IMPACT CONVERGENCE FORUM

Grid-Balancing Support and Renewable Energy Production in the UK: Battery Energy Storage Systems, Pumped Storage Hydropower and Green Hydrogen

ICF Case Study: Illustrative Planned Avoided Emissions Assessment

The Impact Convergence Forum for Private Equity (ICF) is a collaborative group of firms with private equity impact strategies, working to encourage convergence in impact measurement and management practices among LPs and GPs — supporting high-integrity practice while enabling better decision-making.

This is an Illustrative Case Study developed by members of the ICF as part of the 2024–25 Project Frame Content Working Group. It is inspired by methodological choices made in an avoided emissions calculation methodology developed by EQT Infrastructure with support from McKinsey & Company. The data and analysis are illustrative and intended to demonstrate practical methodological considerations for development of a forward-looking avoided emissions impact assessment. This case study does not constitute commercial or financial advice or projections.

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Impact Report

Summary and Context

This case study presents an illustrative forward-looking Planned Avoided Emissions Impact Assessment for a portfolio company that commercialises three solutions that provide essential grid-balancing support and low-carbon energy in a renewables-led power system in the UK. Battery Energy Storage Systems (BESS) and Pumped Storage Hydropower (PSH) are energy storage solutions that store excess renewable electricity and release it during peak demand hours, helping to address the supply and demand challenges of renewable energy. Additionally, surplus renewable electricity can be used to produce green hydrogen, which replaces grey hydrogen and natural gas, supporting the transition to a cleaner energy system.

Scope of the Problem. The core challenge is that renewable energy generation, particularly from wind and solar, does not always align with real-time electricity demand, resulting in over-generation and curtailment when supply exceeds demand, underproduction and grid stress when demand outpaces supply, intermittency due to weather dependence and regional imbalances caused by limited storage and transmission capacity. In the UK, for example, it is estimated that the cost of wind curtailment alone resulted in over £507m of additional cost to consumers, and an additional 1.02 million tonnes (Mt) of CO_2 equivalent emissions per year across 2020 and 2021. This represents 2.0% of total 2020 power sector emissions.[1]

Opportunity to Reduce GHG Emissions through Time-Shifting Renewable Energy and Green Hydrogen Production. This illustrative case is inspired by a UK-based energy company that develops, owns and operates flexible energy infrastructure — including battery storage, pumped storage hydropower and green hydrogen projects. These assets support the rapid deployment of renewable energy by providing the flexible capacity required to balance the grid and reduce carbon emissions. For the purpose of this assessment, we focus on three specific technologies:

- Battery Energy Storage Systems (BESS)
- Pumped Storage Hydropower (PSH)
- Green Hydrogen Production (green hydrogen)

Grid-scale energy storage systems and green hydrogen production not only accelerate renewable energy integration but also enable temporal alignment between supply and demand. This case study evaluates the combined potential avoided emissions impact of these three technologies against an illustrative commercial growth plan (current and planned capacity projections), estimating annual GHG reductions of 5.3 million tonnes CO_2e by 2032 and cumulative avoided emissions of 74 million tonnes CO_2e by 2050, relative to the reference scenario.

Purpose of the Avoided Emissions Assessment. This case study is designed to be instructive, presenting an illustrative forward-looking (ex-ante) Planned Avoided Emissions Impact Assessment (2024–50) for three complementary business lines. It offers a practical example of how planned avoided emissions can be assessed for a company deploying multiple technology solutions, with capacity build-out planned to 2032. It accounts for estimated annual avoided emissions as capacity is forecast to come

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[1] LCP Delta, & Drax. (2022). Renewable curtailment and the role of long-duration storage. Drax. https://www.drax.com/wp-content/uploads/2022/06/Drax-LCP-Renewable-curtailment-report-1.pdf

on line, and considers the annual emissions estimates over a 20-year lifetime of the asset (hence modelled out to 2050). This forward-looking Planned Impact analysis was chosen over a Potential Impact assessment to provide a hypothetical yet realistic directional estimate aligned with a company's business strategy, commercial growth forecasts and technology deployment outlook. The output of this assessment is intended for internal performance target-setting.

Impact Pathways

Primary Impact Pathway(s). The primary impact pathway for the technology solutions are:

- Battery Energy Storage Systems (BESS) store excess renewable electricity that would otherwise be curtailed and discharge it during periods of high demand, displacing fossil fuel peaking power. Short-duration BESS — modelled in this case at one-hour and two-hour cycles — provide critical time-shifting services, balancing short-term supply and demand fluctuations, displacing marginal fossil generation during peak demand and enabling greater integration of variable renewable energy and avoiding associated emissions.
- Pumped Storage Hydropower (PSH) stores surplus renewable electricity by pumping water to an elevated reservoir during periods of low demand, then releases it to generate electricity during peak demand. This long-duration storage — modeled in this case as 15-hour and 19-hour cycles — displaces fossil-based generation on the margin, supports grid stability and enables deeper integration of intermittent renewables, resulting in avoided emissions.
- Green hydrogen produced via alkaline electrolysis using renewable electricity reduces emissions by replacing grey hydrogen or natural gas. It avoids both upstream and combustion-related emissions, cutting CO_2 from steam methane reforming and lowering fossil fuel use in hard-to-abate sectors.

Solution Relevance to Business Sustainability Strategy. In this illustrative case, three business lines (BESS, PSH and green hydrogen) represent over 90% of company revenues. The company also operates flexible thermal power generation using natural gas-fired reciprocal engines to support the grid during periods of low or variable renewable output. Although these gas reciprocating engine assets can run on green hydrogen, they are currently powered by natural gas and are therefore excluded from avoided emissions calculations in line with WBCSD guidance.[2]

Solution Relevance to End-Markets (Type of Solution and Substitution). The energy storage systems, BESS and PSH, are considered to be Enabling (Frame) / System-Optimising Solutions (WBCSD), as they provide critical grid-balancing support to enable increased usage of renewable energy. They are considered improvements to the system for existing electricity demand. Green hydrogen produced is assumed to replace grey hydrogen and natural gas, and therefore considered a Direct Product (Frame) / End-use solution to replace existing demand.

Regulation. The three solutions are not mandated by regulation in the UK, but benefit from policy mechanisms and align with national energy transition strategies:

[2] WBCSD, Eligibility Gate 2: "The solution (or end-solution of the intermediary solution) has mitigation potential according to the latest climate science and recognised sources, and is not directly applied to activities involving exploration, extraction, mining and/or production, distribution and sales of fossil fuels i.e., oil, natural gas and coal.'"

- <u>BESS</u> are not mandated by UK regulation but are strongly encouraged and integrated into energy markets to support decarbonisation, flexibility and reliability. The UK's Net Zero Strategy[3] and National Grid ESO's Future Energy Scenarios (FES)[4] rely on large-scale BESS deployment. All BESS assets can participate in electricity markets such as the Capacity Market, Balancing Mechanism and frequency response services regulated by Ofgem and National Grid ESO. Navigating local and ministerial planning approvals, including designations as Nationally Significant Infrastructure Projects (NSIP) prior to 2020, can lead to delays and uncertainty for deployment.[5]
- <u>PSH</u> is similarly not mandated but plays a critical role in long-term energy system planning as a proven, long-duration, low-carbon storage technology. It is featured in the UK's Net Zero Strategy and FES for managing daily and seasonal variability from renewables. PSH is eligible for the same electricity markets as BESS but involves more complex planning and environmental approvals. NSIP designation and the requirement for Development Consent Orders (DCOs) can create significant planning hurdles, delaying investment and delivery. The UK government is reviewing NSIP policy and designations to better support Long Duration Electricity Storage (LDES) investment through the Planning and Infrastructure Bill, currently in committee as of April 2025.[6]
- <u>Green hydrogen</u> is not mandated but regulated under general energy and environmental laws, with a dedicated framework now emerging. The UK's Low Carbon Hydrogen Standard (LCHS) sets a GHG threshold for low carbon hydrogen of 20g CO_2e/MJ (~2.4kg CO_2e/kg H2) and is required for access to government support schemes like the Hydrogen Production Business Model and the Net Zero Hydrogen Fund.[7,8] Compliance includes lifecycle emissions accounting, independent verification and the use of renewable electricity. While green hydrogen is not formally defined by UK law, it generally refers to hydrogen produced via electrolysis powered by renewable electricity and is referred to as such in this case study.

