



Appraising the Economic Value of Battery Energy Storage: Moving Beyond Static Cost-Benefit Analysis

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23 September 2025

About this publication

This publication is released as the first of three in a series on the appraisal of battery energy storage systems (BESS) by UCL ISR's Centre for Net Zero Market Design, for the European Investment Bank. The authors take full responsibility for the contents of this report. The opinions expressed do not necessarily reflect the view of the European Investment Bank.

For more information on the series and to read the two subsequent publications, please visit our [website](#).

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Acknowledgements

This series has been produced with support from the European Investment Bank.

Executive Summary

This report examines issues and options for evaluation by EIB of the economic case for investment in battery energy storage systems (BESS).

The challenge

Two principal factors define the context:

- First, **electricity storage at scale is an essential element in meeting the EU's goals for energy transition including decarbonisation and security, but current investment is far short of projected needs.** The European Commission projects that the EU goals for 2030 will require at least 130GW *additional* storage compared to the present capacity; the potential for additional pumped hydro is severely limited by geography, and of others, only batteries seem sufficiently mature to contribute at scale by 2030. Yet the EU only has around 25 GW battery storage at present and most of this is 'behind the meter', with only 5GW of industrial, utility-scale battery storage.
- Second, **the EIB currently lacks a clear or consistent methodology for evaluating the economic contribution of storage investments towards EU goals.** In terms of the EIB's methodology, storage evaluation naturally falls into the EIB category requiring comparison against a reference/counterfactual of "*some alternate action that meets the same objective*". But there is no obvious counterfactual meeting this description, and the alternatives tried to date illustrate inconsistencies, contradictions, and/or deep uncertainties.

To illustrate the last point, we conducted simple sensitivity studies of a specific BESS investment, **finding that the Economic Internal Rate of Return could range anywhere from -1.0% to +37% across different counterfactuals**, even without considering operational uncertainties around the evolution of wholesale market prices and volatility thereof.

Recommendation 1: Adopt a forward-looking dynamic appraisal methodology, in place of the current static appraisal approach based on an alternative technology option.

Importance of feedbacks

Batteries form part of the wider electricity system and its technologies, a system which is in a state of major transition. Consequently, beyond direct operation, there are important feedbacks to consider, and since batteries are expected to last for years to decades, there is a need to set appraisal in the context of the system's expected development.

Feedbacks can be considered as dampening or amplifying, and can be visualised using 'causal loop diagrams.' We identify three main potential feedbacks relevant to BESS:

- *Feedbacks between cost and scale of deployment*, mainly associated with learning-by-doing (and learning-by-using), and economies of scale and supply chain development. This may be a dominant consideration for less developed storage technologies, but we consider that, given the relative maturity of lithium-ion batteries and the dominance of the electric vehicle market, this feedback from deployment in the power sector is weak for lithium-ion BESS; it should, however, be considered for other storage technologies, including newer battery technologies, where the predominant application is in the power sector.
- *Feedbacks between deployment of storage and renewables*. Renewables are moving rapidly from being inframarginal in the EU energy system to price-setting in the (marginal-pricing) wholesale market. This is reflected in non-linear growth of periods of negative or zero wholesale prices.¹ This deters renewables investment (at least insofar as it depends on wholesale revenues) but boosts potential BESS revenues – which if deployed, then enhance the economics of more renewables. The feedback between storage and renewables, however, is complex and time-lagged, with a high risk of being trapped in systems which have inadequate supplies of both (i.e. a clearly ‘inferior equilibrium’ in terms of economy and environment).
- *Cannibalisation*. Storage investment has seen rapid cannibalisation of revenues from ancillary services, and other storage services are also potentially subject to cannibalisation. If investors look forward, this has the potential to deter investment; if they do not, it can lead to the opposite, and bankruptcy.

Emissions impact of storage

The emission implications of storage depend on three factors.

Emissions from *battery construction* are in general small (less than 10%) compared to their likely impact on system emissions overall.

In *operation*, batteries can in principle either:

- increase emissions (if they are charged from fossil fuels and the efficiency exceeds any savings associated with displacing other fossil generation);
- or save emissions (if they are charged from lower carbon generation and then displace fossil fuel generation)

We present evidence on why in the large majority of cases, in the current European context, the net *direct* impact of batteries would be expected to reduce system emissions (Box 1).

¹ The relevance of either negative prices or non-positive prices will depend on the structure of support schemes for VRE (i.e. CfDs, FITs, etc) in each member state.

Finally, the *indirect* positive feedback between storage deployment and renewables revenues represents a likely strongly positive contribution to emission savings.

Dynamic appraisal methodologies

The natural comparator for project evaluation would be grounded in forward-looking scenarios, comparing variants with and without the storage project being considered.

Recommendation 2: If pursuing quantified appraisal, adopt a forward-looking scenario-based approach:

- a) Ideally, with model capability to represent directly operation with- and without- the storage project**
- b) Alternatively, adopt proxies for the likely impact of storage in relation to the modelled or inferred range and frequency of price spreads**

The development of scenarios is complex, as is the use of models, but the task can be substantially eased by collaboration with more technical bodies that have complex models and generate scenarios of EU electricity and gas developments, the most obvious being ENTSO-E.

Recommendation 3: Establish/strengthen relationships with scenario modellers at the most relevant other EU institutions.

However, quantified evaluation inevitably involves substantial complexity and deep uncertainties, particularly given: the multiple revenue streams of storage, their dependence on national regulations and market volatility, the multiple feedbacks (both amplifying and dampening), and the structural uncertainties inherent in major transitions. There are concerns that over-emphasis on quantification, aside from giving a false confidence in the robustness or objectivity of results, can bias towards a default ‘status-quo dynamic’ which reflects incumbent interests, technologies, and structures.

The literature has thus identified the potential case for and contributions of non-quantified methodologies to inform decision-making, including a 3-component framework introduced by Ofgem for Regulatory Impact Assessment in the context of the energy transition, and a broader policy evaluation approach emphasising risks and opportunities.

Recommendation 4: Consider adopting a Risk-Opportunity Framework for systematically assessing important qualitative factors, and/or other approaches to complement quantified CBA with additional important information.

Finally, we acknowledge that some of these frameworks have been developed for wider policy or regulatory appraisal, for decisions which likely have potentially bigger impacts than individual storage projects. However, the EIB approach to appraising storage overall could have system-level implications for the achievement of EU decarbonization goals. Given the apparently large gap identified in storage investment relative to the EU's needs, the EIB could frame its contribution in this space in the context of a more programmatic approach to storage.

Recommendation 5: Consider a programmatic approach to storage deployment and the implications this could have for appraisal approaches.

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List of Abbreviations and Acronyms

BESS: Battery energy storage systems

CAPEX: Capital expenditure

CBA: Cost-benefit analysis

CCGT: Combined cycle gas turbine

CEA: Cost-effectiveness analysis

CLD: Causal loop diagram

EIB: European Investment Bank, or “the Bank”

EIRR: Economic internal rate of return

ENTSO-E: European Network of Transmission System Operators for Electricity

ENTSO-G: European Network of Transmission System Operators for Gas

ETS: Emissions Trading System

EU: European Union

FCR: Frequency control reserve

GB: Great Britain

LCA: Life cycle assessment

LDES: Long duration energy storage

MCA: Multicriteria analysis

MW: Megawatt

MWh: Megawatt-hour

NECP: National Energy and Climate Plan

OCGT: Open-cycle gas turbine

PSH: Pumped storage hydropower

ROA: Risk-opportunity analysis

SCC: Social cost of carbon

TOTEX: Total cost of expenditure

TYNDP: Ten-Year Network Development Plan

VRE: Variable renewable energy

1) BESS Background and EU Deployment

This report addresses the economic appraisal of electricity storage. Storage is increasingly important as the electricity system decarbonises, but it is challenging to appraise due to the numerous services it can provide. BESS is of primary focus for this report since the EIB is seeing a growing number of these projects. Long duration energy storage (LDES) is also briefly examined where it can provide a counter perspective to BESS appraisal. Of most relevance to this report is grid-connected, front-of-the-meter utility-scale storage, to be complemented by a briefing paper on behind-the-meter and co-located storage in April 2025. Part two of this report, focusing on BESS financial appraisal, will be delivered in May 2025.

Section 1) covers technical background on BESS's role and current EU storage deployment. Section **Error! Reference source not found.** examines the benefits BESS may bring to the energy system. Section 0 addresses the EIB's current economic appraisal methodology in the context of storage and touches on the choice of counterfactual. Section 4) describes a scenario-based counterfactual approach, adapting CBA to better suit storage appraisal. Section 5) expands appraisal to consider qualitative factors and explores the ability to apply Risk-Opportunity Analysis in this context. Section 6) summarises these findings and highlights key recommendations for the EIB. Supporting documentation can be found in section 7)

1.1 EU Decarbonisation Targets

The European Commission (2021, 2022), through its Fit for 55 and REPowerEU packages, has established a legally binding target to reduce greenhouse gas emissions by 55% by 2030 and to reach net zero emissions by 2050. To reach net zero, the electricity system will need to be decarbonised, transitioning from fossil fuel generators to low-carbon sources, such as nuclear and variable renewable energy (VRE). In the context of the 2030 target, the supply of low-carbon power sources is projected to increase from 47% of electricity generation in 2024 to 69% (Ember, 2025; Ember, 2024).

As the number of VRE generators increases, storage will play an increasingly important role, transferring low-carbon power across time periods, ensuring security of supply, and providing necessary services to keep the electricity system functional. Analysis published by the European Commission (no date) has suggested the EU will need an estimated 200 GW of storage (up from around 70 GW in 2025) by 2030 to align with decarbonisation targets.

As the self-defined European “climate bank,” a significant element of the EIB's (2025a) purpose is to contribute to the bloc's decarbonisation targets. Thus, any projects supported by the EIB should have clear alignment with and the ability to deliver upon EU- and country-level targets. The primary questions then become: to what degree is storage necessary for decarbonisation, how could it contribute to the EU's decarbonisation targets, what role could the EIB play in supporting its deployment, and consequently, how should storage projects be appraised?

1.2 Types of Storage

Hydropower, in widespread use since the 20th century, is the primary form of electricity storage currently used in Europe. Within the EU, there are currently 46 GW of pumped storage hydropower (PSH) (Quaranta *et al.*, 2024). However, PSH is geographically limited, and many potential sites in the EU have already been developed. While modernisation projects are being carried out on existing projects, this capacity alone will not enable the EU to retire sufficient fossil fuel generators to reach its net zero targets. Thus, it becomes necessary to turn to other forms of storage.

BESS is the primary form of short-duration storage currently being deployed (Schmidt and Staffell, 2023). Most BESS deployment currently consists of lithium-ion batteries with a duration of 1-2 hours. Current European BESS capacity has reached around 25 GW (EASE and LCP Delta, 2025). An estimated 5.2GW of this capacity is utility-scale batteries, as many markets are still dominated by residential behind-the-meter batteries (Zimmerman, 2025). Scaling utility-scale BESS will be crucial to meeting the EU's estimated need for 200 GW of storage by 2030.

Lithium-ion batteries have experienced rapid cost reductions, due mostly to their application in consumer electronics and electric vehicles (Schmidt and Staffell, 2023). These batteries are particularly useful due to their high energy density, modular size, and fast response time, leading to their deployment on electricity networks. Cost reductions are expected to continue (an estimated 11% drop is expected in 2025 (BloombergNEF, 2025)), but these batteries also suffer from limited cycle lives and require critical minerals to build. Degradation is also a threat, as the more batteries are cycled, the faster their energy capacity decreases.

Another battery chemistry, sodium-sulphur, shows promise but is currently only deployed in small numbers (Schmidt and Staffell, 2023). Sodium-sulphur batteries might enable BESS to enter the territory of mid-duration storage, discharging for roughly 6-10 hours and require fewer critical minerals. Flow batteries could also become an important battery chemistry. While currently deployed at a very small scale, these batteries might enable BESS to enter into the territory of LDES. However, both technologies have a lower energy density than lithium-ion batteries, requiring more space to deploy systems of an equivalent energy capacity. Resultantly, they have been invested in less than lithium-ion batteries and their costs remain high. For more about other chemistries, see Appendix 1.

What all these battery chemistries have in common, however, is that they require some critical minerals. The evolution of the EU's stance towards minerals and mining will thus impact the deployment of all forms of BESS. The EU's (2023) battery regulations have outlined plans to improve existing methods to test battery performance and durability and to introduce minimum requirements. The change also includes provisions to ensure batteries are safe and the batteries entering the EU uphold human rights standards. These provisions should help offset the human rights and supply chain risks if fully implemented.

In contrast to BESS, LDES technologies generally have a duration over 10 hours, and some may extend to multi-week storage. Thermal and mechanical forms of storage are currently the most suitable forms of LDES although this may change over time. PSH is the most established form of LDES, but there is a considerable range of novel technologies that could come to dominate this category.

1.3 Multiple Potential Roles of BESS

Most BESS projects participate in several energy markets, “stacking” revenue from providing a range of services. This is necessary as individual markets are generally not profitable enough to justify the batteries’ cost (Seagrass and E.ON, 2024). While this stack can vary across geographies, BESS’s primary operating markets are energy trading (arbitrage), capacity markets, and ancillary services (which in many EU states also includes balancing mechanisms). Within these three markets, storage can provide a wide range of services (see Figure 1), depending on market design and battery configuration. Figure 1 illustrates services provided by energy storage in general; LDES is more capable of providing some services (such as seasonal storage) than BESS.

