globally harmonised standard now will reduce the burden associated with testing to multiple standards and provide certainty on performance expectations. As the HESS industry, and associated performance testing standards are still developing, identifying a globally harmonised standard now will reduce the cost burden for industry, governments and consumers down the track. Identifying one performance standard across jurisdictions should be a goal over the long term. In the absence of a clearly identified performance testing standard in the meantime, any policy response must be developed with a clear understanding of the inconsistencies in methodologies, testing metrics and parameters across current performance testing standards and regimes. Independent testing has highlighted metrics and diagnostics that influence RTE performance. • Differentiation of RTE by DC and AC provides equivalent performance information across products regardless of the HESS technical scope or component inclusions. • Ensuring RTE is measured and reported across standard and extreme ambient temperature profiles provides information on product performance across a range of seasonal and regional conditions. Humidity and elevation profiles should also be specified in performance testing standards due to the potential for impact on HESS energy performance, although the impact of these parameters on energy efficiency is less clear at this stage. • Duty-cycle testing replicates specific use cases and tests performance according to the intended use case. An example is PV time shift testing which checks how well the system responds to changes in demand or fluctuations in solar generation over seasonal charge and discharge variations. Energy efficiency is impacted by the state of charge at each charge/discharge cycle, which is both impacted by solar availability and energy use. HESS state of health information could incorporate RTE performance monitoring and reporting information. Monitoring RTE throughout the product lifetime can enable the study of RTE fade and the resulting impact on the energy system. The European Battery Regulation requires the characterisation of RTE fade during product testing [15], however, due

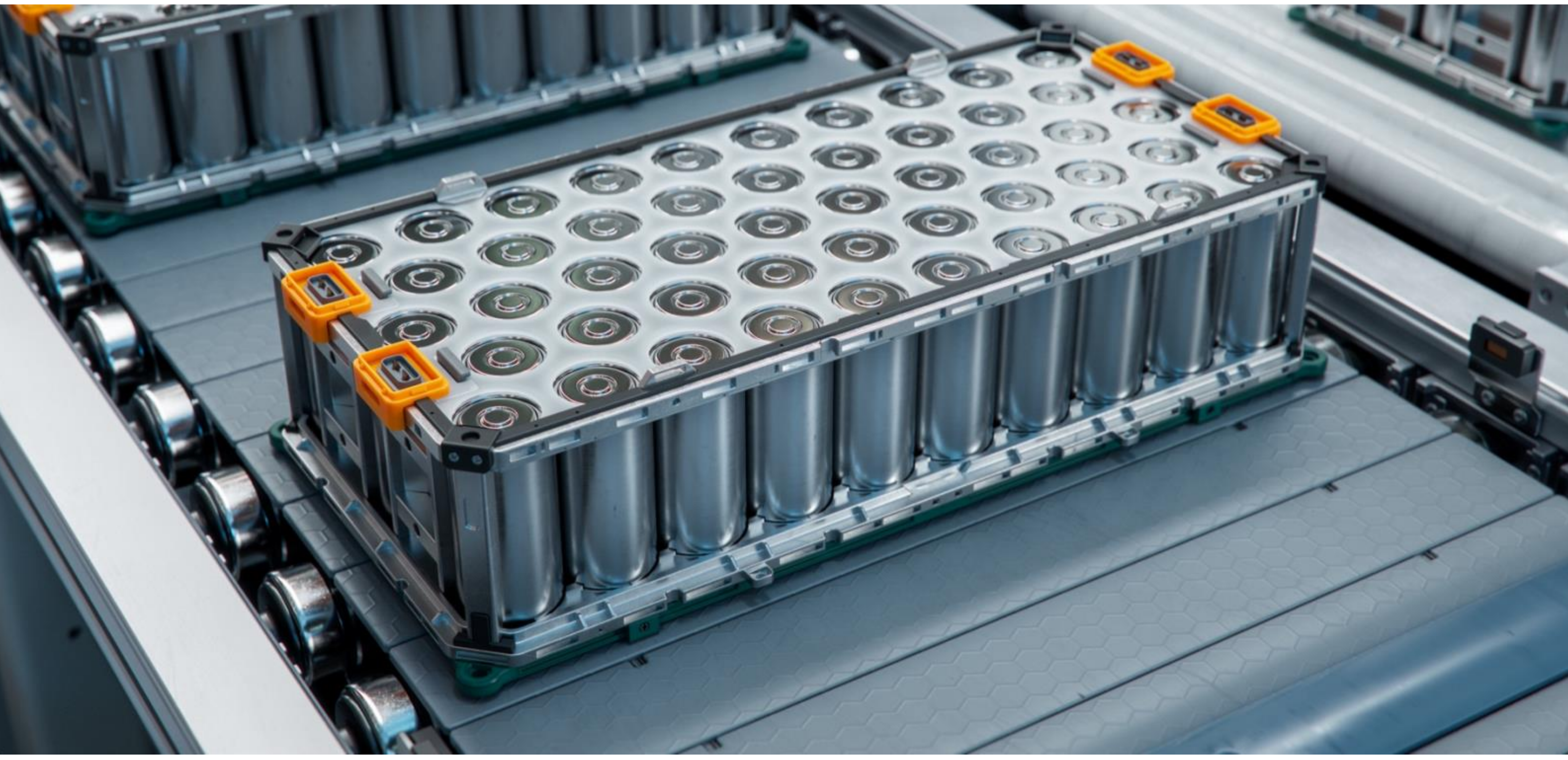
Policy option 1: Mandate energy efficiency performance testing for HESS
to long product lifetimes it is difficult to test this at the outset as performance information needs to be recorded over a longer period. Incorporating monitoring and reporting of RTE performance in state of health information would capture this fade in real-time.

