IMPACT CONVERGENCE

FORUM

Green Hydrogen from Alkaline Electrolysers for Hard-to-Abate Industrial Sectors

ICF Case Study: Illustrative Forward-Looking Potential and Planned Avoided Emissions Assessments

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 illustrative case study on alkaline electrolysers was developed in collaboration with Sunfire by members of the Impact Convergence Forum, as part of the 2024–25 Project Frame Content Working Group. The aim is to advance the practice of forward-looking and backward-looking emissions impact assessments by showcasing methodological approaches and tools. This case is for illustrative purposes only and does not constitute commercial, financial or investment advice.

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Summary and Context

This case study presents two illustrative, forward-looking assessments — Potential and Planned Avoided Emissions Impact — for industrial-scale pressurised alkaline electrolysis technology deployed across Europe. These electrolysers enable the production of green hydrogen for a range of hard-to-abate applications, supporting the decarbonisation of emissions-intensive sectors.

Scope of the Problem. Decarbonising heavy industry remains one of the most challenging steps toward net-zero. Sectors such as steel, ammonia, methanol and refining, among others, rely heavily on fossil fuels and grey hydrogen — produced primarily via steam methane reforming (SMR) of natural gas, a process that releases significant CO_2. Hydrogen is a critical feedstock in these industries, making their decarbonisation particularly complex due to both process- and combustion-related emissions. According to the IEA, global hydrogen production emitted approximately 920 Mt CO_2e in 2023 — about 2.5% of global energy-related emissions.[1] Under the IEA's Net Zero Emissions by 2050 Scenario (NZE), total hydrogen demand is projected to reach 150 Mt by 2030, with 50 Mt produced via electrolysis.[2] Today, less than 1% of global hydrogen is produced using electrolysis,[3] underscoring the scale of transformation required. Barriers such as high costs, limited infrastructure and the need for robust impact measurement tools continue to constrain scale-up. Rapid deployment is critical to meeting global climate goals.

Company Context. This case study is inspired by and developed in collaboration with Sunfire, an electrolysis specialist and leading manufacturer of industrial-scale electrolysers. Sunfire offers two technologies — pressurised alkaline (AEL) and solid oxide electrolysis cells (SOEC) — used to produce green hydrogen from renewable electricity. Operating upstream as a technology provider, Sunfire supplies equipment and service to developers, operators and industrial end-users. The company does not operate hydrogen production assets directly but plays a key role in enabling downstream deployment of green hydrogen solutions.

Purpose of the Avoided Emissions Assessments. The two illustrative assessments represent distinct approaches to estimating the future potential impact of the solution and are both used for internal planning purposes.

- **Potential Impact (2025–30)**: A *top-down* market analysis estimating annual GHG emissions that could be avoided between 2025 and 2030 under various European electrolysis growth scenarios, incorporating assumptions about the manufacturer's market share across projected green hydrogen demand segments.
- **Planned Impact (2025–30)**: A *bottom-up* estimate of avoided emissions based on a hypothetical and specific forecast of installed green hydrogen production capacity using Sunfire's technology from 2025 to 2030. This analysis is intended for internal target-setting and performance measurement.

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

[2] International Energy Agency. (2023). Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update

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

Opportunity to Enable GHG Emissions Reductions through Green Hydrogen. This analysis highlights the potential for GHG reductions enabled by the scale-up of electrolyser capacity in Europe. Under a range of market size, growth and company market share scenarios, the Potential Impact assessment estimates that the company's technology could enable between 0.85 $MtCO_2e$ and 9.0 $MtCO_2e$ in annual avoided emissions by 2030. The Planned Impact assessment, based on a hypothetical commercial growth forecast, suggests the company could enable 3.2–4.3 $MtCO_2e$ in annual avoided emissions by 2030, across a narrower range of market share and deployment assumptions.

Impact Pathways

Primary Impact Pathway(s). The primary impact pathway for AEL electrolysers is the replacement of grey hydrogen and unabated natural gas in key end-use sectors. Green hydrogen produced via alkaline electrolysis using renewable electricity reduces emissions by displacing grey hydrogen in ammonia production, methanol synthesis, refining and emerging synthetic fuels, all of which predominantly rely on steam methane reforming (SMR). It also replaces coking coal in steelmaking, and fossil fuels in shipping and aviation.

Solution Relevance to Business Sustainability Strategy. Sunfire manufactures and sells two solutions — pressurised AEL and SOEC electrolysers — which together represent 100% of the company's revenue. This makes the climate solution fully aligned with its business model and sustainability strategy. Sunfire has no other business lines with adverse climate impacts, and therefore no material negative contributions to be considered in this avoided emissions assessment. As a pure-play electrolyser manufacturer, the company's performance and impact are directly tied to the scale-up of green hydrogen. It is noted that some customer end-uses may involve fossil fuel production; in such cases, WBCSD's 1.5°C-Aligned Hydrogen Investment Guidance[4] recommends evaluating whether the hydrogen is substituting existing grey hydrogen as part of a credible decarbonisation pathway, and warns against uses that may inadvertently support fossil fuel lock-in or new grey hydrogen production.

Solution Relevance to End-Markets (Type of Solution and Substitution). Sunfire's industrial-scale pressurised alkaline electrolysers are classified as Direct Products (Project Frame) and End-Use Solutions (WBCSD), delivering a direct and significant climate impact by enabling the on-site production of green hydrogen from water and renewable electricity. These standalone units are sold to project developers and industrial operators and are used in their final form without further transformation, making them end-use equipment with a clearly defined purpose. The green hydrogen produced using Sunfire's technology is used directly by end-users in hard-to-abate sectors, including refining, green ammonia, green methanol, green methane, direct reduced iron (DRI) processes, synthetic fuels, heavy-duty transport and industrial heating. The solution is materially relevant to decarbonisation outcomes because it enables the substitution of high-emissions inputs such as grey hydrogen (produced via steam methane reforming) or fossil fuel combustion (e.g., coking coal). For purposes of the limited five-year forward-looking assessment presented here, we assume direct replacement of existing demand to maintain methodological clarity and conservatism. While this represents a clear substitution rather than a marginal efficiency gain, the impact should be interpreted within a broader context. Over longer time horizons, rising global demand for hydrogen may reflect not only substitution but also new or additive demand associated with increased economic activity. In addition, potential rebound effects stemming from the

[4] World Business Council for Sustainable Development. (2023). A guide to 1.5°C-aligned hydrogen investments: Practical steps to integrate 1.5°C criteria into investment decisions for hydrogen. https://www.wbcsd.org/wp-content/uploads/2023/09/A-guide-to-1.5%C2%B0C-aligned-hydrogen-investments_full-report.pdf

widespread use of ‘climate-neutral’ end products may influence the net climate benefit and should be taken into account in future assessments.