Model Overview

The forward-looking methodology described in this case study was developed by EQT Infrastructure with support from McKinsey & Company in order to estimate the planned avoided emissions from an illustrative current, consented and in-development project pipeline for a portfolio company. To estimate the anticipated avoided emissions impact of both energy storage (BESS, PSH) and green hydrogen (GH2) production solutions, this case study references and builds from the 'EQT Infrastructure Avoided Emissions Playbook,' an internal methodology developed in consideration of the general accepted principles of WBCSD and Project Frame, but tailored to the infrastructure asset class and refined by EQT

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[3] HM Government. (2021). Net zero strategy: Build back greener. Department for Business, Energy & Industrial Strategy. https://www.gov.uk/government/publications/net-zero-strategy

[4] National Grid Electricity System Operator. (2023). Future energy scenarios 2023. https://www.nationalgrideso.com/future-energy/future-energy-scenarios

[5] Rankl, F., Walker, A., & Rowe, G. (2024, April 19). Battery energy storage systems (BESS) (CBP-7621). House of Commons Library. https://researchbriefings.files.parliament.uk/documents/CBP-7621/CBP-7621.pdf

[6] Department for Energy Security and Net Zero. (2024, October). Long duration electricity storage consultation: Government response. https://assets.publishing.service.gov.uk/media/670660eb366f494ab2e7b57a/LDES-consultation-government-response.pdf

[7] Department for Energy Security and Net Zero. (2023). Low carbon hydrogen standard: Version 2 guidance. UK Government. https://www.gov.uk/government/publications/low-carbon-hydrogen-standard-version-2

[8] Department for Business, Energy & Industrial Strategy (BEIS). (2022). UK hydrogen strategy. UK Government. https://www.gov.uk/government/publications/uk-hydrogen-strategy

and McKinsey for operational relevance. The table below provides a high-level summary of key concepts from the methodology in alignment with WBCSD and Project Frame considerations.

Table 1: Case Study Overview

CATEGORY	DESCRIPTION
SOLUTION DETAILS	
Who is claiming the avoided emissions?	Investor, based on 100% equity share allocation of the portfolio company: Owner and operator of the energy storage (BESS, PSH) and green hydrogen (GH2) production assets
Solution Type	BESS, PSH — Enabling (Frame) / System-Optimising (WBCSD), existing demand, improvement; Green Hydrogen — assumed to replace grey hydrogen and natural gas, Direct Product (Frame) / End-use solution (WBCSD), existing demand, replacement.
Market assessed	United Kingdom
How is the solution implemented?	The solution provider develops, owns and operates flexible energy infrastructure: • BESS/PSH – Energy is stored during periods of low electricity demand or surplus renewable generation and discharged during peak demand, displacing fossil-fuel generation. • GH2 – Renewable electricity is used to produce low-carbon hydrogen via electrolysis, which can be stored and later used to replace grey hydrogen or fossil fuels in power, transport or industry.
ELIGIBILITY GATES	
Gate 1 **Climate Action Credibility**	Solution provider focuses on owning and operating the assets that provide critical grid balancing support in a renewables-led power system in the UK, in line with UK Net Zero Strategy emphasis on critical role of energy storage and hydrogen technologies in achieving its decarbonisation goals. The portfolio company measures and reports its direct emissions and has identified decarbonisation levers for its operations. It will track its emissions intensity of its operations and target reductions. Note: this company and its business model are not currently eligible for SBTi target validation under the sector-specific pathway at this stage.
Gate 2 **Latest Climate Science Alignment**	BESS, PSH, and green hydrogen production align with IPCC AR6 Working Group III Chapter 6 recommendations for decarbonising the energy system through enhanced grid flexibility, increased renewable energy penetration and the electrification of hard-to-abate sectors. All three technologies are also mentioned as critical to the IEA NZE (Net Zero Emissions by 2050) scenario.
Gate 3 **Contribution Legitimacy**	• Decarbonising Impact: YES. BESS and PSH reduce grid emissions by enabling the time-shifting of renewable electricity, while green hydrogen substitutes for high-emission fuels in hard-to-electrify sectors such as industry and heavy transport. • Direct Impact: YES. BESS/PSH store excess renewable electricity during low-demand periods and discharge it during peak hours, displacing fossil-based peaking generation and improving grid flexibility. Green hydrogen provides a lower-carbon alternative to grey hydrogen and fossil fuels, supporting decarbonisation of end-use sectors where direct electrification is not feasible. • Significant Impact (Quantified): YES. BESS/PSH systems operating at ~88/76% efficiency, using a renewable emissions factor of 0.011 tCO_2e/MWh, result in net emissions of approximately 0,0125 and 0.0145 tCO_2e/MWh — significantly lower than the UK operating margin grid emission factor of 0.38 tCO_2e/MWh (UNFCC margin grid EF). Green hydrogen, under the UK Low Carbon Hydrogen Standard, must emit less than 2.4kg CO_2e/kg H_2 (equivalent to 20g CO_2e/MJ LHV) — here assuming 0.0153 tCO_2e/MWh = ~0.80kg CO_2e per kg of H_2 (assuming 52.5 kWh of electricity per kg of hydrogen), a substantial reduction compared to grey hydrogen (10–14kg CO_2e/kg H_2).
REFERENCE AND TIMEFRAME	
Reference Solution Selection	BESS/PSH: the reference scenario is the margin electricity price. The operating margin grid emission factor is assumed fixed at 380g CO_2/kWh (UNFCC margin grid EF) until 2036 and then reduces linearly as the UK grid decarbonises in line with UK National Grid ESO's future energy scenarios. Green hydrogen: the reference scenario is set replacement of at 50% grey hydrogen (12 tCO_2e/kg x 33.33 kWh/kg = 0.360 tCO_2/MWh) and 50% natural gas (TTW+WTT, 0.213 tCO_2e/MWh), for a weighted average of 0.287 tCO_2e/MWh.
Required by regulation	No

Table 1: Case Study Overview

CATEGORY	DESCRIPTION
Type of Substitution	• Existing demand - improvement. BESS, PSH solutions are grid-scale energy storage that shift surplus renewable energy supply to peak demand. • Existing demand - replacement. Green hydrogen is a direct replacement for grey hydrogen and natural gas.
Timeframe	The timeframe for the assessment is 2024–50. For EQT avoided emissions are calculated for the holding period + 5 years and CAPEX investment over lifetime of the asset.
SYSTEM BOUNDARY AND FUNCTIONAL UNIT	
System boundary	UK, attributional approach, marginal electricity costs where only green electricity sold are considered for electrified stored and traded over time. CAPEX assumed 20 years, investment year 2024, calculations through 2050
Functional unit	• Solution functional units are set to MWh of electricity and H2 delivered • Reference functional units are set to margin electricity (MWh), grey hydrogen (MWh) and natural gas (MWh)
Lifecycle stages / process focus for GHG emission calculation	• Solution - BESS/PSH - use-phase emissions (charging/discharging); green hydrogen – production and use-phase • Reference - BESS/PSH - marginal electricity use-phase emissions from energy grid mix; green hydrogen – 50% production and use grey hydrogen, 50% natural gas (direct emissions - TTW (Tank-to-Wheel) and upstream emissions (WTT (Well-to-tank))

Emissions Reduction Calculations

Energy storage (BESS and PSH). The avoided emissions per MWh from Battery Energy Storage Systems (BESS) and Pumped Storage Hydropower (PSH) in a given year are calculated in a similar manner using the following equations (see step-by-step model construction for more detail on specific emissions factors (EF) and data sources):

$$\Delta GHG_{BESS} = (EF_{MARGIN\ ELECTRICITY}) - (EF_{RENEWABLES} \times Efficiency_{BESS})$$
$$\Delta GHG_{PSH} = (EF_{MARGIN\ ELECTRICITY}) - (EF_{RENEWABLES} \times Efficiency_{PSH})$$

Where:

- **$EF_{MARGIN\ ELECTRICITY}$** is the given year operating margin grid emission factor in the UK in a given year
- **$EF_{RENEWABLES}$** is the emissions factor for renewable energy, modelled as wind generation in the UK (held constant over time)
- **$Efficiency_{BESS}$** is the round-trip efficiency accounting for loss during charging, storage and discharging (held constant over time)
- **$Efficiency_{PSH}$** is the round-trip efficiency accounting for loss during charging, storage and discharging (held constant over time)

Total Avoided Emissions in a given year for each solution is calculated as:

$$Avoided\ Emissions_{BESS} = \Delta GHG_{BESS\ (per\ MWh)} \times Power\ Output_{BESS\ (MWh)}$$
$$Avoided\ Emissions_{PSH} = \Delta GHG_{PSH\ (per\ MWh)} \times Power\ Output_{PSH\ (MWh)}$$

Where:

- **Power Output**$_{BESS\ (MWh)}$ = Planned available capacity in a given year x the number of cycles forecasted in a given year according to an internal Least-Cost Pathway (LCP) model. This is calculated per asset depending on whether it has a one-hour or a two-hour cycle
- **Power Output**$_{PSH\ (MWh)}$ = Planned available capacity in a given year x the number of cycles forecasted in a given year according to an internal Least-Cost Pathway (LCP) model. This is calculated per asset depending on whether it has a 15-hour or a 19-hour cycle.

