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Review

When will the hydrogen economy arrive?

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Abstract: The arrival of the hydrogen (H_2) economy has been the subject of many studies. Earlier articles were over-optimistic about the timing and extent of global H_2 uptake, and predicted private vehicles as leading the way to a H_2 economy. The recent strong rise in the global electric vehicle fleet has inevitably led to a reassessment of the prospects for H_2, at least for transport. This review paper examines how researchers over recent decades have envisaged how the H_2 economy would arrive, and why it was desirable, or even inevitable; it also looks at the future prospects for the H_2 economy. The key findings are as follows:

- Among the leading energy forecasting bodies, particularly the International Energy Agency (IEA), even the most optimistic scenarios predict under 10% H_2 penetration by 2050.
- IEA forecasts are very optimistic about the prospects for the introduction of carbon dioxide removal technologies and growth of dispatchable sources of low-carbon energy.
- More realistic IEA forecasts would increase the need for the growth of intermittent energy sources such as wind and solar. The subsequent requirement for energy storage would in turn help the case for H_2 adoption.
- No new technologies are on the horizon to decisively tip the balance in favor of H_2.
- It is concluded that a global H_2 economy is still distant, but it could arise in energy-poor countries such as Japan and South Korea, and it could find a niche in freight transport.

Keywords: climate change; electric vehicles; energy futures; forecasting; H_2 economy; hydrogen fuel cell vehicles; transport

Abbreviations: BECCS: bioenergy with carbon capture and storage; BEV: battery electric vehicle; CCS: carbon capture and storage; CCUS: carbon capture, utilization and storage; CO_2: carbon dioxide; EIA: Energy Information Administration (USA); EROI: energy return on investment; ESME: ecosystem maintenance energy; EV: electric vehicle; GHG: greenhouse gas; H_2: hydrogen; HC: Hydrogen Council; HFCV: hydrogen fuel cell vehicle; ICEV: internal combustion engine vehicle; IEA: International Energy Agency; IJHE: International Journal of Hydrogen Energy; IPCC: Intergovernmental Panel on Climate Change; IRENA: International Renewable Energy Agency; LH_2: liquid hydrogen; LHV: lower heating value; NG: natural gas; OECD: Organization for Economic Cooperation and Development; OPEC: Organization of the Petroleum Exporting Countries; RE: renewable energy; SRM: solar radiation management; WEC: World Energy Council

Units: EJ: exajoule (10^{18} Joule); Gt: gigatonne (10^9 tonnes); GW: gigawatt (10^9 watts); Mt: megatonne (10^6 tonnes); MW: megawatt (10^6 watts); p-km: passenger-kilometer

1. Introduction

Nearly 150 years ago, the French writer and visionary, Jules Verne, foresaw H_2 produced from water as the source of energy for the world [1]. Since then, many forecasts have been made for the advent of the H_2 economy. (Precise definitions of what is meant by the term "H_2 economy" are difficult to come by, but, here, it will be taken to mean hydrogen as the dominant energy carrier.) One interesting development in the latest cycle is the rise in papers published on the topic of the H_2 economy that have included a discussion on liquid hydrogen (LH_2), or ammonia. The rise in interest for ammonia as a hydrogen carrier has largely been a response to the challenges of transporting hydrogen at scale over large distances [2], as is done with (liquid) natural gas (NG), and because of the possibility of ammonia co-firing with existing fossil fuel power stations. As for hydrogen, interest in ammonia has led to the development of the term "ammonia economy" [3], although it is yet to gain wide spread use.

Most of the hydrogen (H_2) forecasts to date have proved to be over-optimistic, but wrong predictions are to be expected, particularly those for decades into the future. As has been said: "prediction is difficult, especially about the future". We have to attempt to predict the future, since, even in our everyday lives, our image of the future shapes our actions in the present. In the energy field, planning to build a new hydro dam or oil pipeline involves not only forecasts of energy demand—and energy prices—decades into the future, but also future river flows for hydro projects, or an oil field output profile for an oil pipeline.

An important consideration when predicting H_2 use is that, in general, it has proved far easier to estimate overall future energy use than it has been to forecast the future use of a specific energy type or carrier. Nuclear energy provides a good example. In the 1970s, the International Atomic Energy Agency forecast that the global installed nuclear energy capacity would be around 2500 GW by year 2000. The actual value was just under 350 GW [4]. Corresponding forecasts for all global energy use were also often in error, but typically by less than a factor of two for a 2–3-decades-ahead forecast [5].

According to Vaughan [1], H_2 research interest today is now backed with multi-billion USD funding pledges from various governments. However, as the International Energy Agency (IEA) [6] has stressed, H_2 has already seen several "hype cycles"; the big question is whether this one is different.

Similar to that shown in the study of [7], Figure 1 shows that interest in the "H_2 economy" (as evidenced by Scopus papers with this term in the title, abstract or keywords) expanded after the early 2000s, but then stagnated. Nevertheless, as can be seen in Figure 1, since 2018, there has been a very marked upsurge in research interest, with hundreds of papers published each year in which there is significant corresponding interest in LH_2 and ammonia production from hydrogen.