Regulation. Electrolysers are not mandated by regulation, but they are increasingly incentivised and supported as key enablers of Europe’s climate and energy transition goals. The EU Hydrogen Strategy (2020) set a target of installing 40 GW of electrolyser capacity in the EU by 2030, laying the groundwork for large-scale deployment across the region. This ambition is reinforced by the REPowerEU Plan, which calls for the production of 10 million tonnes of renewable hydrogen domestically and an additional 10 million tonnes through imports by 2030. Notably, even imported hydrogen may rely on electrolysers manufactured by European companies, further strengthening the strategic importance of the domestic supply chain.

While the use of electrolysers remains voluntary, regulatory frameworks such as the Renewable Energy Directive (RED II and RED III) send strong market signals by defining and setting targets for renewable fuels of non-biological origin (RFNBOs), including green hydrogen. These frameworks are reinforced by the 2023 Delegated Acts, which establish binding sustainability criteria — such as additionality (use of new renewable electricity), temporal correlation (hourly matching starting in 2030) and geographic correlation with renewable sources — ensuring that green hydrogen delivers genuine climate benefits.

Electrolyser deployment is also supported through EU-level funding mechanisms like the Innovation Fund, Horizon Europe, Hydrogen Bank and Important Projects of Common European Interest (IPCEI), which provide capital support to scale up production and deployment. At the same time, EU ETS reforms and the introduction of the Carbon Border Adjustment Mechanism (CBAM) are increasing the cost of carbon-intensive industrial production, indirectly boosting the business case for green hydrogen. Many EU member states have also launched national hydrogen strategies with targeted incentives, such as grants, feed-in tariffs and Contracts for Difference (CfDs), to accelerate electrolyser adoption. In this regulatory context, electrolysers, while not mandatory, are effectively positioned as a foundational solution for industrial decarbonisation and energy system resilience.

Model Overview

The forward-looking methodology described in this case study was developed by Sunfire in order to estimate the potential of and planned avoided emissions from their alkaline electrolysis technology. Below is a brief summary of the case study elements, further described in this and subsequent sections.

Table 1: Case Study Overview

CATEGORY	DESCRIPTION
SOLUTION DETAILS	
Who is claiming the avoided emissions?	European electrolyser manufacturer, although not claiming 100%, rather 25% based on typical LCOH analysis
Solution Type	Alkaline electrolyser (AEL) - Direct Product (Frame), End-Use Solution (WBCSD)
Market assessed	Europe

Table 1: Case Study Overview

CATEGORY	DESCRIPTION
How is the solution implemented?	The solution provider designs, manufactures, and supplies pressurised alkaline (AEL) electrolysers for industrial-scale green hydrogen production. Renewable electricity, typically from wind or solar, powers the electrolysers to split water into hydrogen and oxygen through electrolysis. These systems are implemented by project developers or industrial operators and integrated into broader hydrogen production and use cases. The resulting green hydrogen can be stored and used to replace grey hydrogen or fossil fuels in high-emissions applications such as ammonia synthesis, methanol production, refining, steelmaking and other hard-to-abate industrial sectors.
ELIGIBILITY GATES	
Gate 1 Climate Action Credibility	The company is a pure-play cleantech provider focused exclusively on manufacturing electrolysers for green hydrogen production — a critical solution for decarbonising hard-to-abate sectors. However, it has not yet set or publicly communicated a climate strategy with science-based Scope 1–3 targets. While Potential and Planned Avoided Emissions assessments have been developed, they remain internal; any realised emissions claims should follow the formal adoption and disclosure of such targets.
Gate 2 Latest Climate Science Alignment	The company develops and manufactures AEL and SOEC electrolysers, both of which are recognised by the IEA, IPCC and EU Net Zero Industry Act as critical enablers of industrial decarbonisation. Electrolysers are listed as strategic technologies under EU policy and meet alignment criteria outlined in WBCSD's guidance on 1.5°C-aligned hydrogen investments, provided they support a credible net-zero trajectory and avoid fossil fuel lock-in.
Gate 3 Contribution Legitimacy	The company's solution demonstrates a: • Direct impact by replacing grey hydrogen and natural gas with green hydrogen in high-emission sectors, with emissions reductions traceable through transparent lifecycle assessments and reference scenarios. • Decarbonising function by targeting hard-to-abate sectors like steel, ammonia and refining, aligning with IEA and IPCC pathways and delivering measurable CO_2 reductions. • Significant emissions impact, with green hydrogen from AEL systems avoiding emissions across a range from 5 to 21 t CO_2e/t H_2 depending on end-use, underscoring the materiality and relevance of the impact.
REFERENCE AND TIMEFRAME	
Reference Solution Selection	Weighted average of end-use application scenarios based on current and projected distribution of global hydrogen demand by sector
Required by regulation	No
Type of Substitution	Existing demand - replacement. Green hydrogen is a direct replacement for grey hydrogen, coking coal and natural gas. It is important to note that while direct replacement is possible for grey hydrogen (same product quality), replacing coking coal and natural gas may require further infrastructure investments (e.g., DRI instead of blast furnace for steelmaking).
Timeframe	The timeframe for the forward-looking Potential and Planned Impact Assessments is 2025–30, aligning with the EU Hydrogen Strategy, which targets 10Mt domestic production of green hydrogen by 2030, as well as Clean Hydrogen Monitor (2024) Current Trajectory and Accelerated Adoption Scenarios for annual clean hydrogen supply (Mt H2) in Europe.
SYSTEM BOUNDARY AND FUNCTIONAL UNIT	
System boundary	Cradle-to-end-use (post-application) - system boundary that captures all emissions and benefits from raw material extraction through production, delivery and final use, including the avoided emissions resulting from substituting higher-emission alternatives.
Functional unit	• Tonnes of H2 delivered. The primary functional unit is 1 tonne of green hydrogen delivered to a range of end-use applications. • Unit of impact - tonnes of CO_2 equivalent avoided (t CO_2e) per tonne of hydrogen delivered to end use, based on substitution of conventional fossil-derived hydrogen or natural gas. Avoided emissions are calculated as a projected 2030 weighted market average of avoided emissions potential across hydrogen end-use demand (e.g., 11 t CO_2e/t H_2 for SMR) and scenario-specific net impact adjustments (e.g., transport emissions, leakage).

Table 1: Case Study Overview

CATEGORY	DESCRIPTION
Lifecycle stages / process focus for GHG emission calculation	Full lifecycle of AEL electrolyser Electrolysis process Hydrogen storage, transport and distribution Hydrogen end-use in industrial applications Avoided emissions compared to weighted average baseline scenario

Forward-Looking Emissions Reduction Calculations. Both potential and planned avoided emissions are estimated using annual forecasted hydrogen production volumes (in Mt H_2) across low, medium and high scenarios, combined with corresponding assumptions for avoided emissions based on hydrogen application scenarios (also modelled as low, medium and high). An overview of emissions avoidance calculations is provided below for each type of analysis.

