

ECONOMIC PERFORMANCE AND SYSTEM VALUE OF BATTERY ENERGY STORAGE SYSTEMS AS LONG-LIVED INFRASTRUCTURE ASSETS IN DECARBONIZING POWER GRIDS

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Abstract

The battery energy storage systems (BESS) are being increasingly approached as short-duration flexibility resources, however they are also long-lived infrastructure resources that define investment requirements, reliability performance, and decarbonization economic results. The paper is a synthesis of peer-reviewed evidence regarding the economic performance and system value of BESS in present-day power grids based on the valuation of multiple services, long-term capacity expansion effects, and lifecycle factors including degradation and cost measures. In methods of modeling, one common result is that storage value is extremely system- and penetration-specific and usually motivated by averted generation capacity, less congestion and cycling of traditional plants, congestion reduction and transmission deferral, and enhanced operation flexibility in large portions of variable renewable (de Sisternes et al., 2016; Mallapragada et al., 2020; Denholm and Hand, 2011). Simultaneously, fully monetizing such benefits of the system can be barred by the market and regulation regulations, especially with limited storage to one type of asset or a number of products, which restricts service stacking and increases regulatory risk (Forrester et al., 2017). We also consider cost and performance indicators, such as the levelized cost of storage and levelized cost of energy storage concept, and demonstrate how a lifetime, utilization, and degradation have to be explicitly considered in a long-lived asset analysis (Obi et al., 2017; Comello and Reichelstein, 2019; Zia et al., 2019). Then we describe the framework of how BESS can be evaluated as infrastructure, which combines: (i) value of system planners in the increase of capacity, (ii) market value under changing product definitions, (iii) cost of lifetime and decreasing degradation-aware dispatch, and (iv) resilience in the response to temporal resolution and uncertainty in models (Poncelet et al., 2016; Scott et al., 2019). The synthesis underlines the reasons why BESS investments should be considered as portfolio infrastructure- the long-lived value can be found through the steady planning, flexibility accurate modeling and market designs to enable the storage to give numerous offerings during its life span.

Introduction

Decarbonizing power systems must confront a structural quandary, namely the rising presence of volatile renewable energy (VRE) that forces system flexibility to grow, none of which many traditional sources of flexibility, including thermal generation and large hydro resources, might find themselves, as sources of system flexibility, increasingly used less or phased out of service. BESS have thus become the top candidate to deliver quick, manageable and highly responsive flexibility. But their monetary appeal is far more than capitals in the headline. BESS provide value by way of bundle of system services, which differ depending on location, generation mixes and market designs. Second, batteries are becoming grid infrastructure, a component and resources that are likely to last ten years or more and communicate with the transmission growth, resource sufficiency incentive and dependability criteria (Denholm and Hand, 2011; de Sisternes et al., 2016).

The paper concentrates on the economic performance of BESS and system value when it is considered as long-lived infrastructure assets. We separate system value of the benefit in total system cost or the enhancement in reliability and resilience brought about by storage in the

optimized power system, and the private or market value of the revenues that a storage owner gains in the market and through participation in market and regulated products. These two concepts are in divergence in most jurisdictions. The multifunctionality of storage can no longer be easily categorized using the concept of legacy generation-transmission-distribution, and the existing rules and regulations of market structures are often not capable of rewarding all the services that storage can offer or even allow simultaneous interaction between products (Forrester et al., 2017).

We reconstruct literature in the interdisciplinary field of literature on power system operations and planning, energy economics, and energy policy. The focus is international and technology independent, focusing on insights that extrapolate past a narrow set of market rules or a regional institution. Other methodological concerns that we address are those that have a significant influence on storage valuation, especially in long-horizon studies; temporal resolution, modeling uncertainty, and degradation (Bistline et al., 2020; Poncelet et al., 2016; Scott et al., 2019). Not only system value estimates are informed with these methodological decisions, but also the optimal storage size, duration, and time of deployment are informed. The strategic integration of data-driven artificial intelligence and ethical analytics is essential for firms to achieve a sustained competitive advantage while ensuring that digital transformation remains grounded in privacy, fairness, and stakeholder trust (Akbar et al., 2023; Hassaan et al., 2023). The application of AI-powered predictive analytics has proven essential in optimizing capital deployment, thereby fostering startup resilience and driving sustainable growth in the post-pandemic American economy (Begum, 2022).

The way they perceive battery energy storage systems as infrastructure instead of solely merchant generation assets differently alters the way they ought to be assessed. Infrastructure assets are normally justified by more than recovery of direct revenue, but they increase the reliability of the whole system, their role in supplying security, and cost minimization over the long term. The transmission networks, water systems, and gas pipelines are not often evaluated using short-run profitability; it is rather the ability to facilitate the effective functioning of the system in case of uncertainty. Using the same reasoning to BESS, it is important to point out that their greatest contributions are smoothing out the roads to investment, reducing the risk of systems, and maximizing the strength of the decarbonization efforts (Denholm & Hand, 2011; de Sistantes et al., 2016; Mallapragada et al., 2020).