Policy option 2: HESS performance rating system
Description Implement a HESS performance rating system similar to the System Performance Index developed in Germany [16]. HESS could be rated on their performance by an independent testing body or manufacturers could be required to test to a standard identified as part of Policy option 1. **Reasoning** A performance testing and rating system would enable HESS manufacturers to achieve future product performance enhancements, particularly for batteries with inherent technical differences, before minimum standards are introduced. The effectiveness of a rating system depends on whether consumers respond to ratings and therefore there is a financial incentive or penalty associated with a higher or lower rating. Building energy efficiency rating schemes for example have demonstrated there is an impact on property value from the rating. The question is whether households purchasing batteries – or the intermediaries involved in the supply-chain (e.g. installers) – would be responsive to ratings and select batteries on the basis of the rating. A HESS is an energy storage device and it is unknown whether consumers would be influenced by an efficiency rating in their purchasing. A rating scheme would take some time to develop and implement, it would need to be associated with consumer education and information programs and there would need to be some market testing to establish if a rating scheme was likely to influence consumers. An alternative role for a rating system is as a bridge to a mandatory minimum energy performance standard for HESS. A voluntary rating system could be applied to HESS to enable performance testing and standards before mandating to create a regulatory standard.

Policy option 3: Minimum energy efficiency performance requirements
Description A minimum energy efficiency performance standard mandates a level of energy efficiency upon the manufacturer of a product or appliance before it can be sold in a jurisdiction. Minimum energy efficiency performance (MEPS) standards are a common type of regulation applied to a wide range of consumer products such as lights and household appliances with established processes for evaluation, development and implementation. Minimum energy performance standards may also contain other criteria that influence consumer satisfaction and energy consumption (e.g. lifespan). In the United States, minimum energy performance standards are established based on Federal legislation by the Department of Energy but also at state level (e.g. the Californian Energy Commission). In the European Union, MEPs are harmonised across jurisdictions through the Ecodesign Directive. Other jurisdictions such as Australia have long-standing minimum energy performance standards. A minimum energy efficiency performance could be established for HESS. **Reasoning** Minimum energy performance requirements can be an effective policy option for improving the energy efficiency performance of HESS. By creating a higher efficiency standard across the market, a minimum energy efficiency performance standard is most effective at either lifting the energy efficiency of - or removing from the market - worst-performing products or technologies, which fits the context for HESS where there are some outliers in terms of low energy efficiency performance. Minimum energy efficiency performance standards are also preferable to consumer information and rating systems in contexts where the product is complex, or consumers are not expected to have the time, resources or interests to choose products based on energy efficiency.