Green hydrogen. The avoided emissions per MWh from green hydrogen produced in a given year is calculated as the difference between the Hydrogen Reference Scenario (assuming a replacement rate of 50% grey hydrogen and 50% natural gas) and the green hydrogen solution per MWh emissions (see step-by-step model construction for more detail on specific emissions factors (EF) and data sources):

$$\Delta GHG_{\_GREEN\ H2} = EF_{\_H2\ REFERENCE(tCO2e/MWh)} - EF_{\_GREEN\ H2\ (tCO2e/MWh)}$$

Where:

- $EF_{\_H2\ REFERENCE\ (tCO2e/MWh} = 50\%\ EF_{\_GREY\ H2} + 50\%\ EF_{\_NAT\ GAS}$
  - $EF_{\_GREY\ H2\ (tCO2e/MWh)}$ is the given year estimated emission factor for grey hydrogen (expressed in $kgCO_2e/kg$) divided by (÷) the H2 Conversion Factor (kWh/kg).
    - **H2 Conversion factor**$_{(kWh/kg)}$ assumes the lower heating value (LHV) energy density for hydrogen
  - $EF_{\_NAT\ GAS\ (tCO2e/MWh)} = EF_{\_NAT\ GAS\ (TTW)} + EF_{\_NAT\ GAS\ (WTT)}$
    - $EF_{\_NAT\ GAS\ (TTW)}$ is the tank-to-wheel emissions factor, representing direct emissions from burning natural gas, expressed per MWh (based on gross calorific value), as published in the UK Government's GHG Conversion Factors for Company Reporting$EF_{_NAT\ GAS\ (WTT)}$ is the well-to-tank emissions factor, representing the upstream emissions associated with the extraction, processing and delivery of natural gas before combustion, also expressed per MWh (gross CV), from the same UK Government source
- $EF_{\_GREEN\ H2\ (tCO2e/MWh} = EF_{\_RENEWABLES} \div Efficiency_{\_H2}$
  - $EF_{\_RENEWABLES}$ is the emissions factor for renewable energy, modelled as wind generation in the UK (held constant over time);
  - **Efficiency**$_{\_H2}$ is the electrolyser's conversion efficiency (e.g., 72%), reflecting the proportion of input electricity converted into hydrogen energy.

Total Avoided Emissions in a given year for green hydrogen product is based on the difference between the per unit of energy reference hydrogen solution and per unit of energy low-carbon hydrogen solution, times the annual amount of H2 energy produced (MWh), calculated as:

$$Avoided\ Emissions_{\_H2} = \Delta GHG_{\_GREEN\ H2} \times Power\ Output_{\_H2\ (MWh)}$$

Where:

- $\Delta GHG_{\_GREEN\ H2}$ **is** $EF_{\_H2\ REFERENCE(tCO2e/MWh)} - EF_{\_GREEN\ H2\ (tCO2e/MWh)}$, as defined above

- **Power Output$_{H2\ (MWh)}$ = Rated capacity (MW) x Annual Operational Hours (h) Operational x Efficiency$_{H2}$**
  - **Rated capacity (MW)** - is the total installed capacity of the electrolyser system available in a given year.
  - **Annual Operation Hours (h)** - represents the number of hours the system is expected to operate at full load over the year. The model uses a simplified standardised assumption of 50% capacity factor (4380 hours/year) to estimate H_2 production across all years. This reflects typical annual output for onshore wind generation in the UK, based on BEIS and National Grid ESO assumptions. Using a consistent 50% capacity factor across scenarios ensures comparability, while outputs from the LCP model were used as a reasonableness check to validate operational feasibility and alignment with other dispatch and storage-related calculations
  - **Efficiency$_{H2}$** is the electrolyser's conversion efficiency (e.g., 72%), reflecting the proportion of input electricity converted into hydrogen energy.

Solution Maturity and Technical Alternatives. According to the IEA, grid-scale energy storage such as PSH and BESS are commercially mature technologies and play an important role in the Net Zero Emissions by 2050 Scenario, "providing important system services that range from short-term balancing and operating reserves, ancillary services for grid stability and deferment of investment in new transmission and distribution lines, to long-term energy storage and restoring grid operations following a blackout."[9] Global PSH capacity reached 160 GW (2021), representing over 90% of global electricity storage. Grid-scale BESS, predominantly lithium-ion, is experiencing rapid deployment, reaching 28GW by the end of 2022. The IEA Net Zero scenario references grid-scale battery storage capacity expanding by 35-fold between 2022 and 2023 to nearly 970 GW. In the UK, there is currently 4.5 GW of battery storage capacity (mostly grid-scale), which is expected to increase to 23–27GW by 2030 according to the Clean Power 2030 Action Plan.[10] PSH is categorised as a long-duration flexible technology in the Action Plan, and is the only recognized mature technology other than unabated natural gas for dispatchable long-duration flexible capacity.

Green hydrogen production via alkaline electrolysis is gaining momentum as a versatile solution for long-duration energy storage and industrial decarbonisation. According to the International Energy Agency (IEA),[11] low-emissions hydrogen production technologies are commercially available but have not yet reached full maturity, with alkaline and PEM electrolysis as the most mature. The IEA estimates global electrolyser capacity exceeded 1 GW for the first time in 2023, with alkaline systems representing the largest share due to their lower capital costs and established supply chains. Technology alternatives such as Proton Exchange Membrane (PEM) electrolysis (commercially available), Solid Oxide Electrolysis Cells (SOEC) (emerging), Anion Exchange Membrane (AEM) electrolysis (early stage).

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[9] International Energy Agency. (2021). Net zero by 2050: A roadmap for the global energy sector. Retrieved from https://www.iea.org/reports/net-zero-by-2050

[10] Department for Energy Security and Net Zero. (2024). Clean Power 2030 Action Plan: A new era of clean electricity – main report. Retrieved from https://www.gov.uk/government/publications/clean-power-2030-action-plan/clean-power-2030-action-plan-a-new-era-of-clean-electricity-main-report

[11] International Energy Agency. (2023). Global Hydrogen Review 2023. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2023

Key Assumptions and Limitations

As this case study reflects three separate sets of analyses, we summarise the key assumptions by impact analysis in this table, with further explanation below.

System Boundaries.

- For the BESS and PSH energy storage solutions, we assess specifically the ***use-phase emissions*** of these solutions against the marginal electricity use-phase emissions from the UK energy grid mix. While it is possible to quantify cradle-to-use as a more sophisticated measure, research suggests this would yield 5–10% maximum additional emissions over the entire lifecycle,[12] and so for pragmatic reasons excluded from this analysis. This is a deliberate, transparent trade-off based on materiality (in line with WBCSD principles) and to maintain comparability across solutions.
- This assessment models emissions avoided within the UK system boundaries, using UK policy assumptions. It is not a full global market displacement model and does not account for fossil-fuel phase-out in other regions.
- For green hydrogen, ***production and use-phase emissions*** are assessed against production and use-phase emissions of a 50/50 mix of grey hydrogen and natural gas, reflecting a simplified and conservative assumption across a number of potential end-use applications. Similarly, research suggests production and use-phase emissions are the most material aspect of lifecycle emissions for green hydrogen and so electrolyser manufacturing emissions have been excluded from this analysis.[13]

<u>Electricity assumptions:</u>

- **Electricity traded is renewable**. In this context, ‘electricity traded’ refers to the electricity discharged from the storage system (BESS or PSH) and sold back to the grid. It is assumed that the electricity stored and later discharged is sourced from surplus renewable generation (e.g., wind or solar) that would otherwise be curtailed. When discharged, this stored renewable electricity replaces marginal grid generation — typically the most expensive and carbon-intensive option, such as fossil-fuel peaker plants. In all scenarios, emissions reductions are calculated based on the marginal emissions factor, which represents the generation typically dispatched during peak demand periods when BESS and PSH discharge. This proxy approach reflects the emissions profile of the grid generation that BESS and PSH would displace during high-demand hours.
- **Marginal production emissions factor.** Calculations assume a constant marginal production emission factor of 0,38 tCO_2e/MWh until 2036 (leveraging the UNFCC margin grid EF) and a linearly declining emission factor until 2042 based on the UK National Grid ESO Future Energy Scenarios where unabated gas peaks assumed to be removed from the grid between 2036 and 2046.