Path dependency is also highlighted through this framing of infrastructure. The future development of the grid is influenced by the initial investment of BESS through the change of price volatility, the course of capacity growth, as well as future use of traditional plants. Storage investments hence have dynamic implications that run much deeper than the revenue streams realised by a particular project. The realization of these dynamic interactions makes BESS valuation consistent with classical infrastructure planning in which the assets are selected to minimize long run system costs in deep uncertainty as opposed to that of maximising short run market profits. The in this way, the analysis of BESS as infrastructure actually changes the shorter-term project economics type to the longer-term system design and resilience, which can offer a more relevant basis of planning and policy in the system that is significantly decarbonized.

2. Conceptualizing BESS as Long-Lived Infrastructure

Being BESS treated as infrastructure means that it evaluates value over a long-run of years, with changing system conditions and regimes. The evaluation is transformed by infrastructure framing in 4 approaches. To begin with, storage is not a numerical good: its economic definition will be reliant on the bindingness of systems constraints (capacity adequacy, ramping, curtailment, congestion, voltage, contingency response). Second, the storage can delay or replace generation and network expansion due to the interaction with other investments: long-

lived assets (DiGirolamo et al., 2020). Third, the lifetime performance is endogenous: the cycling habits have an impact on degradation and, hence, cost-effectiveness (Zia et al., 2019; Sarker et al., 2017). Fourth, long-lived assets are prone to policy and market-design risk that overwhelmingly determines short-run profitability (Forrester et al., 2017).

In the system-planning point of view, storage value is often produced by saved spending of funds in capital and enhanced integration of VRE. De Sisternes et al. (2016) demonstrate that storage has the potential to make decarbonization of electricity cheaper through the ability to time shift energy, to minimize curtailment, and by replacing peaking capacity. Mallapragada et al. (2020) rationalise this reasoning in long-run expansion of capacity in terms of capacity building and transmission, and there is often marginal value in storage which derives out of the deferral of generation capacity and transmission enhancement, and decreases as storage penetration deepens.

Framing of infrastructure also explains that BESS should be considered being assessed within the entire range of flexibility. As an instance, Denholm and Hand (2011) measure the increment in flexibility requirements at very large VRE shares in the sense that we should involve storage in addition to curtailment, transmission, and flexible production. Likewise, the studies on strategic long-run storage requirements show high sensitivity to curtailment assumptions, sector any other flexibility alternatives (Zerrahn et al., 2018).

Divergence in Valuation Paradigms: Merchant Asset vs. Strategic Infrastructure

Conceptual Framework Figure 1

	The Merchant View (Current Status Quo)	The Infrastructure View (Proposed Framework)
Role	Short-duration flexibility resource	Long-lived system enabler & transmission alternative
Objective	Short-run profit maximization (Arbitrage)	Long-run system cost minimization & Decarbonization
Lifetime	Exogenous (fixed assumption)	Endogenous (dependent on cycling/degradation)
Risk Profile	Exposure to marginal price volatility	Socialized risk/regulated planning (like pipelines/water)

Key Insight: Path dependency. BESS investments influence future capacity growth and price volatility, consistent with classical infrastructure planning rather than simple commodity trading.

3. Methods for Valuing System Value and Economic Performance

The BESS is valued by the literature with the help of three core modeling families. ((1) Dispatch and production-cost models maximize short-term operations with high-temporal faithful models to modeling by optimizing arbitrage and ancillary-service interactions but normally making investment decisions as exogenous. (2) Capacity expansion models maximize investments and operations on multi-year basis, which offers system-value estimates associated with avoided costs while simplifying to resolve between time periods and detailed unit commitment. (3) Hybrid methods trade investments and dispatch simultaneously in a stylized chronologically rich model, enhancing the modeling of the intertemporality of storage (Go et al., 2016; de Sisternes et al., 2016; Mallapragada et al., 2020).

There is a high influence of model resolution on estimated storage value. Poncelet et al. (2016) and Welsch et al. (2014) demonstrate that a lack of both time and operational specificity may

distort curtailment, operation costs and the requirement of more flexibility resources. Scott et al. (2019) introduce representative-day clustering methods which seek to maintain storage-relevant chronological information and make them computationally efficient. Bistline et al. (2020) review the way in which integrated assessment and long-term models can implement system integration constraints, with an element also applying to storage.

It also concerns the relative economic performance measures. The levelized cost of storage (LCOS) and related indicators have been prevalent in practice, although they can be deceptive when there is a difference in their utilization and service mix. Obi et al. (2017) analyze the situational levelized cost approach to storage technologies, emphasizing the need to have consistent boundaries. Comello and Reichelstein (2019) offer the concept of a levelized cost of energy storage, conditional upon the conditions of break-even of the investor over the lifetime of a storage facility, expressly relating the size and use to economics.