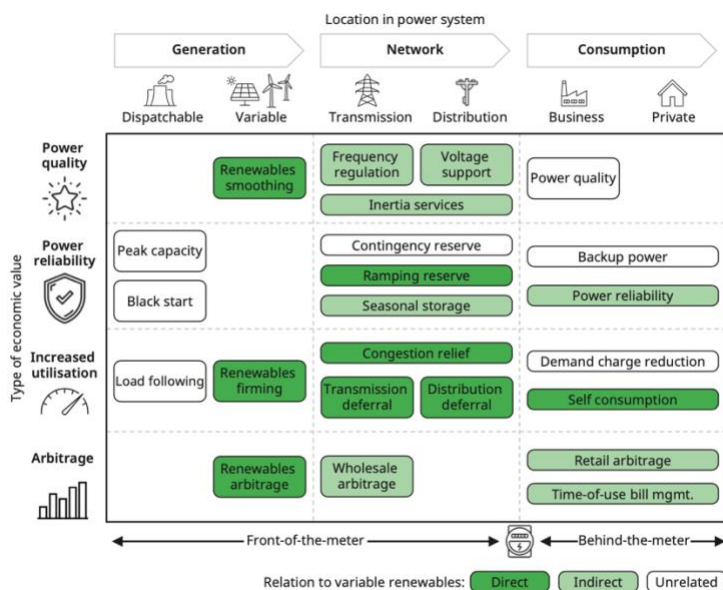


Figure 1: Range of Services Provided by Storage (Schmidt and Staffell, 2023)

A significant challenge of BESS is the “missing money” problem. While BESS provides fundamental system services, many of these are uncompensated as generators are mandated to provide these services (ENTSO-E, 2021; Mays, 2024).² The deployment of BESS

² The scale of this problem varies by member state, with some using markets to procure nearly all ancillary services while others mandate their procurement. ENTSO-E (2021) provides more specific detail for the situation in each country.

is necessary to phase out fossil fuel generators, but batteries will not be invested in if they are unprofitable. This suggests public finance organisations like the EIB might have an outside role in supporting BESS deployment.

1.4 Current EU BESS Deployment

The EU has defined energy storage to mean “deferring the final use of electricity to a moment later than when it was generated, or the conversion of electrical energy into a form of energy which can be stored, the storing of such energy, and the subsequent reconversion of such energy into electrical energy or use as another energy carrier” (European Parliament, 2019). The European Commission (2023) has encouraged all member states to consider reducing regulatory barriers to storage’s market participation, but it is up to each country to determine how it wishes to classify storage and what markets these assets may access (Cesa-Bianchi and Jollands, 2024).

Some member states (like Belgium, Spain, and Germany) have codified storage definitions into national law (European Commission’s Directorate-General for Energy, 2023). These countries have chosen to create a new category for storage within their energy classifications. Other jurisdictions, such as the United Kingdom (UK), have classified storage as a generator (Carvalho and Spataru, 2022). In jurisdictions where these provisions are not in place, storage projects can face double taxation, paying both upon charging and discharging. There is also the underlying threat of future regulatory changes adversely affecting projects since they lack the protections provided by a legal definition.

While rules for operating wholesale electricity markets are consistent across the EU, the treatment of BESS across member states varies. Some countries (like Belgium and Slovenia) have robust ancillary services markets open to BESS (SmartEn, 2022). In contrast, Poland, Romania, and Greece heavily restrict access to ancillary service markets, effectively barring BESS. Access to ancillary services for BESS is expected to improve as countries implement new EU-level provisions related to electricity market design. International collaboration on platforms like PICASSO or MARI (which enable cross-border procurement of frequency restoration services) is also expected to improve BESS access to ancillary services.

BESS’s current deployment varies significantly across the EU (Figure 2). Germany and Austria, for example, have successfully deployed residential batteries at scale but have comparatively little utility-scale BESS (SolarPower Europe, 2024). France and Italy have recently become two of the largest EU markets for utility-scale BESS. While the European Commission and individual member states have funded some BESS, continued divergence in BESS deployment across the bloc is expected in the near-to-medium term.

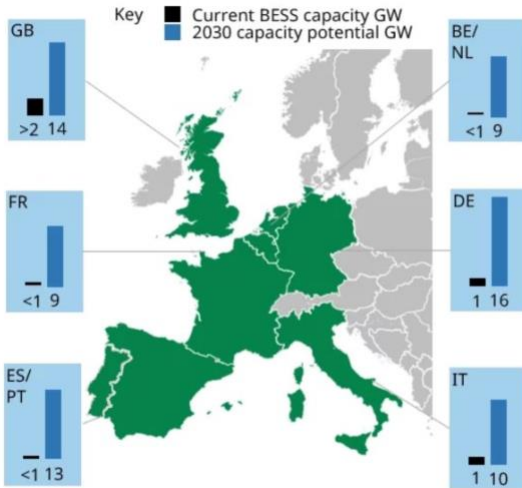


Figure 2: Current Utility-Scale BESS Deployment vs 2030 Growth Potential (Timera Energy, 2023)

Some countries do not provide clear figures for BESS deployment, making it challenging to understand the scale and geographic variation of EU storage (ENTEC, 2023). Reforms to the European Electricity Market Design, requiring all member states to draft storage deployment targets by 2027, will hopefully improve the quality of these data (European Commission, 2024).

2) Systems Change and the Greenhouse Gas Impacts of BESS

2.1 System Dynamics

2.1.1 Definition of Feedback Loops

Storage deployment has both direct and indirect effects, and the EIB's appraisal methodology needs to capture how system elements interact with each other and restrict the impact of changes to the current system (Bennett and Steenmans, 2022). The relationships between system elements can be represented using feedbacks, which can either be dampening or amplifying. Dampening feedbacks keep the system in its current equilibrium when an external stimulus seeks to change it, while amplifying feedbacks help the system to move to a new equilibrium when faced with change. External stimuli may include investment from an organisation like the EIB or EU policy. In the subsequent sections, three primary feedback loops will be discussed: the potential for learning-by-doing, BESS's relationship with VRE deployment, and BESS cannibalisation. These feedbacks are not exhaustive, but they are those most likely to add or detract from a project's attractiveness in the near to medium-term.

Causal loop diagrams (CLDs) offer an analytic tool to consider feedbacks. CLDs depict different coloured arrows to represent dampening and amplifying feedbacks. In Figure 3, the red arrows represent dampening feedbacks while the blue represents amplifying ones. The reinforcing loop suggests that deploying low-carbon energy over fossil fuel will enable learning-by-doing, reducing the costs of the low-carbon technology. CLDs will be used as a visual aid in the subsequent sections.

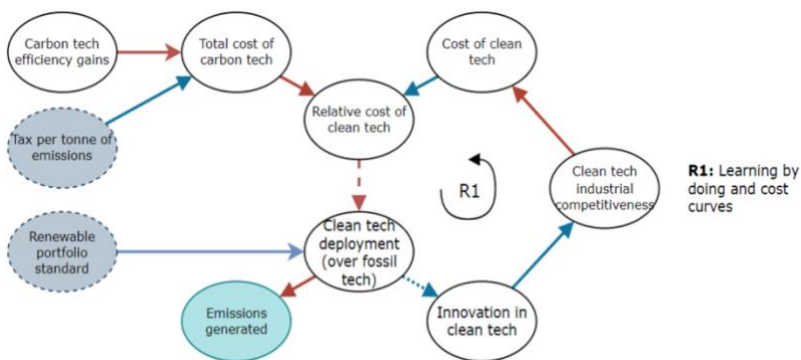


Figure 3: Example Causal Loop Diagram (Sharpe and Murphy, 2024)

2.1.2 Definition of Tipping Points

Closely related to feedback loops are tipping points. Mealy *et al.* (2023) define these as the “most obvious points in systems where a small change or perturbation can have a big impact.” Once a tipping point is reached, feedbacks become self-sustaining and self-

reinforcing, and the system equilibrium can become unbalanced or change completely. In energy systems, where inertia and path dependency may constrain change, the location of tipping points illustrates where the energy system is most capable of change (Bretschger and Leuthard, 2024).

Feedback loops and tipping points illustrate that some projects or policy interventions can have an outsize (positive or negative) impact. Understanding the existing feedback loops and predicting where tipping points might lie can amplify a project's decarbonisation potential.

For example, greater deployment of VRE generators in European energy systems that do not face significant demand increases means that these renewable generators displace thermal generation. If there are fewer fossil fuel generators on the system, then ancillary services must be procured from other energy assets (such as BESS). As the share of VRE generation increases, the number of ancillary services markets open to non-fossil generators is expected to increase. This would highlight an amplifying feedback.

In this way, it is also easy to see how, if VRE is not deployed at expected rates, then more fossil generators will remain on the system and there will be less incentive for market operators to open traditional ancillary services to BESS. This could dampen signals to deploy BESS as ancillary services are likely to form a core revenue stream for storage.³

While it might be too ambitious to expect that every project the EIB funds has transformational potential, ensuring that these projects enable tipping points to be reached more easily in future can ensure the EIB's impact is maximised (Lenton *et al.*, 2021). In fact, due to the multiplier between public and private funding (Espinoza, Gamboa-Arbelaes, and Sy, 2020), investments in BESS by the EIB might be themselves tipping points, crowding in further investment.

The fundamental challenge, however, is that it is very difficult to identify tipping points *ex ante* (Lenton *et al.*, 2021). As systems approach tipping points, they often become less resilient, adapting to external shocks at a slower pace (Scheffer *et al.*, 2009). This can be an important factor to aid in the identification of tipping points *ex post*, but these indicators are not necessarily visible enough to aid in the precise identification of tipping points before they have been reached.

Overall, while there is considerable literature on the impact of tipping points in systems (e.g. Sharpe and Lenton, 2021., Farmer *et al.*, 2018), Lenton *et al.* (2021) describes these works as “rather theoretical, speculative and rarely specific enough to guide actions.” Thus, tipping points are most useful as a conceptual framework for identifying the types of systems interventions that may lead to non-linear change. This is not necessarily a tool that can be easily translated into quantitative methodologies (i.e. scenarios modelling), however.

³ Food and Land Use Coalition (2021) contains some more examples of feedback loops but these do not relate directly to storage.

2.2 BESS Emissions

As BESS projects do not generate their own energy, they do not unambiguously contribute to a reduction in emissions. How should the direct emissions of building the batteries for BESS systems be accounted for? How significant are these emissions? Can BESS reduce system emissions when operating in an energy system powered by fossil fuels?

BESS emissions can be broken into two distinct categories: direct and indirect emissions. Direct emissions refer to the emissions incurred in battery construction, as well as operational emissions (from charging/discharging using carbon intensive power). Indirect emissions refer to the BESS's broader emissions reduction potential due to the presence of system feedbacks.

2.2.1 Direct Emissions

Embodied battery emissions can be quantified through a battery life cycle analysis. Estimates indicate that these emissions are low compared to the emissions-saving potential of BESS (Aquila Capital, 2023). Battery emissions could decrease further if battery chemistries less reliant upon critical minerals (and the emissions-intensive mining thereof) replace lithium-ion (Schmidt and Staffell, 2023) or recycling rates increase (Sadhukhan and Christensen, 2021).

The next factor is whether BESS might increase emissions if charged using fossil fuel energy. Because storage is never 100% efficient, charging using fossil-generated power could increase system emissions compared with a system where a fossil generator provides the same service. Analysis by Mansfield *et al.* (2024) of Texas's electricity system found that 92% of batteries on the system charged primarily using fossil fuel power, concluding that BESS therefore increased system emissions. Yet, battery emissions are not so simple, and Texas's nodal electricity system and generation mix cannot be taken as a direct proxy for the EU.⁴

These batteries were likely charging using fossil fuel power because these plants set the lowest merit order prices due to their high turndown costs. In the EU, carbon pricing pushes the most emissions-intensive generators further back in the merit order, ensuring that even if BESS charges using fossil fuel energy, it is likely to be the least emissions-intensive of these generators. Additionally, when fossil fuel generators are ramping up or down, they are not fully efficient. When present, batteries can smooth demand curves, reducing the frequency of fossil generator ramping. This ensures that fossil generators operate at their maximum efficiency more frequently.

Demand smoothing is also relevant to nuclear power, which is especially important in the French context. In nuclear-dominant systems, nuclear generators must be turned down

⁴ While Texas's generation mix varies significantly from some member states, it is not dissimilar from the Netherlands' current mix, with both wind, solar, and natural gas. These differences in generation mix also make it challenging to compare to member states with fundamentally different mixes.

when supply outpaces demand. This effectively wastes low-carbon power. Batteries can absorb this power during periods of low demand, increasing the usefulness of inflexible nuclear power.

Finally, transmission constraints have become a significant problem in European power markets. When power is trapped behind transmission constraints, these generators must be paid for their output, while unconstrained generators are paid (at a higher price) to operate. Such redispatch costs are expected to rise in the EU from €4 billion in 2022 to over €20 billion by 2030 (Thomassen, 2024). This rise is a consequence of increasing VRE generation, located farther from demand centres. While transmission upgrades will be needed, BESS could delay or even eliminate the need for some upgrades. BESS located behind these transmission constraints can absorb curtailed power that would otherwise be wasted, while BESS located on the other side of these constraints can replace fossil fuel generators that would likely be called on to operate.

There is, thus, no single tipping point at which BESS begins to reduce rather than contribute to system emissions. The electricity system's average carbon intensity becomes a helpful proxy for BESS's emissions contribution. Figure 4 maps the charge/discharge patterns of 2-hour batteries to the electricity system's carbon intensity over the past 16 years in Great Britain (GB). The y-axis illustrates the carbon intensity during lowest-price (the optimal time to charge a battery) and highest-price periods (the optimal discharge time) over the past 15+ years. GB was chosen as a representative example because its electricity system has decarbonised rapidly, and it has Europe's largest utility-scale BESS capacity.