<u>General technology assumptions:</u>

- **Geography**. United Kingdom

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[12] NREL (2024), “New NREL Tool Estimates Lifetime GHG Emissions of Grid-Scale Storage – Hydropower,” emphasizing most PSH emissions come from grid electricity for pumping; “LCA studies that included both manufacturing and use-phase impacts for stationary BES consistently find that use-phase impacts are a, if not the, major contributor to environmental endpoints such as emissions (Baumann, 2017; Ryan, 2018; Vandepaer, 2018).”
— Electric Power Research Institute (EPRI), 2020

[13] IEA, Global Hydrogen Review 2024, page 210: “For hydrogen production using water electrolysis, emissions are largely defined by the electricity input.”

- **Capacity build-out**: The estimated MWh capacity by solution is projected based on an illustrative projected current, consented and in-development project pipeline for a portfolio company (full potential plan).
- **Renewable electricity emissions factor**. Renewable electricity in the UK is assumed to have a marginal emissions factor of 11g CO_2e/kWh, reflecting the median value for wind power and held constant over time in the analysis. This reflects the current and projected dominate role of wind within renewables in the UK, and is a more conservative assumption than the weighted average emissions factor of the market mix of other renewable sources (solar, hydro, marine, etc)
- **Asset timeline for avoided emissions**. All assets modelled assumed to operate for 20 years, with 2050 as latest date modelled.

<u>Battery Energy Storage Systems (BESS)</u>

- Energy source. Assumed to be charged with renewable electricity and electricity sold is assumed to be replacing marginal production.
- Capacity. Total projected capacity of 3490 MW is estimated to peak in 2032 (internal estimate).
- Average efficiency rate: 88%, the average round-trip efficiency for the company's lithium-ion battery energy storage systems (internal estimate).

<u>Pumped Storage Hydropower (PSH)</u>

- Energy source. Assumed to be charged with renewable electricity and electricity sold is assumed to be replacing marginal production.
- Capacity. Total projected capacity of 2000 MW is estimated to peak in 2032 (internal estimate).
- Average efficiency rate: 76%, the average round-trip efficiency for the company's pumped storage hydropower solutions (internal estimate).

<u>Green Hydrogen (H2)</u>

- Energy source. Alkaline electrolysis utilising renewable energy.
- Capacity. Total projected capacity of 3000 MW is estimated to peak in 2032 (internal estimate).
- Efficiency rate: 72%, estimated efficiency rate for the company's alkaline electrolysis production of hydrogen.
- Reference scenario mix: for modelling purposes, we assume a 50% replacement of grey hydrogen and a 50% replacement of natural gas with low-carbon hydrogen. This simplification reflects the diverse applications of hydrogen across industrial and energy sectors in the UK. It is a conservative simplification based on UK policy and modelling scenarios for early hydrogen deployment. The model reflects expected substitution of green H_2 for grey H_2 across multiple industrial and power end-uses — such as hydrogen replacing grey hydrogen in industrial processes and displacing natural gas in hydrogen turbines or dual-fuel power generation systems. This assumption does not imply physical co-firing or blending of hydrogen in pipelines. The emissions factors applied are based on UK Government GHG Conversion Factors (2023).
  - *Grey Hydrogen emissions factor.* Assumed constant over time at 12kg CO_2e/ kg H_2.
  - *Natural Gas (TTW) emissions factor*. Assumed constant over time at 0,183 tCO_2e / MWh.
  - *Natural Gas (WTT) emissions factor.* Assumed constant over time at 0,03021 tCO_2e / MWh.
  - *Hydrogen conversion rate*. Based on the lower heating value of hydrogen (LHV) at 33,33 kWh/kg. This is a conservative approach because LHV provides a more modest estimate of the

energy content of hydrogen, avoiding overestimation of avoided emissions. Using LHV is also consistent with standard emissions reporting practices (e.g., IEA, UK Government).

Methodological choices. In any avoided emissions assessment there are a number of methodological choices and assumptions. The table below, co-developed by EQT and McKinsey & Company, illustrates the range of methodological options, from pragmatic to rigorous, and those choices used in this case study (highlighted in orange).

Table 2: Avoided Emissions Methodological Choices Used for this Case Study

	Options						
Design parameter	**More pragmatic**			**More rigorous**			**Implicatons for Case Study**
1.1 System boundaries and conditions							
Global Warming Potential Standard	**GWP 100**			GWP 20			GWP100 emissions factors used
Climate solution eligibility assessment	No assessment - all emission avoiding activities are accepted		Exclusion based on public minimum requirements		**EQT infrastructure eligibility assessment**		Focus only on BESS, PSH and electrolysers in analysis
Investor impact definition	**Portfolio impact**			Investor impact			Avoided emissions attributed based on company avoided emissions claim, not on investor contribution
Timeframe for avoided emissions measurement	Holding period only		Fixed time span of X years		**Holding period + 5 years - CAPEX investments at realisation**		Focus only on BESS, PSH and electrolysers in analysis
Temporal attribution of avoided emissions over lifetime	In-year impact		Lifetime Impact		**Lifetime, except for CAPEX investments not created by Investor**		In year for company, lifetime for investor
Geographic boundaries	Global	Regional		**Country**		Municipality	Emissions factors based on UK data
System attribution boundaries	Attributional		Consequential		**Case-by-case**		Attributional approach taken where only green electricity sold is considered for electricity stored and traded over time
Value chain boundaries	Scope 1v2 only	Scope 1–2, Scope 3 upstream		Scope 1–2, Scope 3 downstream		**Scope 1–3, full inclusion**	All scopes considered
CO_2 emissions over time	**Constant value**			Discounting rate at social rate of carbon			Emissions held constant over time
Adjustment for impact uncertainty	**No adjustment**		Fixed % factor adjustment		Discounting of future uncertainty		Attributional approach taken where only green electricity sold is considered for electricity stored and traded over time
1.2 Reference scenario							

Table 2: Avoided Emissions Methodological Choices Used for this Case Study

Design parameter	Options: More pragmatic		Options: More rigorous	Implicatons for Case Study
Reference/alternative solution logic (incumbent/status quo)	Closest possible comparable unit	**Final product substituted**	Case by case	Calculation based on final product substituted (i.e., electricity)
Reference CO_2e metric	Industry average (green to average)	Industry average (green to brown)	**Case by case**	Industry margin (i.e., most expensive production route is phased out) assume for electricity produced
Reference CO_2e value	Leveraging peer benchmarks	**Leveraging external LCA inventory databases**	Bottom-up modelling based on external emission intensity metrics on sub-component level	External data used for emission factors
Reference CO_2e development over time	Static		**Dynamic (changing over time)**	Reference scenario is dynamic where applicable and where there is reason to believe that there is substantial change over time. In this case, marginal grid emission factor is held constant to 2036 and then decreased linearly, in line with the UK National Grid ESO's future energy scenarios
Reference CO_2e intensity forecast logic and sources	Top-down linear decline or exponential reduction rate	**Based on established future scenarios (e.g., IEA where available)**	Bottom-up modelling case by case	Due to absence of data, future reference emissions are based on bottom-up calculations based on UK National Grid ESO's future energy scenarios
1.3 Solution scenario				
Solution CO_2e value	Peer benchmark		**Bottom-up modelling based on emission intensity data**	Solution emissions are bottom-up calculated by increasing renewable electricity emissions by the efficiency loss factors per BESS, PSH and electrolysers
Solution CO_2e development over time	Static		**Dynamic (changing over time)**	Dynamic used, but no change expected over time apart from composition of different technologies in the illustrative growth plan
Solution CO_2e intensity forecast logic and sources	Linear decline in line with company commitment / target	Based on external future projections (where available)	**Bottom-up modelling**	End result not dependent on extensive modelling of solution emission intensity over time (solution already close to zero emissions) and no reason to believe that there is a substantial change over time
1.4 Avoided Emissions Calculation				
Accounting for some products being additional	Assume 100% substitution	Apply blanket statement substitution share for all cases	**Assume 0–100% substitution case by case**	100% substitution is assumed (i.e., margin grid is replaced)

Table 2: Avoided Emissions Methodological Choices Used for this Case Study

Design parameter	Options: More pragmatic			Options: More rigorous		Implicatons for Case Study
Horizontal attribution (% of total avoided emissions allocated to given solution in value chain)	**100% (accept double-counting)**	Blanket split	Commoditisation matrix	**TCO / CAPEX Split**	Split according to stakeholder consensus	100% attribution to company assumed as business activity directly avoids emissions and is essential in the renewable energy value chain. This risks double-counting against claims by other value chain actors (e.g., renewable energy producers)
Functional unit scale-up method	Scale by revenue		**Scale by 'average units sold' (if discrete product exists)**			Scaled by estimated MWh output from illustrative growth plan
Calculation Approach	Top-down	Bottom-up		**Case by case**		Bottom-up approach used in this case
Company growth projection used	Global/regional average GDP growth		**Business plan growth projection applied**			Illustrative growth projection is used
1.5 Investment Avoidance Intensity						
Vertical attribution (% of avoided emissions allocated to given shareholder of company)	100% (accept double-counting)	**Allocate by equity share based on equity stake**		Split by total funding share including debt		Investor equity share used
Assumed development of future avoided emissions at point of exit	Assume no future avoided emissions	Assume future yearly avoided emissions remain the same as that of exit year		**Assume future yearly avoided emissions follow business forecasts, exclude impact of CAPEX investments made after exit**		Portfolio company growth forecast is used

Limitations and Risks. While balancing pragmatic and rigorous methodological choices and assumptions in developing this forward-looking avoided emissions impact model, there are a number of limitations and inherent risks to estimating future projections based on these assumptions.