4. Core Value Streams Provided by BESS

4.1 Arbitrage and energy shifting.

Energy shifting value is a result of changing the old electricity price of either glutted or low-priced periods to the price or scarcity bouts. Arbitrage alone may frequently not be an incentive to invest in early cost regime, however, the larger the VRE of a system and the greater the price movement, the greater the value of arbitrage. Sioshansi (2009) evaluates the effect that the arbitrage storage can have on the market outcomes and the welfare. Zafirakis et al. (2016) present the evidence on arbitrage value in the European electricity markets and demonstrate that the opportunities depend on the structure of markets and their integration.

4.2 Flexible capacity and adequacy of capacity.

BESS may be used in place of peaking capacity and offer resource adequacy in place of specific short-duration reliability requirements. Cutter et al. (2014) posit that the traditional capacity measures might be inadequate in systems with flexibility features of importance, and encourages measures that factor in ramping and duration. Storage can often play a role in long-run planning models including alleviating the requirements of new thermal capacity and making higher VRE penetrations possible (de Sisternes et al., 2016; Mallapragada et al., 2020; Zerrahn & Schill, 2017).

4.3 supplementary services and prompt response.

BESS is highly applicable in providing frequency regulation and reserve because of its rapid ramping nature and controllability. The storage is however subject to market rules and product definitions which determine whether it can secure revenues out of the benefit of a system. Forrester et al. (2017) indicate that policy and market barriers are main barriers, especially they cause storage to be unable to stack its services or encounter uncertainty in the regulations in new markets.

The engineering journals in optimization and bidding give examples of how storage can be planned and bidden in markets to offer a variety of services in case of uncertainty. Dvorkin et al. (2017) suggest the look-ahead bidding strategy of participating in real-time electricity markets, storing energy, and Jiang et al. (2012) demonstrate the possibility of using storage-like flexibility as a part of strong unit commitment formulations with the wind uncertainty.

Transmission and network value discusses how new markets can be established within an industry.

4.4 Transmission and network value

BESS has the capability of offering non-wires alternatives of decongestion, voltage support and postponing the transmission or distribution upgrades. Aguado et al. (2017) model the joint transmission expansion planning where there is storage resource that the location of storage can be used to replace network reinforcement. Mallapragada et al. (2020) also discover that the

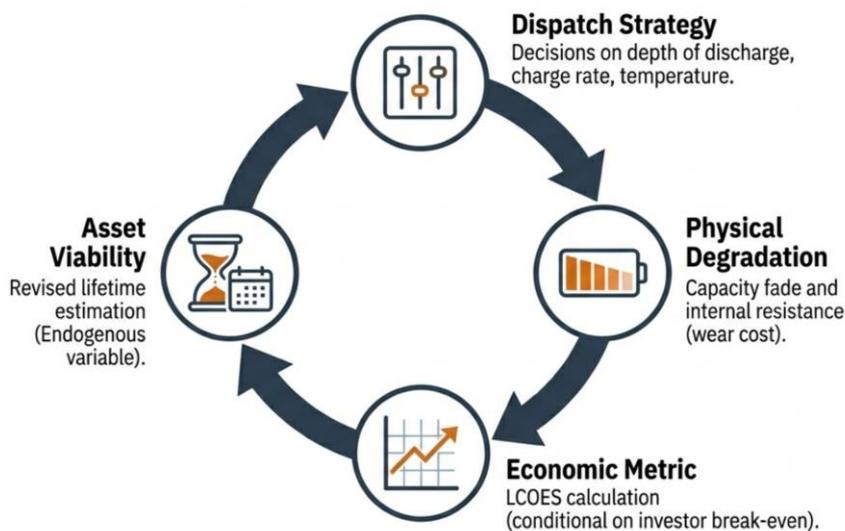
transmission delay can potentially become a significant source of system value in future high-VRE grids.

4.5 System properties of resilience and reliability.

Storage, besides economic efficiency, may enhance resilience through the supply of back-up energy, black-start facility, and expedient reaction to contingencies. According to Balducci et al. (2021), reliability and resilience value streams of grid-scale storage are reviewed with a strong emphasis that most of its benefits are not fully paid in the designs of the market. Infrastructure framing implies that the planners need to consider the reliability and resilience benefits as the elements of the public value, even in the cases when market monetization is not complete.

Lifecycle Economics:

The Endogenous Feedback Loop of Degradation and Cost



- Disregarding degradation leads to **distorted dispatch (excessive cycling)** and **inflated profitability** estimates.
- LCOES **must be conditional** on utilization over the specific lifetime.

