Clean hydrogen not at all costs, not at any cost but at the right cost

Preface

This paper emerges from a specialist webinar hosted by Pinsent Masons in February 2026 as part of Hydrogen Ireland's EU Presidency Series, a programme designed to advance structured, evidence-based dialogue on Ireland's role within Europe's evolving clean-energy landscape. The session brought together policymakers, industry leaders, researchers and legal experts to examine the shifting economic, environmental and societal parameters shaping the deployment of clean hydrogen across Europe.

The discussion highlighted a central challenge in contemporary energy policy: the inadequacy of traditional, price-centric evaluation frameworks for assessing the role of clean hydrogen in a net-zero energy system. Participants emphasised that hydrogen's value cannot be captured through a single economic denominator, and that a more comprehensive analytical model—one that integrates financial, system, societal, environmental and geopolitical dimensions—is required to guide effective decision-making.

This paper synthesises the insights generated during the webinar and situates them within the broader academic and policy discourse on energy transition. It advances the argument that cleans hydrogen should not be pursued *at all costs*, nor dismissed *at any cost*, but instead developed *at the right cost*: a cost that reflects its full multi-value contribution to a resilient, equitable and strategically secure energy future. In doing so, the paper seeks to provide a conceptual foundation for policymakers, investors and practitioners as they navigate the complexities of hydrogen deployment during Ireland's EU Presidency period and beyond.

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Background

The increasing focus on reducing greenhouse gas emissions and transitioning to a low-carbon economy has led to a growing interest in clean hydrogen as a clean energy carrier. However, the production of green hydrogen, which is derived from renewable energy sources, comes with a significant cost premium compared to traditional hydrogen production methods. As the demand for clean hydrogen grows, it is essential to strike a balance between the need for a low-carbon energy source and the economic viability of its production and its use cases.

1.0 Introduction

Clean hydrogen has captured the imagination of policymakers, industry, and investors and for good reason. It holds the promise of deep decarbonisation, industrial transformation, and new economic opportunity. But as enthusiasm grows, so too does the risk of distortion. The mantra must be clear: green hydrogen is not worth pursuing at all costs, nor at any cost — only at the right cost.

The word “cost” must be understood in its fullest sense. For too long, energy systems, especially fossil-fuelled ones — have been built around a single denominator of cost: economics. The cheapest barrel, the lowest price per kilowatt-hour, the fastest route to return. Environmental damage, climate risk, and social disruption were too often treated as externalities, invisible on the balance sheet, but painfully real in the world.

Clean hydrogen, by contrast, enters the stage in an era that demands a new energy equation — one with three interdependent denominators: economic, environmental, and social. It must make commercial sense. It must reduce emissions. And it must strengthen the communities and systems it serves. Green hydrogen will only succeed if it earns its place in all three columns of that ledger.

In 1892, Oscar Wilde wrote that *“a man who knows the price of everything and the value of nothing”* is the very definition of a cynic. More than a century later, that observation feels uncomfortably relevant to today’s energy crisis. We live in an age where price is instantly visible, endlessly compared, and politically amplified, yet true cost remains largely hidden. We can calculate euros per kilogram, model LCOH curves, and benchmark capex to the second decimal place, but we struggle to measure the deeper worth of the energy choices we make.

Hydrogen sits at the centre of this tension. It is simultaneously a commodity, a strategic asset, and a system enabler. Yet too often it is judged only by its sticker price. Wilde’s insight reminds us that price is not cost, and cost is not value. If we allow the debate to collapse into a race to the lowest €/kg, we risk building a hydrogen economy that is numerically efficient but strategically hollow.

1.1 Why Wilde Matters in the Hydrogen Debate

The energy transition is increasingly crowded with projects that look attractive on a spreadsheet but deliver little real impact. These are the “promotional value” projects designed for announcements, not outcomes. They inflate ambition but do not strengthen systems. They create noise, not resilience. They distract from the real work of decarbonisation, integration, and industrial transformation.

Wilde’s line is a warning: when we focus only on price, we lose sight of value. And in the hydrogen sector, value is where the real story lies, energy independence and resilience.

1.2 Defining the “Right Cost” for Clean Hydrogen

The central question is no longer *“How cheap can hydrogen become?”* The real question is: *‘What is the right cost for hydrogen that delivers genuine societal, environmental, and economic value?’*

The *‘right cost’* is not the lowest number on a tender sheet. It is the point where ambition and affordability meet, where hydrogen delivers:

- System value — flexibility, storage, grid stability, and renewable integration
- Societal value — jobs, skills, regional regeneration, and community resilience
- Environmental value — deep decarbonisation where no other vector works.
- Geopolitical value — reduced exposure to volatile fossil markets
- Industrial value — competitiveness, innovation, and long-term capability

Clean hydrogen must be measured not only in euros and dollars, but in the avoided costs of inaction, the resilience it creates, and the strategic autonomy it unlocks.

1.3 Price, Cost, and Value: A More Honest Framework

- Price

The visible number, $/kg, £/kg €/kg, capex/MW, opex/year are the single denominator in the old energy equation where verything has a single financial value. Whilst useful, in today’s works of multiple values it is out of date, and incomplete.

- Cost

The full lifecycle burden, environmental, social, regulatory, and infrastructural. This includes water use, land use, grid impacts, and long-term system integration.

- Value

The strategic contribution hydrogen can make:

- decarbonising hard-to-electrify sectors.
- enabling renewables at scale
- stabilising grids
- powering industry
- strengthening national resilience

This is where the real debate must sit.

1.4 Separating Real Potential from Promotional Distractions

To define the right cost, we must distinguish between:

- projects that deliver measurable system value, and
- projects that deliver only promotional value.

The latter are distractions — window dressing that absorbs attention and resources without advancing decarbonisation or resilience. The former are the backbone of a credible hydrogen economy.

Quantifying real potential requires assessing:

- load-shifting and grid headroom.
- industrial decarbonisation impact
- regional economic uplift
- long-term cost avoidance
- resilience and security benefits

Only by measuring these dimensions can we identify hydrogen's true value.

1.5 The Old Energy Equation: When Price Was the Only Denominator

For most of the past century, the energy system operated on a single, simple equation. Everything was reduced to one denominator: financial price.

$/kg. £/kg. €/kg. Capex per megawatt. Opex per year. Levelised cost curves. Discount rates. Payback periods.

This was the language of the old energy world a world where value was assumed to be fully captured by price, and where the cheapest option was automatically

considered the best. It was a world built on visible numbers and invisible consequences.

That equation worked or at least appeared to work in an era of abundant fossil fuels, stable geopolitics, and limited environmental constraints. But in today's world, that single-denominator model is out of date, incomplete, and increasingly dangerous.

The old equation cannot account for the cost of:

- climate instability
- energy insecurity
- stranded assets
- air pollution and public health impacts
- grid congestion and system inflexibility.
- geopolitical exposure
- failing to decarbonise hard-to-electrify sectors.

Nor can it capture the positive value created by clean hydrogen: resilience, flexibility, industrial competitiveness, regional regeneration, economic reversal, technology shifts and long-term strategic autonomy.

In short, the old equation knows the price of everything and the value of nothing.