- **UK grid decarbonisation.** Calculations are based on current projections of grid decarbonisation rates according to UK Future Energy Scenario which suggest unabated natural gas will be removed from the grid between 2036 and 2046. The marginal grid emissions factor is assumed therefore to decrease linearly to 2042. A more accelerated decrease would risk over-estimation of potential impact, while a slower decrease risks under-estimation of potential impact. This emphasises the importance of ongoing updates to reflect the latest policy and grid decarbonisation pathways.
  - *Small deviations in policy implementation or technology uptake could materially alter marginal emissions profiles and therefore shift avoided emissions projections, especially in later years.*
- **Annual grid emissions factors.** The model uses annual average emissions factors, which do not capture real-time grid carbon intensity or hourly dispatch patterns. While this is a reasonable approach for long-term planning and aggregate avoided emissions modelling, it does not reflect intraday variability or specific market dynamics (e.g., dynamic pricing or curtailment risk).

Incorporating hourly emissions factors would provide a more granular and accurate representation of avoided emissions, particularly for energy storage technologies like BESS and PSH, and is a potential enhancement for future iterations of this analysis.

- *This limits the model's applicability for evaluating technologies whose impact is highly sensitive to temporal emissions variations.*

- **Constant grey hydrogen and natural gas emissions factors.** While upstream methane mitigation efforts may reduce emissions factors for natural gas and grey hydrogen over time, this model does not speculate on the degree or pace of such improvements. Instead, a constant emissions factor is applied as a conservative simplification, acknowledging the uncertainty around industry-wide adoption of methane reduction strategies.
  - *If methane abatement becomes widespread faster than expected, this could lead to a conservative bias in avoided emissions estimates.*
- **Policy and regulatory uncertainty.** The assessment assumes that none of the solutions (BESS, PSH, Green H_2) are mandated by regulation during the forecast period. Future policy changes (e.g., hydrogen blending mandates, capacity market reforms) may affect the baseline or reference scenario, thereby altering the estimated avoided emissions.
  - *Policy-driven demand shifts could significantly affect baseline emissions assumptions and change the comparative value of each technology.*
- **Geographic specificity.** The methodology was developed for the UK market, spending heavily on local grid conditions, marginal generation and load profiles, and therefore may not be directly applicable or transferable to other regions.
  - *Applying this methodology elsewhere without adjustments could misrepresent emissions impacts due to structural and policy differences.*
- **Performance efficiency.** The methodology assumes constant performance efficiency over time, incorporating conservative estimates that account for standard operational maintenance (O&M) practices and expected system conditions. While this approach simplifies the model, it may slightly underestimate the impact of real-world degradation, which could modestly reduce avoided emissions over time.
  - *Efficiency degradation may be nonlinear and context-specific, potentially amplifying uncertainty over longer horizons.*
- **Attribution assumptions.** The model attributes 100% of avoided emissions to the project company. This assumption is based on the company's role as a direct enabler of decarbonisation, particularly for technologies that bridge renewable generation and demand. However, in the future, industry norms may evolve toward shared value chain attribution, which could affect how emissions are allocated across stakeholders.
  - *A shift to shared attribution models could materially reduce the proportion of emissions claimed by a single actor.*
- **Capacity factor.** The operational capacity factor assumed, 50% may not reflect annual variations for operating assets.
  - *Unforeseen technical issues or weather variability could cause meaningful deviations from projected capacity factor over time.*

- **Least-Cost Pathway (LCP) model.** The Least-Cost Pathway (LCP) model referenced is a forecast tool based on conservative assumptions, which yields an estimate of actual hours operational or cycle times per year. There is inherent accuracy risk in any forward-looking model.
  - *Even conservative forecasts can diverge sharply from reality if market dynamics shift or deployment is delayed.*
- **Replacement assumption of 50/50 grey hydrogen and natural gas.** Blue hydrogen was excluded from the Planned Impact analysis. Avoided emissions from blue hydrogen involve separate technologies and assumptions related to carbon capture, and were not considered in this specific analysis due to data gaps and policy uncertainty. However, future methodological iterations could consider assumptions about blue hydrogen uptake in the UK and adjust the 50/50 grey hydrogen and natural gas market mix accordingly to reflect a more nuanced market dynamic
  - *Increased blue hydrogen uptake could materially affect marginal emissions factors and alter the impact profile.*
- **Accounting for end-use cases.** The model focuses on energy-equivalent substitution of hydrogen for natural gas and does not account for operational or efficiency differences in specific combustion use-cases. Conversion losses and combustion efficiency variations between hydrogen and natural gas are not modelled, which could impact real-world avoided emissions outcomes. This case applies a simplified substitution model based on energy content (MWh), aligned with UK government and IEA assumptions for blended hydrogen use. While this provides a pragmatic estimate, it does not capture differences in thermal conversion profiles across off-takers (e.g., industrial processes vs. turbines). Accounting for such variability represents an opportunity for future methodological refinement.
  - *Omitting these variations may lead to over- or under-estimations depending on sector-specific efficiencies.*
- **Hydrogen leakage.** This model does not account for hydrogen leakage during production, storage or transport, which may result in an underestimation of lifecycle emissions impacts. Given the high global warming potential of hydrogen (GWP20 = 40), this is an important area for future methodological development, particularly for any realised avoided emissions claims.
  - *If leakage rates are significant, actual net climate impact could be lower than modelled avoided emissions suggest.*
- **Rebound effects.** Rebound effects — such as increased hydrogen demand enabled by lower production costs or efficiency gains — are not included in this Planned Impact model, which uses an attributional approach focused on direct avoided emissions. While this is considered optional under Project Frame, it nonetheless is a modelling limitation, as rebound effects could reduce net emissions benefits over time.
  - *Increased end-use demand or induced consumption may reduce the net climate benefit if not bounded by supply-side constraints.*
- **Rated capacity (MW).** Operational capacity (MW) of BESS, PSH and green hydrogen assets is based on illustrative internal projections and reflects the anticipated current, consented and in-development project pipeline for a portfolio company. There are a number of factors that could delay the year in which the assets become operational. Only those projects currently forecast during the hold period are included in the model, limiting the risk of over-estimation.

- *Even modest project delays or cancellations could shift the timeline for emissions impact, especially in early forecast years.*

Product Classification

- **UN Central Product Classification (CPC):** CPC treats electricity supply and hydrogen production as different product domains. Electricity generation/transmission falls under utilities services or energy goods (CPC 17100 and related services), whereas hydrogen is categorised under chemical manufacturing products (CPC 34600). Therefore, these business activities straddle two CPC sections.
- **Global Industry Classification Standard (GICS):** The grid-balancing (BESS/PSH) assets fits within GICS Sub-Industry 55105010 – Independent Power Producers & Energy Traders, under Industry Group 5510 – Utilities. Given the emphasis on renewable energy integration, it could also fit under 55105020 – Renewable Electricity. The green hydrogen production aspect of the business may be classified under GICS 10102050 – Coal & Consumable Fuels (within the Energy sector).

Forward-Looking Avoided Emissions Impact Analysis

Planned Impact

Here we illustrate a forward-looking Planned Impact Assessment 2024-2032 to estimate the aggregated annual avoided emissions impact from forecasted BESS, PSH and green hydrogen capacity of a given portfolio company in the UK. Given the assumption of a CAPEX lifetime of 20 years for operating assets, the estimated impact is calculated annually through 2050 based on forecasted rated capacity and operating assumptions using an internal least-cost planning (LCP) model. The analysis only includes assets either currently or forecasted operational by 2032, and does not include estimates of additional capacity added beyond the modelled hold period (2032).