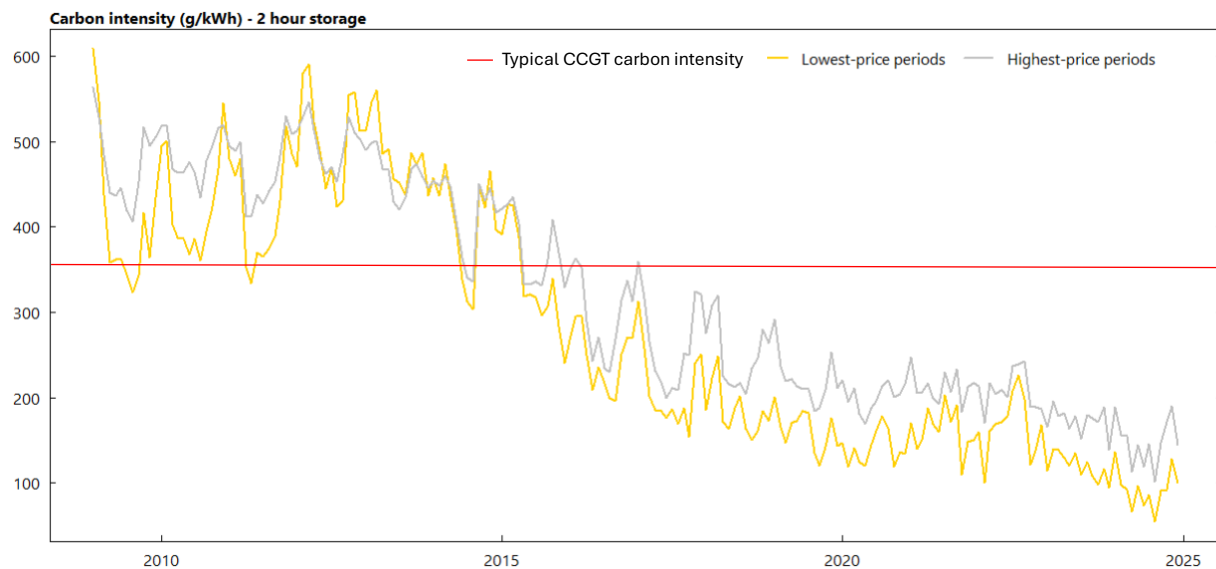


Figure 4: Carbon Intensity over Time of GB BESS (chart courtesy of Iain Staffell using data from Drax Electricity Insights)

Figure 4 highlights two important dynamics. The first is that, within a relatively short period (less than 5 years, from around 2013 to 2018), the carbon intensity of optimal periods to charge BESS (the yellow line) dropped from greater than that of a CCGT plant (the red line) to

below the carbon intensity of a CCGT plant. This implied that BESS had been charging at least some of the time using even more emissions-intensive generators like coal. Within the subsequent five years, the carbon intensity continued declining, reaching the point today where, when BESS charges, the carbon intensity is likely to be very low.⁵

Another element illustrated by Figure 4 is the correlation between carbon intensity and prices. Until around 2015, there was little correlation between prices and carbon intensity (as seen by the frequent intersection of the yellow and grey lines). These intersections suggested there was no clear correlation between price and emissions intensity, with batteries charging using any form of power.

Over time, however, a clear gap emerged between the lines, demonstrating that BESS is now much more likely to charge during periods of low carbon intensity and discharge during periods of higher intensity. The scale of this gap indicates the emissions BESS is offsetting; any time BESS is charging using energy that is less carbon intense than the system average, it is reducing emissions. In line with this finding, Jennings (2024) estimates that BESS's contribution to emissions has grown from an offset of 1% in 2021 to saving 4% of system emissions in 2024 (Figure 5).

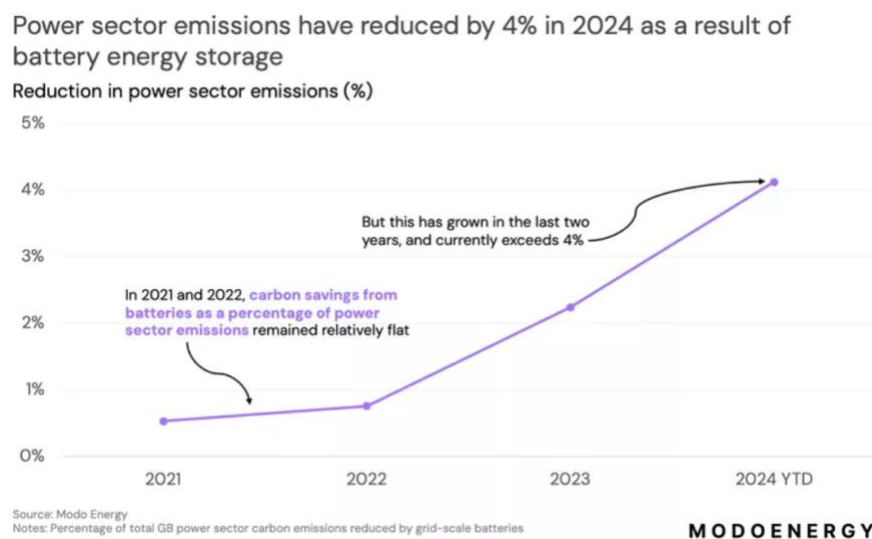


Figure 5: BESS Impact on GB System Emissions (Jennings, 2024)

⁵ The scale of difference between the highest-price and lowest-price periods is less than might be expected (and far less than the gap between VRE and gas power), as gas still sets the price in the UK system most of the time - 98% of the time in 2021 (Zakeri et al., 2023). This is a much higher percentage than in other European countries and means that even in low-price periods, there will be some gas generation on the system (perhaps providing ancillary services or due to transmission constraints), elevating the system's carbon intensity.

Thus, in a system that is rapidly decarbonising, BESS's potential to save emissions becomes incredibly clear. How these emissions might be quantified in different markets is explored in Box 1⁶.

⁶ Additional simplifications include: VRE embodied emissions, construction emissions, and battery degradation. While low, VRE generation also incurs emissions from the building and installation of generators. Given the site-specific nature of these figures, estimates for the carbon intensity of installing the batteries have also been omitted. Battery degradation has also been discounted as this is highly dependent upon the BESS's operating strategy and therefore can vary widely. Over time, BESS should also be displacing unabated fossil fuel generators less frequently, as they are phased off the system or fitted with CCS technologies.

Box 1: Simplified Estimate of BESS Emissions

While a life cycle assessment (LCA) would be the most robust way to understand BESS's emissions impact, for the sake of simplicity, some illustrative figures related to BESS emissions are explored here.

Emissions from battery construction: While there will be differences in embodied emissions depending on where a battery was manufactured and the type of energy used to produce it, estimates are available. Published estimates vary widely, due partially to uncertain boundaries in what should be included in an embodied emissions calculation. Rapier (2022) estimates 89 kgCO₂e/kWh, while Le Varlet et al. (2020) recommend 200 kgCO₂e/kWh. As a point of comparison, the lithium-ion batteries used in electric vehicles are estimated to produce 61-106 kgCO₂e/kWh, contextualising the utility-scale figures (Emilsson and Dahllof, 2019). Using the average of the first two figures, this means a 100MWh battery would emit 14,450 tCO₂e in the manufacturing process.

BESS lifetime emissions savings: Using a simple illustration, what might the operational emissions of a 100MWh battery performing arbitrage in a solar-dominated system be? Assumptions: the battery charges 1x/day, it has a 96.8% efficiency, it is sunny enough to discharge its full capacity 300 days per year, it always charges using solar power, and it always displaces CCGT. Assuming the CCGT has a carbon intensity of 360 kgCO₂e/MWh, over the course of a year, the BESS's operation would displace 10,454.4 tCO₂e. Assuming it can operate in the same way over 15 years, then it displaces 156,816 tCO₂e, far exceeding the embodied emissions.

BESS's true impact on emissions is likely to be lower than what is estimated in the simple calculation above. While Figure 4 illustrates the strong correlation between prices and carbon intensity as the electricity system decarbonises, BESS may sometimes charge using fossil fuel power as the system transitions. This illustration considers only embodied emissions and arbitrage operation; BESS may be more willing to charge using fossil fuel power when providing ancillary services or when called upon in a capacity market, depending on the relative cost of charging at this time. Yet, Jennings (2024) illustrates that most of BESS's emissions savings currently come from displacing fossil fuel generators in ancillary services provision (at least in GB). While there is some ambiguity in what the true emissions savings from BESS availability and operations may be, they do seem to far outweigh their embodied emissions.

2.2.2 Indirect Emissions

Additionally, batteries play an important role in catalysing further VRE deployment by de-risking these assets, which will be examined in further detail in section 2.3. If the presence of BESS in an electricity system optimises the participation of other low-carbon capacity, then the emissions-saving potential of BESS becomes even more powerful.

What the GB example illustrates is that in a rapidly decarbonising power system, BESS quickly reduces rather than contributes to emissions. Even in fossil fuel-dominant systems, BESS could still contribute to emissions reduction. If the EIB is still concerned that BESS might increase short-term emissions, there are simple operating strategies to ensure that BESS charges using only low-carbon power (Keske *et al.*, 2024). While such strategies come with a small decrease in profitability, the EIB could require projects it funds to implement such strategies.

2.3 Economic Benefits of Storage Deployment

2.3.1 Learning-by-Doing Feedback: Beyond Lithium-Ion BESS

Over time, as assets are invested in, they can experience learning effects whereby the cost of the technology declines due to both the impact of scale economies and learning effects that streamline producing and deploying these technologies (Haas *et al.*, 2022). In this sector, learning effects indicate a negative correlation between the installed capacity of a technology and its cost. Technologies like solar PV have been found to experience relatively stable cost reductions as their installed capacity rises.

Learning-by-doing effects for lithium-ion BESS are already well underway, so any EIB investment is unlikely to catalyse further change. This feedback is worth mentioning, however, as it can be relevant to LDES and other BESS battery chemistries. Figure 6 illustrates the stages of cost reductions through learning-by-doing and its effect on a generic technology. While EU industrial strategy is shown as an input, others could exist as well, such as the EIB's support or the EU's net zero targets.

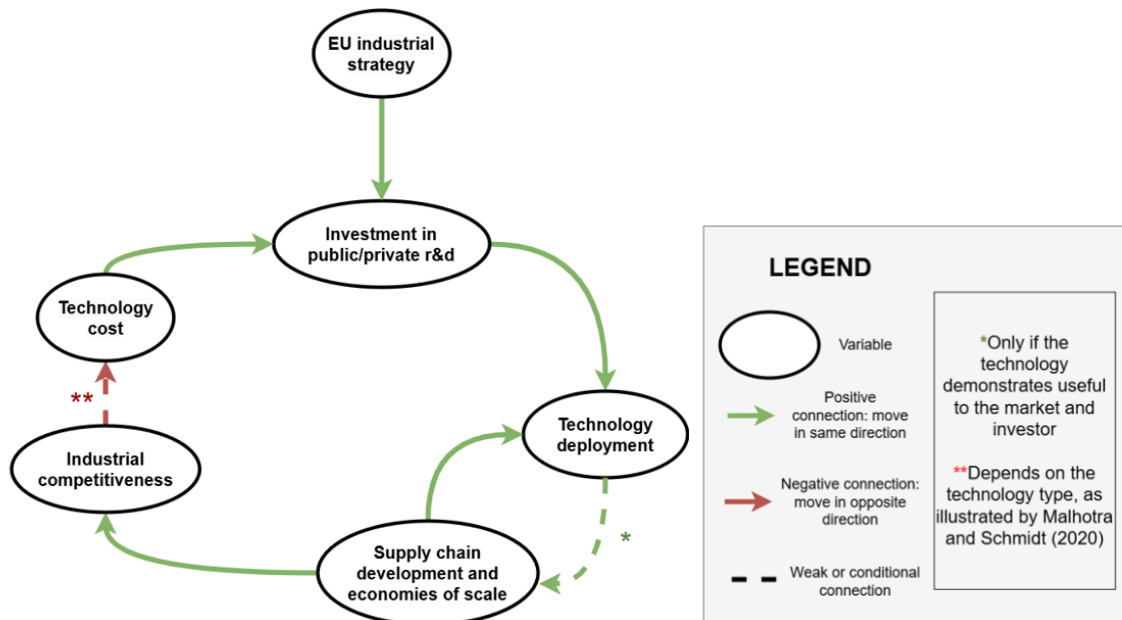


Figure 6: Generalised Learning-by-Doing Feedback

The key to learning effects, however, is that not all technologies are likely to see cost reductions or to experience them in the same areas. Malhotra and Schmidt (2020) created a representation of energy-related assets, categorising them on two axes: design complexity and degree of customisation (Figure 7). Assets most likely to experience cost reductions have a low design or installation complexity and relatively little need for customisation at each installation.