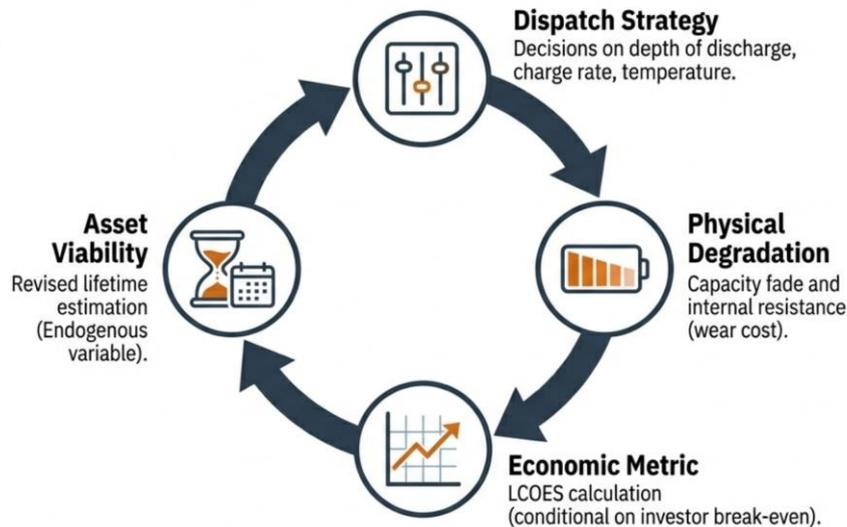
5. Lifecycle Economics: Degradation, Lifetime, and Cost Measures.

One of the peculiarities of batteries as durable resources is that the lifetime is related to the use. External variables are used to manipulate the depth, temperature, and charge rate to affect capacity fade and internal resistance development to allow us to make use of the energy and power. Disregard of degradation may distort dispatch to a state of excess cycling and at the level of inflated profitability or system value (Sarker et al., 2017).

The models of operation with awareness of degradation fully explicitly include a cost of battery wear. The article by Zia et al. (2019) builds a useful model of degradations in Li-ion batteries and demonstrates the impact of degradation on the best schedules of microgrids. Sarker et al. (2017) also study the tradeoff between economic operation and battery life in an energy management scenario. These methods facilitate infrastructure valuation through the bridge between the strategies of revenue stacking and asset life.

On the cost-metric side, Obi et al. (2017) synthesize levelized cost of storage methods to storage technologies, and Comello and Reichelstein (2019) introduce a levelized cost of energy storage framework that can be used to make consistent comparisons among designs. Lai and McCulloch (2017) apply the concept of levelized thinking to the PV-plus-storage systems, which show how the size and geographical location of storage can impact economic performance due to resource variability.

Lifecycle Economics: The Endogenous Feedback Loop of Degradation and Cost



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6. System Value is contingent upon Technology Cost-performance and System Context.

The storage value is highly associated with the parameters of technology (power, cost of energy, efficiency, cycling limitations) and the system setting (VRE penetrations, thermal fleet flexibility, network constraints). Braff et al. (2016) offer a general guide to juxtaposing between the storage technologies of wind and solar integration, focusing on the interaction between the energy and power cost and the grid conditions to derive value. Their discussion shows that there is no single storage arrangement that prevails in all situations.

The analysis in the long-run systems supports the fact that the value of storage reduces with increased penetration because of a decreasing marginal returns and a shift in binding constraints. As Mallapragada et al. (2020) demonstrate, marginal value decreases with incremental storage deployment, with the most lucrative time and network constraints utilised being satisfied initially and with more storage vying with them, arbitrage and capacity prospects of the identical nature. Schill and Zerrahn (2018) and Zerrahn et al. (2018) also demonstrate that the storage needs and economic appeal depend on the assumptions of curtailment, other means of flexibility, and design.

The two outcomes also suggest that the BESS as infrastructure should be evaluated based on a scenario-based planning. This is because the economic justification of strongly hour-based or long-duration storage is different to short-duration batteries, particularly when the balancing concern of the system changes to multi-day or multi-season variability. Technology appraisals and reviews represent general evidence of where the various durations of storage and technologies can apply to grid-scale (Argyrou et al., 2018; Obi et al., 2017).