1.6 Why the Old Equation Fails in a Multi-Value Energy World

Today's energy system is no longer a single-value environment. It is a multi-value ecosystem, where decisions must balance:

- financial cost
- environmental impact
- system integration value
- societal benefit
- geopolitical resilience
- industrial competitiveness

The old equation cannot process these dimensions because it was never designed to. It treats energy as a commodity, not as a strategic asset. It rewards short-term savings over long-term stability. It favours the lowest bidder, not the highest value.

Hydrogen exposes this flaw more clearly than any other energy vector.

If we judge hydrogen solely by €/kg, we will underbuild the infrastructure, underinvest in innovation, and misunderstand its purpose. We will compare it to fossil fuels on the wrong terms and conclude — incorrectly — that it is “too expensive.”

But if we judge hydrogen by its system value, its societal value, and its strategic value, the equation changes entirely.

1.7 From Price to Value - Rewriting the Energy Equation

The transition from the old equation to the new one requires a fundamental shift:

- Price is what we pay today.
- Cost is what we carry over time.
- Value is what we gain as a society.

Clean hydrogen must be assessed across all three dimensions.

The “right cost” is not the lowest cost. It is the cost that delivers the highest value — economically, environmentally, and geopolitically.

This is the foundation for a credible hydrogen strategy. This is how we separate real potential from promotional distractions. This is how we ensure hydrogen is deployed where it matters most. And this is how we build an energy system that is resilient, affordable, and future-proof.

1.8 Beyond the “Green Premium Framing Hydrogen’s True Worth

The old framing of a “green premium” implies that clean fuels are an expensive luxury. That narrative is outdated. Clean hydrogen is not a premium product — it is a strategic necessity. The question is not whether it costs more today, but whether it delivers more tomorrow.

The framing of our paper — *clean hydrogen at the right cost* — is more honest and more strategic. It recognises that:

- cheap hydrogen that delivers no system value is not a bargain.
- higher-cost hydrogen that unlocks resilience may be the better investment.
- the right cost is contextual, sector-specific, and time-dependent.
- value must be measured across decades, not quarters.

This is the narrative that moves the debate beyond simplistic €/kg comparisons.

If we judge and measure hydrogen only by its price, we will underbuild, underdeliver, and misunderstand its purpose. If we judge it by its true value, we will invest at the right cost and build an energy system worthy of the future.

Clean hydrogen must be measured not only in financial terms but in its broader societal and environmental value. This session frames the debate around what "right cost" truly means, balancing ambition with affordability and long-term sustainability.

2.0Technology Pathways and Innovation

Efficiency First - Scaling Clean Hydrogen Without Waste in the value system.

Section will explore breakthroughs in electrolysers, storage, and system coupling that reduce costs while maximizing impact.

Innovation is the key to making hydrogen cost-effective without compromising quality or impact. Explore advances in electrolyzers, storage, and system integration that reduce waste and improve efficiency, ensuring hydrogen delivers maximum benefit at minimal expense.

2.1 Efficiency First - Scaling Clean Hydrogen Without Waste in the value system.

Innovation is critical to making hydrogen cost-effective without compromising quality or impact. The most common route to produce low emissions hydrogen from renewables is via water electrolysis, whereby an electrolyser splits water into hydrogen and oxygen using electricity generated from renewables, such as wind or solar.

Currently the average levelized cost of hydrogen from renewables far exceeds that of hydrogen produced via emission intensive alternatives i.e. steam methane reforming (SMR) or gasification of coal. In 2024, the European Hydrogen Observatory found that in Europe the average levelized cost of hydrogen produced via electrolysis directly connected to a renewable electricity generation source was 6.71 EUR/kg, ranging from 4.3- 10.5 EUR/kg (based on an average between 100MW alkaline and PEM systems). (1) This is almost twice that of the cost of hydrogen produced via SMR, which averaged 3.33 EUR/kg. (1)

The European Hydrogen Observatory gives a breakdown of the average levelized cost of hydrogen produced via electrolysis directly connected to a renewable electricity generation source in 2024 as: (1)

- 57.3% (3.85 EUR/kg) related to CAPEX
- 39.0% (2.62 EUR/kg) to electricity consumption

- 3.4% (0.23 EUR/kg) to other OPEX

CAPEX - Includes upfront capital cost of the electrolyser system e.g. the stack, balance of plant (compressors, pumps, power electronics, cooling), utilities, buildings and storage infrastructure.

Electricity Consumption – The cost of renewable electricity supply.

OPEX - Relates to operating costs such as ongoing operating and maintenance costs, water purification and filtering, water supply, replacement of stack components, labour and insurance.

A number of interdependent factors determine the cost of producing low-emission hydrogen from renewable electricity and improvements require a whole-system view. An illustration of a typical electrolyser system is shown in Figure 1. (16) At the core is the electrolyser stack, where material choices, stack design, and conversion efficiency directly influence capital and operational costs. Subsequent processing stages, including hydrogen purification and compression also contribute significantly to overall costs, particularly where a high purity or high-pressure output is required. Additionally, water sourcing and treatment add to overall costs, with implications for project siting and environmental performance.

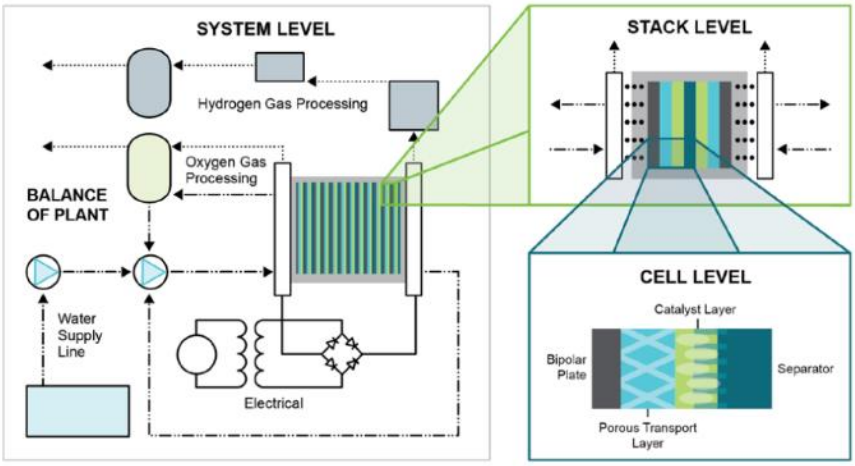


Figure 1 illustration of a typical water electrolyser system consisting of the stack and balance of plant components. (16)

In parallel to system performance, the way in which the electrolyser is integrated with the renewable generation source is critical: coupling strategies, operating regimes, and the achievable capacity factor all affect system efficiency and asset utilisation which significantly affect the cost of the hydrogen produced by spreading capital costs and impacting asset lifetimes.

Finally, hydrogen storage requirements, both short-term buffering to manage renewable intermittency and larger-scale or seasonal storage, depend on the scale of production and the nature of the end-use demand. Considering these elements

holistically is essential to reducing the cost of renewable hydrogen and enabling efficient and reliable supply chains.

The following sections will explore advances in electrolysers, storage, and system integration that aim to reduce waste and improve efficiency, ensuring hydrogen delivers maximum benefit at minimal expense.