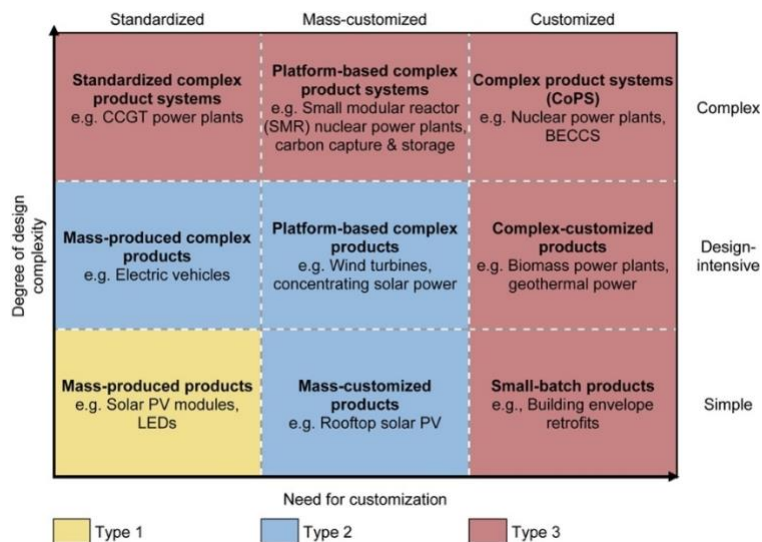


Figure 7: Framework for Learning-by-Doing in Energy Technologies (Malhotra and Schmidt, 2020)

The framework divides assets into three categories, where the potential for cost reductions declines as the type number increases (Malhotra and Schmidt, 2020). Type 1 technologies

experience rapid learning due to their modular nature. Type 2 technologies can be subject to learning effects, but these feedbacks must often be supported by external factors like industrial policy. Type 3 technologies are characterised by large scale and complexity, long deployment timescales, and the need for specificity, meaning they have limited scope for learning-by-doing or scale economies, and costs remain high. While these types are based largely on the technological factors inherent to each technology, significant investment can change technologies' type.

While storage does not appear in Figure 7, the same framework applies. Complex and geographically dependent LDES falls into Type 3. These technologies will require government support and are unlikely to experience cost reductions. PSH is an example of a Type 3 technology where, due to the high degree of customisation needed, the technology has not experienced scale economies. In contrast, some more novel forms of LDES (like compressed air energy storage) are likely to fall into Type 2. While they must be customised, the greater their modularity, the greater the potential for learning effects to reduce costs. BESS falls into Type 1, representing a highly modular technology perfectly suited to economies of scale. For quantified expectations of anticipated cost reductions in storage, see Appendix 1: BESS Evolution: Battery Chemistries and Expected Cost Reductions.

2.3.2 Feedback Loop between VRE and BESS

As discussed in section 2.2, BESS's significant value comes from absorbing low-carbon power that would either be curtailed due to transmission constraints or an imbalance between supply and demand. Brown *et al.* (2024) found that, given current UK renewable targets, by 2030, low-carbon power is expected to be in surplus for more than 50% of the year (with no absorptive storage capacity). Even as storage is added to the system, the amount of surplus does not dramatically reduce.⁷ Similar estimates have been made for the Netherlands, where by 2030, renewables are likely to be oversupplied for more than 50% of the year (Kampenaar *et al.*, 2024).

What is surprising about this research is how quickly surplus VRE can cause problems. Hirth (2013) estimates that significant surplus arises at 15% solar or 30% wind penetration, and once these levels are achieved, the surplus frequency increases non-linearly (Peña, Rodriguez, and Mayoral, 2022). Surplus VRE has been present in the Spanish energy system since 2014 and has undermined the investment case for building more VRE. Modelling of the Baltic States anticipates that by 2029, revenue for VRE projects will drop so significantly due to surplus that projects will no longer be bankable (Kozlovas *et al.*, 2024).

This is not simply a future problem. In Sweden, energy prices are expected to be near zero for large percentages of 2025 and 2026 due to significant surplus VRE (Paulsson, 2024). The

⁷ When 5 GW and 10 GW of unconstrained storage in each hour were added to the model, the number of negative-price hours decreased from around 50% of the year to around 25-33% of the year. While reduced, this is still a considerable number of negative-price hours.

number of hours with negative electricity prices has increased rapidly across Europe in recent years, as demonstrated by Figure 8. This rate of change indicates that, from a systems perspective, batteries are undersupplied, and rapid VRE deployment targets will exacerbate this dynamic if storage deployment does not keep pace.

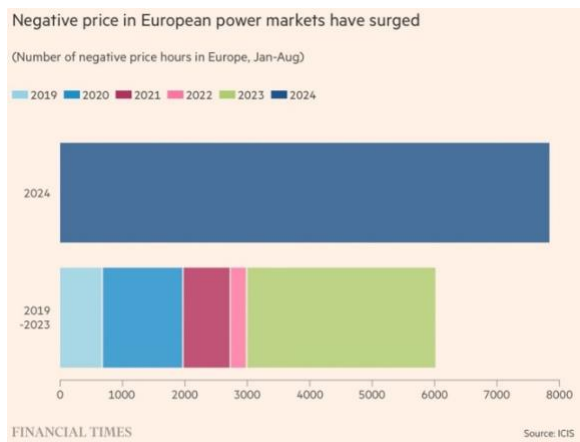


Figure 8: Negative European Electricity Price Hours 2019-2024 (Tani and Millard, 2024)

It is clear, therefore, that BESS plays an important role in an energy system with inflexible power, and these periods of negative prices would be an ideal opportunity for BESS to profit. In an ideal world, the greater the number of VRE generators, the greater the instance of surplus VRE, the greater the incentive for BESS and other forms of storage (Figure 9). BESS should, in turn, reduce the risk of further VRE development by mitigating the threat of declining revenues for developers due to negative wholesale prices.

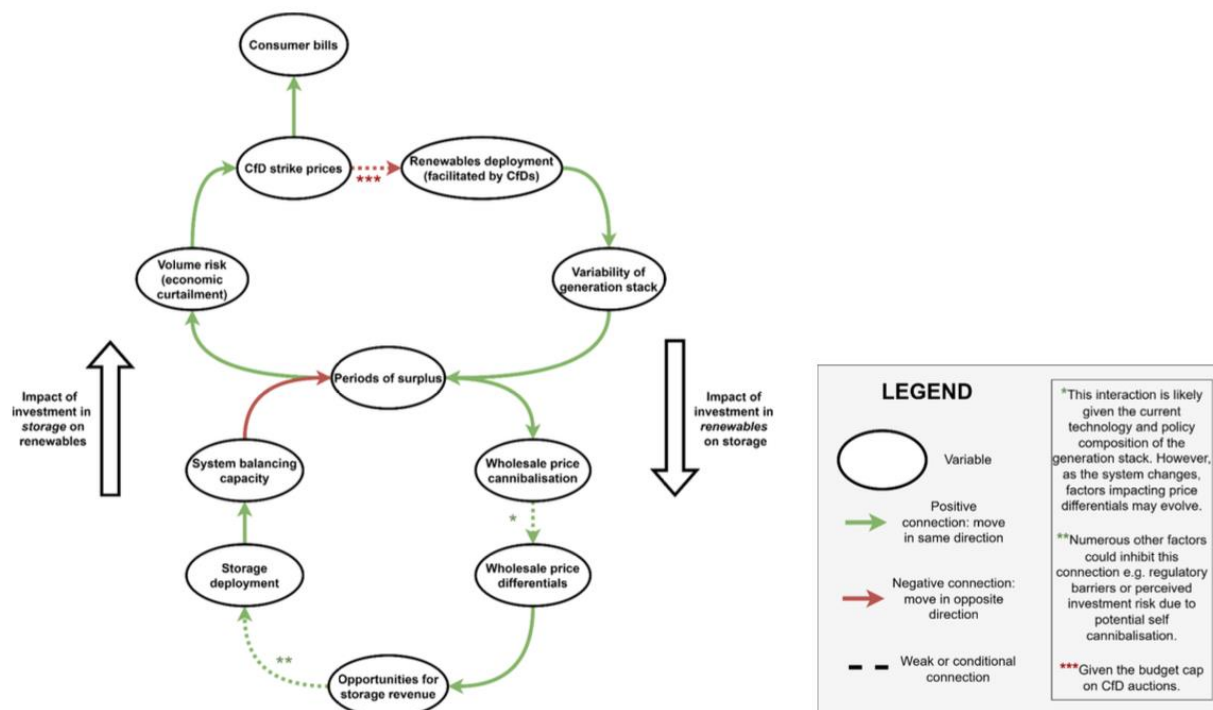


Figure 9: CLD Representing the Feedback between VRE and Storage (Brown et al., 2024)

The challenge, however, is that once there is sufficient BESS capacity to absorb the current levels of surplus VRE, there is a dampening feedback whereby arbitrage revenues decline and significantly reduce incentives to build more BESS. Over time this dampening effect should lessen as, if instances of negative electricity prices decline, VRE generators' volume risk will also reduce, and more VRE will likely be built. This will again lead to periods of surplus VRE, creating incentives to deploy more BESS. The challenge, however, is the mismatch in VRE and BESS deployment, suggesting there could be periods where BESS could be so oversupplied that multiple revenue streams are cannibalised. Such a scenario could risk the EU's decarbonisation targets, but also highlight that investment by the EIB could in itself serve as a tipping point. If by investing in BESS, the EIB reduces the risk for greater VRE deployment in some member states, the Bank's investments could in themselves reduce the likelihood of these dampening feedbacks being encountered. Identifying whether an investment would succeed in this is complex, however, but the gap between installed capacity of BESS and VRE as compared to policy or modelled targets is likely to be a helpful indicator. This approach will be examined in more detail in section 4.2.

2.4 Threat to Storage Deployment: Cannibalisation

The feedback between VRE and storage illustrates how opportunities for BESS to profit from arbitrage could be cannibalised. Revenue from BESS's other markets, ancillary services and capacity markets are not guaranteed either. GB has recently seen significant cannibalisation of its ancillary services market. As VRE generators were deployed and fossil fuel operators were pushed out of the merit order more frequently, other assets were needed to provide ancillary services, leading to significant BESS deployment (Bush, 2024). Growing VRE deployment is also changing the mix of ancillary services required, increasing system needs for fast frequency and voltage control (Viola *et al.*, 2024). BESS was also made more attractive as an asset by the rapid decline in lithium-ion prices experienced in recent years. However, these factors resulted in an oversupply of BESS in ancillary services. In GB, prices for frequency control response (FCR) were 7x lower in 2024 than in 2022, leading FCR to drop from over 90% of BESS revenues in 2021 to an average of 23% in 2024 (Figure 10).

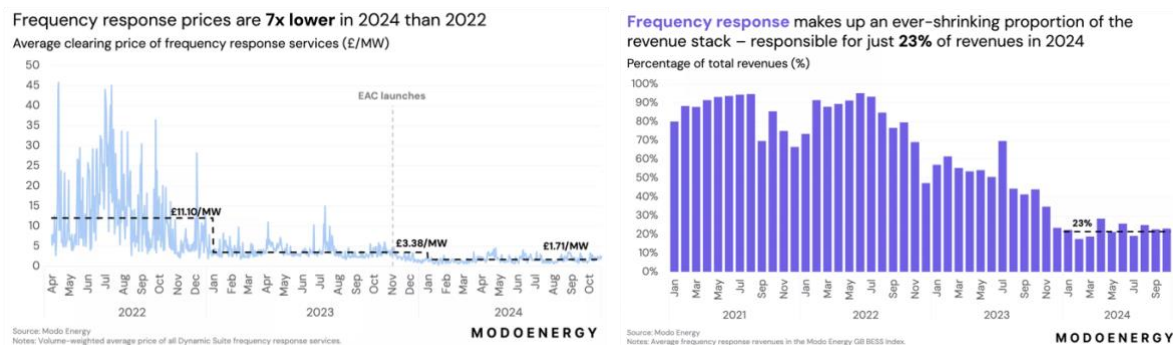


Figure 10: Cannibalisation of BESS Revenues in the GB FCR Market (Bush, 2024)

Ancillary services markets are particularly vulnerable to cannibalisation due to their fixed market size and shallow depth. Arbitrage is a deeper market, so even if there are incentives to deploy storage to absorb surplus VRE, there are insufficient incentives to deploying it for ancillary services provision. Over time, the market for ancillary services will grow as fossil fuel generators exit the system, but there could still be considerable problems in the short term. Figure 11 illustrates this dynamic.

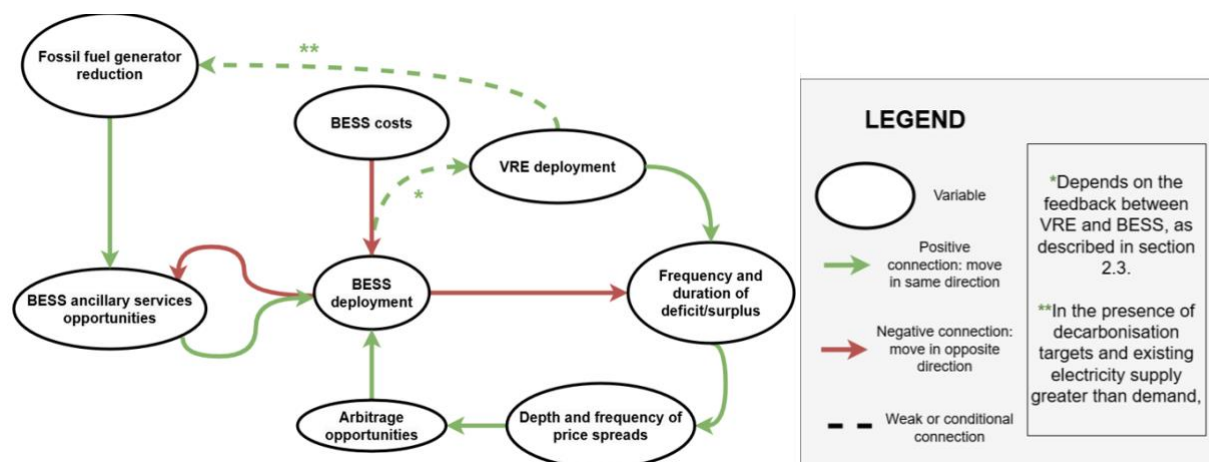


Figure 11: Cannibalisation of BESS Operations⁸

There is also a potential contagion effect whereby once one market is cannibalised, BESS operators seek out new markets, quickly cannibalising all other markets. The speed with which such cannibalisation occurs suggests that even if projects would have significant operating opportunities at the point of funding, they might ultimately enter a market with limited operating opportunities.