7. Policy, Regulation, and Market Design for Long-Lived Storage Assets

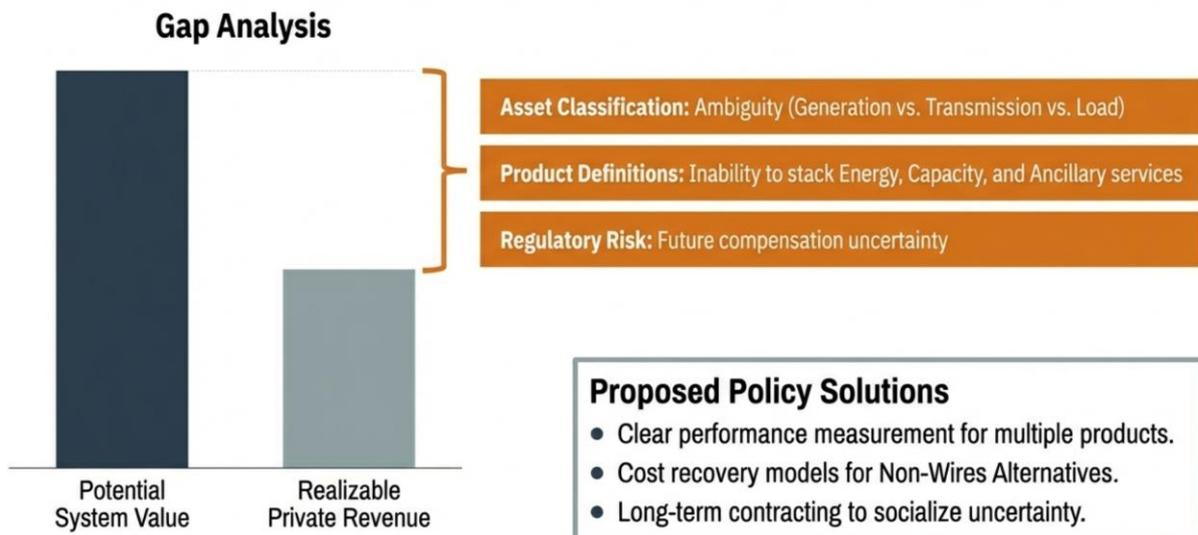
Since storage may act as generation, load fold in addition to network assistance, market structure and regulatory categorization have become pivotal fundamental driving forces underlying private investment. In the article by Forrester et al. (2017), the limitation of profitability by treating storage as a traditional single-purpose assets class is recorded along with why investments that would otherwise be beneficial to a system view may be discouraged. They underline service stacking as the tool to enhance utilization and risk of regulations, and also observe that the change of rules may bring about uncertainty.

The structure of ownership and the markets of power are also considered in economic analyses, as Sot: The storage can potentially transform the price formation and spreads in arbitrage.

Sioshansi (2009) shows that the operation of storage affects the market prices and welfare, which means that policy needs regarding participation and compensation can be distributed. Based on the high-renewables systems, revenue adequacy of storage and other resources can be further complicated by pricing issues and missing-money dynamics affecting high-renewables systems, enhancing the significance of coherent capacity and ancillary service products (Cutter et al., 2014; de Sisternes et al., 2016).

The policy design on infrastructure should thus relate market rules with the services which are provided by storage as a form of infrastructure. This comprises (i) facilitating action on the energy, ancillary, and capacity products where clear performance measurement is accessible, (ii) specifying how to treat cost recovery and interconnection of storage as an alternative to non-wires system, and (iii) design of the long-term contracts or regulatory mechanisms where it is clear that system benefits are intended as nearly a fully public good (Aguado et al., 2017; Balducci et al., 2021).

Regulatory Friction and Market Barriers to Service Stacking

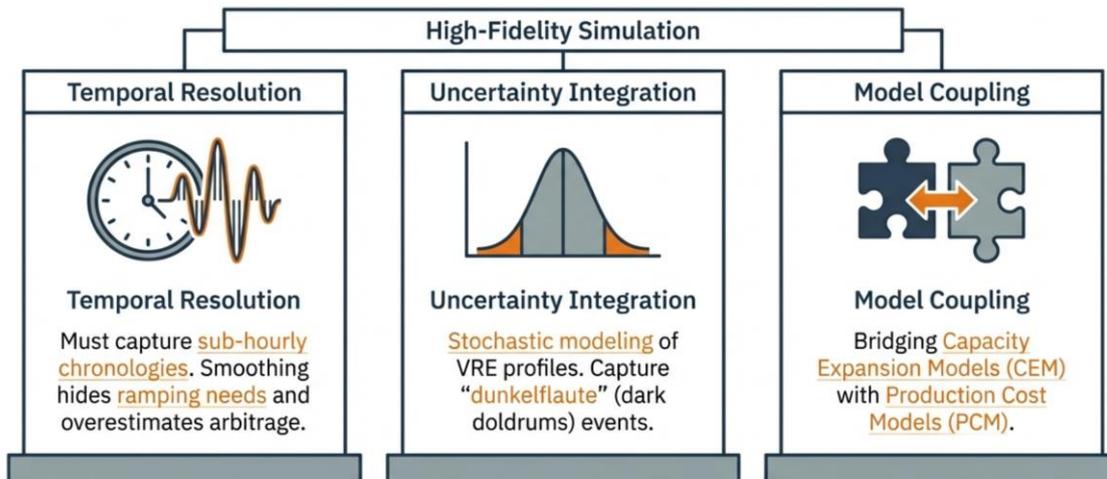


8. Modeling Challenges and Best Practices for Long-Horizon Storage Valuation

Two issues are repeated in the literature, those are; temporal resolution and operational constraint representation. Storage value by nature is intertemporal and thus more aggressive compression of time can mimic arbitrage, ramping requirement, and curtailment. Poncelet et al. (2016) demonstrate that the temporal and operational detail can have a significant impact on the results with systems with high shares of renewable. Welsch et al. (2014) offer one of the first examples of how flexibility limitations are to be incorporated into the detailed energy system models. Scott et al. (2019) suggest representative-day clustering techniques which are more storage-relevant.