2.2 Electrolysers

There are several key technology pathways under active development within the water electrolysis sector:

- Alkaline
- Anion exchange membrane (AEM)
- Polymer electrolyte membrane (PEM)
- Solid oxide electrolyser cells (SOEC)

According to the IEA's Energy Technology Perspectives (ETP) Clean Energy Technology Guide, as of 2025 alkaline and PEM electrolysers have reached TRL 9, indicating they are fully ready for commercial sale and licensing. SOECs are assessed at TRL 8, reflecting their deployment in first-of-a-kind commercial scale systems, while AEM electrolysers are at TRL 7, having been validated at precommercial scale. Each electrolyser technology offers distinct operational advantages, yet across the board the levelized cost of hydrogen remains significantly higher than that of more emissions-intensive production pathways. (5) Despite commercial readiness, research and innovation to bring down the cost of hydrogen produced remains essential.

Key strategies include: (2, 3)

- Increasing the electrical efficiency of the electrolyser to reduce the electricity requirements per unit of hydrogen produced and overall footprint/land use.
- Reducing the cost of electrolyser materials e.g. reducing reliance on precious metals, achieved either by substitution, reduced loading of critical materials or increased end-of-life recycling.
- Enhancing the durability of electrolysers to increase their lifetime and performance, especially when operating dynamically
- Advanced manufacturing of electrolysers and economies of scale

In 2024 the US National Renewable Energy Laboratory published an analysis on pathways to reduce the capital costs of PEM electrolysers which found that the total system manufactured costs (including balance of plant and stack) could be reduced by 50% through a combination of manufacturing economies of scale, advanced manufacturing techniques and advanced system and materials engineering.(4) This analysis also looked at opportunities to reduce the cost of the stack and balance of

plant equipment by optimising the amount of expensive materials used and alternative component designs. Catalyst used in PEM are particularly expensive because they contain iridium and platinum. They found that largest cost reductions could be achieved from lower anode catalyst loading (how much catalyst material is used per unit area on the electrodes) and increased current densities (how much current you push through per unit area of electrode). These optimisations translate to reducing the amount of costly catalyst used and increasing hydrogen output per unit of equipment. (4) Through combined advances in stack design and manufacturing costs they show that for a 1MW total system manufactured cost could be reduced by 58% (from 891 $/kW to 374 $/kW) – the largest part of this reduction coming from stack manufactured costs which reduced by 90% (from 316 $/kW to 31 $/kW). (4)

Work is also being done to improve electrolyser efficiency, durability and reduce costs via materials engineering. This now includes using AI tools to enhance materials screening for new catalyst materials to speed up what would otherwise be a labour-intensive trial and error process. (6,7) Enhancing these properties reduces the cost of hydrogen per kilogram either by reducing the upfront cost of electrolysers, minimising electricity consumption or improving performance over the asset lifetime.

2.3 Renewables and Production Coupling

While the electrolyser stack is a critical component, it represents only one element of a much broader system. Effective integration with renewable energy infrastructure remains a key challenge and area where innovation is required to drive down costs and improve operational efficiency. Intermittent operation can cause issues for electrolysers as this can cause stress on the materials and take the electrolysers out of the optimised production range which has a knock-on effect for asset lifetime and levelized cost of hydrogen per kilogram.

One project which has demonstrated an innovative approach to system integration is ERM's Dolphyn Hydrogen project in the UK. (8,9) This project aimed to find the most economical way to produce hydrogen at scale from floating offshore wind. Floating offshore wind turbines tend to be in deep water at long distances from shore, where wind is at its most plentiful. This project's technical and economic evaluation led to a decentralised design with individual floating hydrogen production units alongside the turbines, sending hydrogen back to shore via pipeline. By producing hydrogen offshore, projects can avoid the energy losses associated with transmitting electricity to shore via high-voltage cables and then converting it to hydrogen on land. Key areas this project were looking to understand through demonstration were the impact of the environment conditions on electrolyser performance, performance under variable load (due to intermittency of wind), performance in response to changing stimulated demand and the impact of variable water quality on performance. (8,9)

Also looking at integration is the ATMOSPHERE consortium led by Iberdrola in Spain. Their site in Puertollano connects a 100 MW photovoltaic (PV) plant with a 5 MW lithium-ion battery system and a 20 MW PEM hydrogen production system (16 stacks each of 1.25 MW). (10,11) They have looked at integrating a battery system to mitigate the intermittency of solar power, allowing electrolysis to be powered by a stable and continuous supply which maximises the hydrogen output and electrolyser lifetime. (10) This project demonstrates an advanced systems control strategy deployed to maximise efficiency.

2.4 Hydrogen Storage

Once hydrogen is produced, and if not directly used, it then must be stored safely and efficiently to allow for transport to off-takers or long-term seasonal storage. An effective storage system is key for balancing a variable hydrogen production level with variable demand. (12) There are many types of hydrogen storage technologies, with varying scale and application (All TRLs are as of 2025 according to IEA Clean Energy Technology Guide) (5):

- Materials-based hydrogen storage
    - Metal hydrides (TRL 5 – Large prototypes tested)
    - Adsorbents storage (TRL 3 - Components tested)
- Physical-based storage above ground
    - Ammonia (TRL 9 – technically ready for sale)
    - Liquid hydrogen storage tank (TRL 9)
    - Pressure vessel storage (TRL 9)
- Physical-based storage below ground
    - Aquifer storage (TRL 3)
    - Depleted gas field (TRL 5)
    - Salt cavern (TRL 9)
    - Fast-cycling salt cavern (TRL 6)
    - Lined hard rock cavern storage (TRL 5)

Underground hydrogen storage offers an effective long-term, large-scale solution to storing excess renewable energy. Projects like Underground Sun Storage 2030 led by RAG Austria AG in Upper Austria have demonstrated large volume storage and re-extraction from an underground sandstone gas reservoir coupled with hydrogen production from solar energy using PEM electrolysis. (14,15) The conversion from a depleted gas reservoir to hydrogen storage facility took approximately two years which then enabled up to 4.2 GWh of hydrogen to be stored for several months and extracted from the reservoir in high purity. Two cycles have been successfully completed in the first demonstration, with further storage cycles being planned for a follow up project.

3.0 Policy, Regulation, and Market Design

3.1 Smart incentives: aligning policy with sustainable economics.

The previous section highlighted how technological innovation and system integration are essential to and indeed making progress in reducing the cost of renewable hydrogen production. However, technological progress alone cannot determine whether hydrogen is deployed effectively or inefficiently. Even where technologies are commercially available, high capital costs, infrastructure requirements, and uncertain demand create barriers that markets alone often struggle to overcome. Energy systems are therefore shaped not only by engineering and innovation but also by the policies, market structures, and regulatory frameworks that determine how technologies compete within the wider energy system. In the case of clean hydrogen, policy is not merely supportive—it is foundational.

Across Europe and globally, the emerging hydrogen economy is being built through deliberate regulatory frameworks that seek to balance climate ambition with economic practicality. The European Union has developed one of the most comprehensive hydrogen policy architectures to date through the Fit-for-55 package, the revised Renewable Energy Directive (RED III), and the Gas and Hydrogen Decarbonisation Package adopted in 2024. Together these measures establish rules for hydrogen infrastructure, market operation, and the certification of renewable and low-carbon hydrogen, aiming to enable a cost-effective and integrated hydrogen market across the EU. (17)

These frameworks illustrate a key principle: the cost of hydrogen cannot be understood purely as the cost of production. It is shaped by the regulatory environment in which hydrogen competes with incumbent energy systems.

