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REVIEW

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Striking the right balance: understanding the strategic applications of hydrogen in transitioning to a net zero emissions economy

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Abstract

The hydrogen economy has been a major vision for many futurists, for over half a century, as a way to transition to a world not dependent on fossil fuels (Bockris, Science 176:1323, 1972). As with many world views, the hydrogen economy has a complete perspective from which all potential change can be viewed. It therefore has a passionate if somewhat fundamentalist following. This paper outlines how electrification has now superseded much of the originally envisaged hydrogen economy and thus it deconstructs what is left of this vision to highlight hydrogen's strategic, niche, yet important roles, that remain for supporting the transition to a global net zero emissions economy. In our view, it is critical that policy-makers, industry and researchers take a strategic view on striking the right balance on the adoption of hydrogen. Here we propose a framework for hydrogen development globally, with support directed towards enabling the decarbonisation of harder-to-electrify sectors using renewable hydrogen, including, but not limited to: steel, cement, fertilisers, chemical feedstocks, shipping, and aviation.

Keywords Hydrogen, Strategic applications, Electrification, Emissions, Energy

Introduction

There is a strengthening consensus regarding how global power systems will be able to decarbonise in the relatively near future on the basis of rapidly falling renewable generation and energy storage costs. But what about fuel for transport, heating sources for metals and building products, heating of residential buildings, or chemical feedstocks for fertilisers? For these sectors there is a growing split between those who favour hydrogen versus those who favour electrification. We would suggest that both have roles to play, and that both offer significant economic development opportunities in the new, green economy.

For over 50 years hydrogen has been championed as a clean-burning gas that could help reduce greenhouse gas emissions [1]. The idea of a "hydrogen economy" is now enjoying a new wave of enthusiasm — but it is far from a silver bullet. Amid the current hydrogen hype, there is little discussion about when the technology can realistically become commercially viable, or the best ways in which hydrogen can be strategically used to rapidly cut emissions around the world.

Given the number of stakeholders, and different government agencies involved in potential hydrogen applications, a whole-of-government approach is required, combined with comprehensive consultation of broader

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stakeholders, including industry, researchers and the community, to deliver strategic and efficient outcomes.

Countries must use hydrogen intelligently, or otherwise risk supporting the development of a comparatively energy-intensive global economy that prioritises the use of hydrogen in applications that do not make economic or environmental sense. Such an approach would lead to a significant waste in valuable renewable energy resources and land space, increase costs for consumers and business, all while ultimately slowing emissions reduction, and jeopardising the achievement of a net zero emissions economy by 2050.

Here we outline the important role that different energy carriers have to play in the decarbonisation of the global economy, with a specific focus on the role of renewable hydrogen. Critically, however, we emphasise the need for striking the right balance to ensure hydrogen ultimately supports a reduction in emissions along a trajectory aligned with limiting global warming to 1.5 degrees, with inefficient applications avoided as far as possible, i.e. wherever energy-efficient alternatives exist.

Background

To reach net zero emissions by 2050, the global economy will need to rely on a mix of primary energy sources and energy carriers [2]. While zero-carbon electricity is expected to play a particularly important role – both as a primary energy source and direct energy carrier, other energy carriers, such as hydrogen and biofuels, also have critical roles to play [2, 3].

In recent work, carried out by the Energy Transitions Commission, it was forecast that electricity will need to make up between 67 and 72% of the global final energy share by 2050 in order to reach net zero emissions [3]. This will include powering the majority of transport, heating, and agriculture.

The next most significant energy carrier is expected to be hydrogen at 13 to 15%. Hydrogen's major direct roles are expected to be in cement, steel, and chemical feedstocks, with minor direct roles in heavy industry, heating, land transport, shipping, and aviation. Hydrogen may also have a critical role to play in producing ammonia and synthetic fuels for shipping and aviation [2].

Biofuels and/or bioenergy are also expected to play a minor role in heating, heavy industry, shipping, aviation, and agriculture – at around 4% of the global final energy share in 2050 – under a net zero emissions scenario [3].

The ETC also expects that fossil fuels will still represent around 7 to 10% of the final energy share in 2050, but will be combined with the use of carbon capture and storage (CCS) technologies.