Secondly is the need to match market-value simulation and system-value estimates. In least-cost planning models, system value is generally computed and externalities internalized to enable the coordination of investment, whereas market value is determined based upon product definition, bidding strategies, as well as service-stacking constraints. The gap between these necessitates the connection of the planning models and market simulation, or the inclusion of policy constraints in the planning models. Bistline et al. (2020) promote the use of cross-model methods and the regularity of variability and the integration constraints in assessing the storage in a long-term context.

Modeling Frontiers: Requirements for High-Fidelity Storage Simulation



Insight: Simplified models drastically distort the optimal size, duration, and deployment time of storage.

9. A Practical Framework for Evaluating BESS as Infrastructure

Based on the literature reviewed, it is possible to conduct a practical appraisal of BESS as long-lived infrastructure on the basis of four related evaluations.

To begin with, estimate system-planner value of capacity expansion: quantify avoided investments in generation and networks, modification of curtailment, optimization of the cost of operation over likely decarbonization pathways (de Sisternes et al., 2016, Mallapragada et al., 2020 and Aguado et al., 2017).

Second, approximate the market value assuming current and realistic market rules: model the stacking of revenues of energy, capacity and ancillary services based on the constraint of coinciding participation and policy risk (Forrester et al., 2017; Sioshansi, 2009; Dvorkin et al., 2017).

Third, physically embodiment of lifecycle cost and degradation-conscious operations: model cycling-sensitive wear costs and performance decadence to prevent over-allocating profit and picking operating policy-based on infrastructure life (Zia et al., 2019; Sarker et al., 2017; Obi et al., 2017).

Fourth, model resolve tests and are sensitive to uncertainty: ensure comparison of results between alternate temporal resolutions or in alternative representative time-sampling methods, and sensitivity to VRE profiles and fuel prices (Poncelet et al., 2016; Scott et al., 2019; Zafirakis et al., 2016).

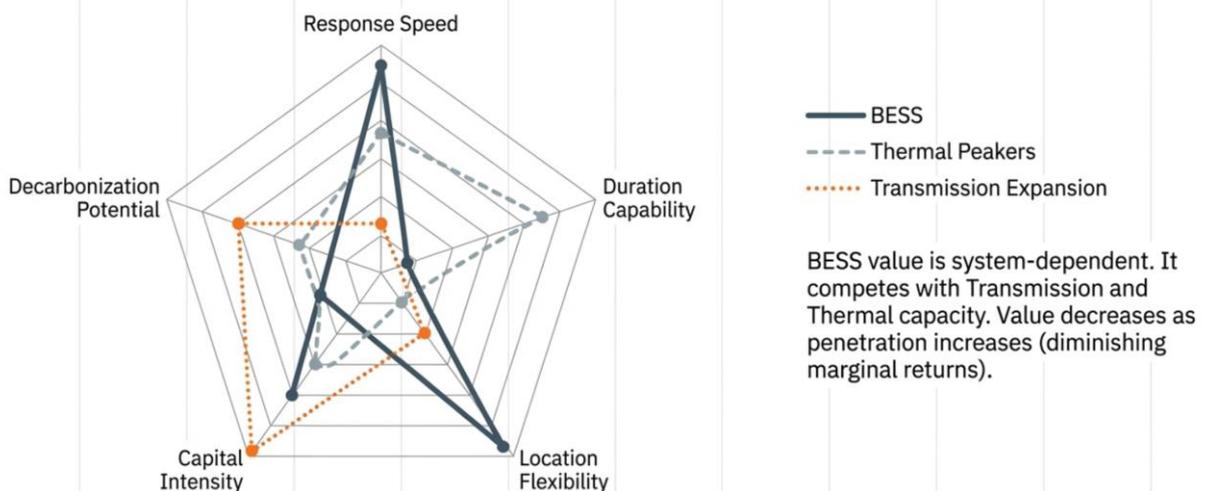
10. Comparative Evaluation of BESS Against Alternative Flexibility Options

It is necessary to explicitly compare battery energy storage systems with other flexibility resources that can also facilitate reliability and renewable integration when it comes to acting as infrastructure resources. The options are flexible thermal generation, demand response, expansion of the transmission, curtailment strategies, and sector coupling technologies, i.e., power-to-heat or power-to-hydrogen. Denholm and Hand (2011) also point out that storage is not the sole component of a set of increased flexibility resources, and its fringe benefit relies on the presence and expenses of replacements. Storage can be of less importance in those regimes where expansion of transmission is cheap, or where the presence of flexible gas generation is large, and of increasing importance in constrained systems with large VRE infiltration.