Potential Avoided Emissions Impact

This is a top-down analysis in which potential avoided emissions are calculated on an annual forecasted volume of green hydrogen produced and an estimated GHG avoidance after end use. The model assumes three scenarios for market size and three scenarios for market share, with estimated potential annual emissions avoided calculated as follows:

$$\Delta GHG\_H_2 = UNIT\ IMPACT\_H_2 \times VOLUME\_H_2$$

Where:

- **ΔGHG_H_2 =** Total gross avoided greenhouse gas (GHG) emissions from green hydrogen use (in metric tonnes CO_2 equivalent, Mt CO_2e) in a given year
- **UNIT IMPACT_H_2 =** Transport-weighed GHG emissions avoided per tonne H_2, set at 10.04 $tCO2e/tH_2$. This is an estimate of avoided emissions after transport and end-use across a weighted distribution of H_2 end-use applications (IEA Global Hydrogen Review 2024 and German National Hydrogen Council (NWR)), further accounting for leakage, storage and transport emissions from H_2 production to end-use according to the 'Environmental lifecycle assessment (LCA) comparison of hydrogen delivery options within Europe' and projected transport pathways (onsite production, domestic pipeline C-H_2, shipping L-H_2) according to the REPowerEU Strategy (2022) to produce 10 million tonnes and import 10 million tonnes of green hydrogen by 2030. (See emissions factors for detailed calculations)
- **VOLUME_H_2 =** Estimated amount of green hydrogen used across all end-use applications, based on *market size x market share*:
    - **Market size (Mt H_2)** - three scenarios (low/med/high) for the projected size of the water electrolysis market in Europe. Forecasted market size data is taken from the Clean Hydrogen Monitor 2024 Current Trajectory and Accelerated Adoption Scenarios for annual clean hydrogen supply (Mt H_2) in Europe (2025-2030), 2025–30, with modelled scenarios defined as follows:
        - SIZE_Low - 50% of the current trajectory scenario
        - SIZE_Med - the current trajectory scenario

        - SIZE_High - the accelerated adoption scenario
    - **Market share (%) -** three scenarios (low/med/high) for the percentage of the market capture by the company's solution, defined in the model as follows:
        - SHARE_Low - 10% market share
        - SHARE_Med - 20% market share (base)
        - SHARE_High - 30% market share
    - **VOLUME_H_2(Mt H_2)** - combining the three (3) market size and three (3) market share scenarios yields a range of speculative market share volumes, taking the lowest, mid and highest of the range:
        - VOLUME_H_2_Low= SIZE_Low x SHARE_Low
        - VOLUME_H_2_Med = SIZE_Med x SHARE_Med
        - VOLUME_H_2_High = SIZE_High x SHARE_High
- **Total potential annual emissions [Mt CO_2eq]** are then calculated for each year under the three market size and market share scenarios as follows:
    - **Potential ΔGHG_H_2_Low:** UNIT IMPACT_H_2 x VOLUME_H_2_Low
    - **Potential ΔGHG_H_2_Med:** UNIT IMPACT_H_2 x VOLUME_H_2_Med
    - **Potential ΔGHG_H_2_High:** UNIT IMPACT_H_2 x VOLUME_H_2_High

Planned Avoided Emissions Impact

The Planned Avoided Emissions Impact assessment methodology is a bottom-up analysis based on illustrative commercial projections for annual operational capacity (2025–30), and includes the same estimate of unit impact, incorporating leakage, storage and transportation emissions. The model assumes three scenarios for operational capacity (pessimistic, medium and optimistic) based on commercial growth forecasts, as well as product-specific operating parameters for Sunfire's AEL electrolyser. The estimated planned annual emissions avoided are calculated as follows:

ΔGHG_H_2 = UNIT IMPACT_H_2transport × VOLUME_H_2

Where**:**

- **ΔGHG_H_2 =** Total gross avoided GHG emissions from green hydrogen use (in metric tonnes CO_2 equivalent, Mt CO_2e) in a given year
- **UNIT IMPACT_H_2 =** Transport-weighed GHG emissions avoided per tonne H_2, set at 10.04 tCO2e/tH_2
- **VOLUME_H_2 =** Estimated amount of green hydrogen produced by Sunfire AEL electrolysers in a given year based on i) annual commercial operational capacity forecast (MW) and ii) Sunfire's projected volume produced [Mt] under the operational assumptions of 200kg H_2 per hour per 10MW, and the Clean Hydrogen Production Pathways (2024) base utilisation scenario of 5,500 operational hours per year
    - *VOLUME_H_2 [Mt]* = Operational Capacity (MW) x (200kg H2/h ÷ 10 MW) x 5,500 h/y ÷ 1,000,000
    - *Operational Capacity (MW)* is expressed in three scenarios:

    - Low - Pessimistic, ranging from 20 MW (2025) to 2,857 MW (2030)
    - Med - Baseline, ranging from 20 MW (2025) to 3,357 MW (2030)
    - High - Optimistic, ranging from 20 MW (2025) to 3,857 MW (2030)
- **Total projected annual emissions** are then calculated for each year under the three operating capacity scenarios as:
    - **Planned ΔGHG_H_2_Low** = UNIT IMPACT_H_2 x VOLUME_H_2_Low
    - **Planned ΔGHG_H_2_Med** = UNIT IMPACT_H_2 x VOLUME_H_2_Med
    - **Planned ΔGHG_H_2_High** = UNIT IMPACT_H_2 x VOLUME_H_2_High

Solution Maturity and Technical Alternatives. Green hydrogen production via electrolysis is progressing rapidly, with alkaline and PEM electrolysers now commercially available and operating at full technical readiness (TRL9). Alkaline systems are the most established, benefitting from lower capital costs and decades of industrial use. Solid Oxide Electrolysis Cells (SOEC) are nearing commercialisation, with recent multi-megawatt deployments and scale-up plans by Sunfire and other firms like Topsoe and Bloom Energy, particularly in industrial settings with access to high-temperature heat. Anion Exchange Membrane (AEM) electrolysers remain at an earlier stage, with limited commercial deployment. Efficiency varies by design: alkaline and PEM systems are flexible and grid-compatible, while SOEC can achieve higher electrical efficiencies (up to 84% LHV) with heat integration. These electrolysis-based systems represent a low-carbon alternative to conventional hydrogen production methods such as Steam Methane Reforming (SMR), Autothermal Reforming (ATR) and coal gasification, which currently dominate global supply but are associated with high GHG emissions unless paired with carbon capture.

Key Assumptions and Limitations

These forward-looking assessments are based on a number of key assumptions and, by nature, involve uncertainty. Results should be interpreted as illustrative rather than predictive, and depend heavily on the realism of inputs such as market forecasts, emissions factors, deployment timelines and technology performance. While care has been taken to ensure methodological transparency, the outputs are scenario-based estimates designed to explore possible avoided emissions outcomes.

Market Size and Share Assumptions. The Potential Impact model uses European hydrogen demand forecasts from the Clean Hydrogen Monitor 2024 (1.7 Mt H_2 in the medium scenario, 3.0 Mt in the optimistic scenario) to estimate the serviceable addressable market (SAM) for green hydrogen production via water electrolysis in Europe. While the total addressable market (TAM) for European electrolyser manufacturers like Sunfire may be broader, including potential sales of electrolysers for hydrogen production outside Europe, this case study focuses solely on the European market for directional consistency. Within the SAM, the model does not attempt to forecast the specific technology mix (e.g., alkaline vs. PEM vs. SOEC), given the early-stage and evolving nature of the market. The serviceable obtainable market (SOM) is estimated using Sunfire's illustrative market share assumptions of 10%, 20% or 30%, reflecting potential competitive positioning within the alkaline electrolyser segment.