Table 3: Forecast MW Capacity* by Asset Class

ASSET CLASS	2024	2032
BESS	300	3,490
PSH	0	2,000
H2	0	3,000

Source: Illustrative estimates from Internal Projections

Under these assumptions, and the emissions factors detailed in the model overview, **Planned CO_2e avoided is estimated to reach 5.3 Mt CO_2e emissions avoided annually by 2032**, based on the i) commercial forecast MW-capacity and ii) forecast operating capacity (hours, cycles) for the assets using an internal least-cost planning (LCP) model:

Table 4: Annual Avoided Emissions Projection for 2032

ASSET CLASS	FUNCTIONAL UNIT MWh	UNIT IMPACT tCO_2e/MWh	VOLUME TWh*	AVOIDED EMISSIONS Mt CO_2e
BESS	Green Electricity	0.37	3.37	1.25
PSH	Green Electricity	0.37	3.96	1.47
H2	Green Hydrogen	0.27	9.46	2.55
Total Projected Annual Avoided Emissions (2032)				**5.27 Mt**

Source: Forecasted MW Capacity x Forecasted LCP-derived operating hours/cycle to drive Forecasted Annual Volume (Two)

Using this same approach on an annual basis across the modeled timeframe, aggregating the annual projected avoided emissions totals, **we estimate a total cumulative 74 Mt CO_2e emissions until 2050,** based on existing and anticipated BESS, PSH and H2 production capacity and expected CAPEX lifetime of 20 years per asset from 2024 to 2050.

These estimates are internal and not published as avoided emissions claims. In line with WBCSD guidance, it is recommended that avoided emissions claims, once reported, will be reported separately from Scope 1–3 emissions.

Realised Emissions

This case study does not cover Realised Emissions Assessment. However, we anticipate realised emissions calculations to use the same functional units and emissions factor-derived unit impact estimates (for a given year, updated annual based on the latest available information). Volume will be based on realised operational output (TWh) in a given year.

Potential Emissions

As the energy storage solutions analysed are mature, commercially established technologies, and green hydrogen is an emerging but commercially viable solution with growing deployment — yet still facing scale-up challenges — this case study focuses on a Planned Impact assessment rather than a broader Potential Impact assessment. A Potential Impact assessment, which estimates the theoretical maximum impact across an unconstrained market, was not prioritised, as the aim was to present a realistic, directional analysis aligned with the company's business strategy, commercial growth forecasts and technology deployment outlook.

Data Sources / Additional Information

Reference Scenario

- **Combined Margin Grid Emission Factors** (g CO_2/kWh) and Operating Margin Grid Emission Factors (gCO_2e/kWh) for the UK taken from United Nations Framework Convention on Climate Change (UNFCCC). (2022). Methodological approach for the common default grid emission factor dataset (Version 01.1). Retrieved from https://unfccc.int/sites/default/files/resource/IFITWG_Methodological_approach_to_common_dataset.pdf
  - *Operating Margin Grid Emission Factor of 380g CO_2e/kWh (0,38 tCO_2e/MWh)*
- **Projections of total electricity generation output by technology (TWh)** are from the National Grid ESO Future Energy Scenarios. Carbon intensity of electricity generation assumed fixed until

2036 and then decline linearly toward 2042 according to net-zero scenarios from the ESO (2023): National Grid ESO. (2023). Future Energy Scenarios 2023 – Data Workbook (Version: July 2023). Retrieved from https://www.neso.energy/document/283061/download

  - *Operating Margin Grid Emission Factor declines linearly after 2036 to 2042*

- **Emissions intensity of grey hydrogen** is assumed stable over time and derived from the IEA (2023): International Energy Agency. (2023). Towards hydrogen definitions based on their emissions intensity – Executive summary. Retrieved from https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity/executive-summary
  - *Grey hydrogen emission factor of 12kg CO_2e / kg H_2*
- **Hydrogen conversion (33,33 kWh/kg H_2)** based on Lower Heating Value (LHV) of 120 MJ/kg, converted using https://www.iea.org/data-and-statistics/data-tools/unit-converter
- **Natural gas emissions factors (Tank-to-Wheel (TTW) and Well-to-Tank (WTT))** are assumed stable over time and derived from: UK Department for Business, Energy & Industrial Strategy (BEIS). (2022). Greenhouse gas reporting: Conversion factors 2022. UK Government. Retrieved from https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022 and Department for Energy Security and Net Zero. (2023). Greenhouse gas reporting: Conversion factors 2023. UK Government. Retrieved from https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023
  - *Natural gas (TTW) emissions factor of 0.183 tCO_2e/MWh*
  - *Natural gas (WTT) emissions factor of 0.030 tCO_2 e/MWh*
  - *Natural gas (WTW) emission factor of (TTW+WTT) = 0.213 tCO_2e/MWh*
- **Green hydrogen** is assumed to have an emission factor equal to the emissions factor of renewables divided by the efficiency factor of 72% (internal estimate). We use the carbon intensity of wind generation at 11g CO_2e/kWh as the renewable electricity emissions factor, taken from U.S. Department of Energy. (2024, August 21). How wind can help us breathe easier. https://www.energy.gov/eere/wind/articles/how-wind-can-help-us-breathe-easier and further cited from Dolan, S. L., Heath, G. A., & Vorum, M. (2012). Life cycle greenhouse gas emissions of natural gas-fired electricity generation: Systematic review and harmonization. Journal of Industrial Ecology, 16(S1), S53–S72. https://doi.org/10.1111/j.1530-9290.2012.00464.x
  - *We use an efficiency factor of 72%, in line with IEA (2022) Global Hydrogen Review estimates of electrolysis efficiency for state-of-the-art systems in the 70-75% range.*
  - *Green hydrogen emission factor of 0.011 tCO_2e/MWh ÷ 72% = 0.0153 tCO_2e/MWh and assumed constant over time.*
- **BESS and PSH emissions factors** are assumed to be similarly equivalent to the renewable emissions factor divided by the efficiency factor of each technology, 88% and 76% respectively. These are based on company solution estimates and are in line with IEA and industry estimates.
  - *Emissions factor renewables BESS of 0.011 tCO_2e/MWh ÷ 88% = 0.0125 tCO_2e/MWh and assumed constant over time.*
  - *Emissions factor renewables PSH of 0.011 tCO_2e/MWh ÷ 76% = 0.0145 tCO_2e/MWh and assumed constant over time.*

Analysis & Commentary

Analysis Summary

Calculating forward-looking GHG impact analysis requires a number of assumptions and the practical constraints of data availability and quality, balancing rigour with pragmatism across a wide range of methodological considerations (see Table 2 above).

Here we detail the step-by-step model construction based on these methodological choices.

Step-by-Step Model Construction

1. Qualify Impact. We start from the well-supported assertion that Battery Energy Storage Systems (BESS), Pumped Storage Hydropower (PSH), and gareen hydrogen solutions provide viable alternatives to fossil-based energy and fuels in the UK energy system. The impact results from the displacement of high-emissions energy sources — specifically marginal grid electricity (for BESS and PSH), and a 50/50 mix of grey hydrogen and natural gas (for Green Hydrogen) — with cleaner, lower-carbon substitutes.

We define the system boundaries (see above for more detail on system boundaries) as:

- BESS and PSH: Energy storage solutions operating on the UK electricity grid, displacing marginal generation as defined by the operating margin emissions factor.
- Green hydrogen: Electrolysis-based hydrogen production using renewable electricity, replacing fossil-derived hydrogen and natural gas in industrial and energy applications.

We use functional units of:

- 1 MWh of electricity discharged from BESS or PSH
- 1 MWh of green hydrogen H_2 delivered (based on the LHV of 33.33 kWh/kg)

We define unit of impact (avoided emissions per functional unit) as tCO_2e per MWh of energy delivered. We estimate impact over a forecasted hold and investment period (2024–32) and forward-looking 20-year asset lifetime (2024–50), consistent with average expected operational life for each asset class.

2. Construct Baseline Scenario. We define the **baseline (reference) scenario** as the greenhouse gas (GHG) emissions that would have occurred in the absence of Battery Energy Storage Systems (BESS), Pumped Storage Hydropower (PSH), and green hydrogen deployment.