Monthly storage needs, as shown by Zerrahn and Schill (2017) and Schill and Zerrahn (2018) are extremely sensitive to the assumptions on curtailment tolerance and the existence of other flexibility sources. In an example, the limited curtailment can become moderate to considerably lower the optimum storage capacity. Equally, renewable variability can be spatially smoothed by investing in transmission, and local storage lessened. The implications of these findings are that BESS should be treated as infrastructure which needs to incorporate integrated planning structures that mutually optimize storage, networks and generation as opposed to considering storage independently.

BESS has benefits compared to conventional peaking plants of response speed, modularity and location flexibility, though not the energy duration of fuel generation. Cutter et al. (2014) state that capacity measures using only nameplate power capacity are inadequate, since in high-renewable systems flexibility and duration are more important aspects. Storage offers high quality capacity to short events but it influences longer reliability event with regard to the energy capacity and recharge opportunity. This brings out yet again the infrastructural analogy: BESS value, like in the case of transmission or hydro reservoirs, is determined by its integration within the larger system structure.

Comparative Flexibility: BESS vs. Alternative Grid Resources



11. Long-Duration Storage and the Limits of Short-Duration BESS

All consumer grid-scale BESS to date have less than two to four hour durations, optimized to short scale balancing, frequency regulation and peak shaving. But over time (with renewable penetration) systems experience multi-hour and multi-day imbalances, caused by weather patterns. As demonstrated by Schill and Zerrahn (2018), it is true at very large renewable shares that short-duration storage continues to be valuable in day-to-day balancing, but long-duration storage resources or other facilities that add to them are required.

In infrastructure terms, it means that BESS investment plans are not to be fixed at one point but flexible. The introduction of early-stage can focus on supporting power capacities, short lifetimes whereas late-stage decarbonized might support longer times or find solutions that are intermediate. Argyrou et al. (2018) underline that it takes various storage technologies to occupy various economic niches due to the duration, efficiency, and capital-intensiveness. Although among battery technologies, the range of time greatly alters both cost realms and also cycling, both as with LCOS and as with revenue models.

This time transformation also contributes to the argument of planning and controlling storage as an infrastructural facility. When long-lived assets are intact, they should be useful under a variety of system conditions, and an economy concerning the viability of the long-lived assets requires policy stability and a suitable adaptive market structure. The information presented by marketed short-run merchant revenue could not be enough on its own to inform investment decisions about the optimal storage portfolio in social terms.

12. Uncertainty, Risk, and Investment Under Long Asset Lifetimes

Infrastructure investment is inherent with uncertainty in terms of costs of technology, cost of fuel, the policy regime and market structure. In the case of BESS, these uncertainties are compounded by the fast changing technology and new regulation treatment. The regulatory risk that Forrester et al. (2017) emphasize as a significant impediment to storage investment can greatly change the siting of projects based on the variation of services eligibility or compensation structure and interconnection regulations, over the short time frame.

When it comes to the system-planning, Mallapragada et al. (2020) demonstrate that the storage worth is contingent on the long-term conditions of renewable costs and load increase. Uncertainty must as such be captured in planning models by conducting a large amount of sensitivity analysis. Scott et al. (2019) show that even the modeling decisions regarding the representative days can alter the optimum investment in the storage willing to be made, which supports the necessity of the effective decision-making models.

The fact that BESS is treated as a type of infrastructure implies that some of this uncertainty ought to be socialized by having regulated planning or long-term/contracts. Storage, like transmission or generation capacity investments, can be possible candidates of sorts of cost recovery aids that the aspects of public good, especially given that its benefits are seen in reliability, resilience and decarbonization, and not in short-loop arbitrage.

13. Impacts to the Utilities, System Operators, and Policymakers.

In the case of utilities, infrastructure-based valuation suggests that storage be included in the resource adequacy plan, distribution system plan, and non-wire alternative analysis. It demonstrates that the reasons may be effectively low costs of the whole system because of the co-optimal approach to storage and transmission (Aguado et al., 2017). According to Balducci et al. (2021), the value should be assigned at many grid levels to realize the entire benefits of storage.

In the case of system operators, the market design needs to be changed between single-service and multi-service storage. Market products and network performance checks must be coordinated to allow the storage to provide energy, storage reserves, capacity and network support at the same time. According to Sioshansi (2009), the ownership structure and the bidding behaviour may affect the welfare outcomes and that the market power and strategic operation must also be considered with the efficiency objectives.

In the literature, it is apparent that policymakers need to classify assets clearly and treat them stably in terms of regulation. According to Forrester et al. (2017), any ambiguity in the features of generation versus transmission role will discourage investment. A framing infrastructure would help understand that storage is a hybrid between a public and a private good, which should be planned and coordinated with transparent compensation systems and long-term policy indicators.

14. Technical Modeling of BESS in Capacity Expansion and Dispatch Frameworks

Fidelity of BESS in the models of planning and operations is important in valuing infrastructure. Models should at least have state-of-charge dynamic, charging and discharging efficiency, power/energy capacity limit and intertemporal coupling between hours and days. BESS is usually modeled as an electricity conversion resource that transforms electricity over

time with losses; useful in substituting peaking generation and eliminating renewable curtailment (de Sisternes et al., 2016; Mallapragada et al., 2020).