3.2 Internalising the Real Cost of Energy

For decades, energy markets have operated within a framework where the environmental and social costs of fossil fuels were largely externalised. The price of coal, oil, and gas has rarely reflected the full costs associated with air pollution, climate change, public health impacts, or ecosystem degradation. The International Monetary Fund's 2025 update on fossil fuel subsidies illustrates the scale of this distortion. The IMF estimates that explicit fossil fuel subsidies reached approximately

US $725 billion globally in 2024 (around 0.6 % of global GDP). When the under-pricing of environmental damages and other externalities is included, total subsidies rise to around US $7.4 trillion—equivalent to roughly 6.4 % of global GDP. The majority of these implicit subsidies arise from the failure to price the costs of local air pollution and climate change associated with fossil fuel consumption. These figures highlight that the apparent price advantage of fossil fuels often reflects structural policy distortions rather than intrinsic economic efficiency. (18).

In this context, the often-cited “green premium” attached to hydrogen must be interpreted cautiously. The premium is not solely a function of hydrogen’s technological immaturity, but also the legacy of energy markets that have historically failed to price carbon emissions and environmental impacts accurately. Correcting this imbalance is a central objective of modern energy policy.

3.3 Carbon pricing and market signals

One of the most influential policy tools in Europe is the EU Emissions Trading System (EU ETS), which places a price on carbon emissions from energy-intensive sectors. By requiring polluters to pay for emissions allowances, the ETS gradually internalises environmental costs and improves the competitiveness of low-carbon alternatives such as clean hydrogen.

As carbon prices rise and coverage expands—including sectors such as maritime transport—the economic case for hydrogen strengthens in industries where direct electrification is difficult, such as steelmaking, chemicals production, and heavy transport.

However, carbon pricing alone is insufficient in early-stage markets were technologies face high upfront capital costs and infrastructure barriers. Complementary policy instruments are therefore required to bridge the gap between early adoption and commercial maturity. (19)

3.4 Strategic Incentives and Market Formation

To accelerate deployment while avoiding inefficient spending, policymakers increasingly favour competitive, market-based support mechanisms rather than open-ended subsidies. The European Union’s flagship instrument in this regard is the European Hydrogen Bank, which distributes financial support through competitive auctions funded largely through revenues from the EU Emissions Trading System via the Innovation Fund. In these auctions, hydrogen producers bid for the lowest subsidy required per kilogram of renewable hydrogen, with the EU paying a fixed premium for up to ten years once production begins. (20)

The first auction round in 2024 allocated approximately €720 million to seven projects, with winning bids ranging between €0.37 and €0.48 per kilogram of hydrogen. At first glance, these low bids suggest that the EU is securing relatively strong value

for public funds compared with other international support schemes. However, the results also highlight important structural challenges. First, the scale of funding remains modest relative to the investment required to build a full hydrogen economy. Estimates suggest that meeting the EU's hydrogen deployment targets by 2030 could require €335–€471 billion in total investment, far exceeding the resources currently available through auction mechanisms.

Second, while the auction mechanism is designed to promote cost efficiency, it may favour projects located in regions with exceptional renewable resources or existing infrastructure advantages, potentially concentrating development geographically rather than supporting a more balanced industrial transition across Europe. Early auction results also raise questions about whether some bids reflect optimistic cost assumptions or rely on additional layers of public support beyond the Hydrogen Bank itself.

3.5 Public Funding Ecosystem: Innovation Fund and Infrastructure Support

In practice, hydrogen deployment in Europe relies on a combination of funding instruments. The EU Innovation Fund supports large-scale demonstration projects in low-carbon technologies, including renewable hydrogen production, through grants funded by revenues from the EU ETS. With tens of billions of euros expected to be distributed this decade, it has become one of the world's largest – and more competitive - public funding programmes for industrial decarbonisation.

Alongside production funding, the Connecting Europe Facility for Energy (CEF Energy) provides financial support for cross-border energy infrastructure projects designated as Projects of Common/Mutual Interest (PCIs/PMIs). This also includes hydrogen pipelines, storage facilities, and port infrastructure required to enable future hydrogen trade and integration into the European energy system.

This layered funding architecture can significantly reduce early-stage investment risks. However, it also highlights an important policy challenge: ensuring that public funding accelerates market formation without creating long-term subsidy dependence or distorting price signals.

In this context, the effectiveness of public funding mechanisms should ultimately be judged not by the number of projects announced or subsidised, but by whether they contribute to the creation of a self-sustaining hydrogen market.

3.6 Demand-Side Regulation and Market Creation

While supply-side incentives are critical in the early stages of market development, long-term viability ultimately depends on the emergence of reliable demand. Recognising this, European policymakers have increasingly complemented production subsidies with demand-side regulatory mandates.

The revised Renewable Energy Directive (RED III) establishes binding targets for the use of renewable fuels of non-biological origin (RFNBOs), including renewable

hydrogen, across several sectors. The directive requires that 42 % of hydrogen used in industry be renewable by 2030, rising to 60 % by 2035, while the transport sector must achieve a minimum 1 % share of RFNBOs by 2030.

These measures aim to create predictable demand for renewable hydrogen in sectors such as refining, chemicals, and heavy transport, helping to overcome the “chicken-and-egg” problem that often slows the adoption of new energy technologies.

Nevertheless, implementing these targets raises important economic considerations. Industrial users face significantly higher costs when replacing conventional hydrogen with renewable hydrogen, particularly while production costs remain elevated. Policymakers must therefore balance regulatory ambition with industrial competitiveness, ensuring that demand mandates are accompanied by sufficient financial support, infrastructure investment, and market transparency.

3.7 Certification, Standards, and Market Transparency

Another critical element of hydrogen market design is the development of robust certification systems. In order to trade hydrogen across borders and sectors, market participants must be able to verify its carbon intensity and production method.

The European Commission has introduced detailed rules defining RFNBOs, including requirements for additionality, temporal correlation, and geographical correlation between renewable electricity generation and hydrogen production.

These rules are designed to ensure that renewable hydrogen genuinely contributes to emissions reductions rather than diverting renewable electricity from existing uses. At the same time, they have been the subject of ongoing debate within industry, as strict requirements may increase production costs or limit operational flexibility.

Certification systems, including Guarantees of Origin for hydrogen, will play an essential role in building market confidence and enabling international trade. However, policymakers must strike a careful balance between environmental integrity and economic feasibility. Overly rigid certification frameworks could slow investment and hinder the scale-up of hydrogen production during the critical early stages of market development.

3.8 Designing Policy for the “Right Cost”

The central challenge for policymakers is therefore not simply to subsidise hydrogen production, but to design markets in which hydrogen can compete fairly and sustainably.

Achieving this requires three key principles:

- Internalising environmental costs, ensuring fossil fuels no longer benefit from hidden subsidies.
- Targeted and competitive incentives that support early-stage deployment while driving cost reductions.

- Coordinated infrastructure planning and market regulation that ensures hydrogen is deployed where it delivers the greatest decarbonisation value.

When these elements align, policy does more than support hydrogen—it ensures that hydrogen is deployed at the right cost, delivering genuine economic, environmental, and societal value.

In this sense, regulation is not a constraint on the hydrogen economy. It is the mechanism through which technological potential is translated into credible, scalable, and economically sustainable energy systems.