- **For BESS and PSH**, the baseline reflects the emissions from marginal grid electricity displaced at the time of discharge. These are represented by the UK Operating Margin Grid Emissions Factor, which captures the fossil-based generation most likely to be curtailed during storage discharge events.
- **For green hydrogen**, the baseline assumes a 50/50 replacement of grey hydrogen and natural gas use. This is consistent with UK government and IEA modelling assumptions for early green hydrogen adoption and reflects the combined emissions associated with conventional hydrogen production via steam methane reforming and natural gas combustion and extraction.
- The **solution scenario** reflects the operation of BESS, PSH and green hydrogen assets in a given year. For BESS and PSH, the emissions intensity of electricity discharged is determined by the carbon intensity of the renewable electricity stored and discharged, scaled by each system's

round-trip efficiency. For green hydrogen, emissions are calculated based on the carbon intensity of renewable electricity used in electrolysis, divided by the system's conversion efficiency.

- **Forecasted power output volumes (in TWh)** are based on capacity forecasts and internal least-cost planning (LCP) model estimates for operating hours and cycle frequency. The avoided emissions calculation assumes that energy delivered by each solution displaces fossil-based supply. This is validated through alignment with National Grid ESO's Future Energy Scenarios (2023), which outline expected system decarbonisation pathways.

3. Obtain Emissions Factors. We obtain emissions factors from established third-party and government sources to quantify both baseline and solution scenarios.

- **Solution emissions factors**: We use a fixed value of 11g CO_2e/kWh for renewable electricity, based on the median lifecycle emissions intensity of wind power reported by the U.S. Department of Energy (2024) and harmonised in global LCA literature (Dolan, Heath & Vorum, 2012). This value is applied across BESS, PSH and green hydrogen, and adjusted using technology-specific efficiency rates: 88% for BESS, 76% for PSH, and 72% for electrolysis.
- **Baseline emissions factors**:
  - *Electricity Grid Displacement: 380g CO_2e/kWh (0.38 tCO_2e/MWh) from the UNFCCC Common Default Dataset, aligned with PCAF.*
  - *Natural Gas (TTW + WTT): 0.18293 tCO_2e/MWh (TTW) + 0.03021 tCO_2e/MWh = 0.213 tCO_2e/MWh, derived from the UK Government GHG Conversion Factors (BEIS, 2022; DESNZ, 2023).*
  - *Grey Hydrogen: 12kg CO_2e/kg H_2, per IEA's 2023 hydrogen emissions intensity report.*
  - *Hydrogen Conversion: Based on the LHV of 33.33 kWh/kg, as standardised by the IEA Unit Converter.*

We anticipate that emissions factors will be reviewed and updated annually where material changes are warranted. For consistency with national decarbonisation pathways, we model the UK operating margin emissions factor as fixed through 2036, with a linear decline toward 2042, following National Grid ESO Future Energy Scenarios (2023).

4. Calculate Unit Impact.

Assumptions

- **EF_MARGIN ELECTRICITY** = 0.38 tCO_2e/MWh (UK Operating Margin Grid Emission Factor)
- **EF_RENEWABLES** = 11g CO_2e/kWh = 0.011 tCO_2e/MWh (emissions from renewable electricity)
- Adjustment for round-trip efficiency:
  - *BESS efficiency = 88% → EF_BESS = 0.011 / 0.88 = 0.0125 tCO_2e/MWh*
  - *PSH efficiency = 76% → EF_PSH = 0.011 / 0.76 = 0.0145 tCO_2e/MWh*
- **EF_H2 REFERENCE = 50% EF_GREY H2 + 50% EF_NAT GAS**
  - *EF_GREY H2 = 12kg CO_2e/kg H_2 →Converted via LHV (33.33 kWh/kg) → 12 / 33.33 = 0.36 tCO_2e/MWh*
  - *EF_NAT GAS (tCO_2e/MWh) = 0.18293 tCO_2e/MWh (TTW) + 0.03021 tCO_2e/MWh (WTT) = 0.213 tCO_2e/MWh*
  - *Blended reference: (0.36 + 0.213)/2 = 0.2865 tCO_2e/MWh*

- **EF_GREEN H2 = EF_RENEWABLES ÷ Efficiency_H2** → 0.011 / 0.72 = 0.0153 tCO_2e/MWh

Calculations:

Unit level impact is defined as Unit Impact (tCO_2e/MWh) = EF_Reference - EF_Solution, and summarised in the table below:

Table 5: Unit Impact Calculations

ASSET CLASS	REFERENCE EF tCO_2e/MWh	SOLUTION EF tCO_2e/MWh	UNIT IMPACT tCO_2e/MWh
BESS	0.38	0.0125	0.37
PSH	0.38	0.0145	0.37
H2	0.2865	0.0153	0.27

Calculations described above

Specificity Level - MEDIUM-HIGH. In line with WBCSD recommendations, we assess the specificity level of the avoided emissions calculations as MEDIUM-HIGH (for the Planned Avoided Emissions estimates):

- **Solution (S) - High** – we perform a detailed calculation of emissions associated with specific use case scenarios (specific MW and LCP forecasts), coupled with average company-specific efficiency factors.
- **Reference (R) - Low** – we use market average marginal electricity emissions factors (for grid), specific to the UK.

Attribution/allocation. Given that the scope of the avoided emissions assessment focuses on the marginal electricity traded as a result of the BESS and PSH assets, as well as the direct impact from green hydrogen products, we assume 100% value chain attribution in our analysis for purposes of the Planned Avoided Emissions Impact Assessment. This reflects our assessment that the portfolio company is the key enabler for bridging the renewables into peak hours and for producing the green hydrogen. Without this role in the value chain, less green electricity / hydrogen would enter the market, hence a full attribution is suggested. In this case study, the investor uses a methodological choice of allocating vertical attribution according to equity share based on equity stake (100% in this case). However, the avoided emissions attribution only includes avoided emissions for the holding period + 5 years, and CAPEX investment over the lifetime of the asset (20 years).

Eligibility Gates

The WBCSD establishes the following eligibility gates in its guidance on Avoided Emissions calculations. This illustrative case concerns a growth-stage company with a relatively low operating footprint.

Gate 1: Climate Action Credibility. *The company has set and externally communicated a climate strategy consistent with the latest climate science, providing robust GHG footprint measurement and including science-based informed targets covering Scope 1, 2 and 3, transparently reporting on progress on a regular basis.*

In this example, the portfolio company has not yet set and externally communicated a climate strategy with science-based informed Scope 1–3 targets, particularly because there is currently no sector-specific SBTi pathway for this business model. GHG emissions will be reported, decarbonisation levers have been identified and emissions intensity will be tracked with reduction targets in place. The results of the Planned Avoided Emissions Impact Assessment have not been made public.

Gate 2: Climate Science Alignment. *The solution (or end-solution of the intermediary solution) has mitigation potential according to the latest climate science and recognised sources, and is not directly applied to activities involving exploration, extraction, mining and/or production, distribution and sales of fossil fuels i.e., oil, natural gas and coal.*

Both the IPCC and IEA recognise energy storage solutions such as Battery Energy Storage Systems (BESS) and Pumped Storage Hydropower (PSH) as critical infrastructure for enabling low-carbon energy systems. The IPCC highlights that integrating variable renewable energy like wind and solar requires enhanced system flexibility and acknowledges the role that BESS and PSY play in supporting increased deployment of variable renewable energy (VRE).[14] The IEA similarly identifies PSH and BESS as essential for balancing supply and demand, maintaining grid stability and supporting the reliability of renewable-powered grids.[15]

The International Energy Agency's (IEA) Net Zero Emissions by 2050 Scenario (NZE)[16] outlines the substantial scale-up of low-emission hydrogen production necessary to achieve global climate goals. By 2030, the scenario envisions approximately 50 million tonnes (Mt) of hydrogen produced via electrolysis and over 15 Mt derived from fossil fuels equipped with carbon capture, utilisation and storage (CCUS), collectively accounting for about half of the global hydrogen production at that time. Achieving this target requires an installed electrolyser capacity of 560 gigawatts (GW), necessitating rapid expansion in both electrolyser manufacturing and dedicated renewable energy capacity to power these electrolysers.[17]

Gate 3: Contribution Legitimacy. *The solution has a direct and significant decarbonising impact (Direct Product, Direct Component)*

Energy storage solutions and green hydrogen demonstrate contribution legitimacy according to WBCSD guidelines:

- **Decarbonising**. Battery Energy Storage Systems (BESS), Pumped Storage Hydropower (PSH), and green hydrogen contribute to decarbonisation by enabling reduced GHG emissions compared to fossil-intensive reference scenarios. BESS and PSH displace higher-emitting peaking generation and support integration of variable renewables, while green hydrogen replaces grey hydrogen and natural gas in hard-to-abate sectors. These avoided emissions are quantifiable using established

[14] Clarke, L., Wei, Y.-M., De La Vega Navarro, A., Garg, A., Hahmann, A. N., Khennas, S., Azevedo, I. M. L., Löschel, A., Singh, A. K., Steg, L., Strbac, G., & Wada, K. (2022). Energy Systems. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, & S. Some (Eds.), Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157926.008

[15] International Energy Agency. (n.d.). Energy storage. Retrieved April 3, 2025, from https://www.iea.org/energy-system/electricity/grid-scale-storage

[16] International Energy Agency. (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector. https://www.iea.org/reports/net-zero-by-2050

[17] International Energy Agency. (2024). Global Hydrogen Review 2024. Retrieved April 3, 2025, from https://www.iea.org/reports/global-hydrogen-review-2024

emissions factors from sources such as the UK Government Conversion Factors and IPCC guidance, applied to modelled dispatch, efficiency and grid marginal intensity assumptions.