The International Energy Agency (IEA) has also recently released its Net Zero Emissions scenario. Under this projection, the IEA predicts that around 50% of the global final energy share would be electricity by 2050. This is followed by 20% from fossil fuels, 14% from biofuels / bioenergy and 9% from hydrogen [4].

While there are some differences between the ETC and IEA scenarios, clearly both suggest a major role for direct electrification, and a more minor role for indirect

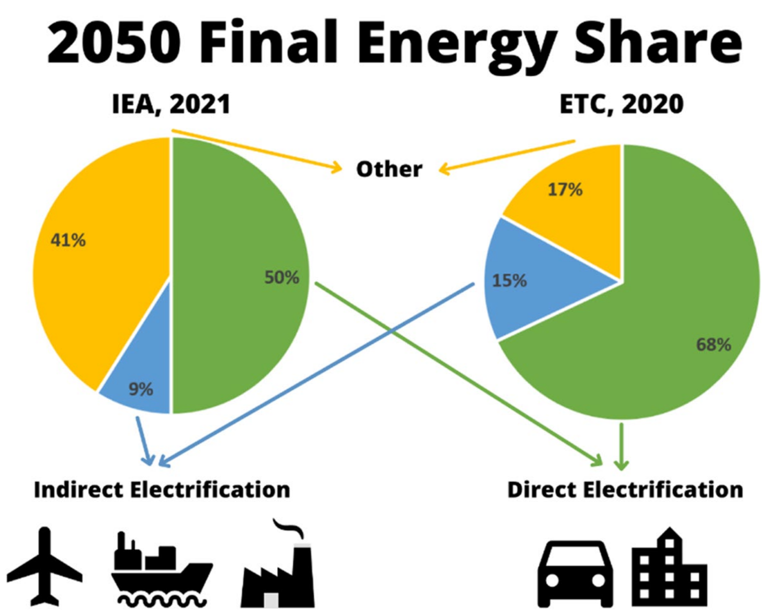

Fig. 1 Comparison of projected final energy shares in 2050 for IEA and ETC net zero emission scenarios. Author supplied

electrification, such as the use of renewable hydrogen – see Fig. 1.

Both the ETC and IEA scenarios align with findings in the Intergovernmental Panel on Climate Change's (IPCC's) report on Global Warming of 1.5 degrees. This report highlighted that the most stringent carbon reduction pathways are expected to rely heavily on electrification, with hydrogen having a more minor role [5]. Equally, however, these stringent pathways may have a lower feasibility compared to pathways where the strategic application of hydrogen is increased [2].

In comparison to direct electrification, renewable hydrogen - generated using renewable-sourced electricity - is energy-intensive to produce [6]. As a result, a lack of strategic planning on the use of hydrogen could lead to increases in emissions, relative to business-as-usual, by diverting renewable energy away from more energy- efficient applications that could deliver greater emission reductions. This is a critical risk to achieving net zero emissions by 2050.

Inefficient use of renewable energy would also necessitate higher investment in electricity generation, greater land space usage, and higher energy costs [7]. This leads to a diversion of capital and investment from more efficient applications, further slowing down the transition to a global net zero economy.

On the other hand, targeted applications of hydrogen are likely to be necessary to increase the likelihood of achieving net zero emissions globally by 2050, particularly in harder-to-electrify applications, such as: cement, steel, fertilisers, shipping, and aviation.

Herein lies the significant challenge for policy-makers, industry (including financiers) and researchers attempting to support a whole-of-economy, global transition to net zero emissions, while understanding the careful balancing act that must be struck in prioritising the utilisation of different energy carriers, particularly hydrogen.

All stakeholders must work together to achieve this balancing act, however, policy-makers must be particularly sensitive to the signals they send to the market with regard to prioritising one energy carrier over another for different applications. It is critical that there is a clear understanding of what the realistic economic costs and energy implications are of less energy-efficient carriers, like hydrogen, before prioritising their use.

There is no doubt that hydrogen has an important role to play in the global decarbonisation agenda, yet the current hype around the re-emergence of a hydrogen economy should be tempered by the reality of what the widespread use of hydrogen would actually mean for the global economy and achieving net zero emissions by 2050.