Ultimately, the effectiveness of hydrogen policy cannot be measured solely through the volume of projects financed or tonnes of hydrogen produced. Regulatory frameworks must also ensure that hydrogen development contributes to broader societal objectives, including environmental protection, equitable economic development, and public trust in the energy transition. Markets and incentives may shape investment decisions, but long-term success will depend on whether hydrogen systems deliver tangible benefits for communities and ecosystems. It is therefore essential to examine how hydrogen deployment interacts with society and the environment—an issue explored in the next section.

4.0. Societal and Environmental Impact

4.1 Societal and Environmental Impact – Communities at the Core of the Energy Transition

Clean hydrogen not at all costs, not at any cost, but at the right cost, means putting people and ecosystems at the centre of the transition. Hydrogen cannot succeed as a purely technical or economic project. Its legitimacy, longevity, and licence to operate will depend on whether communities experience real benefits, whether environmental integrity is protected, and whether the transition is fair.

This section explores how hydrogen can and must deliver value beyond kilowatts and carbon metrics.

4.2 Environmental Integrity Hydrogen That Protects, Not Depletes

Clean hydrogen will only succeed if it earns its place not through slogans or subsidies, but through genuine environmental integrity and real value for people. For too long, energy systems were built around infrastructure first and communities second. The shift to clean hydrogen gives us a rare opportunity to reverse that order. If this transition is to be credible, it must be designed around the people and places it touches, ensuring that hydrogen strengthens communities, protects ecosystems, and supports a fair and lasting shift away from fossil fuels.

Clean hydrogen earns its environmental credibility through:

- Low or zero lifecycle emissions, green hydrogen powered by renewables, or blue hydrogen with *verified* carbon capture and transparent monitoring.
- Minimal environmental trade-offs, responsible water use, careful land planning, and sustainable sourcing of electrolyser materials.
- Durability in a net-zero pathway, hydrogen must be a long-term climate solution, not a temporary fig leaf masking continued fossil fuel expansion.

Environmental performance is no longer a footnote. It is a denominator against which every project will be judged by regulators, investors, and communities.

Environmentally, the stakes could not be clearer. Continuing to rely on fossil fuels locks us into higher emissions, deeper climate instability, and the ongoing erosion of biodiversity. Every year of delay makes net-zero targets harder to reach and exposes communities to more severe climate impacts. Clean hydrogen offers a pathway out of this cycle, but only if it is produced and deployed with integrity. That means hydrogen with genuinely low or zero lifecycle emissions, whether through renewable-powered electrolysis or carbon capture systems that are transparent, verifiable, and accountable. It means avoiding the environmental trade-offs that have undermined past energy transitions — excessive water use, poorly planned land impacts, or unsustainable mining for critical materials. And it means positioning hydrogen not as a temporary bridge, but as a durable component of a long-term climate solution. Environmental performance is no longer a footnote in the energy story; it is the denominator against which every project will be judged.

4.3 Social Acceptance, Hydrogen for People, Not Just Systems

But the environmental case alone is not enough. Social acceptance has become a structural requirement for any major energy project. Communities have long memories of extractive industries that arrived with promises and left with profits. Clean hydrogen cannot repeat that pattern. It must demonstrate that it brings local value — jobs, skills, investment, and opportunity — rather than simply exporting energy and wealth elsewhere. It must involve communities meaningfully, not as an afterthought but as

partners whose insights shape the design and delivery of projects. And it must support a just transition for workers and regions whose livelihoods have been tied to fossil fuels for generations. If clean hydrogen is perceived as a new form of extractivism dressed in green, it will face resistance. If it is seen as a pathway to renewal, resilience, and shared prosperity, it will earn the social licence it needs to scale.

As one political figure put it in 2025, “Drill baby drill” captured the old paradigm, extraction first, communities second. Clean hydrogen must represent the opposite: value first, extraction last.

Hydrogen earns its social licence only when communities can see, feel, and shape the benefits.

4.4 The Social Costs of Inaction, What Happens If We Delay

The social costs of inaction are equally significant. Without clean hydrogen, air and water pollution will persist, disproportionately affecting vulnerable communities and widening existing inequalities. Energy access disparities will deepen, as fossil-based systems rarely prioritise equitable distribution. Climate-related displacement will accelerate, with more frequent extreme weather events straining social systems and uprooting families. And regions dependent on fossil industries will face unmanaged decline rather than a planned, supported transition. Clean hydrogen is not a cure-all, but it is a stabilising force in a destabilising climate — a tool that can help societies manage the turbulence ahead rather than be overwhelmed by it.

In the Interreg Nort West Europe funded GenComm project Mark Welsh from Energia famously stated ‘*Clean hydrogen is not a silver bullet, it is more a silver buckshot, having different impact in different regions. It is a stabilising force in a destabilising climate.*’

4.5 Environmental and Social Safeguards. The Conditions for Public Trust

To ensure hydrogen projects deliver real value, safeguards must be embedded from the start:

- Transparent lifecycle emissions accounting
- Responsible water and land management
- Community benefit-sharing frameworks
- Skills pathways and local employment guarantees
- Environmental monitoring and biodiversity protection
- Clear governance to prevent greenwashing or speculative development.

These safeguards are not barriers they are enablers of durable, investable, socially legitimate hydrogen ecosystems.

4.6 The Human Dimension of Innovation. Technology That Serves Society

Innovation and technology also carry a societal dimension. If we delay investment in clean hydrogen, we risk falling behind countries that are already building the industrial capacity, supply chains, and skills base needed for the next energy era. That loss is not abstract; it translates into fewer jobs, weaker competitiveness, and diminished energy sovereignty. A diverse energy system, with clean hydrogen as one of its pillars strengthens national resilience and reduces exposure to geopolitical shocks and volatile global markets. Technological leadership, in this sense, is not just about efficiency gains or new electrolyser designs; it is about ensuring that innovation serves society, not the other way around.

Ultimately, the societal and environmental impact of clean hydrogen comes down to a simple principle: hydrogen must work for people and for the planet. It must clean the air, protect ecosystems, create opportunities, and support communities through the transition. When done well, it becomes a catalyst for resilience and renewal. When done poorly, it risks repeating the mistakes of the fossil era. The challenge and the opportunity are to ensure that hydrogen is pursued not at all costs, nor at any cost, but at the right cost, with communities and ecosystems at the centre of every decision.

Hydrogen must earn its place environmentally, socially, and economically. When done right, it delivers cleaner air, stronger communities, skilled jobs, climate resilience, and long-term energy security. When done poorly, it risks repeating the mistakes of the fossil era.

5.0 Global Partnerships and Strategic Investment

5.1 The Shift from Local Valleys to Global Systems

Clean hydrogen began as a series of local experiments pilot valleys proving that production, storage, transport, and end-use could be integrated in real communities. But the next phase is fundamentally different. Scaling hydrogen from regional clusters to a global energy system requires more than technology; it requires trust, alignment, and shared purpose across borders.

Hydrogen's future will be shaped by the partnerships we build and the investment choices we make. No single nation can create a hydrogen economy alone. The infrastructure, standards, supply chains, and capital flows required are inherently international. The question is not whether we collaborate, but how — and on whose terms.

5.2 Energy Volatility as the Catalyst for Change

For decades, the global energy system has been defined by the volatility of fossil fuels. Oil and gas prices have surged and collapsed in response to geopolitical tensions, supply disruptions, cartel decisions, and market speculation. Every shock from the 1970s oil crises to the 2022 gas price spike has exposed the fragility of a system built on fuels that are globally traded but regionally controlled.