There are a number of issues that should be considered when implementing a minimum energy efficiency performance standard:

- If there are inherent, technical features that underpin some or most of the difference in energy efficiency between lead-acid and lithium chemistries, care might need to be taken with standards to ensure there is still an opportunity for technical development and innovation of these HESS. That is, it is possible that lead-acid chemistries could still develop to become a superior or competitive HESS and a minimum standard should not have the effect of excluding this technology. It could be for example minimum energy efficiency performance standards need to be set for different types of HESS at this point;
- Mandatory standards are slower and more resource-intensive to develop than voluntary standards because of the economic and market impacts. Voluntary standards could be implemented as a step before mandatory standards as a quicker option and to test impacts. Conversely, policy-makers might take the view that it is preferable to move directly to mandatory standards, especially if there is confidence in the technical information underlying the performance standard;
- Minimum energy efficiency performance standards are effective at ‘lifting the bottom’ but if the aim is to provide incentives or resources to improve best-practice standards then an alternative policy mechanism could be required.



5. References

[1] DNV-GL. Gap analysis of existing Battery Energy Storage System Standards. 2019.

[2] International Energy Agency. Batteries and Secure Energy Transitions. 2023.

[3] Orth N, Munzke N, Weniger J, Messner C, Schreier R, Mast M, et al. Efficiency characterization of 26 residential photovoltaic battery storage systems. J Energy Storage 2023;65. https://doi.org/10.1016/j.est.2023.107299.

[4] ITP Renewables. Testing the Performance of Lithium Ion Batteries n.d.

[5] Solar Quotes. Solar batteries compared 2025. https://www.solarquotes.com.au/battery-storage/comparison-table/ (accessed January 13, 2025).

[6] ITP. Lithium-ion Battery Testing-Public Report 12. 2022.

[7] ITP. Battery test centre report 1. 2016.

[8] Munzke N, Schwarz B, Büchle F, Hiller M. Evaluation of the efficiency and resulting electrical and economic losses of photovoltaic home storage systems. J Energy Storage 2021;33. https://doi.org/10.1016/j.est.2020.101724.

[9] International Electrotechnical Commission. IEC 61427-2:2015+AMD1:2024 Secondary cells and batteries for renewable energy storage - General requirements and methods of test. 2024.

[10] Liebrich F, Mendis N, Bhatt AI, Munnings C, Hollenkamp AF, Smith W. PV Connected Battery Performance Evaluation Best Practice Guide. 2020.

[11] Beckers C, Hoedemaekers E, Dagkilic A, Bergveld HJ. Round-Trip Energy Efficiency and Energy-Efficiency Fade Estimation for Battery Passport. 2023 IEEE Vehicle Power and Propulsion Conference, VPPC 2023 - Proceedings, Institute of Electrical and Electronics Engineers Inc.; 2023. https://doi.org/10.1109/VPPC60535.2023.10403325.

[12] Conover DR, Ferreira SR, Crawford AJ, Schoenwald DA, Fuller J, Rosewater DM, et al. Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems. 2016.

[13] DNV-GL. Development of a Proposed Performance Standard for Battery Storage System connected to a Domestic/ Small Commercial Solar PV system. 2020.

[14] NEMA. ESS 1-2019 Standard for Uniformly Measuring and Expressing the Performance of Electrical Energy Storage Systems. 2019.

[15] European Union. Regulation (EU) 2023/1542 of the European Parliament and of the Council Concerning batteries and battery wastes. 2023.

[16] Weniger J, Orth N, Meissner L, Schluter C, Rautenkranz J von. Energy Storage Inspection 2024. 2024.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