Understanding the challenges of producing and utilising hydrogen

While hydrogen is the most abundant element in the universe, rarely is it freely available. It must be unlocked from water (H_2O) or fossil fuels, such as methane (CH_4), then generally compressed or liquefied for transport and use.

Energy is lost at every step of the energy chain, as dictated by the laws of thermodynamics, which in turn leads to higher energy input requirements, and ultimately higher energy costs. This is illustrated through a simplistic comparison between the energy chain required to power a hydrogen fuel cell vehicle (HFCV) compared to a battery electric vehicle (BEV) – see Fig. 2.

In the example shown in Fig. 2, there are several more steps required for the delivery of energy to the HFCV, as compared to the BEV. Across each of these steps, energy is progressively lost, ultimately to the point where the quantum volume of energy required to power the HFCV is several times greater than that of the BEV. The result of this is higher energy costs, and a larger amount of land space required to support sufficient renewable energy generation. This in part outlines why in some applications, such as the majority of land transport, HFCVs are not expected to be competitive, nor a strategic approach.

What's more, in the case of many land transport applications it appears the market has already largely made up its mind, with vehicle manufacturers investing over $300 billion in the development of BEVs [8], leading to more than 350 models available on the market today [9]. This compares to fewer than 5 HFCVs.

Through this investment, BEVs have been able to achieve superior driving range to HFCVs, and while they will require longer periods for charging, they offer the added convenience of being able to charge while parked during the day, and/or overnight.

As for trucks, the US Department of Energy does not expect hydrogen semi-trailers to be competitive with diesel until around 2050, mainly due to the higher costs and lower durability of hydrogen fuel cells [10].

While hydrogen trucks may have a role to play in 20 to 30 years, this will be too late to assist in reaching a 2050 net zero target. As such, we must explore more energy-efficient options in the short to medium-term, including: electric trucks, electrified roads and electrified trailers.

This further emphasises the importance of prioritising the use of hydrogen in strategic, niche applications

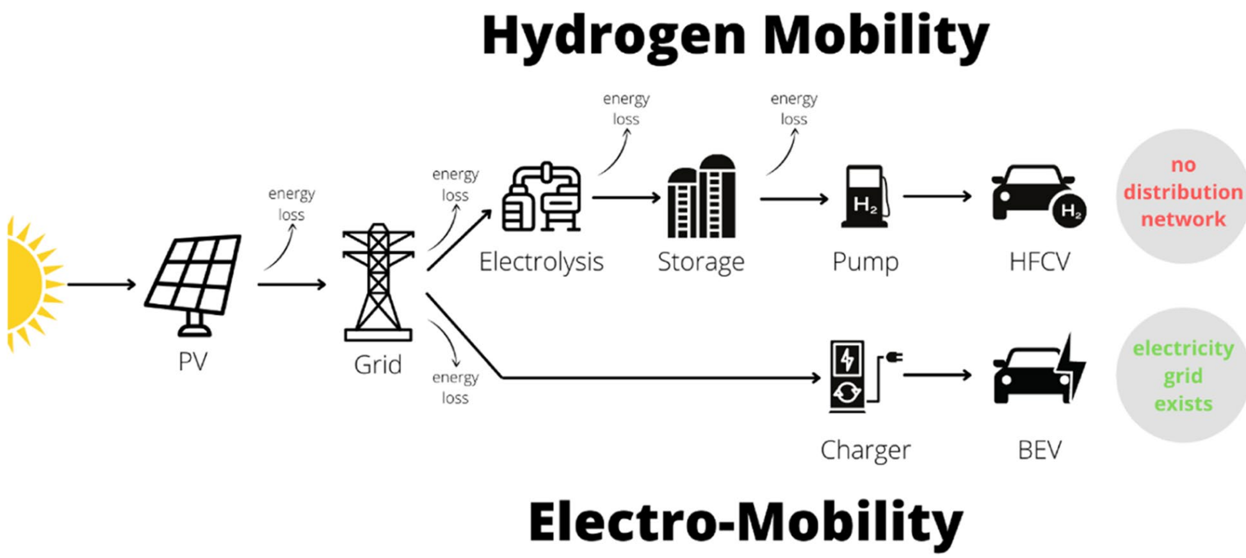

Fig. 2 Indicative energy flow comparison between using electricity directly to power electric vehicles versus using electricity to produce hydrogen to power fuel cell vehicles. Author supplied

where it is competitive, but at levels that do not significantly increase electricity generation requirements.