BESS's usefulness in capacity markets is also likely to reduce over time, meaning revenue from this market could diminish. In most capacity markets, de-rating factors are applied by technology to ensure a reliable amount of power is tendered for (Seagrass and E.ON, 2024). LDES will become increasingly important to enable continued system decarbonisation and will likely be privileged over BESS due to its greater role in ensuring security. De-rating factors for batteries of 1–2-hour duration would then increase, to reflect statistically lower security contributions, decreasing the revenue BESS can generate from participation in this market.

One might ask why cannibalisation is relevant to an economic appraisal since it relates to profitability. If a market is functioning optimally, financial appraisal should be a reliable indicator of economic value. Yet if BESS is not financially viable due to cannibalisation, it cannot provide its expected economic benefit. The feedbacks discussed above indicate a clear economic value for BESS, yet the financial situation may create a clear imbalance in

⁸ This figure represents some factors contributing to BESS cannibalisation, as they are understood in an economic appraisal. These feedbacks will be revisited in part two of this project to understand whether any information from this research would alter these relationships.

the level of flexible storage needed by the system and the amount of storage deployed by the market (to be explored further in part two of this project).

3) Current EIB BESS Appraisal Methodology

3.1 EIB's Current Approach to BESS Appraisal

Cost-benefit analysis (CBA) (taken here to mean the aggregated monetisation of all costs and benefits related to a proposed project) and its variants have long been used to appraise projects. Particularly useful in contexts of marginal change where outcomes are relatively certain and there is a narrow set of involved interests, CBA provides a consistent and structured appraisal framework. This methodology requires a counterfactual, an alternative state of the world that illustrates a project's potential performance in different states of the world.

At the EIB (2023), CBA serves as the default methodology for economic appraisal, followed by cost-effectiveness analysis (CEA) and multicriteria analysis (MCA). While the latter two are more flexible than CBA, they still require quantification, limiting their effectiveness in highly uncertain contexts (Lindhe *et al.*, 2013). Additionally, none explicitly captures the influence of feedback loops or tipping points.

The EIB's (2023) methodology presents three options for a counterfactual. The first is to adopt a do-nothing approach, which is applied to capacity rehabilitation projects. The second approach is a do-minimum, which captures the cost of maintaining the infrastructure at its present level of functionality (applied to capacity expansion or upgrade projects). The third approach is to do something else, comparing a project against a scenario that meets the same objectives (generally represented by an alternative technology, project scale, or location). This approach is used once it has been determined that "something must be done" to modify the relevant system. In practice, given the urgency of meeting the EU's and country-specific decarbonisation targets, BESS projects are likely to fall into the third category. The question then becomes how to determine what alternative delivers the same objectives as BESS.

3.2 Methodological Comparison

Might the appraisal approaches of other public organisations offer clues for BESS projects? Both the World Bank and the European Network of Transmission System Operators for Electricity (ENTSO-E) have published detailed methodologies on their approaches to appraisal and make suitable comparisons due to their overlapping work with the EIB.

3.2.1 World Bank Approach

Using the World Bank's (2020) specific BESS methodology, if a proposed project is deemed incremental, the expected energy balances with and without the proposed project are calculated. These results then inform the project's benefits. For projects that substitute for an existing power source, the counterfactual is the "next best project" to be built in place of

the proposed project. Like the EIB approach, this requires identifying a suitable technological alternative. Rather than applying a one-size-fits-all approach, however, the World Bank methodology reads more like a series of yes/no questions with divergent approaches depending on the project context. So, while traditional CBA is still applied, analysts have greater flexibility depending on project-specific criteria.

3.2.2 *ENTSO-E Approach*

ENTSO-E (2023a) does not have a BESS-specific approach, but it does detail its appraisal methodology, which combines MCA with CBA. Qualitative factors (representing those that cannot be “objective[ly]” quantified) are also included, such as environmental impacts and climate/disaster resilience. Rather than use a technology-based counterfactual, ENTSO-E integrates a project into its Ten-Year Network Development Plan (TYNDP) scenarios (created in collaboration with the European Network of Transmission System Operators for Gas (ENTSO-G)). It then models the performance of the energy system with and without the proposed project. This approach, while complex, enables a more holistic comparison of a project’s performance over time.

Within this framework, because there are qualitative and quantitative factors, ENTSO-E has a clear list of the benefits (such as emissions reduction and security of supply) it measures, along with the costs and residual impacts of a project. This long list of factors provides decision-makers with a more complete picture of a project’s impact than the model output alone. As of 2023, however, while ENTSO-E’s (2023b) market simulation model could represent BESS, the only type of storage discussed in its methodology was PSH.

While both the World Bank and ENTSO-E’s methodologies illustrate a movement towards flexible appraisal, neither provides definitive suggestions for the choice of counterfactual.

3.3 Illustration of the EIB’s Methodology

A simplified CBA using a range of counterfactuals is presented here to test the choice of counterfactual for BESS. The basic features of the CBA (which are based on figures from a real EIB-approved project) are the same in each case. The project was assumed to be constructed in 2026 and begin operation in 2027 for a 15-year lifetime. The tested counterfactuals include: do-nothing (Table 1), an OCGT project (Table 2), the same OCGT project with two different carbon prices (

Table 3, However, the expected ETS price is significantly lower than the EIB’s (2023) mandated social cost of carbon. If the EIB’s figures are instead used to calculate the cost of the OCGT plant’s emissions, the EIRR increases drastically to 37% (**Error! Not a valid bookmark self-reference.**).

Table 4), and a PSH project (Table 5). Appendix 2: Methodology for Simplified CBA Figures provides greater detail on how these counterfactuals were calculated.

The "do-nothing" counterfactual closely mirrors the counterfactual used in the original project. This CBA assumed that because due to its lower operating costs, BESS would push PSH out of the merit order for FCR provision. Thus, the difference between the cost of procuring PSH or BESS for FCR represents the proposed project's benefits. reduced costs of FCR provision are not sufficient to justify the costs of the building the BESS project, however, as the economic internal rate of return (EIRR) is calculated to be -1.0%.

Table 1: "Do Nothing" Counterfactual Example

	Economic Assumptions	Units	NPV*	0 2026	1 2027	5 2031	10 2036	15 2041
(1)	Installed Capacity	MW	105					
(2)	Energy Capacity	MWh	100					
(3)	Project Cost	MEUR	50					
(4)	Degradation	% per year	1					
(5)	Cost of FCR Provision	EUR/MWh	5					
(6)	O&M	%	3					
Physical Output								
(7)	Power Capacity	MW	1090		105	105	105	105
(8)=(2)*(4)	Energy Capacity	MWh	977		100	96	91	87
Expenditures								
(9)=(3)	CAPEX	MEUR	50	50				
(10)=(3)*(6)	OPEX	MEUR	16		1.5	1.5	1.5	1.5
(11)=(9)+(10)	TOTEX	MEUR	62	50	1.5	1.5	1.5	1.5
Revenues								
(12)=(5)	Economic Value of Storage	MEUR	48		4.6	4.6	4.6	4.6
(13)=(12)	Total Revenues	MEUR	48		4.6	4.6	4.6	4.6
(14)=(13)-(11)	Economic Cashflow	MEUR	-4	-50	3.1	3.1	3.1	3.1
(15)	Economic Rate of Return	%	-1%					
(16)=(11)/(7)*10 ⁻³	LCOC (5%, 15 years)	kEUR/MW	57.3					

*NPV is the net present value at year 0 using the applicable social discount rate (5% for Europe at time of writing)

Table 2 illustrates the second counterfactual implemented in the original project: an OCGT plant. Here, the BESS is assumed to prevent a new OCGT plant from being built. Thus, the cost of building and operating (i.e. total expenditure or TOTEX) the OCGT plant is compared to the cost of building and operating the BESS. This calculation resulted in a low but perhaps marginally viable EIRR of 6%. However, all this figure truly indicates is that the TOTEX of the OCGT plant is higher than that of the BESS project.

Table 2: OCGT Counterfactual Example

	Economic Assumptions	Units	NPV*	0 2026	1 2027	5 2031	10 2036	15 2041
(1)	Installed Capacity	MW	105					
(2)	Energy Capacity	MWh	100					
(3)	Project Cost	MEUR	50					
(4)	Degradation	% per year	1					
(5)	Economic Value of Storage	EUR/MWh	63					
(6)	O&M	%	3					
Physical Output								
(7)	Power Capacity	MW	1090		105	105	105	105
(8)=(2)*(4)	Energy Capacity	MWh	977		100	96	91	87
Expenditures								
(9)=(3)	CAPEX	MEUR	50	50				
(10)=(3)*(6)	OPEX	MEUR	16		1.5	1.5	1.5	1.5
(11)=(9)+(10)	TOTEX	MEUR	62	50	1.5	1.5	1.5	1.5
Revenues								
(12)=(5)	Economic Value of Storage	MEUR	69		6.6	6.6	6.6	6.6
(13)=(12)	Total Revenues	MEUR	69		6.6	6.6	6.6	6.6
(14)=(13)-(11)	Economic Cashflow	MEUR	27	-50	5.1	5.1	5.1	5.1
(15)	Economic Rate of Return	%	6%					
(16)=(11)/(7)*10 ⁻³	LCOC (5%, 15 years)	kEUR/MW	57.3					

*NPV is the net present value at year 0 using the applicable social discount rate (5% for Europe at time of writing)

Table 3 diverges from the approach used in the original project. The same OCGT plant is modelled, but the OCGT plant's operational emissions are calculated, and a carbon price is added to estimate the plant's operational emissions. Given the significant potential for BESS to offset emissions (as explored in Box 1), the BESS project is assumed to produce no operational emissions, allowing the counterfactual to represent only the effect of the BESS displacing OCGT. The embodied emissions of the OCGT plant and the BESS plant are ignored for the sake of simplicity. The original example provided figures estimating the EU Emissions Trading System (ETS) price over the project's lifetime. If these figures are used to estimate the cost of the OCGT plant's emissions, the BESS project's EIRR rises to 11% (

Table 3).

Table 3: OCGT Counterfactual Example with Market Carbon Price

		Units	NPV**	0 2026	1 2027	5 2031	10 2036	15 2041
Economic Assumptions								
(1)	Installed Capacity	MW	105					
(2)	Energy Capacity	MWh	100					
(3)	Project Cost	MEUR	50					
(4)	Degradation	% per year	1					
(5)	Economic Value of Storage	EUR/MWh	81					
(6)	O&M	%	3					
Physical Output								
(7)	Power Capacity	MW	1090		105	105	105	105
(8)=(2)*(4)	Energy Capacity	MWh	977		100	96	91	87
Expenditures								
(9)=(3)	CAPEX	MEUR	50	50				
(10)=(3)*(6)	OPEX	MEUR	16		1.5	1.5	1.5	1.5
(11)=(9)+(10)	TOTEX	MEUR	62	50	1.5	1.5	1.5	1.5
Revenues								
(12)=(5)	Economic Value of Storage	MEUR	88		8.5	8.5	8.5	8.5
(13)=(12)	Total Revenues	MEUR	88		8.5	8.5	8.5	8.5
(14)=(13)-(11)	Economic Cashflow	MEUR	55	-50	7.0	7.0	7.0	7.0
(15)	Economic Rate of Return	%	11%					
(16)=(11)/(7)*10 ⁻³	LCOC (5%, 15 years)	kEUR/MW	57.3					

*NPV is the net present value at year 0 using the applicable social discount rate (5% for Europe at time of writing)

However, the expected ETS price is significantly lower than the EIB's (2023) mandated social cost of carbon. If the EIB's figures are instead used to calculate the cost of the OCGT plant's emissions, the EIRR increases drastically to 37% (**Error! Not a valid bookmark self-reference.**).

Table 4: OCGT Counterfactual Example with EIB SCC

		Units	NPV*	0	1	5	10	15
				2026	2027	2031	2036	2041
(1)	Economic Assumptions							
(2)	Installed Capacity	MW	105					
(3)	Energy Capacity	MWh	100					
(4)	Project Cost	MEUR	50					
(5)	Degradation	% per year	1					
(6)	Economic Value of Storage	EUR/MWh	88					
(7)	O&M	%	3					
(8)	Physical Output							
(9)	Power Capacity	MW	1090		105	105	105	105
(10)	Energy Capacity	MWh	977		100	96	91	87
(11)	Expenditures							
(12)	CAPEX	MEUR	50	50				
(13)	OPEX	MEUR	16		1.5	1.5	1.5	1.5
(14)	TOTEX	MEUR	62	50	1.5	1.5	1.5	1.5
(15)	Revenues							
(16)	Economic Value of Storage	MEUR	208		20.1	20.1	20.1	20.1
(17)	Total Revenues	MEUR	208		20.1	20.1	20.1	20.1
(18)	Economic Cashflow	MEUR	229	50	18.6	18.6	18.6	18.6
(19)	Economic Rate of Return	%	37%					
(20)	LCOC (5%, 15 years)	kEUR/MW	57.3					

*NPV is the net present value at year 0 using the applicable social discount rate (5% for Europe at time of writing)

Finally, Table 5 uses a PSH counterfactual. Because the TOTEX of the PSH project are much higher than those for the BESS project, the resulting EIRR is 18%. However, this methodology cannot capture any of the operational differences between BESS and PSH, nor can it provide guidance on how the benefits of each technology may differ.