Electrolyser Capacity Forecasts. Capacity estimates for the Planned Impact assessment are based on a hypothetical commercial growth forecast, combining the expected capacity from announced projects (2025–27), the company's strategic growth ambitions and scenario-based projections for new installations between 2028–30. The 3,000–4,000 MW electrolyser capacity assumption for the Planned Impact scenario reflects a medium/optimistic growth outlook, aligned with European policy targets and market projections. These reflect a combination of expected projects. The EU Hydrogen Strategy calls for at least 40 GW of domestic electrolyser capacity by 2030, while the Clean Hydrogen Monitor (2024) models 30 GW to supply 3.15 Mt of renewable hydrogen annually by 2030. Achieving the EU's full domestic and import hydrogen targets by 2030 would require an estimated 200 GW of electrolyser capacity. While Europe's installed capacity was 385 MW in 2024, scaling to multi-GW levels is considered feasible given strong policy support, ongoing project pipelines and the positioning of European electrolyser manufacturers to meet regional demand.

Functional Unit Selection. This assessment uses a system-level functional unit of green hydrogen produced (tonnes H_2) rather than an end-product-specific unit (e.g., tonnes of steel or ammonia) as WBCSD would recommend in mature markets. This methodological choice reflects the role of the electrolyser manufacturer as an upstream technology provider with limited data specificity from downstream hydrogen end-use applications. While a functional unit aligned to specific end products would provide more precise use-case attribution, such an approach is better suited to mature projects or hydrogen producers who control end-use. For this early-stage, directional assessment, the use of sectoral average substitution factors was considered appropriate, with transparent disclosure of assumptions and limitations.

Fixed GHG Avoidance Factors. Both the Potential and Planned models apply fixed avoided emissions factors per tonne of green hydrogen over the five years, adjusted for transport emissions under the projected 2030 breakdown of domestic vs. imported volumes according to REPowerEU Strategy (2022). The weighted average transport-adjusted factor of 10.04 tCO_2eq/tH_2 incorporates delivery-related emissions and represents a market-weighted sectoral substitution. This approach, while reasonable for early-stage directional estimates — where project-level primary data is often unavailable — has limitations. Fixed emissions factors assume static baseline conditions over time, while in reality, baseline emissions from conventional hydrogen production and other industry carbon footprints may decline due to improved energy efficiency, grid decarbonisation and competing low-carbon technologies. As a result, the unit avoided emissions impact of green hydrogen is likely to decrease over longer timeframes, eventually converging toward zero as green hydrogen becomes the market standard. Future iterations of this model, especially for mature projects, would benefit from integrating dynamic baseline trajectories that reflect evolving decarbonisation pathways, sector-specific data and regulatory scenarios.

- **Evolving Use Cases**: Early H_2 deployment is expected to substitute steam methane reforming, while higher-impact applications like green steel and ammonia may ramp up later — leading to increasing net GHG avoidance over time.
- **Onsite Production Dominating Initial Years**: Early reliance on onsite H_2 production may offer higher net GHG avoidance, as infrastructure for large-scale imports, port facilities and cross-border pipeline transport may take longer to materialise.

Other Low-Carbon Hydrogen Pathways. This assessment focuses on green hydrogen — produced via electrolysis using renewable electricity — as the benchmark for avoided emissions. However, other lower-carbon hydrogen pathways, such as blue hydrogen (grey hydrogen with carbon capture and storage), may also play a role in decarbonisation strategies, especially when considering trade-offs beyond emissions alone. The relative adoption of green versus blue hydrogen will depend on factors such as policy incentives, regulatory signals, technology costs, market demand and local resource constraints. While blue hydrogen can reduce emissions compared to grey hydrogen, it still involves ongoing fossil fuel use and may not provide the same long-term decarbonisation benefits. Future analyses could explore different hydrogen pathway mixes, along with their emissions profiles and broader environmental impacts such as water use, to inform more comprehensive decision-making.

Electrolyser Performance and Capacity. The model assumes a constant nameplate capacity of 200kg H_2/hour for a 10 MW alkaline electrolyser (AEL) unit, operating 5,500 hours per year, and does not explicitly account for performance degradation over time. This simplification is appropriate for a 1–5 year modelling window, where degradation effects on output are relatively limited. Importantly, performance degradation — and the resulting increase in electricity consumption per unit of hydrogen — is already reflected in the emissions factor derived from the solution lifecycle assessment (LCA). As such, incorporating separate degradation adjustments would not materially affect the differential between the product and reference emissions factors. Solid oxide electrolyser cell (SOEC) technology, which offers higher efficiency in specific applications, is not modelled separately; AEL assumptions are used throughout for consistency and simplicity.

Hydrogen Capacity Factors and Sectoral Variability. The model does not account for sector-specific economic thresholds for hydrogen capacity factors. In practice, some industries may prioritise high renewable content and accept lower capacity factors (and higher costs), while others may seek to maximise capacity factors by blending grid electricity, lowering the renewable share. This trade-off will vary across sectors depending on end-use requirements, regulatory signals and customer expectations. A sector-specific sensitivity analysis on capacity factors and economic feasibility would strengthen future assessments.

System Boundaries and End-Use Emissions. This analysis uses sectoral average substitution factors that already account for the fact that both renewable fuels and their chemically identical fossil counterparts release similar GHG emissions during combustion, while differing significantly in production-phase emissions (with conventional fuels typically higher). The climate benefit of hydrogen-derived fuels lies in these upstream emission savings, assuming low-carbon electricity and biogenic or air-captured CO_2. While combustion of synthetic fuels like green methane still emits CO_2, net avoided emissions depend on upstream inputs and how combustion-phase emissions are allocated across the fuel's molecular components (e.g., green H_2 vs. carbon feedstock). Future analyses could further refine allocation assumptions and lifecycle boundaries.

Use-Case Allocation and Market Dynamics. The model assumes a weighted market-average allocation of hydrogen across sectors (e.g., ammonia, steel, refining), which may not reflect actual deployment patterns — especially if adoption skews toward higher- or lower-impact applications. Additionally, it does not account for differences in the unit cost of green hydrogen relative to incumbent fuels (e.g., grey hydrogen, natural gas) in each sector. Including relative cost assumptions such as the competitiveness of green ammonia versus grey ammonia could strengthen the model's ability to reflect market adoption dynamics. A sector-by-sector sensitivity analysis of unit costs and substitution likelihood would enhance future assessments.

Hydrogen Transport and Infrastructure. Both the Potential and Planned Impact models assume 50% onsite production and 50% transported hydrogen (via pipeline or ship), using a transport emissions differential of 1.3 tCO_2/tH_2 based on JRC (2024) estimates. Future developments in infrastructure or delivery methods may reduce or alter this figure.