What about using fossil-based hydrogen?

Some argue that the cheapest and most efficient pathway to a hydrogen economy would be via the widespread use of fossil-based hydrogen, which could later be complemented by carbon capture and storage (CCS) technologies to become a 'clean' form of hydrogen [11, 12] – so-called 'blue' (steam methane reforming combined with CCS) and 'turquoise' (pyrolysis of methane combined with CCS) hydrogen.

The argument follows that the energy input requirements would be lower as the significant energy stored in fossil fuels could instead be utilised, rather than having to increase renewable energy generation to support the production of renewable hydrogen.

The major concern with this approach, however, is what guarantee is there that CCS technologies will be introduced in the future? And how long before these technologies are widely adopted for the production of hydrogen?

We would ask policy-makers and industry to carefully consider whether a fossil fuel pathway towards a hydrogen economy, based on the promise of a possible future introduction of CCS, could actually lead to an increase in emissions? In our view, this is a major risk that we should not accept, particularly at this critical juncture in the global climate situation [13].

As such, together with others [14], we argue that the focus should primarily be on hydrogen produced from renewable energy sources, in order to maximise emissions reduction, and minimise the risk of further increasing global dependency on fossil fuels, via hydrogen as an energy carrier. We expect there will be a role for blue or turquoise hydrogen, but in a minor capacity compared to renewable-based hydrogen.

It is also worth noting that in both the ETC and IEA scenarios previously outlined, CCS is relied upon to reach net zero emissions by 2050. We also agree that CCS has a critical role to play [15], but only as a last resort given the potential costs and risks to investors with regard to stranded assets [16, 17]. For example, with continuing cost reductions for wind, solar and other renewable energy generation, further investment in fossil fuel extraction today, based on the promise of CCS becoming economically-viable, is not only a risky proposition, but diverts much-needed capital away from emission-reduction technologies, such as renewable energy generation, batteries and electric vehicles.

Massive increases in electricity generation are already required

As outlined above, in order to limit global warming to 1.5 °C it is expected that up to two-thirds of the global final energy share will need to be met through direct electrification, and a further 10 to 15% will need to be met through indirect electrification e.g., hydrogen [18].

A massive, and unprecedented increase in electricity generation will be required to achieve this global final energy share. This increase will be in the order of 2.5 to 5 times total global electricity generation in 2020.

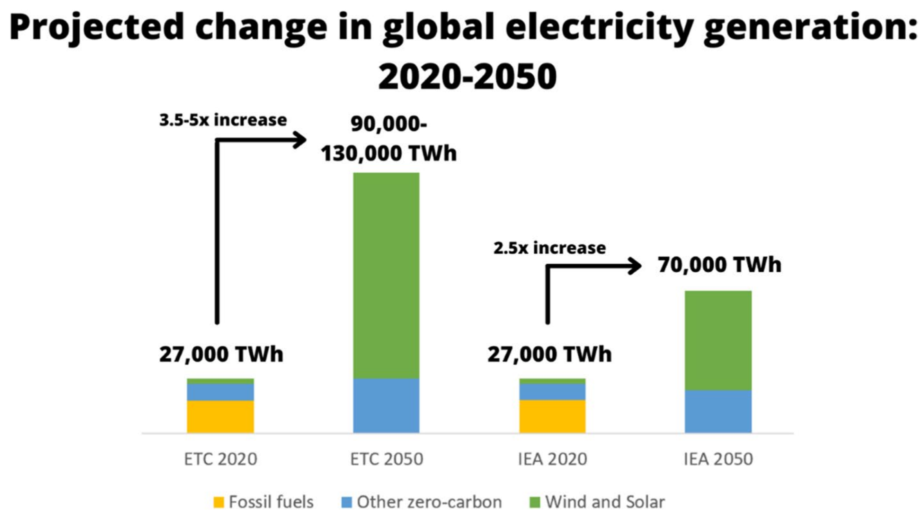

Fig. 3 Comparison of projected change in global electricity generation between 2020 and 2050 in both the ETC and IEA net zero emission scenarios. Author supplied

Importantly, to achieve net zero emissions by 2050, this massive increase in electricity generation will need to be primarily sourced from renewables – see Fig. 3 [18, 19].