This volatility is not incidental; it is structural. And it is precisely this instability that is now pushing countries to rethink their energy foundations.

Renewables and clean hydrogen offer something fossil fuels never could: predictability. Wind and solar have no fuel cost. Electrolysers run on domestic resources. Once built, renewable-hydrogen systems are insulated from the geopolitical turbulence that defines fossil markets.

For governments, industries, and investors battered by price shocks, this stability is becoming a strategic advantage and a geopolitical asset.

5.3 Correcting the Cost Narrative, Beyond the "Green Premium"

For decades, the global energy system has been shaped by oil and gas subsidies that remain enormous when measured as a percentage of GDP. These subsidies distort markets, obscure the true cost of fossil fuels, and create the illusion that clean hydrogen is inherently expensive.

The idea that clean hydrogen is "too expensive" persists largely because fossil fuels have been subsidised for decades. When measured as a percentage of GDP, oil and gas subsidies remain one of the most distortionary forces in the global economy. They mask the true cost of fossil fuels and inflate the perceived cost of clean alternatives.

Once externalities are properly accounted for, climate impacts, health burdens, environmental degradation, and geopolitical risk the economics of hydrogen look very different. The "green premium" is not a premium at all; it is the price of honesty in a system that has long externalised its true costs.

When these are included, clean hydrogen is not a costly alternative, it is a strategic hedge against the far greater costs of inaction. Strategic investment is therefore not

about subsidising an uncompetitive technology; it is about correcting decades of structural imbalance.

Hydrogen's value lies not only in decarbonisation, but in de-risking national economies.

5.4 Hydrogen as a Stabilising Force in a Volatile World

Countries are increasingly recognising that the real cost of fossil fuels is not the price on the day, but the volatility over decades. Volatility drives inflation, undermines industrial competitiveness, and exposes households to energy poverty.

Clean hydrogen, by contrast, has a cost curve that moves in one direction: downwards. As renewable capacity expands and electrolyser manufacturing scales, hydrogen becomes a macroeconomic stabiliser — a tool for long-term price certainty.

Hydrogen valleys are therefore evolving from demonstration projects into economic stabilisation zones. And when these valleys connect across borders, they become the backbone of a new global energy architecture built on stability rather than volatility.

5.5 Financing the Future, Blended Models for a Global Market

Scaling hydrogen requires investment models that blend public leadership with private capital. Early projects need public guarantees to de-risk technology and infrastructure. Long-term growth depends on predictable regulation, transparent certification, and stable demand signals.

Countries that can offer these conditions will attract the industrial investment needed to build electrolyser factories, storage hubs, port infrastructure, and hydrogen corridors. Those that cannot fall behind as global supply chains consolidate elsewhere and watch as the opportunities migrate elsewhere.

Hydrogen is no longer a speculative technology. It is an emerging asset class.

5.6 International Trade: Building a Trusted Global Hydrogen Market

Hydrogen will only become a global commodity if nations align on standards, safety, and certification. Without this, the world risks a fragmented patchwork of incompatible systems. With it, hydrogen becomes a trusted, tradable energy vector capable of supporting industrial decarbonisation and energy security across continents.

This is where Europe is already shaping the global conversation. Through RFNBO rules, Guarantees of Origin, and emerging hydrogen certification frameworks, the EU is defining what "clean" means — and in doing so, setting the terms of global trade.

5.7 The Euro as the Currency of Clean Energy

A profound shift is emerging; the Euro is positioning itself as the currency of clean energy.

Driven by EU legislation, carbon border mechanisms, and hydrogen certification rules, Europe is creating a regulatory and financial ecosystem where:

- clean hydrogen contracts are denominated in Euro.
- cross-border Guarantees of Origin are priced in Euro.
- EU-backed investment vehicles anchor hydrogen infrastructure in Euro.
- global producers align with EU standards to access the world's largest decarbonisation market.

This is not accidental. It is strategic.

As the world transitions from fossil fuels to clean molecules, the currency that underpins clean energy trade will gain geopolitical influence. The Euro backed by the world's most advanced climate legislation is emerging as the natural anchor for hydrogen pricing, certification, and long-term offtake agreements.

When hydrogen becomes a globally traded commodity, the currency that underpins its contracts will gain geopolitical influence. The Euro, backed by the world's most advanced climate legislation, is emerging as the natural anchor for clean-energy trade.

In a world tired of fossil volatility, a Euro-denominated hydrogen market offers something rare - *stability.*

If Europe succeeds, the Euro becomes not just a currency of trade, but a currency of transition, a stabilising force in a volatile global energy landscape.

5.8 Ensuring Fairness Avoiding a New Era of Extractivism

Global hydrogen partnerships must avoid repeating the patterns of the fossil era, where resource-rich regions bore environmental burdens while others captured the value. Strategic investment must ensure that producing regions whether in Europe, Africa, Latin America, or the Middle East benefit from jobs, skills, and long-term industrial development.

Hydrogen must be a catalyst for shared prosperity, not a new form of dependency.

5.9 The Pathway Forward Collaboration as the Engine of Scale

The journey from pilot valleys to global trade is not simply technical or financial. It is geopolitical, economic, and ethical. It requires nations to align ambition with pragmatism, to balance national interests with global responsibility, and to invest not only in infrastructure but in relationships.

If we get this right, hydrogen becomes more than a fuel. It becomes a platform for cooperation, resilience, and economic renewal a system where the Euro anchors clean energy markets, where global partnerships drive shared value, and where investment decisions reflect the true cost of climate action.

Hydrogen's future will be built on collaboration. And the right cost is the cost that delivers shared value across borders, sectors, and generations.

6.0 System Integration at the Right Cost

6.1 Define the energy service and the counterfactual.

The project should first define the service it must deliver. The service may include firm electricity, industrial heat, seasonal heating, process hydrogen, transport fuel or emergency power. Each use has a required temperature, pressure, purity, response time and tolerance for interruption. Hourly and seasonal demand profiles should guide plant size and operating strategy.

The counterfactual should describe the most credible alternative. Options may include grid reinforcement, batteries, thermal storage, direct electrification, biomethane, demand response or imported fuel. Each option should use the same system boundary. The comparison should include production, conversion, compression, storage, transport, backup, network costs and carbon intensity. This method measures the cost of the energy service delivered to the user.

Site assessment should cover local renewable profiles, water, waste heat, biogenic CO2, storage geology, roads, ports, pipelines and electricity capacity. It should also cover planning limits, safety distances, workforce skills and maintenance access. Multi-year weather data should test low-wind periods, heatwaves, floods, icing and other local risks. The Haeolus project in Arctic Norway used remote monitoring, protective housing and hydrogen storage because winter access and grid constraints shaped the design. [1]

6.2 Dynamic capability and system flexibility

Flexible electrolysis can absorb variable renewable electricity and provide grid services. The whole plant sets the useful response range. Compression, water treatment, gas quality, heat supply and storage can limit the stack. PEM electrolysers provide fast response. HyBalance operated a 1.2 MW PEM system for more than 16,000 hours. It supplied industry and transport, responded within ten seconds for

frequency reserve, and reported lower energy costs from grid-service revenue under Danish market conditions. [2]

Alkaline and SOEC systems provide different benefits. Alkaline electrolysers can follow renewable output within their operating limits. SOEC systems achieve high electrical efficiency when steam and useful heat are available. They also need careful thermal control. GrInHy2.0 used steelworks waste heat and reported 84.6% maximum electrical efficiency for its SOEC unit. Its cold start took about 36 hours. Hot standby supported faster restart. [3,4]

A hybrid plant can assign fast changes to PEM or suitably controlled alkaline capacity. SOEC can operate near a stable and efficient point. Shared heat, water treatment, drying, compression and storage can reduce duplication. Recovered SOEC heat may support alkaline feedwater preheating or warm-standby auxiliaries when temperatures match. A battery can filter short electrical changes. Hydrogen storage can protect continuous customer supply.