Policy and Market Risks. The model assumes continued regulatory and financial support for hydrogen scale-up aligned with the EU Hydrogen Strategy and REPowerEU targets. However, delays in permitting, infrastructure or incentive schemes could limit deployment. Similarly, modelled market share and volume projections may not reflect future market conditions, competition or technology adoption rates. Demand for green hydrogen is expected to grow gradually over time, while demand for fossil-based hydrogen decreases, as outlined in IEA 2024 forecasts by industry and sub-sector. How quickly green hydrogen gains market share will depend on the effectiveness of regulatory push-and-pull mechanisms and end-user commitments to decarbonisation. There is also a trade-off in how low-carbon hydrogen supply is prioritised across markets: investments in blue hydrogen risk locking in fossil fuel reliance, while a strong policy and market preference for green hydrogen could accelerate the transition. Some industries may partially integrate green hydrogen to meet customer or regulatory requirements, while maintaining a broader reliance on fossil-based production. These dynamics will influence both the scale and timing of avoided emissions realisation.

End-Use Risks and Contribution Validity. In line with WBCSD's A Guide to 1.5°C-Aligned Hydrogen Investments, avoided emissions are considered valid only when green hydrogen substitutes for grey hydrogen in a decarbonisation-aligned use case (e.g., replacing SMR-based H_2 in refining). Use cases that support fossil fuel expansion or create new demand for grey hydrogen would not meet contribution legitimacy criteria. Based on current project visibility, there is no indication that end-use cases involve fossil fuel expansion or the creation of new grey hydrogen demand. However, this remains an important area for ongoing monitoring and validation, particularly as hydrogen markets and applications continue to evolve.

Product Classification

- **UN Central Product Classification (CPC)**: Electrolyser manufacturing is treated as a machinery and equipment activity within CPC, distinct from both hydrogen production and electricity generation. It falls under CPC Section 4: Metal products, machinery and equipment, most likely within CPC 4693 – Electrical equipment n.e.c. (including… apparatus for electrolysis)
- **Global Industry Classification Standard (GICS)**: Electrolyser manufacturers are classified within the Industrials sector (Sector 20), specifically under Industry Group 2010 – Capital Goods. The most applicable category is 201040 – Electrical Equipment, likely falling within Sub-Industry 20104010 – Electrical Components & Equipment or 20104020 – Heavy Electrical Equipment, depending on the scale and integration of the technology. They are not classified within the Energy or Utilities sectors, even though their products support renewable hydrogen production and grid decarbonisation efforts.

Forward-Looking Avoided Emissions Impact Analyses

Potential Impact. Here we present a forward-looking Potential Impact Assessment for the period 2025–30, estimating annual avoided emissions under three market size scenarios and three market share scenarios. The tables below illustrate the estimated avoided emissions in year 2030, based on i) total projected market share and volume (Table 2) and ii) GHG avoidance factors across low, medium and high scenarios (Table 3):

Table 2: Illustrative Potential Market Share (Mt H2)

2030	MARKET SIZE (MT H2)		
SCENARIOS	**Low (0.85 Mt H2)**	**Med (1.7 Mt H2)**	**High (3.0 Mt H2)**
Low (10% market share)	0.085*	0.170	0.260
Med (20% market share)	0.170	0.340*	0.500
High (30% market share)	0.300	0.600	0.900*

* Volumes for Low, Med and High are taken as the lowest, mid and highest value and serve as the basis for the GHG avoidance calculation below.

The potential H_2 production volumes for Low, Med and High scenarios are then multiplied by the estimated avoided emissions factor of 10.04 tCO2e/tH_2 in order to determine the estimated planned avoided emissions values by year (Table 3):

Table 3: Illustrative Gross GHG Avoidance After End-Use [Mt CO_2eq]

2030	MARKET SIZE (MT H2)		
SCENARIOS	**Low (0.85 Mt H2)**	**Med (1.7 Mt H2)**	**High (3.0 Mt H2)**
Low 10.04 tCO2e/tH2	**0.85**	–-	–-
Med 10.04 tCO2e/tH2	–-	**3.41**	–-
High 10.04 tCO2e/tH2	–-	–-	**9.03**

* To demonstrate the full range of potential impact, only the low/low, med/med and high/high scenarios are calculated.

Under these assumptions, **potential CO_2e avoided is estimated to range from 0.85 to 9.03 Mt CO_2e annually by 2030**. These estimates are illustrative in nature and are intended for internal use only; they are not published or presented as formal avoided emissions claims.

Planned Impact. For the illustrative Planned Avoided Emissions Impact Assessment (2025–30), a commercial operating capacity (MW) forecast (Table 4) is used along with the operating assumptions of the AEL electrolysers.

Table 4: Illustrative Forecasted Operational Capacity (MW)

SCENARIOS	2025	2026	2027	2028	2029	2030
Low (Pessimistic)	20	106	267	657	1,457	2,857
Med (Base case)	20	106	267	857	1,857	3,357
High (Optimistic)	20	106	267	1,107	2,107	3,857

Given the **nameplate capacity** of 200kg H_2/hour a 10 MW AEL, and the Clean Hydrogen Production Pathways (2024) base utilisation scenario of 5,500 operational hours per year, we estimate the projected output (Table 5):

- *Reference*: VOLUME_H_2 [Mt] = Operational Capacity (MW) x (0.2 t H_2/hour ÷ 10 MW) x 5,500 h/y ÷ 1,000,000

Table 5: Illustrative Projected Production Volume (Mt H2)

SCENARIOS	2025	2026	2027	2028	2029	2030
Low (Pessimistic)	0.002	0.012	0.029	0.072	0.160	0.314
Med (Base case)	0.002	0.012	0.029	0.094	0.204	0.369
High (Optimistic)	0.002	0.012	0.029	0.122	0.232	0.424

The planned H_2 production volumes are then multiplied by the estimated avoided emissions factor of 10.04 t CO_2eq/t H_2 in order to determine the estimated planned avoided emissions values by year (Table 6):

Table 6: Illustrative Planned GHG Avoided After Transport End-Use (Mt)

SCENARIOS	2025	2026	2027	2028	2029	2030
Low (Pessimistic)	0.02	0.12	0.29	0.72	1.61	3.15
Med (Base case)	0.02	0.12	0.29	0.95	2.05	3.71
High (Optimistic)	0.02	0.12	0.29	1.22	2.33	4.26

Under these assumptions, and the emissions factors detailed in the model overview, **Planned CO_2e emissions avoided is estimated to reach between 3.15 and 4.26 Mt annually by 2030**. Again, these illustrative estimates are internal and not published as avoided emissions claims.