While this may seem like a daunting task for the global economy, pause for a moment and consider the implications of increasing reliance on indirect electrification, such as hydrogen, beyond 15%. The end use of renewable hydrogen, and hydrogen-derived fuels, is energy-intensive, consuming two to fourteen times more electricity than direct electrification [6]. As a result, increasing the use of hydrogen would dictate the need for even greater investment in global electricity generation – beyond the unprecedented increases already required under a relatively energy-efficient, electrification-dominated pathway [3].

While it is hard to predict whether it will be feasible to achieve the already required significant increase in global energy generation – specifically in a time frame congruent with limiting global warming to 1.5 degrees celcius – it is certain that policy-makers and industry should act to reduce further inflationary pressure on increases in renewable electricity generation. Hydrogen is a clear inflationary pressure, requiring significant volumes of renewable electricity to be produced, and for many applications can, and should be avoided in favour of more energy-efficient alternatives, such as direct electrification.

This again highlights why a careful balance needs to be achieved, with the strategic use of hydrogen directed towards those harder-to-electrify applications.

So where are the strategic applications for hydrogen?

While electrification has emerged as the most energy-efficient, and cost-effective way to decarbonise the majority of the global economy [20], there are still some applications where electrification is expected to remain challenging for the foreseeable future. It is here that renewable hydrogen — produced from wind, solar and hydro energy — will be most important. The spectrum between those applications, spanning from where the use of hydrogen is unavoidable, to those applications where it is uncompetitive, is outlined in Fig. 4.

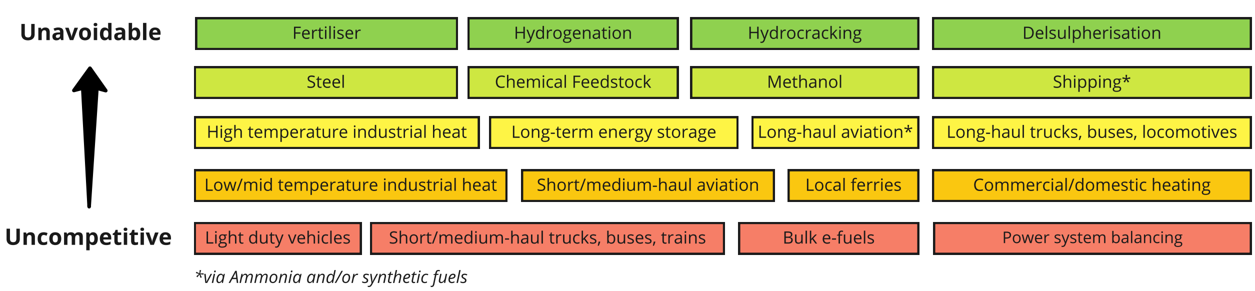

Fig. 4 Example of the spectrum of potential hydrogen applications spanning from unavoidable to uncompetitive. Author supplied; concept credit: Liebreich Associates [21]

Clearly there are many important applications where hydrogen has a critical role to play. Key among these is the production of fertilisers, without which there would undoubtedly be global food shortages, yet under current production pathways, remains heavily reliant on fossil-based hydrogen [22–24].

Moving down the spectrum of potential applications, hydrogen is also expected to play an important role in:

- the manufacturing of green steel (using renewable hydrogen for smelting instead of coking coal) [25, 26] as well as other mineral processing including battery minerals,
- as a chemical feedstock [27], and,
- in international shipping in the form of ammonia, or another hydrogen-based synthetic fuel [28–30].

It is expected that there will be little alternative to synthetic fuels for decarbonising aviation, however, the costs of production are significant [3]. Long-haul heavy vehicles are another potential application, but again are challenged by the total cost of ownership and the lack of a fuel distribution network [31].

While Fig. 4 helps to illustrate the spectrum of potential hydrogen applications, what it does not capture is the feasible timing of these applications. In the following section we propose a roadmap for policy-makers and industry to follow to support the adoption of strategic uses of hydrogen, aligned with the spectrum of applications outlined above.