Nevertheless, the simplified forms of storage can give biased outcomes. Poncelet et al. (2016) demonstrate that the lack of system operational detail disrupts system cost and investment decision-making, especially in high-renewable systems where the storage operation relies on the short-term constraints. Scott et al. (2019) show that clustering methods should maintain extreme events and ramping behaviour in order to properly value storage. Otherwise failure to do so can underrate the amount of storage required as well as the part played by storage in reliability.

The dispatch models based on engineering offer valuable complementary information by solving storage behavior at the high time resolution. As Jiang et al. (2012) and Dvorkin et al. (2017) demonstrate, storage can play a role in unit commitment and real-time under uncertainty market as well, and look-ahead scheduling and stochastic bidding are crucial strategies. These models point to the fact that not only do energy movements create storage value, but also uncertainty reduction and the timely provision of a corrective response form.

The problem of bridging between dispatch and planning models is a key topic of research. Bistline et al. (2020) note the necessity of the uniform representation of variability, uncertainty, and flexibility between modeling paradigms. Infrastructure. This integration is needed: long-term investment choices should be made on realistic operational performance, and operation simulation on realistic long term system structures is needed.

15. Regulatory Models for Treating BESS as Infrastructure

Conventional electricity control draws a clear line between generation, transmission and distribution. BESS burden the taxonomy since it is able to offer services to all three domains. According to Forrester et al. (2017), such ambiguity creates regulatory friction that inhibits the socially optimal investment. Treatment in infrastructure would presuppose the explicit consideration of storage as a multi-purpose network resource that can have its value shared between the participants of the system.

One regulation method is to enable utilities to rate-base strategically placed BESS in which the social good of the system is dovft and the advantages are largely those of the community like transmission deferral or distribution reliability. Aguado et al. (2017) indicate the possibility of network reinforcement to be substituted by storage and prove the argument in favor of controlled ownership in some scenarios. Balducci et al. (2021) also mention that storage must be remunerated at more than one grid level.

Long-term contracting to acquire storage capacity and flexibility is another method that is similar to contracts applied to generate adequacy. This is consistent with de Sisternes et al. (2016), who demonstrate the role of storage in the cost reduction of decarbonization, which means that its advantages go beyond market arbitrage. These kinds of contracts minimize the risk of investment and are closer to infrastructure-style economics.

Conclusion

Unanimous across peer-reviewed sources, battery energy storage systems (BESS) are able to provide system value when applied to current power grids, both when subjected to high penetrations of variable renewable energy (VRE). This is, however, not a value that is inherent and universal, and it depends on the context of the system, the cost-performance of the technology, as well as the market design. As long-lived infrastructure, BESS must be measured based on multi-service value, long-run avoided investment and lifecycle degradation using combined frameworks. The studies on long-run models point out that the marginal value of storage tends to decrease with the deployment and that the planning outcomes are affected by time resolution and flexibility representations (Mallapragada et al., 2020; Poncelet et al., 2016). Meanwhile, the policy reviews indicate that market and regulatory obstacles might allow

storing owners to fail to earn revenues in proportion to the overall system benefits that they can deliver, which prompts the need to implement reforms that would allow the service stacking and better explain the classification of assets (Forrester et al., 2017). All in all, BESS should be treated as a type of infrastructure, rather than a single-market product, in order to better integrate the investment choices, which focus on decarbonization, reliability, and cost objectives.

Considered through an infrastructure prism, the battery energy storage systems are not just optional market entrants, but they are strategic enablers of the energy transition. They are based on the essence of transforming cost, risk, and feasibility of deep decarbonization pathways. The literature analyzed in this paper demonstrates that despite the non-weighting of those benefits in the private revenues, storage lowers total system cost, improves its reliability, and makes it more operationally flexible (de Sisternes et al., 2016; Mallapragada et al., 2020; Forrester et al., 2017). This disalignment between social and private value is exactly what makes infrastructure assets unique in comparison with more traditional resources of merchant and prevents the necessity of planning and regulatory measures that would internalize the benefits of the whole system.

This reframing does not only allow concluding that an underinvestment in storage is not an issue of market failure but also an issue of infrastructure planning failure. Additionally to the same way transmission expansion and generation adequacy would be ensured by coordinated planning and regulatory control, storage adequacy must be regarded as a system core mission. The research and policy matters that need to be addressed in the future should not be about whether storage in the current market structures is profitable or not but on how the institutions can make sure that deployment of storage remains in tandem with the long-term societal goals. To do that, it is necessary to consider BESS as an explicit part of capacity expansion planning, reliability standards, and decarbonization on the one hand, and construct regulatory and market mechanisms in such a way that BESS is considered a core element of a resilient low-carbon power system.

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