Table 5: PSH Counterfactual Example

		Units	NPV*	0	1	5	10	15
				2026	2027	2031	2036	2041
(1)	Economic Assumptions							
(2)	Installed Capacity	MW	105					
(3)	Energy Capacity	MWh	100					
(4)	Project Cost	MEUR	50					
(5)	Degradation	% per year	1					
(6)	Economic Value of Storage	EUR/MWh	106					
(7)	O&M	%	3					
(8)	Physical Output							
(9)	Power Capacity	MW	1090		105	105	105	105
(10)	Energy Capacity	MWh	977		100	96	91	87
(11)	Expenditures							
(12)	CAPEX	MEUR	50	50				
(13)	OPEX	MEUR	16		1.5	1.5	1.5	1.5
(14)	TOTEX	MEUR	62	50	1.5	1.5	1.5	1.5
(15)	Revenues							
(16)	Economic Value of Storage	MEUR	116		11.1	11.1	11.1	11.1
(17)	Total Revenues	MEUR	116		11.1	11.1	11.1	11.1
(18)	Economic Cashflow	MEUR	95	-50	9.6	9.6	9.6	9.6
(19)	Economic Rate of Return	%	18%					
(20)	LCOC (5%, 15 years)	kEUR/MW	57.3					

*NPV is the net present value at year 0 using the applicable social discount rate (5% for Europe at time of writing)

3.4 How Could CBA Be Improved?

With such a significant range of results (from -1% to 37%), there is still no clear answer to which counterfactual is realistic and provides the optimal point of comparison. Firstly, any counterfactual must be logical and realistic. Where the local geography is unsuitable for PSH, this technology is not a suitable counterfactual. Additionally, as of the end of 2021, the

EIB (2025b) no longer funds fossil fuel projects. Thus, OCGT is not a suitable counterfactual either.

However, the more fundamental problem is that, even if a single technology could capture the numerous services BESS provides, it would still only illustrate a static representation of the energy system. Net zero targets ensure that no energy system in the EU will remain static over the next 25 years. This transition will bring operational uncertainties, including the evolution of wholesale market prices and volatility. A helpful counterfactual would capture this change. Otherwise, an appraisal could inadvertently quantify the benefits of decarbonisation rather than of the proposed project.

4) Best Practice for Conducting Quantified BESS Appraisal: Implementing a Scenario-Based Counterfactual

4.1 Modelling Approach

If the EIB wishes to continue using a quantitative approach to economic appraisal, then rather than relying upon static technological counterfactuals, the Bank should consider adopting a scenario-based counterfactual approach. Like the “with and without” modelling used by the World Bank and ENTSO-E, this approach would situate a proposed project within its relevant energy system, assessing its performance in this context. This approach requires modelling two outcomes: one with the project and one without.

Mapping the BESS’s performance against a broader scenario of how the energy transition will evolve is the best way to understand a project’s impact on the broader electricity system. The EIB does not need to construct scenarios for energy system evolution itself as such scenarios are already widely available. The natural choice for scenarios would be those generated by ENTSO-E and ENTSO-G’s (2024) TYNDP. Using these scenarios would be logical because they have been generated by a fellow EU body and would simplify ENTSO-E collaboration.

The latest version of the TYNDP contains three scenario storylines: National Trends, Distributed Energy, and Global Ambition. All assume the EU meets its 2030 decarbonisation goal, although they diverge in how they reach the 2050 net zero target. A project should ideally be assessed against all three of these storylines to capture a broad understanding of factors affecting future performance. ENSTOE-E (2023b) recommends using models suitable for energy market simulation, like Plexos or Antares, to represent these scenarios.⁹

While modelling two outcomes of a scenario can be complex, proxies can be used for variables similar across projects, simplifying the computational process. One such proxy could represent emissions, as discussed in Box 1, ensuring such factors are not excluded from the analysis. To the extent feasible, sensitivity analysis should then be conducted to systematically reveal the key variables driving model outputs (Saltelli *et al.*, 2019). This step would align the EIB’s methodology with the European Parliament’s (2022) guidance on ENTSO-E and ENTSO-G’s CBA methodology. Questions to explore using sensitivity analysis could include: if VRE is deployed at a slower rate than anticipated, does the proposed BESS project still deliver a benefit? If BESS technology costs decline faster than anticipated, how significantly are operating opportunities for the proposed project affected? Such questions, while inherently uncertain, will shed light on the robustness of a project’s performance.

⁹ However, these models can have limitations regarding their ability to represent storage. ENTSO-E also uses two internal models to represent the TYNDP scenarios, and it may be worth the EIB investigating whether these models are more suitable.

4.2 Interpreting Model Results

Cumulative emissions (as compared to annual emissions) are fundamental to reducing climate change, so the difference in this figure between the two outcomes becomes a useful proxy for environmental impact. These figures could be transformed into monetary values using the EIB's SCC. This monetised benefit could then be compared to the project's costs (a monetisation of the battery's embodied emissions and the present value of the project's TOTEX). This approach re-contextualises the modelling outputs into standard CBA thinking. While the modelling approach will not be able to fully quantify the impact of system feedbacks, it will provide a fuller picture than a static technology counterfactual.

If the project's benefits outweigh its costs, then it is economically viable. If a project cannot demonstrate quantitative benefit to the energy system in any scenario, then it is up to the EIB's decision-makers to determine whether to proceed. It is possible, however, that the TYNDP scenarios fail to illustrate a project's true benefit. These scenarios already assume significant storage deployment, so the model may indicate little benefit to an additional project.

It could consequentially be useful to assess whether the proposed project would provide benefit in a scenario that does not comply with the EU's net zero target. The International Energy Agency's (2024) Stated Policies scenario or Eurelectric's (2018) EU pathways are examples of scenarios that demonstrate emissions reduction at a pace slower than required for meeting net zero by 2050. This would require additional modelling capability, however, so a helpful proxy would be the scale of difference between the current deployment of storage and expected deployment in the TYNDP scenarios.

Energy systems are susceptible to lock-in, so once certain technologies have been widely adopted, it is hard to transition the system due to high switching costs (van der Meijden and Smulders, 2017). This can be true both for fossil fuels and low-carbon power. Thus, if a system is off track to meet net zero by 2050, investing in additional BESS capacity would likely reduce the threat of fossil fuel lock-in and enable low-carbon lock-in. In this case, given the EIB's mandate to help the EU deliver its legislated objectives, a presumption in favour of support is likely valid.

For technologies well on their way to being established (like lithium-ion BESS), it is possible that if improperly sited or sized, a project might not contribute significantly to system decarbonisation. In contrast, investment in novel technologies, such as CAES or hydrogen storage, might require slightly different considerations. These projects are more likely to generate intangible benefits and thus might still be worth investing in even if the modelling is ambiguous due to the presence of feedbacks.

4.3 Challenges of Conducting a Scenario-Based CBA

Comparing the energy system's performance with and without a proposed project against a range of future scenarios is not a simple exercise. In particular, there are two challenges: complexity and the system's inherent structural uncertainty. There will, therefore, be an

inherent trade-off between the model's granularity and the ability to conduct robust sensitivity testing. Time pressures will only stress this balance further. While the TYNDP scenarios are publicly available and the EIB could collaborate with ENTSO-E and/or ENTSO-G to better understand how to model these scenarios, ENTSO-E's (2023a, 2023b) own documentation highlights such models' fundamental complexity. Yet despite the challenges of implementing such an approach, how complete could such an exercise be?

Mercure *et al.* (2021) argue that CBA requires an increasingly complex series of adjustments to account for the pervasive change of the energy transition and the dynamic feedbacks present in this system. While implementing a scenario-based modelling approach will enable a more complete picture of the direct effect a BESS project can have on the energy system, feedback loops are not captured.

In this context, rather than providing investment certainty and aiding investment decision-making, CBA can contribute to a misleading sense of objectivity and a bias towards inaction (Grubb *et al.*, 2021). Given the presence of feedback loops, the true answer of BESS's economic value likely lies far higher than any direct calculation in a CBA can distil and represent. Mercure *et al.* (2021), therefore, suggest that in contexts of structural change (like the energy transition), any appraisal must include a robust means of assessing qualitative factors.

5) Incorporating System Feedbacks: Investigating Risk-Opportunity Analysis

5.1 Context for Adopting a New Approach

The dual challenges of complexity and structural uncertainty have become particularly important in the context of the purposive energy transition underway. Thus, some government agencies have already begun to modify their policy appraisal methodologies to better capture transition dynamics. The UK Treasury (2022) has adapted its CBA methodology to incorporate systems mapping. Also in the UK context, Ofgem, GB's energy regulator, uses a three-pronged impact assessment approach, including monetised aggregate CBA, a consideration of social/distributional impacts, and strategic/sustainability issues (Grubb *et al.*, 2025). This approach enables the continued use of CBA, while including relevant qualitative factors. ENTSO-E's (2023b) CBA methodology is also evidence of a shift towards an expanded view of appraisal.

5.2 Introduction to Risk-Opportunity Analysis

One proposed approach to better capture energy system dynamics is Risk-Opportunity Analysis (ROA), as described by Mercure *et al.* (2021). ROA, of which CBA is a particular use-case when all factors can be sufficiently quantified, harmonises qualitative and quantitative elements of an appraisal. Originally developed to help policymakers take strategic decisions, the methodology is particularly helpful for analysing system feedbacks that cannot be captured in a CBA. While the impacts of the EIB's individual investment decisions may seem far smaller than policymaking, the EIB has been tasked with delivering the EU's strategic goals. This requires that the EIB's appraisal methodology suitably incorporate strategic dimensions.

Rather than framing thinking around monetised costs and benefits, ROA assesses broader risks and opportunities to the entire system in which a project would operate. Risks lead to system harm or would prevent a project from realising its estimated potential. Low profitability is also a risk (to be explored in the second part of this project). Opportunities, in contrast, represent the project's direct benefits and the future options it creates for the system.

As an example, as detailed in Grubb *et al.* (2025), Ofgem struggled to determine whether GB should develop a revenue support scheme for interconnectors; CBA results proved inconclusive, being highly dependent on the input parameters used for the calculations. An assessment of the interconnector regime's option value demonstrated that interconnectors could increase energy security and reduce emissions, while also creating options to use in future unknown contexts. The interconnectors built because of the support regime made vital contributions during the 2022 energy crisis (which combined the gas crisis with low

hydro and nuclear availability), illustrating an option that could not have been quantified in a CBA.

In the subsequent sections, both BESS and LDES will be used as examples to illustrate how ROA could function. The contrast between the two technology types provides a more comprehensive overview of ROA application. Any examples mentioned are not meant to be exhaustive but to demonstrate how ROA could be developed in practice.¹⁰

5.3 Steps to Conducting a Risk-Opportunity Assessment (ROA)

Initially developed for policy appraisal, Box 2 illustrates a 5-step approach to conducting ROA. The remainder of this section uses this framing to consider potential application in relation to the EIB's more project-specific context.

5.3.1 ROA Step One: Determine Scope

First, determine the relevant scope of project impacts. Key factors include the primary geographic area of influence and the relevant regulatory environment. The timeframe for any appraisal should align with the project's expected lifetime (likely around 15 years), as in a CBA. For geographic scope, while there could be spillover effects to other countries due to interconnection, the simplest scope is to consider an individual pricing zone. In most EU member states, this will be the entire country but could differ in markets with zonal electricity pricing.

This means national regulation will likely be of most relevance. The regulatory system's main impact on economic appraisal is through the markets legally open to BESS and thus, projects' possible revenue stacks. New regulation could increase market access, allowing BESS to provide greater system benefit. However, unless it is highly likely that the regulator will expand BESS's market access, the appraisal should only consider the markets currently available to batteries.

¹⁰ While ROA is described only in the context of storage projects, this approach could be applied other energy technologies like floating offshore wind or interconnectors. Due to these technologies' high upfront costs, standard CBA may suggest that the costs significantly outweigh any benefits. For floating offshore wind, once learning effects are considered and the technology's ability to increase system stability by locating in areas less correlated to existing VRE generators' output, the investment outlook improves considerably. The same applies to interconnectors, which, as the UK case demonstrated, can have tremendous option value and reduce fossil fuel dependency (Grubb *et al.*, 2025). ROA could also be applied renewable energy investments more broadly where traditional CBA is still used, although if the traditional methodology proves sufficient, it can be retained for simplicity.

Box 2: Mercure *et al.*'s (2021) Proposed Steps for Conducting Policy Risk-Opportunity Assessment (ROA)

- 1) *Determine Scope*: Identify the boundaries of the system considered and map out all relevant feedbacks between components, considering their magnitudes and directions. Choose or develop suitable dynamical quantitative and/or qualitative analysis models and datasets accordingly.
- 2) *Estimate Quantifiable Outcomes*: Estimate median (not mean) outcomes and impacts on the process and direction of evolution and on the structure of the system itself, in a chosen relevant set of measurable metrics, associated with each comprehensive policy portfolio proposed, under various plausible scenarios of economic evolution through time. Indicate ranges of uncertainty or degrees of confidence for each outcome metric.
- 3) *Assess Risks*: Carry out, using a stress test or other method, a risk assessment for each policy portfolio under study, to identify possible extreme unintended detrimental consequences and worst-case scenarios, estimating their severity and likelihood, under each dimension considered.
- 4) *Assess Opportunities*: Carry out, using scenario variation analysis or other methods, an opportunity assessment, identifying all possible option creation potentials for each policy portfolio under study, under each dimension considered. Option creation potentials are elements of scenarios and systems that expand the ranges of possible desirable futures.
- 5) *Communicate Results*: Report median impacts, direction of system change feedbacks, risks and opportunities, in all dimensions considered, along with uncertainty ranges and/or confidence levels. Report both qualitative and quantitative evidence, against current regulatory norms and risk tolerances. The normative weighting or valuation of outcomes is not considered part of ROA.