Data Sources / Additional Information

Market Forecasts

- **Potential Impact - European electrolysis market size**: Clean Hydrogen Monitor 2023 – Hydrogen Europe (2023): market growth scenarios for European clean hydrogen supply (Current Trajectory and Accelerated Adoption)
- **Planned Impact - operational capacity**: Illustrative Sunfire commercial assumptions: Forecasts of operational MW capacity for 2025–30

Avoided Emissions Factors

- **AEL electrolyser emissions factor**: LCA (May 2023) conducted by external consultancy
- **Potential and Planned Impact - weighted average avoided emissions factor**: Weighted average constructed from a combination of data source: IEA Global Hydrogen Review 2024, GHG avoidance potential by H_2 applications provided by external consultancy; German National Hydrogen Council (2024, May 3)
- **Accounting for transport emissions from H_2 production to end-use**: EU's hydrogen strategy and REPowerEU plan (accessed 2025); JRC (2023): Environmental lifecycle assessment (LCA) comparison of hydrogen delivery options within Europe; and Van der Spek, M., & Faaij, A. (2024): Worldwide greenhouse gas emissions of green hydrogen supply chains

Policy & Regulatory Frameworks

- **Net Zero Industry Act (2024)**: Defines electrolysers as net-zero technologies eligible for policy support
- **Renewable Energy Directive** (RED II & III): Establishes criteria for RFNBOs (e.g., green hydrogen) and sets temporal/geographic correlation rules
- **REPowerEU Strategy (2022)**: Establishes targets for 10 Mt domestic and 10 Mt imported renewable hydrogen by 2030
- **Delegated Acts (2023)**: Provide regulatory requirements for additionality, hourly matching and sustainability of hydrogen

Economic & Technical Parameters

- **AEL electrolyser operating assumptions**: 200kg H_2/hour per 10 MW system; 5,500 operating hours/year, Sunfire technical documentation
- **Capacity utilisation rate**: 5500 h/y from Hydrogen Europe Clean Hydrogen Production Pathways Report 2024

Methodology & Guidance Documents

- **WBCSD (2023): Guidance on Avoided Emissions**: Helping business drive innovations and scale solutions toward net zero. https://www.wbcsd.org/resources/guidance-on-avoided-emissions-helping-business-drive-innovations-and-scale-solutions-towards-net-zero/

- **WBCSD (2023): A Guide to 1.5°C-Aligned Hydrogen Investments**: Practical steps to integrate 1.5°C criteria into investment decisions for hydrogen. https://www.wbcsd.org/wp-content/uploads/2023/09/A-guide-to-1.5%C2%B0C-aligned-hydrogen-investments_full-report.pdf
- **Project Frame (2024): Project Frame methodology**: Evaluating GHG impact for early-stage investments. https://projectframe.how/s/2024-Project-Frame-Methodology.pdf

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.

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 electrolyser-based green hydrogen solutions — particularly alkaline (AEL) electrolysis systems — offer viable and scalable alternatives to fossil-based hydrogen and natural gas in Europe's industrial and energy systems. The climate impact results from the displacement of high-emission energy sources, namely grey hydrogen (produced via SMR) and unabated natural gas in industrial applications, with low-carbon green hydrogen produced from renewable electricity.

System boundaries (see model overview for detailed assumptions) are defined as follows:

- **Green hydrogen**: Cradle-to-end-use (Post-application): Hydrogen produced via AEL or SOEC electrolysis powered by renewable electricity (wind or solar), replacing grey hydrogen and/or natural gas in hard-to-abate industrial applications such as refining, ammonia, methanol, synthetic fuels, steelmaking and high-temperature heat. The model accounts for full upstream emissions, including electricity source and delivery-related emissions (transport, leakage, and storage).
- **Timeframe**: A forecasted operational deployment window (2025–30) aligned with near-term EU hydrogen targets and Sunfire's illustrative commercial planning horizon, for both Potential and Planned Impact.
- **Geographic boundary**: European Union
- **Substitution**: The model assumes substitution of existing demand, not creation of new markets or efficiency gains. Avoided emissions are only counted where green hydrogen replaces an equivalent fossil-derived input.
- **Attributional modelling**: This model uses an attributional approach: allocating avoided emissions based on modelled market share and production volumes of the electrolyser provider (Sunfire), without including broader system effects or rebound effects.
- **Functional unit - tonnes of H_2 delivered**: The primary functional unit is 1 tonne of green hydrogen delivered to a range of end-use applications.
- **Unit of impact -** tonnes of CO_2 equivalent avoided (t CO_2e) per tonne of hydrogen delivered to end use, based on substitution of conventional fossil-derived hydrogen or natural gas. Avoided emissions are calculated using a projected 2023 weighted market average emissions avoidance factor (i.e., 11 t CO_2e/t H_2 for SMR) and scenario-specific net impact adjustments (e.g., transport emissions, leakage).

2. Construct Baseline Scenario

The baseline scenarios are an annual production volume of green hydrogen and assume a weighted-average market mix of end-use applications.

For Potential Impact - three scenarios are defined (low/med/high) in reference to the projected size of the water electrolysis market in Europe. Forecasted market size data is taken from the Clean Hydrogen Monitor 2024 Current Trajectory and Accelerated Adoption Scenarios for annual clean hydrogen supply (Mt H2) in Europe (2025–30), with modelled scenarios defined as follows;

- **SIZE_Low** - 50% of the current trajectory scenario
- **SIZE_Med** - the current trajectory scenario
- **SIZE_High** - the accelerated adoption scenario

Three market share scenarios (10%, 20%, 30%) are then applied to estimate the potential volume share of the forecasted market by scenario.

For Planned Impact, we anchor the projections on three illustrative scenarios that reflect a hypothetical commercial operating forecast of installed electrolyser capacity on an annual basis from 2025–30. This is based on i) current projects becoming operational 2025–27; and ii) three scenarios (pessimistic, medium, optimistic) of total MW produced per year from new installations (under forecasted commercial operation dates 2028–30).

3. Obtain Emissions Factors

Estimated avoided emissions factors were derived by combining data from multiple sources, including an external consultancy's lifecycle assessment (LCA) and emissions factors published by the German National Hydrogen Council (NWR, 2023).[5] Table 7 on the next page summarises these emissions factors across key end-use applications for 2030, integrating findings from both sources.

We then calculate a ***weighted average avoided emissions factor*** based on forecasted Global H_2 demand by end-use application, according to the NZE scenario in the IEA Global Hydrogen Review 2024.

This **weighted average avoided emissions factor (11.0 t CO_2e/t H_2)** is then further adjusted to reflect estimated emissions from leakage, storage and transport. A transport-related markup is applied for hydrogen delivered either domestically (via pipeline as compressed hydrogen, C-H_2) or internationally (via shipping as liquefied hydrogen, L-H_2). According to the European Commission Joint Research Centre,[6] the lifecycle climate impact of delivered hydrogen for compressed hydrogen (C-H_2) and liquid hydrogen (L-H_2) is approximately the same at 1.9kg CO_2e/kg H_2, compared to 0.6kg CO_2e/kg H_2 for on-site production. For this model, these are assumed to be the dominant hydrogen delivery pathways, and this results in a transport-related emissions differential of 1.3 t CO_2e/t H_2, which is used to adjust avoided emissions calculations for delivered hydrogen. While technically feasible, Liquid Organic Hydrogen Carriers (LOHC) and Methanol (MeOH) delivery pathways are excluded from this model given their higher lifecycle GHG emissions — often near or above the EU taxonomy threshold — and lower energy efficiency due to added conversion steps.