An illustrative calculation shows the value of flexible demand. A 10 MW electrolyser operating for 1,000 hours absorbs 10,000 MWh. At 57 kWh/kg, it produces about 175 tonnes of hydrogen. A price difference of €50/MWh gives a gross electricity-cost benefit of €0.50 million, or about €2.85/kg. This screening estimate excludes capital, storage, network charges, standby energy and degradation. In 2025, 2,139 GWh of wind energy was dispatched down across Ireland and Northern Ireland. Electrolysis can capture part of this energy when its location and operating rules match the constraint. [5,6]

Long-duration storage should use local infrastructure. Pressure vessels suit short periods. Pipelines, road delivery, ports and geological storage can support longer periods and wider networks. Hydrogen can also be converted into methane, methanol, ammonia or other fuels. The final choice should match storage duration, transport distance, end use and import security. The IEA identifies pipelines and underground storage as key infrastructure, with major gaps between announced capacity and committed projects. [7]

Regional hubs should combine technologies with different response rates. Batteries and flexible demand can manage fast changes. Hydrogen-capable turbines or PEM fuel cells can provide peak and backup power. SOFC systems can provide efficient steady power and useful heat. Their thermal limits require controlled load changes. Transport demand also needs careful selection. Battery vehicles suit most passenger travel. Hydrogen fuel cells fit high-use fleets when range, payload and refuelling time create a clear service need. [8]

6.3 Classic integrated hydrogen architectures

6.3.1Renewable electricity electrolysis storage and power generation

This chain links variable generation to hydrogen storage and dispatchable power. Short-term storage can smooth daily demand. Caverns or transportable fuels can

cover longer periods. PEM fuel cells suit fast-start duties. SOFC systems suit steady combined heat and power. Gas turbines can provide peak power where fuel inventory has high security value. Batteries usually serve short electrical shifts with higher round-trip efficiency. Chronological modelling should select the best mix. [1,8]

6.3.2 Hybrid alkaline electrolysis and SOEC

The SOEC train should use stable power and available steam. Alkaline or PEM capacity should handle faster renewable changes. Thermal storage can maintain steam and reduce thermal cycling. Plant control should account for electricity price, storage pressure, gas purity and equipment life. Hybridisation has strongest value at sites with both useful heat and flexible electricity.

6.3.3 Electrolysis anaerobic digestion and methanation

Anaerobic digestion provides methane and a CO2-rich stream. Renewable hydrogen can convert this CO2 into additional methane through catalytic or biological methanation. The fuel can use existing gas storage and distribution assets. Echaea reported 1 MW industrial biological methanation prototypes that produced grid-quality e-methane. The same site may share oxygen, heat, water treatment and compression. [9]

6.4.4 Sector coupling across electricity hydrogen heat and fuels

A local energy hub should route each energy carrier to its highest-value service. Electricity can be exported, stored or converted. Hydrogen can supply industry, transport, power generation or fuel synthesis. Heat can support steam production, digestion, drying and buildings. A regional network can share storage, reserve and maintenance resources. Each conversion step should have a defined service or contracted market.

6.4 Extending the value chain.

Electrolysis produces about 8 kg of oxygen per kilogram of hydrogen. The 175-tonne example would produce about 1,400 tonnes of oxygen before recovery losses. Saleable oxygen requires suitable purity, pressure, timing and local demand. Wastewater aeration, fermentation, oxy-fuel combustion, metals processing and gasification are possible uses. One 2025 study estimated hydrogen supply-cost savings of up to €0.39/kg from wastewater use under favourable conditions. Scale and transport distance controlled the result. [10]

Oxygen can also support methane partial oxidation and autothermal reforming. Partial oxidation converts methane and limited oxygen into hydrogen and carbon monoxide. Autothermal reforming uses this reaction to supply process heat and produce syngas. Electrolyser oxygen can reduce air-separation demand when purity and pressure match. Lifecycle emissions still depend on the methane source, leakage and carbon capture. Methane pyrolysis is a separate oxygen-free route that produces hydrogen and solid carbon. [11]

Heat should be used through a temperature cascade. High-grade heat can raise steam or support industrial processes. Lower-grade heat can preheat water, support digestion, dry materials or supply district heating. Heat storage can bridge timing differences. Distance and seasonal demand set the practical value.

SOEC co-electrolysis can convert steam and CO2 into syngas. The H2/CO ratio can support methanol, dimethyl ether or Fischer-Tropsch fuels. Ports may favour methanol or ammonia because storage and trade infrastructure already exist. Gas-connected inland sites may favour renewable methane. Chemical clusters may use syngas directly as feedstock. [4]

The business case should report gross hydrogen cost, delivered cost, contracted co-product revenue and whole-system cost against the counterfactual. Carbon intensity, renewable utilisation, service availability, water use and storage duration should also be reported. Stress tests should cover weather, grid outages, import limits, water shortages and equipment failures. This approach produces a place-based hydrogen system with clear services, measured benefits and resilient operation.

7.0 Storing Hydrogen at the Right Cost: Right Place, Right Time

Here is an uncomfortable truth about hydrogen: making it is the glamorous part. Electrolysers get the ribbon-cuttings and the press releases; nobody has ever cut a ribbon on a salt cavern. Yet the question of where we keep the stuff may decide whether clean hydrogen arrives at the right cost or at a very wrong one. Section 2.4 set out the options; here we ask what they cost.

Hydrogen is the lightest molecule there is, and it behaves like it knows it. At atmospheric pressure one-kilogram fills more than eleven cubic metres, so we squeeze it to hundreds of bar, chill it to −253 °C, or lock it inside ammonia. Every one of those steps costs energy, and energy costs money. At terawatt-hour scale, storage becomes a strategic question, far cheaper to get in the right place and at the right time than to fix later.

7.1 Right place, right time

A study for Gas Infrastructure Europe puts Europe's hydrogen storage needs at around 70 TWh by 2030 and 450 TWh by 2050. Repurposing every existing gas storage site would provide at most about 265 TWh, and repurposing takes 1 to 7 years, while new sites take 3 to 10 years [1]. The storage needed for the mid-2030s has to be started more or less now. Geology does not do next-day delivery. Location matters just as much: storage between where hydrogen is made (windy coasts) and used (industrial clusters, ports) makes the whole system cheaper. In the wrong place, you pay twice: to store and to move.

7.2 The supply chain is where the real price is made.

Most of the cost debate, is about the levelised cost of hydrogen (LCOH) at the electrolyser gate, around €6.71/kg in Europe. But nobody buys hydrogen at the gate; they buy it delivered on demand. The IEA warns that over long distances, transmission and distribution can cost up to three times as much as producing it [2].