- **Direct**. BESS, PSH, and green hydrogen technologies directly reduce greenhouse gas emissions by substituting for higher-emitting energy sources. These reductions are evidenceable and traceable through modelled dispatch patterns, emissions factors, efficiency rates and published electricity market data.
- **Significant**. While the carbon intensity of electricity and hydrogen supply varies by location and time, substituting marginal fossil-based electricity generation with BESS- or PSH-stored renewable electricity, or substituting grey hydrogen or natural gas with green hydrogen represent substantial shifts in emissions intensity. For BESS and PSH, we estimate this to be a difference of 0.0125 tCO_2e/MWh (BESS) and 0.0145 tCO_2e/MWh (PSH), as compared to the operational margin grid emissions factor for the UK of 0.380 tCO_2e/MWh (a 26–30x lower marginal emissions factor per unit of energy MWh). Similarly, assuming a replacement of 50% grey hydrogen and 50% natural gas, green hydrogen (at 0.015 tCO_2e/MWh) offered a significantly lower emissions factor than the two reference scenarios of grey hydrogen (0.36 tCO_2e/MWh) or natural gas (0.21 tCO_2e/MWh), or a weighted average of 0.29 tCO_2e/MWh. See model calculations for more detail.

Challenge & Side Effects

In developing this methodology, a significant number of assumptions are necessary (see Table 2: Avoided Emissions Methodological Choices and section above). Recognising the absence of absolute answers in many areas, this methodology reflects a number of informed choices balancing pragmatism with rigour, and emphasises transparency around the choices and assumptions adopted. Divergence in views on assumptions is both expected and natural; therefore, clarity and openness are essential. Both EQT and the Impact Convergence Forum members acknowledge that the table outlining the balance between pragmatic and rigorous approaches is particularly valuable, both during the assessment development process and as a key tool to foster transparency with stakeholders.

Improved grid stability and renewable energy enablement (BESS, PSH) – While not modeled specifically in this Planned Avoided Emissions Impact Assessment given the relative complexity and level of assumptions, a case can be made that BESS and PSH energy storage also enable additional renewable energy production. We identify three key challenges with quantifying, claiming and adding ‘enablement’ of renewables into the avoided emissions figures, which have been excluded from this quantified analysis:

- The relationship between energy storage and renewable energy enablement is highly location-specific and difficult to quantify, making it challenging to credibly estimate how much renewable generation is ‘enabled’ per installed MWh of storage capacity.
- Applying an allocation principle based on CAPEX can skew results: because BESS is more capital-intensive than PSH, it may be attributed a disproportionately higher share of avoided emissions, regardless of actual system contribution.
- The current method of calculating avoided emissions based on ‘bridging renewables in time’ is effectively a subset of broader enablement claims and carries a risk of double-counting, especially if emissions savings are also attributed to the renewable generation itself.

Excluded Solutions – Flexible Thermal Generation. This illustrative case highlights an excluded business line from the avoided emissions calculation: flexible thermal generation assets (gas reciprocating engines). The emissions or avoided emissions impact associated with these assets, which represent less than 10% of the company revenues in this example, are not included in this analysis. These technologies play an important role in ensuring grid stability and balancing renewables within the UK's Net Zero strategy. However, their current reliance on natural gas precludes them from avoided emissions calculations under WBCSD guidance.

Supply Chain Risks and Impacts. The deployment of BESS (Battery Energy Storage Systems), PSH (Pumped Storage Hydropower), and green hydrogen technologies raises important supply chain and human rights considerations. Battery supply chains, particularly for lithium, cobalt and nickel, are associated with risks such as child labour, unsafe working conditions and environmental degradation, especially in high-risk sourcing regions. Green hydrogen technologies depend on rare or specialised materials (e.g., iridium for PEM, nickel for AEL), which also pose sourcing and traceability challenges. While PSH systems have a lower materials footprint, they may involve land use and water rights impacts, particularly in sensitive ecological areas or regions with complex stakeholder claims. Ensuring responsible sourcing, traceability and compliance with international labour and environmental standards is critical across all three technologies to align with sustainability and ESG expectations, and is a core part of investor diligence and sustainability KPIs.

Environmental and Biodiversity Impacts: BESS and PSH projects can affect local ecosystems through land use changes and habitat disruption. These potential negative impacts can be mitigated by conducting thorough environmental impact assessments, integrating biodiversity enhancements into project designs and ensuring compliance with local and national planning regulations as a core part of project development process and ongoing operations.

Community Engagement and 'Not In My Backyard' (NIMBY) Concerns: Large-scale energy projects may raise concerns among local residents related to visual impact, noise and land use. Mitigation efforts often include early and transparent community engagement, incorporation of local feedback into project design and visual screening through landscaping or strategic site placement. Ensuring that community interests are considered during the planning process can help build local understanding and support.

Health and Safety Risks: The construction and operation of BESS, PSH and green hydrogen facilities involve distinct HSE risks, including fire and explosion hazards, equipment failure and construction-related incidents. Green hydrogen projects require particular attention due to hydrogen's flammability, small molecular size (which can increase leak potential) and potential for accumulation in confined spaces. Mitigation measures include compliance with hydrogen-specific safety codes (e.g., ISO/IEC standards), robust leak detection systems, proper ventilation and emergency response planning. Construction-phase risks across all technologies — such as worker safety, traffic impacts and environmental disturbance — are typically addressed through comprehensive HSE management systems and regulatory oversight.

Water Usage Considerations: Water-related impacts vary across technologies — BESS involves significant upstream water use for raw material extraction, particularly lithium and cobalt; PSH systems rely on large volumes of water, with potential evaporation losses and ecological impacts; and green hydrogen production via electrolysis requires ~9 litres of high-purity water per kg of hydrogen, raising concerns in water-scarce regions. Responsible siting, resource planning and water-efficient technologies are critical to managing these risks.

Hydrogen Leakage: Though not a direct GHG, hydrogen is an indirect greenhouse gas with warming effects if leaked in large quantities (affects methane and ozone chemistry). This was not evaluated in this model.

Validation & Verification

This methodology has not been subject to independent third-party verification or validation. However, it was developed with the support of McKinsey & Company, which provided valuable external and informed perspectives and objectivity.

Case Study Reflections

In preparing this illustrative case study, members of the Impact Convergence Forum (ICF) share the following reflections:

- **ICF acknowledges that developing a case study of this nature is time-consuming.** We have erred on the side of completeness for illustrative purposes
- **ICF recommends a convergence and alignment of nomenclature for solution types and type of substitution** categorisation across Project Frame and WBCSD.
- ICF notes the **best practice of full disclosure of methodological choices**. This case study included a clear framework of 25 design parameters to guide consistent and transparent assessments across fund investments, and to support communication of estimates with stakeholders.
- **ICF notes the importance of defining and communicating system boundaries**: this illustrative case focuses on the system boundary of *use-phase emissions* for materiality and comparability across asset types, aligned with WBCSD Relevance and Consistency principles. However, broader boundaries may suit other contexts.
- **ICF notes the challenge of comparing functional units across assessments.** In this case, MWh was used for comparability across asset classes, differing from the tonne H_2 unit in the other hydrogen case. This highlights the difficulty of aligning assessments conducted for different purposes.
- **Simplification vs. speculation.** To model long-term deployment of three asset types, simplified assumptions were used (e.g., 50/50 grey H_2/natural gas replacement, 50% capacity factor, 0.38 tCO_2e/MWh grid factor) instead of more speculative alternatives. This reflects the trade-off between simplicity and speculation, with Frame and WBCSD guidance favouring conservative, transparent and plausible assumptions.

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Their contributions reflect a range of perspectives and expertise, but this does not imply endorsement of the analysis, conclusions or methodology presented herein. The case study is intended as an illustrative example to surface key methodological questions and considerations in avoided emissions analysis. As such, this case study does not constitute commercial or financial advice or projections.