A roadmap towards the strategic application of hydrogen

Policy-makers, together with industry, play a critical role in prioritising the strategic application of hydrogen across the spectrum of use cases previously described. While several governments around the world have already developed hydrogen strategies [32–34], what is still lacking is a higher degree of strategic prioritisation.

As such, we propose a clear roadmap for supporting the acceleration of renewable hydrogen production, and ultimately a reduction in the cost of producing renewable hydrogen to spur adoption – see Fig. 5.

This roadmap consolidates the broad range of evidence on the necessary steps for expanding renewable hydrogen production, and the strategic applications of hydrogen for decarbonisation previously discussed. It also presents a clear overview of the four key steps that policy-makers and industry should follow to maximise the emission-reduction potential of hydrogen.

As a first step, significant investment will be required in renewable energy generation to support the decarbonisation of the global economy, including the production of renewable hydrogen. Overall, total annual hydrogen production is expected to need to increase to more than five times 2019-levels by 2050 [35, 36]. This will require significant investment in both renewable energy generation and renewable hydrogen production.

Second, to assist with scaling the production of renewable hydrogen, policy-makers and industry (including financiers) should initially prioritise transitioning existing fossil-based hydrogen uses to renewable hydrogen. Some taxation measures may be necessary in the short-term to increase the competitiveness of renewable hydrogen with fossil-based hydrogen, but overall, it is expected that as renewable energy prices continue to fall, and production scales, it can become cost-competitive in the 2030s, and eventually cheaper by 2050 [37]. Regulating and/or mandating the use of renewable hydrogen over fossil-based

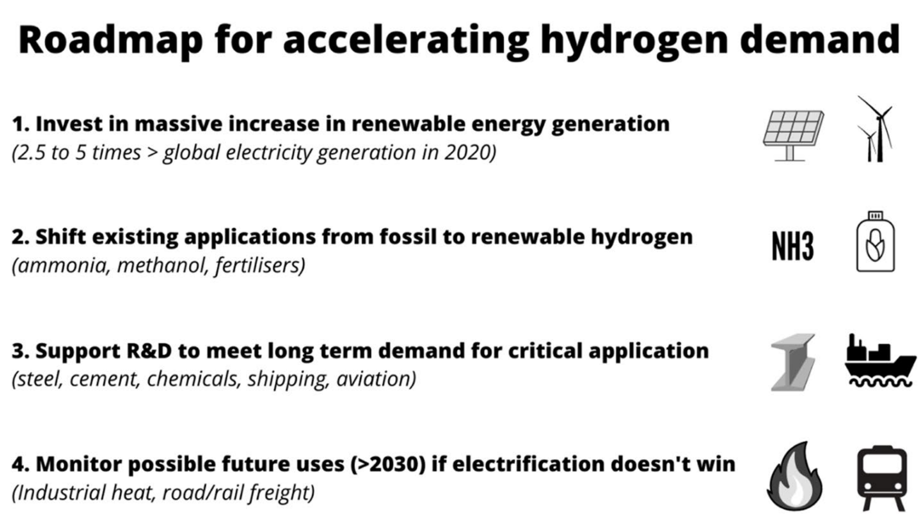

Fig. 5 Proposed roadmap for accelerating global hydrogen demand. Author supplied

hydrogen may also prove important if renewable hydrogen costs do not fall at a fast enough rate.

Third, while many potential hydrogen applications are not yet competitive, several are likely to be unavoidable on the journey towards net zero emissions. For example, the manufacturing of green steel, fertilisers and shipping fuel. Significant investment will be required to support R&D in these applications today, to meet this demand as it emerges over the medium-to-long term.

Finally, while it is too early to say whether hydrogen will play a role in some applications – such as long-haul trucking and residential heating – policy-makers and industry should continue to monitor developments. Supportive policies for these less competitive applications should be weighed against the unavoidable applications described above, within an appreciation that the more applications that are prioritised for hydrogen across the spectrum (see Fig. 4), the greater the energy generation requirements, land space, and costs will be - beyond those massive increases already forecast for a relatively energy-efficient, low-hydrogen uptake scenario.

As such, it is our view that these uncompetitive applications should not be a priority of policy-makers and industry in the short-term, but reassessed as the amount of feasible renewable energy generation that can be installed in the next 20 to 30 years becomes apparent. Only with this understanding will it be possible to make a clear determination regarding how much of the economy can afford to transition to hydrogen.