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[5] https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/EN/2024/2024-05-03_NWR-White_paper_Update_

[6] European Commission, Joint Research Centre. (2024, May 31). ***Delivering hydrogen to the EU's industry: Which are the greenest options?*** https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/delivering-hydrogen-eus-industry-which-are-greenest-options-2024-05-31_en

Table 7: Derivation of Weighted Avoided Emissions Factors Across End-Use Applications, 2030

GLOBAL H2 DEMAND, HYDROGEN USE BY SECTOR (Mt pa H2)				
	2030	**2030**	**2030**	**2030**
	Mtpa H_2	**%****	**Relative % industry Split**	**Avoided tCO_2e/tH_2**
Total	148	100 %		
Other	3	2 %		**5***
Power	19	13 %		**8 †**
Synfuels	18	12 %		**7.5***
Transport	5	3 %		**5***
Refining	33	22 %		**10.7 †**
Industry				
Industry Split				
Ammonia	34	23 %	49 %	**13.7 †**
Methanol	18	12 %	26 %	**9.5 †**
Steel	13	9 %	19 %	**21.0 †**
Other	5	3 %	7 %	**8 †**
Weighted Average Avoided Emissions Factor				**11.0 ‡**

* data from German National Hydrogen Council (NWR) whitepaper 'Greenhouse gas savings and the associated hydrogen demand in Germany' 1 February 2023.
** Forecasted Global H2 Demand based on the NZE scenario in the IEA Global Hydrogen Review 2024
† LCA data provided by an external consultancy
‡ calculated values

In line with the EU 2030 target of 20 Mt of green hydrogen, we assume a 50/50 split between domestic production and imports, and within the domestic share, a further 50/50 split between on-site use and pipeline transport. This results in a transport- and market-weighted average avoided emissions factor of 10.04 $tCO_2eq/t\ H_2$ (see table 8 below):

Table 8: Accounting for Transport Emissions from H2 Production to End-Use Transport of H2 to End application in Europe

EU TARGET 2030 20 Mt Green H2	ASSUMPTIONS	ADDITIONAL CO_2eq per t H2	NET GHG AVOIDED per t H2
10 MT Domestic Production	5 Mt onsite	0	11.0
	5 Mt pipeline C-H2	1.3	9.7
10 MT Imports	10 Mt shipping L-H2	1.3	9.7
Transport-Weighted GHG Avoided per t H2			**10.04**

4. Calculate Unit Impact

GHG emissions for producing green hydrogen are already included in the chosen emission factors (see Table 7: Derivation of weighted avoided emissions factors across end-use applications, 2030). Interrogating the assumptions behind each of the avoided emissions sources further confirms that electrolyser emission factors generally fall in the range of 0.3 to 1.0kg CO_2e/kg H_2, consistent with both the solution LCA of 0.58kg CO_2eq/kg H2 and external benchmarks.

The solution LCA assumes 100% wind energy from a specific wind farm configuration and could vary with different renewable electricity sources, therefore the ranges reflected in the chosen avoided emissions factors are consistent with potential ranges for the company's technology and taken as given for modelling purposes..

The unit impact per t H_2 is therefore held constant at the derived 10.04 transport-weighted GHG avoided per t H_2.

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

- **Solution (S) - Medium (Company-Specific)**: The model uses forward-looking estimates of commercial operating capacity (in MW), based on illustrative company-specific growth forecasts. Electrolyser output is calculated using product-specific performance parameters, including efficiency rates (e.g., 200kg H_2/hour per 10 MW AEL electrolyser) and utilisation factors from published scenarios (e.g., Clean Hydrogen Production Pathways 2024). This results in a solution-side estimate grounded in actual technology characteristics and deployment assumptions.
- **Reference (R) - Low (Market Average)**: we use a weighted market average for end-use application H2 replacement based on IEA 2030 Net Zero Emissions forecasts and estimates of average emissions factors per end-use application.

Attribution/Allocation. This assessment focuses on avoided emissions from the production of green hydrogen enabled by electrolyser deployment. While the manufacturer does not directly produce or consume hydrogen, its upstream contribution is foundational: downstream production and use of green hydrogen in hard-to-abate sectors depends on the availability of electrolyser technology.

For the purposes of the Planned and Realised Avoided Emissions Impact Assessments, the manufacturer's role is framed as enabling emissions reductions achieved by its clients. This approach reflects the critical function of electrolyser deployment in unlocking downstream decarbonisation, without attributing full ownership of the resulting avoided emissions.

Although some practitioners apply proportional attribution based on cost breakdowns such as the Levelised Cost of Hydrogen (LCOH), among other approaches, this assessment does not apply a specific attribution factor due to the lack of methodological consensus in the market. Acknowledging this, the framing of 'enabled avoided emissions' offers a transparent and decision-useful approach. For example: "Company technologies enable our clients to avoid X tonnes of CO_2e in year Y," reflecting a material contribution while recognising that avoided emissions result from multiple actors across the value chain.

Eligibility Gates

The WBCSD outlines a set of eligibility gates in its guidance for assessing avoided emissions. This illustrative case focuses on a growth-stage cleantech company specialising in alkaline and solid oxide (SOEC) electrolysis technologies for the production of green hydrogen — recognised by both the IEA and IPCC as a key technology for enabling a net-zero future.

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 Scopes 1, 2 and 3, transparently reporting on progress on a regular basis.*

In this example, the portfolio company has not yet set or publicly communicated a climate strategy that includes science-based Scope 1–3 targets. While the results of the Potential and Planned Avoided Emissions Impact Assessments have been developed, they have not been shared publicly. Any future realised emissions claims should be made only after such targets are formally established and communicated.

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.*

The portfolio company develops and manufactures Alkaline (AEL) and Solid Oxide Electrolysers (SOEC) — both key technologies for green hydrogen production. These technologies are widely recognised by the IEA and IPCC as critical enablers of industrial decarbonisation, particularly in hard-to-abate sectors such as steel, ammonia, chemicals and heavy transport. The IEA's Net Zero Emissions by 2050 Scenario calls for ~50 Mt of hydrogen to be produced via electrolysis by 2030 and ~560 GW of installed electrolyser capacity (IEA, 2021), while the IPCC highlights hydrogen's role in supporting deep emission cuts where electrification is not feasible (IPCC, 2022). SOEC systems offer particularly high energy efficiency when paired with industrial waste heat, and AELs remain the most mature and widely deployed technology. Both technologies contribute meaningfully to displacing high-emission hydrogen from steam methane reforming (SMR) and other fossil fuel use and align with global net-zero transition pathways.