In the UK, moving hydrogen 100 km by pipeline costs about €0.30–0.36/kg; moving it by tube trailer costs €2.40–4.70/kg, with compression alone making up 30–60% of the trucking bill [3]. Converting hydrogen into an easier-to-carry form has its own price: liquefaction uses 30–36% of the hydrogen's energy, an ammonia round trip can lose about half, and releasing hydrogen from liquid organic carriers (LOHC) takes 25–35% [4]. Add €2/kg of avoidable logistics to a €6.71/kg molecule and that's a 30% markup for nothing. The overall price of clean hydrogen will be shaped as much by how it is stored and moved to the end user as by how it is produced. The cheapest kilogram of hydrogen is the one that does not have to be converted, trucked or shipped twice.

7.3 So what does storing hydrogen cost?

There is no single storage solution. A recent state-of-the-art review sorts the options by scale, from metal hydrides and LOHC (small), through compressed, liquid and cryo-compressed hydrogen (medium to large), to geological storage (very large), and each suits a different job [5]. Table 1 gives indicative costs.

Storage option	Best suited to	Indicative storage cost (€/kg H_2)	The catch
Compressed gas tanks	Hours to days, small volumes	~0.50; ~1.60 incl. compression [3]	Very little hydrogen per euro of steel
Liquid hydrogen	Shipping, high-density uses	~1.60 incl. liquefaction [3]	Liquefaction uses 30–36% of the energy [4]; boil-off
Ammonia / LOHC	Long-distance trade	Storage cheap; conversion is the real cost	A round trip can lose about half the energy [4]
Salt caverns	Weeks to months, frequent cycling	~0.30 (3); ~0.74 across Europe [7]; 0.38–2.37 at Larne [13]	Needs suitable salt; brine disposal
Depleted gas fields / aquifers	Seasonal, very large volumes	~0.28 (3); ~1.38 across European sites [7]	Large cushion gas; purity; shown in Austria

Table 1. Indicative storage costs from different studies and assumptions (cycling frequency matters a lot), so read them as orders of magnitude. Converted at £1 = €1.15 and $1 = €0.92.

The pattern is hard to miss. For bulk, long-duration storage, underground beats above-ground by a wide margin. Capital costs tell the same story: roughly €15–90 per kilogram of capacity for salt caverns, depending on size, against about €470 for buried pipe storage [6]. The review cited above puts location-specific large-scale options mostly at €0.25–1.5/kg, with salt caverns the most promising for pure hydrogen [5]. And it isn't new: Teesside has stored hydrogen in salt caverns for about 50 years [8].

7.4 Think like an oil company: geological storage as a regional asset.

Here is the key message for policy makers: stop looking at geological storage as a line on a cost spreadsheet and start looking at it the way the oil and gas industry looks at a reservoir: as an asset. A region with the right rocks beneath it owns something that cannot be imported or copied. Europe's technical salt cavern potential has been estimated at 84.8 PWh of hydrogen, 23.2 PWh of it onshore [9], against about 1.1 PWh for Europe's entire gas storage fleet [1].

Take the island of Ireland. Since the Kinsale storage facility closed in April 2017 [10], Ireland has been one of five EU member states without domestic gas storage, and the State is now planning an emergency floating LNG terminal holding around seven days of national gas demand [11]. Meanwhile, the SEAI-funded HYSS study found room for up to 271 salt caverns in the Kish Basin off Dublin; eight of them, beneath the proposed Dublin Array wind farm, could hold about 1 TWh of hydrogen [12]. That is roughly the energy of the whole LNG ship, but clean, home-grown and refilled by Irish wind.

This is where the headline numbers undersell the opportunity. A levelised cost only prices a kilogram sitting in a cavern, and scale changes everything: in the Larne salt field in Northern Ireland, the storage cost falls from €2.37/kg for one rarely cycled cavern to €0.38/kg for seven regularly cycled caverns holding around 10 TWh [13]. Add what months of energy security in the ground are worth (surplus wind stored rather than curtailed, steadier prices in a supply shock, industry drawn to a reliable hub, lower risk premiums) and the benefits do not just add up; they compound. In the terms of the new energy equation, storage is where much of hydrogen's system and geopolitical value is earned.

7.5 Not at any cost: the honest caveats

None of this means drilling everywhere. Underground storage needs cushion gas, roughly 20% of working gas in salt caverns and around 50% in depleted fields [7], which ties up capital. Porous reservoirs raise purity, microbial and loss questions; salt caverns need brine disposal and monitoring for leakage and salt creep [13]; and communities must be part of the decision. The biggest risk, though, is economic: storage built ahead of demand is a stranded asset. Fed by a 20 MW electrolyser, the same Larne cavern would take about two and a half years to fill and push costs to around €10/kg [13]. The answer is staged storage: start with caverns built i] and

hydrogen valleys, as the GIE study expects up to 2030 [1], and expand as supply grows.

7.6 What policy makers should do (before someone else does)

- Map it and keep it. Treat subsurface data as public infrastructure and assess every gas field for hydrogen reuse before decommissioning.
- Solve the chicken-and-egg problem together. Plan wind, electrolysers, pipes and caverns as one hub.
- Start the clock now. Decisions made in 2026 set the price of hydrogen in 2035.

Clean hydrogen at the right cost needs storage in the right place, at the right time. Nature already built the vaults; the least we can do is show up with a plan.

8.0 CONCLUSION

Clean hydrogen will only succeed if it is pursued with integrity, environmentally, socially, and economically. The transition ahead is not simply about replacing one energy molecule with another; it is about reshaping the relationship between energy systems and the communities they serve. If hydrogen is to earn its place, it must protect ecosystems, reduce emissions, and strengthen resilience while also creating real opportunities for people, regions, and workers. The cost of inaction is already visible in rising climate impacts, widening inequalities, and the erosion of energy security. The cost of doing hydrogen poorly is a repeat of the extractive patterns of the past. But the value of getting it right is profound: cleaner air, healthier communities, skilled jobs, restored landscapes, and a more stable climate.

lean hydrogen cannot be pursued at all costs, nor justified at any cost. It must be developed at the right cost, the point where financial, environmental, social and strategic value align to deliver durable, net-positive outcomes for society.

For more than a century, energy decisions were governed by a single denominator: price. That narrow equation is no longer fit for purpose. The clean energy economy demands a multi-value energy equation, where hydrogen is assessed not only by €/kg but by its contribution to system flexibility, industrial competitiveness, community resilience, environmental integrity and geopolitical security. In this framing, hydrogen often appears “expensive” only when measured against the wrong metric.

The real risk is not that clean hydrogen costs too much today, but that failing to invest wisely will impose far greater economic, environmental, social and technological costs tomorrow, stranded fossil assets, missed industrial opportunities, weakened energy security, degraded ecosystems, and communities left behind in the transition.

Achieving the right cost means rejecting symbolic or uneconomic projects, avoiding hype-driven deployment, and focusing instead on hydrogen solutions that are targeted, scalable, and integrated into real system needs. It requires policies that reward long-term value, not short-term optics; technologies that deliver environmental integrity, not greenwashed claims; and projects that earn social licence through fairness, transparency and local benefit.

Ultimately, clean hydrogen succeeds not when it is cheapest, but when it is most aligned economically viable, environmentally regenerative, socially legitimate, and strategically essential. The right cost is therefore not a number, but a balance: a calibrated investment that maximises net energy value across all denominators.

This is the energy equation a serious clean-energy economy must adopt and the only pathway through which hydrogen becomes a transformative force rather than a costly illusion.

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