Leveraging hydrogen clusters to support strategic adoption in ports

The world must focus efforts on where renewable hydrogen can deliver the greatest environmental and economic benefits. Arguably, in the near-term, this is likely to be at and around ports [38–40]. The key value in this is that hydrogen does not need to be stored or distributed far from its generation and application. This will minimise the significant economic and energy losses that are fundamental to hydrogen's thermodynamic limitations.

Ports are generally co-located with or close to many industries. Ideally, renewable hydrogen clusters would be established at ports that are co-located with existing, fossil-based hydrogen users. As outlined previously, these applications form critical, initial off-take pathways for renewable hydrogen to utilise and, in turn, scale production.

Cement, steel and other heavy industries are also generally located at, or nearby ports. As outlined previously, these are priority applications for the use of renewable hydrogen given the large amounts of emissions they produce, and the challenges faced in fully electrifying these applications [2]. While there may be challenges in transitioning these end use cases in the short-term, co-location provides the opportunity for trials, and eventually adoption. Co-location also significantly improves the overall business case for the production of renewable hydrogen by having multiple, potential offtake applications.

Focussing on hydrogen production at ports also unlocks the ability to use hydrogen, or hydrogen-derived fuels, such as ammonia, to power ships. Additionally, it opens the opportunity to export hydrogen, or hydrogen-derived fuels, directly from the port, with minimal land transport costs.

Often airports and sea ports are also co-located in close proximity. This again would provide another potential offtake pathway by means of producing synthetic fuels for reducing aviation emissions [2, 41, 42].

Finally, if the development of hydrogen fuel cell truck technology accelerates before 2050 [31], renewable hydrogen would be available to power the significant number of semi-trailers that travel to and from shipping ports.

This targeted, and strategic approach to hydrogen production and application can spread the upfront risk across multiple applications (and associated industry and government stakeholders), while minimising the chance of early investment leading to stranded assets e.g. a national network of hydrogen refuelling stations for a fleet of hydrogen vehicles that may or may not exist in the future.

An overview of the range of potential end-use applications for renewable hydrogen at clusters formed at ports is shown in Fig. 6.

Conclusions

Clearly electrification, hydrogen, biofuels, and other energy carriers, all have important roles to play across the economy in supporting the achievement of global climate targets. It is important that the right balance be struck in the mix of energy carriers that is adopted in order to minimise the additional energy generation necessary to support the transition to net zero emissions by 2050, at the lowest cost.

As outlined in this paper, renewable hydrogen is a scarce and valuable resource with significant spatial implications in terms of the renewable generation requirements for production. As such, hydrogen should be directed towards those applications which are most difficult to electrify, and in turn, where its direct use, or the use of hydrogen-derived fuels, is effectively unavoidable.

Delaying the electrification of some applications – such as road transport and residential heating – on the promise of hydrogen eventually becoming competitive, will only perpetuate the continuing use of fossil fuels,

Fig. 6 Potential strategic applications of hydrogen clustered at ports. Author supplied

and seriously jeopardise the world's chances of limiting global warming to 1.5 degrees.

Here we have outlined a number of strategic applications for the use of hydrogen, which align with global scenario forecasts of what a net zero emissions economy will need to look like by 2050. It is crucial that a strategic approach to prioritising the use of hydrogen is adopted to minimise the inflationary pressure that increasing hydrogen usage will have on renewable energy generation. Policy-makers and industry should aim to avoid inducing additional pressure on energy generation, given the already unprecedented ramp-up in renewables installation that will be required, even under the most energy-efficient transition pathways that have minimal reliance on the use of hydrogen.

An acceleration in the ramp-up of renewable hydrogen is critical for achieving net zero emissions, but countries must follow a strategic roadmap – such as outlined in this paper – with ports forming an attractive starting point for these actions by policy-makers and industry. Only then can at least the remnants of a hydrogen economy be truly realised.

Abbreviations

BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
CH4	Methane
ETC	Energy Transitions Commission
H2O	Water
HFCV	Hydrogen Fuel Cell Vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
R&D	Research and Development
SRU	The Germany Advisory Council on the Environment

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