Once the scope is established, identify the most relevant feedbacks (both amplifying and dampening) within the determined region. Feedbacks could be incorporated in two ways: represented qualitatively using system mapping techniques or quantified using multipliers. It is up to the EIB to determine which approach is most suitable.

Option 1- Mapping: As illustrated, systems mapping typically involves illustrating the primary elements relevant to a feedback and understanding the relationship between these elements. CLDs are an appropriate method to formalise the consideration of system dynamics. Such maps are ideally generated collaboratively, ensuring that all relevant stakeholders share a common understanding of drivers in the current system and how these may change over time. While CLDs have been the primary means of systems mapping in this

report, there are other suitable visual approaches to represent these feedbacks, as described in Appendix 3.

Option 2- Multipliers: In contrast to qualitative CLDs, it may be possible to represent feedbacks quantitatively using multipliers. Keynes (1936) first developed multipliers to illustrate that some investments can catalyse GDP growth, generating an outsized financial influence compared to the initial expenditure. Multipliers are often used to describe the crowding-in of investment, especially where public investment increases private investment in the same sector (Saccone *et al.*, 2022).

Although the multipliers discussed here are not the same, multipliers offer a bridge towards quantification (notwithstanding all inherent uncertainties). Feedbacks indicate there could be a substantial multiplier effect, with projects catalysing greater system impact than their immediate output. Multipliers for offshore wind development have long been discussed, with the Scottish Government (2024) estimating an average multiplier of three. It must be acknowledged, however, that this approach is limited by the need to quantify highly uncertain values.

5.3.2 ROA Step Two: Estimate Quantifiable Outcomes

Step two is broadly consistent with the scenario-based counterfactual approach described in section 4). The outputs of scenario modelling can provide an estimate of the quantifiable benefits and costs of deploying the proposed BESS project – ideally, through direct modelling of storage, or alternatively, through less direct proxies for storage utilisation from indices on the like spread of prices and carbon intensities, and the correlation between these. Derived estimates of emission savings can then also be compared to estimates or benchmarks of the embodied emissions from battery construction. Sensitivity analysis would ideally provide a helpful perspective on the degree of confidence in some of the outcomes.

5.3.3 ROA Step Three: Identify Project Risks

Next, assess the risks that could materially impact a project. Feedback loops are a helpful, although not comprehensive tool, to identify some relevant risks. Aside from construction cost risks, financial viability risks could arise from cannibalisation of BESS revenues. The severity of this risk will depend on a project's reliance on this market for revenue, for which a proxy might be to estimate the market depth for ancillary services in the relevant country today and compare this to the spread of market prices (a proxy for arbitrage market depth). The degree of mismatch between these two reflects the threat of near-term cannibalisation, although the speed with which negative prices have increased in European power markets (see Figure 8) suggests that historical data can quickly become obsolete and lose its relevance.

A strategic risk arises from a mismatch in timescale between VRE and BESS deployment, as described in section 2.3. If storage capacity outpaces VRE deployment, arbitrage profits will be significantly reduced until there is sufficient VRE capacity to increase price spreads.

While ideally, the feedback would kick in and eliminate this risk, the dampening effects could be strong enough to deter private funding, preventing further VRE and/or storage deployment.

The electricity system could then land in an inferior equilibrium, with either (or both) insufficient storage or VRE. In this case, the risk to public investment from storage should be modest, and the EIB, by funding the missing technology, could potentially push the system out of its inferior equilibrium and enable the return of private finance.

As LDES technologies are more novel, it is not yet clear whether one technology or a range will dominate the provision of longer-term storage. There is a direct risk that the EIB invests in technologies that prove ultimately inferior and are overtaken by other innovations, which would need to be balanced against the opportunities (step 3).

Some LDES technologies in particular will be more suited to the provision of certain services than others, and this differentiation should reduce the scale of this risk; the diversity of services and contexts for storage may thus mitigate this risk, depending somewhat on the pace of expected payback. At the same time, however, if LDES is required primarily for security of supply and the technologies cycle infrequently, these assets might cannibalise simply due to shallow market depth. Regulatory support regimes, like GB's forthcoming LDES cap-and-floor, would insulate these assets from some cannibalisation risk, but it is unclear whether such support mechanisms will spread across European power markets.

Not all these risks can be quantified, especially those relevant to novel LDES given the scale of fundamental uncertainties. Part two of this project, focusing on financial appraisal, will shed light on factors influencing the financial viability of storage investments, which should provide a greater understanding of the factors leading to cannibalisation and risks impacting BESS deployment more broadly.

5.3.4 ROA Step Four: Identify Opportunities

Next, understand the opportunities and option potential enabled by a project. The two most relevant feedbacks are the potential for learning-by-doing and the relationship between VRE and storage. Security could also play a role in determining option value.

Learning-by-Doing and Industrial Development contributions: While lithium-ion BESS is still experiencing significant cost reductions (40% year-on-year between 2023 and 2024), scale economies have already been activated (BloombergNEF, 2025), drawing on developments outside utility battery applications (notably, EVs). Thus, while battery costs are expected to continue declining, new individual BESS projects funded by the EIB would likely have negligible direct impacts on cost reduction (at least, for Li-I batteries).

If BESS were deployed programmatically, however, there might be more potential synergies with the EU's industrial strategy, and induced cost reductions for battery systems specialised for utility storage, particularly for some of the less developed battery technologies costs (see Annexes). Given the noted path-dependency of energy technologies

and systems, significant BESS investments would make positive contributions to the EU's overall stated energy objectives, given the indications that storage investments at present fall far short of what is needed.

In contrast to BESS, individual novel LDES projects have more potential to catalyse cost reductions because each deployment is a new opportunity to test whether the technology is viable. Almost none of these technologies have been deployed at the scale necessary to enable cost reductions through scale economies. For LDES, strategic complementarities may emerge, increasing the usefulness of these technologies (Aghion *et al.*, 2019). For example, complementarities could emerge between sites used to produce green hydrogen and repurposed gas transmission pipes carrying this new gas. The cost of repurposing these pipes may decline as conversions begin to take place at a greater scale, simplifying the process of transporting green hydrogen and potentially increasing its use cases. These dynamics illustrate one way that investment in some technologies can result in net benefits far greater than anticipated for the singular project.

A multiplier for these reductions could be estimated from the figures in Appendix 1: **BESS Evolution: Battery Chemistries and Expected Cost Reductions**, inevitably subject to larger uncertainties for the less developed or more novel technologies.

VRE Synergies: The relationship between VRE and BESS could also catalyse significant opportunities if a project reduces the risk of dampening feedbacks. Theoretically, net-zero targets should facilitate the deployment of VRE, ensuring a constant role for storage in the electricity system. Batteries that can technically provide a wide range of services will likely prove more useful to the system than those that can only provide one, like FCR. This way, if some markets are cannibalised for certain periods of time, the batteries will have a strategic advantage as they wait for VRE deployment to better align with storage capacity.

The VRE feedback, while likely still important for LDES, will be weaker than for BESS¹¹. Mid-duration storage will likely operate similarly to BESS, transferring VRE power across limited time periods. For these assets, arbitrage will likely be a key revenue source. Beyond a certain point however, longer durations of storage would naturally tend to discharge less frequently (eg. particularly in solar-dominated systems, BESS may be able to charge and discharge on almost daily basis). Thus, these assets' relationship on VRE deployment may be more tenuous. However, LDES could prove less expensive than alternatives like gas with CCS, making it a key enabler of full electricity system decarbonisation. In this context, LDES might be fundamental for de-risking the last ~10-15% of VRE required to reach net zero electricity

¹¹ While the deployment of longer-duration LDES will likely be correlated to deficits in VRE power, the degree of correlation in charging and discharging is not as close as for VRE/BESS. Because it is unclear how frequently monthly/seasonal LDES would be able to discharge, increased VRE deployment and market forces will not necessarily bring about suitable investment in what is likely to be an expensive form of storage.

emissions, but this depends on the support schemes available for the relevant technologies.¹²

Representing this feedback using a multiplier requires quantifying the degree to which storage has the potential to de-risk further VRE deployment. While this feedback loop is intuitive, it is still fundamentally theoretical, and the scale to which storage is affecting VRE investment behaviour is unknown. For BESS, the multiplier is likely to be greatest in systems where VRE deployment is high enough that surplus power is generated during some periods, but low enough that negative pricing periods have not led to significant storage deployment. As data for BESS and LDES deployment becomes more available, it will become possible to transition analysis from being largely qualitative to more quantitative. This quantitative data should make it easier to understand the scale and impact of identified tipping points and how these would interact with multipliers.

Security of Supply: A final opportunity to consider, oft-overlooked, is contribution from BESS to electricity system security - potentially beyond that obtained from regular arbitrage. Distributed batteries, in particular, could form the core of a key backup after weather events or cyber-attacks disrupt transmission or distribution. Despite their short duration, batteries can restart the electricity system by providing black start (essentially jump starting all other generators). This distributed reliability could prove far more valuable to electricity system operators than typically understood, demonstrating an important option value created by deploying BESS.

Batteries' contribution to resource adequacy can be quantified (Dratsas, Psarros, and Papathanassiou, 2021), providing a proxy for these assets' contribution to security of supply. Such figures are highly dependent on the system energy mix, however, meaning this calculation will need to be repeated for each project. This approach also requires Monte Carlo simulation, highlighting a key area where qualitative analysis may provide a clearer and less time-intensive result. A simpler proxy may be the value of black start provision, acknowledging that this approach cannot fully capture BESS's impact on security.

Insofar as BESS reduces emissions, the corollary also is reduced dependence on imported fossil fuels.

5.3.5 ROA Step Five: Present Results

ROA approaches do not yield the simplicity of a numeric result. However, as well as providing potentially better outcomes, a structured ROA approach can offer greater consistency and transparency in the appraisal process (a key rationale also for the Ofgem approach to Regulatory Impact Assessment). Key to this is ensuring decision-makers are provided with a range of outputs from the ROA. In contrast to a CBA where the analyst determines the

¹² This might not apply in all country contexts. Country-specific modelling to capture the patterns of variability in high VRE deployment scenarios would help clarify the relationship between VRE and LDES in various regions.

balance of the costs and benefits and may provide only a single value, an ROA provides structured information to decision-makers on several dimensions, to inform a judgement on the balance the risks and opportunities associated with a project, based on the ROA results. In so doing, it provides a framework for consistent decisions that doesn't depend upon opaque and complex modelling, and is far less likely to ignore important but intrinsically hard-to-monetise factors. The information necessarily has to strike a balance between detail/complexity and brevity/accessibility, and would be up to the EIB to determine an appropriate format to present this information to decision-makers.

6) Conclusions and Recommendations

6.1 Complementarity with the EIB's Partners

Any storage appraisal methodology should ideally align with other departments in the EIB. How these approaches might affect the Bank's external collaborators (like ENTSO-E) should also be considered. If the EIB were to adopt a scenario-based counterfactual approach, this could be designed to align closely with ENTSO-E's methodology to reduce friction on any shared projects. Results of a scenario-based counterfactual could also be formatted into a simplified spreadsheet-based appraisal, ensuring compatibility with partners using standard CBA.

In adopting ROA, a quantified CBA could still be one component of this methodology, allowing the EIB to meet any requirements that it conduct monetised CBA. Yet, the assessment of risks and opportunities will provide greater strategic insight into how the EIB's projects align with EU goals. This makes the methodology fundamentally different from other approaches, which will make it necessary to educate decision-makers, analysts, and any external partners engaging with the EIB's methodology.

6.2 Conclusion and Recommendations

Despite the EU's ambitious goals on storage deployment, the gap between the benefits storage brings to its operator and the benefits these assets bring to the electricity system suggests storage will continue to be under-deployed. Regulatory barriers play a significant role in this gap (Artelys *et al.*, 2020), as do questions about cannibalisation and profitability.

Yet, the feedbacks in section **Error! Reference source not found.** emphasise that storage plays an important role in delivering the EU's strategic economic and sustainability objectives. The EIB's mandate suggests the Bank should be supporting the deployment of storage to help the EU meet its power decarbonisation timelines. However, the EIB's current approach to project appraisal cannot capture these assets' strategic value and will underestimate their benefits.

Recommendation 1: Adopt a dynamic appraisal methodology

Consequently, we recommend that the EIB embrace a methodology capable of illustrating a dynamic energy system and which includes a forward-looking assessment of the evolving role for storage. While this change can inevitably complicate the process of appraisal, modifying the current approach seems unavoidable. Static methodologies will instead create increasingly complex trade-offs for analysts and force an oversimplification of an energy system that is rapidly evolving.

Recommendation 2: If pursuing quantified appraisal, adopt a forward-looking scenario-based approach with model capability to represent with- and without- the storage project

Regardless of the approach the EIB pursues regarding storage deployment, this research highlights the need for the Bank to embed its storage appraisal methodology within a forward-looking scenario framework.

Recommendation 3: Establish/strengthen relationships with scenario modellers at other EU institutions

Adopting a scenario-based approach will bring its own challenges, but the Bank does not need to create internal scenarios. Numerous electricity system decarbonisation scenarios exist. Collaborating with EU organisations with modelling expertise, like ENTSO-E, could simplify the EIB staff's transition process by pooling technical expertise.

Recommendation 4: Consider adopting ROA to systematise assessing qualitative factors

The complexity of storage appraisal, combined with these technologies' strategic importance, suggests the EIB needs to consider carefully the extent to which it relies on quantification. The EIB must choose between pursuing a quantified approach to appraisal with the best available numbers and an approach expanded to include quantitative factors. While a quantified approach risks missing some of the system's dynamism, it does not necessarily reduce uncertainty or the subjective nature of results. ROA would provide a consistent framework to systematically examine system feedbacks (either using systems mapping or multipliers), better highlighting the strategic role storage could play in electricity system decarbonisation. Many feedbacks and proxies are likely similar across projects, simplifying the process of integrating these elements.