The company's technologies also meet criteria outlined in the EU Net Zero Industry Act (Regulation (EU) 2024/1735), which explicitly lists electrolysers as strategic net-zero technologies eligible for supportive industrial policy. Moreover, according to the WBCSD's guidance on 1.5°C-aligned hydrogen investments, green hydrogen production via electrolysis — particularly when powered by renewable energy — meets alignment criteria if it follows a decarbonisation trajectory consistent with the IEA NZE curve and avoids fossil fuel lock-in or subsidies (WBCSD, 2024). The guidance emphasises reducing full lifecycle carbon intensity, including infrastructure emissions and distribution, and prioritising hydrogen use in sectors with no viable low-carbon alternatives. By focusing on AEL and SOEC, the company delivers climate-relevant solutions that pass Gate 2 based on robust alignment with climate science and policy.

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

Green hydrogen production via AEL and SOEC electrolysis demonstrates contribution legitimacy under the WBCSD guidelines, as it meets the criteria of being ***decarbonising***, ***direct*** and ***significant*** in its impact:

- **Decarbonising**: Green hydrogen produced via alkaline (AEL) and solid oxide (SOEC) electrolysis supports decarbonisation by replacing grey hydrogen (from steam methane reforming) and natural gas in hard-to-abate sectors such as steel, ammonia, refining and heavy transport. These replacements are consistent with net-zero transition pathways recognised by the IEA and IPCC, and offer measurable GHG reductions.
- **Direct**: Electrolysis-based hydrogen production directly reduces GHG emissions by displacing higher-emitting alternatives. These reductions are evidence-based and traceable, relying on transparent system boundaries, lifecycle emissions accounting (e.g., 0.58 tCO_2eq/tH_2 for AEL in recent LCAs), and well-documented comparisons against reference scenarios (IEA). For SOEC systems, additional emissions reductions may be achieved via heat integration, further enhancing carbon efficiency.
- **Significant**: The emissions intensity gap between green hydrogen and fossil alternatives is material. For example, the difference between the EU Taxonomy Reference SMR H2 value of 11.28 tCO_2eq/tH_2 and lifecycle emissions of Gunfire's 10MW AEL electrolyser at 0.58 tCO_2eq/tH_2 is significant. Estimated values of GHG avoidance potential by end-use application range from 8.0 tCO_2eq/tH_2 (industry heat) to 21 tCO_2eq/tH_2 (Direct Reduced Iron). These avoided emissions are clearly quantifiable and decision-useful, consistent with WBCSD's contribution legitimacy framework.

Challenge & Side Effects

Challenges

Building this forward-looking avoided emissions model surfaced several challenges, particularly in balancing methodological rigour with limited data availability and practical modelling constraints.

Range of End-use Applications. One of the most time-consuming aspects was estimating avoided emissions per tonne of green hydrogen across different industrial end-use applications. While the IEA and other sources provide indicative values, the variation by sector (e.g., ammonia, steel, refining) required synthesising and weighting multiple fragmented datasets.

Utilization Rates. Utilisation rates for electrolysers vary significantly depending on electricity source, end-use application and infrastructure readiness. While some projects may operate at lower hours due to variable renewables or intermittent demand, others — particularly industrial applications with steady off-take like ammonia or methanol — can achieve high utilisation. Selecting a representative average is challenging given this variability: a rate of 5,500 hours/year was chosen as a conservative but realistic baseline, consistent with assumptions used in the Clean Hydrogen Production Pathways (2024) and reflective of commercially viable operating patterns.

Transport-related Emissions Adjustments. Incorporating transport-related emissions — particularly for imported hydrogen — was data-intensive and required relying on lifecycle assessments from recent academic and EU research (e.g., JRC 2024).

Side Effects

In line with Project Frame and WBCSD guidance, several potential side effects and rebound effects should be considered when evaluating the avoided emissions of AEL electrolysers:

Grid Carbon Intensity. If AEL electrolysers are powered by grid electricity in carbon-intensive regions (rather than renewables), the resulting hydrogen may have higher lifecycle emissions, reducing or reversing climate benefits. This illustrative case is developed in collaboration with Sunfire, where all end-use applications are assumed to be powered by renewables so as to qualify as green hydrogen.

Rebound Effects from New Demand. According to the IEA (Global Hydrogen Review 2024), hydrogen use in new applications — such as heavy industry, long-distance transport and energy storage — accounts for less than 1% of global demand, despite rapid growth. Introducing green hydrogen into these sectors could unintentionally stimulate new demand, rather than displacing grey hydrogen, potentially resulting in increased total emissions. Given the five-year timeline of this analysis, it is assumed that all green hydrogen is replacing existing demand (grey hydrogen or natural gas) in existing end-use applications. If a longer-term time horizon will be used, then accounting for new applications (new demand) should be considered.

Fossil Fuel Lock-in Risks. There is a risk that green hydrogen used in fossil-aligned sectors (e.g., refining) may prolong the life of carbon-intensive infrastructure, rather than accelerating its phase-out. WBCSD guidance flags this risk, particularly where green hydrogen substitutes only a portion of grey hydrogen without aligning to a broader decarbonisation trajectory.

Water Usage. Electrolysis requires significant volumes of purified water, which may present sustainability risks in water-scarce regions, especially at scale. Accounting for water usage and risks is outside the scope of this avoided emissions analysis but is an important consideration for project developers and operators.

Hydrogen Leakage Risks from Electrolysers. Electrolytic hydrogen systems primarily emit through start-up/shutdown venting, hydrogen cross-over and operational purging, with casing leakage considered negligible. Operational purging is the most significant source, with losses potentially reaching up to 10% if unmanaged. However, industry experts expect widespread adoption of recombination technologies, which convert purged hydrogen back into water — particularly as electrolyser deployment scales. This modelling assumes such mitigation is in place, keeping leakage from production relatively low and likely smaller than transport-related losses.

Lifecycle Infrastructure Emissions. Transport, compression and storage of hydrogen (particularly via shipping or long-distance pipelines) can introduce non-trivial emissions, as noted by the JRC (2024), and should be transparently accounted for when estimating net impact.

Validation & Verification

The company has not yet pursued a third-party verification of these results. The lifecycle assessment (LCA) was developed by a third-party, reputable consultancy.

Case Study Reflections

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

- **ICF recommends a convergence and alignment of nomenclature** for solution types and type of substitution categorisation across Project Frame and WBCSD.
- **ICF recommends Planned Avoided Emissions Assessments cover a minimum of a five-year timeframe if data allows.** In this case study, ICF illustrates a Planned Avoided Emissions Assessment based on an illustrative operating capacity growth plan.
- **Timeframes**: Choice of limiting both ‘top-down’ (Potential) and ‘bottom-up’ (Planned) analyses to shorter policy-aligned timeframes (2025–30) may not fully align with Project Frame guidance for Potential Impact: determined to be more decision-useful timeframe for the investor and company.
- **Reference scenario mix**: Methodological challenge of balancing pragmatism with rigour and data availability; chose forecasted market averages for end-use demand based on credible sources, transparently disclosing conservative assumptions in line with WBCSD recommendations. Forward-looking assumptions may not hold for Realised Impact assessments. There is a clear opportunity for deeper analysis into customer-specific end-use data where possible once Realised Impact analysis is conducted (not in this analysis).
- **ICF acknowledges that developing a case study of this nature is time-consuming.** We have erred on the side of completeness for illustrative purposes.

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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.