Recommendation 5: Consider a programmatic approach to storage deployment

While the EIB is considering revising its appraisal methodology, it may also want to consider locating storage within a programmatic approach. One individual BESS project is unlikely to catalyse significant system change; an entire program designed to deploy both BESS and LDES could. Such an approach could enable scale economies and learning-by-doing, generating important synergies with the EU's industrial competitiveness.

Overall, this report has demonstrated that storage will play a key role in enabling energy system decarbonisation; if it is not deployed at scale, countries will likely struggle to meet their emissions reduction targets. By implementing either a scenario-based counterfactual in CBA or moving away from CBA to implementing ROA, the EIB could better target its investment decisions to reflect the broader energy system's needs. Such a shift would increase the EIB's ability to support EU decarbonisation and could help align the bloc's net zero targets with its ambitions to boost industrial competitiveness.

7) Appendices

Appendix 1: BESS Evolution: Battery Chemistries and Expected Cost Reductions

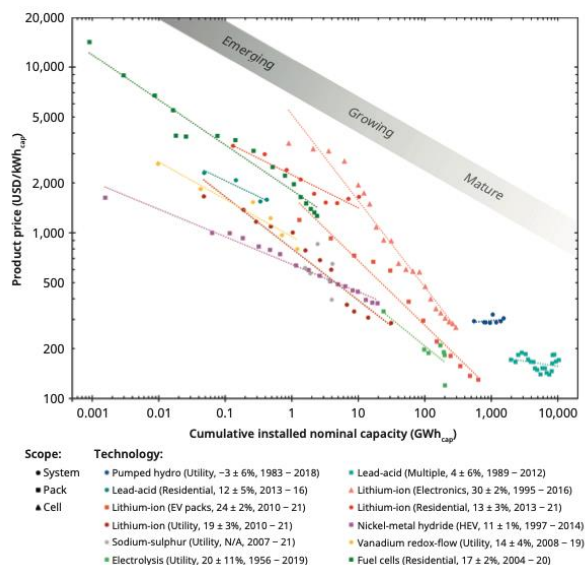
Alternative Battery Chemistries:

Sodium-sulphur batteries are another viable battery type, well-suited to operating for a 6–7-hour duration, and requiring fewer critical minerals than lithium-ion batteries to manufacture (Schmidt and Staffell, 2023). However, they have a lower energy density, meaning a battery of the same capacity as an equivalent lithium-ion battery would require more space. Currently more expensive than lithium-ion batteries, further cost reductions may be slow to materialise as the supply chain for developing these batteries is very limited.

Flow batteries have been identified as a technology with significant potential due to their long lifetime and limited degradation (Schmidt and Staffell, 2023). These batteries could be optimal for energy arbitrage and congestion management. However, they have a low energy density compared to other technologies, a higher system complexity, and require numerous critical minerals. Only around 1% of currently utility-scale BESS projects utilise flow batteries (Bielewski *et al.*, 2024). Other battery chemistries may be relevant in future, such as solid-state batteries. More information on battery chemistries can be found in Schmidt and Staffell (2023).

Expected Cost Reductions:

Numerous research studies have aimed to estimate the cost reductions of storage technologies over time. Figure 12 charts historical technology costs as installed capacity increases, demonstrating a strong correlation, with costs decreasing as technologies are deployed at scale. Note that these figures chart only the upfront investment costs of technologies, not other elements like grid connection costs or the cost of financing.



The next question, however, is what might these past trajectories indicate about the evolution of prices in future? Figure 13 predicts what the price ranges of various storage technologies could be at 1 TWh of deployment, demonstrating that cost decreases are expected for most technologies even if the speed at which this decline occurs varies.

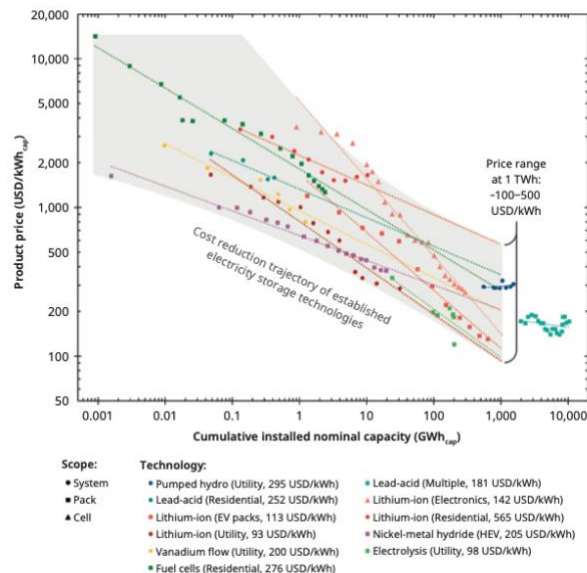


Figure 13: Expected Future Price Evolution of Storage (Schmidt and Staffell, 2023)¹³

The U.S. Department of Energy (2024) has also generated forecasts of how the prices of storage technologies could be expected to change until 2030 and which elements of these technologies are most likely to see cost reductions. These reports have been completed both for lithium-ion BESS and for a range of LDES technologies. Also in the American context, the National Renewable Energy Laboratory has charted the likely cost reductions for utility-scale lithium-ion BESS (Cole and Karmakar, 2023). Over a longer horizon, Mauler *et al.* (2021) have estimated battery cost reductions to 2050.

The danger of these types of calculations, however, is that modelling future cost reductions is fundamentally uncertain and such predictions can often be swayed by present bias, underestimating how much costs can be reduced (Creutzig, 2017). This phenomenon proved especially true for VRE generators, where even expectations of cost reductions that were viewed as aggressive at their time of drafting, have continually been proven far too cautious (Rozen and Trutnevte, 2021).

¹³ A caveat to this image is that, while utility-scale BESS deployment has not yet reached 1 TWh globally, costs have already declined to the levels presented in this graph. This shows the extent to which lithium-ion battery costs have reduced more significantly than anticipated in recent years, while also highlighting the benefit of relying on qualitative estimates like those used by Malhotra and Schmidt (2020).

Appendix 2: Methodology for Simplified CBA Figures

The simplified CBA figures presented in section 3.3 were based on Figure 14, which was developed by the EIB (2023) to illustrate its CBA methodology using a hypothetical onshore wind project. The specific figures for the BESS project were provided from an appraisal conducted for an EIB-funded BESS project in France. Simplified figures for installed capacity, energy capacity, project cost, degradation, operating costs, and the cost of FCR provision for the do-nothing counterfactual came from this original project.

Table 20-1: Calculation of the economic rate of return for an onshore wind project

Units				NPV ^{*)}						
				-1	0	1	5	10	15	20
Economic Assumptions										
(1)	Installed capacity	MW	240							
(2)	Project cost	MEUR	261							
(3)=(1)*(4)*(5)*8.76	Net power production		714							
(4)	Load factor	%	35%							
(5)	Turbine Availability	%	97%							
(6)	Economic Value of Power	EUR/MWh	86							
(7)	Curtailment		low/rising							
(8)	O&M	%	2%							
Capital Expenditures										
(9)	Investment cost		240	87	174					
Physical output										
(10)=(3)	Production	GWh	8,068	-	-	714	714	714	714	714
(11)	Curtailment	GWh	718	-	-	7	36	71	107	143
(12)=(10)-(11)	Net sales	GWh	7,350	-	-	707	678	642	607	571
Expenditures										
(13)=(9)	CAPEX	MEUR	240	87	174					
(14)=(9)*(8)	OPEX	MEUR	59	-	-	5	5	5	5	5
(15)=(13)+(14)	TOTEX	MEUR	299	87	174	5	5	5	5	5
Revenues										
(16)=(6)*(12)	Economic Value of Power	MEUR	632	-	-	61	58	55	52	49
(17)=(16)	Total revenues	MEUR	632	-	-	61	58	55	52	49
(18)=(17)-(15)	Economic Cashflow	MEUR	333	-87	-174	56	53	50	47	44
Economic Rate of Return^{*)}										
(19)	LCOE (5%, 15 years)	EUR/MWh	41							
	Unit cost	EUR/kW	1.1							

^{*)} NPV is the net present value at year -1 using the applicable social discount rate i.e. 5% for Europe at the time of writing

Figure 14: Simplified CBA for Onshore Wind Project

To generate Table 1, one counterfactual from the EIB project was used, whereby it was estimated that the BESS project would enable BESS to replace PSH as the marginal generator for FCR. This would bring the average FCR price from €7.5/MWh to €2.5/MWh, a difference of €5/MWh. Assumptions for the frequency with which the BESS would operate in this market were also provided by the original example, enabling a quantification of the difference in the cost of FCR provision between PSH and BESS over a 15-year period. This figure was used as the “Economic Value of Power,” or the counterfactual.

To generate Table 2, figures representing the levelised cost of capacity (LCOC) of an OCGT plant from the original example were used. The OCGT plant’s levelised cost of energy was estimated to be €63/kW. It was then assumed that the OCGT plant would have the same capacity as the BESS project (105 MW). Thus, the €63/kW was multiplied by this total capacity and converted from kW to MW to calculate the value of the same amount of power from each asset. This ensured the value of the OCGT could be fully monetised to enable it to be compared against the costs of the BESS project. While de-rating factors would likely mean that a BESS project would require a greater power capacity than an OCGT to provide the same level of guaranteed output, this has been discounted for the sake of simplicity.

Table 3 aimed to add an extra layer of complexity to the content presented in Table 2 by adding a carbon price. The emissions intensity of an OCGT plant in tonCO₂/MWh was provided by Thurber and Verheijen (2022). The rate of change in the base and high CO₂ prices were provided by the original example were then modelled forward to 2041, assuming a constant rate of change. The emissions intensity factors were then multiplied by the amount of electricity produced (provided in the original example) to determine both an annualised base and high cost of emissions. The average of the base and high CO₂ LCOC figures was taken. This was then multiplied by the capacity of the BESS project using the same methodology as in the paragraph above.

For However, the expected ETS price is significantly lower than the EIB's (2023) mandated social cost of carbon. If the EIB's figures are instead used to calculate the cost of the OCGT plant's emissions, the EIRR increases drastically to 37% (**Error! Not a valid bookmark self-reference.**).

Table 4, the same process was used as for

Table 3 except rather than using the CO₂ prices provided in the original example, the EIB's (2023) stated SCC figures were used. Assuming the same time range from 2026-2041, the resulting LCOC was much higher than in

Table 3. This makes sense because the much higher SCC would make it far less attractive to develop the OCGT plant, especially when the BESS is not subject to carbon pricing.

Finally, for Table 5, an estimate of the capital expenditure (CAPEX) for PSH along with an estimate for operation/maintenance costs as a percentage of CAPEX were provided by the European Associate for Storage of Energy (EASE) (2016). While these figures are somewhat old, but Figure 12 demonstrates that PSH has not experienced cost reductions in recent years, making the EASE figures suitable for use. The PSH is not assumed to produce any emissions, in line with estimates from the original example, which did not calculate any emissions for this technology.

Appendix 3: Tools for Illustrating System Dynamics

One approach to systems mapping is CLDs, which provide a consistent framework and visual language to understand complex system dynamics (Barbrook-Johnson and Penn, 2022). CLDs have been used to assess system dynamics since the 1970s, although their formalisation for use in energy systems has increased considerably in the past decade. An example is provided in Figure 15 where a reinforcing feedback (what has been referred to in this report as an amplifying feedback) is present. Structured steps for how to develop CLDs can be found in Barbrook-Johnson and Penn (2022), as well as numerous other sources on system dynamics.

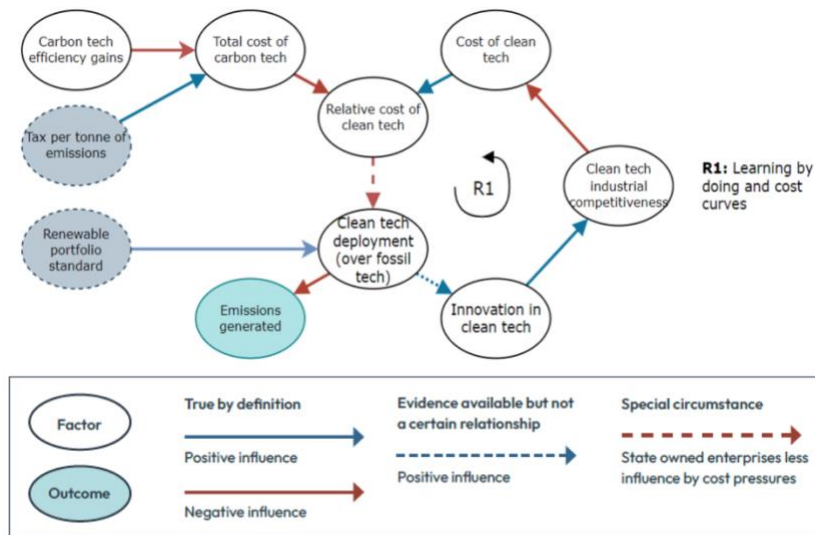


Figure 15: Example CLD (Sharpe and Murphy, 2024)

If the relationships and feedbacks between system elements are well understood by the analysts and/or decision-makers, these dynamics may not need to be represented through CLDs. Figure 16 identifies only the primary tipping points that contributed to the phase-out of coal from UK electricity rather than illustrating all feedbacks in the greater energy system (Sharpe and Lenton, 2021). While less detailed than a CLD, this method may be suitable in contexts where a broader overview is desired.

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