Although, as documented in this paper, there have been many reviews on the H_2 economy, this review has the majority of references from years 2020 to 2022, and it thus provides a much-needed update. This is important, since the recent rise of electric vehicles (EVs) has altered the way in which the future of the H_2 economy is now envisaged. Also new is a discussion on how technological fixes like CO_2 removal (CDR) and solar radiation management (SRM), as well as fossil fuel depletion, will affect the uptake of H_2.

The rest of this review is organized as follows. Section 2 briefly discusses the methods used in this review. In Section 3, views on the H_2 economy before the rise of EVs are discussed. Section 4 examines the rise of EVs and their impact on H_2 prospects. Section 5 evaluates possible future trajectories for the H_2 economy, particularly those of the IEA, while Section 6, spells out the implications of these energy choices for H_2. Section 7 investigates possible developments that could favor H_2 uptake, Section 8 discusses the limitations of the study and Section 9 offers conclusions.

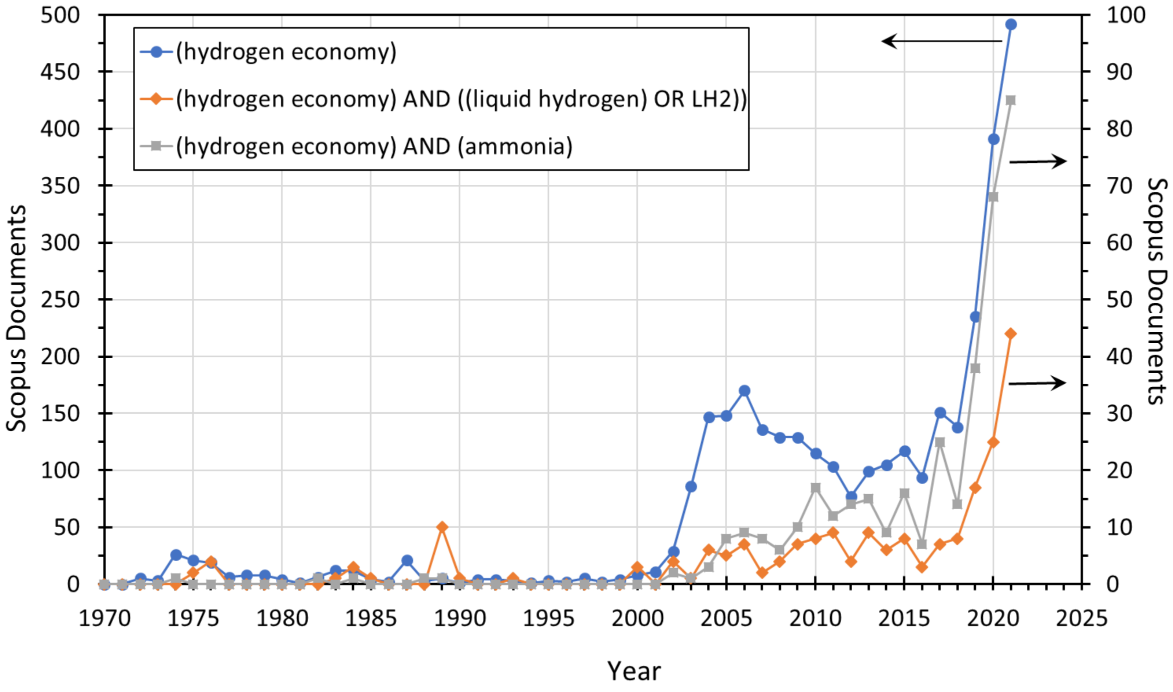

Figure 1. Documents published annually from 1970 to 2021 found in the Scopus database using the search terms, as shown in the legend, appearing in either the title, abstract or key words.

2. Methods

Given the vast number of published reviewed papers on the future of H_2 shown in Figure 1 (over 1100 on the "H_2 economy" alone in the three years from 2019 to 2021), only some representative papers can be included in this review. Figure 2 diagrammatically represents the approach taken in selecting papers for this review. H_2 economy forecasts were divided into those published before 2017, and those on or after 2017. For forecasts made before 2017, preference was given to papers with numerical model-based predictions or scenarios for H_2 uptake at various times in the future, especially for the year 2050. Also included in this group are some papers and books which were critical of H_2 use, based on such factors as the existing cost of alternatives or perceived technological barriers at the time of writing. The rest of the papers were on new H_2 sources and markets, global environmental problems which provide a background for future energy choices, global energy forecasts and miscellaneous papers not easily classifiable. Nearly all papers, apart from the pre-2017 H_2 papers, were published between 2020 and 2022.

For EVs, only the most recent data and forecasts available were used. Several non-reviewed web publications were also included to provide the latest industry-based forecasts. Eight publications of the IEA were included, reflecting the importance of their energy scenarios and modeling.

H_2 economy forecasts made after the rapid rise in EVs were, in general, more modest, particularly those made by the various IEA scenarios [8], which are discussed in detail. Some recent optimistic futures for H_2 were also reviewed, but none were based on modeling, and are better viewed as desirable or aspirational targets rather than probable H_2 futures.

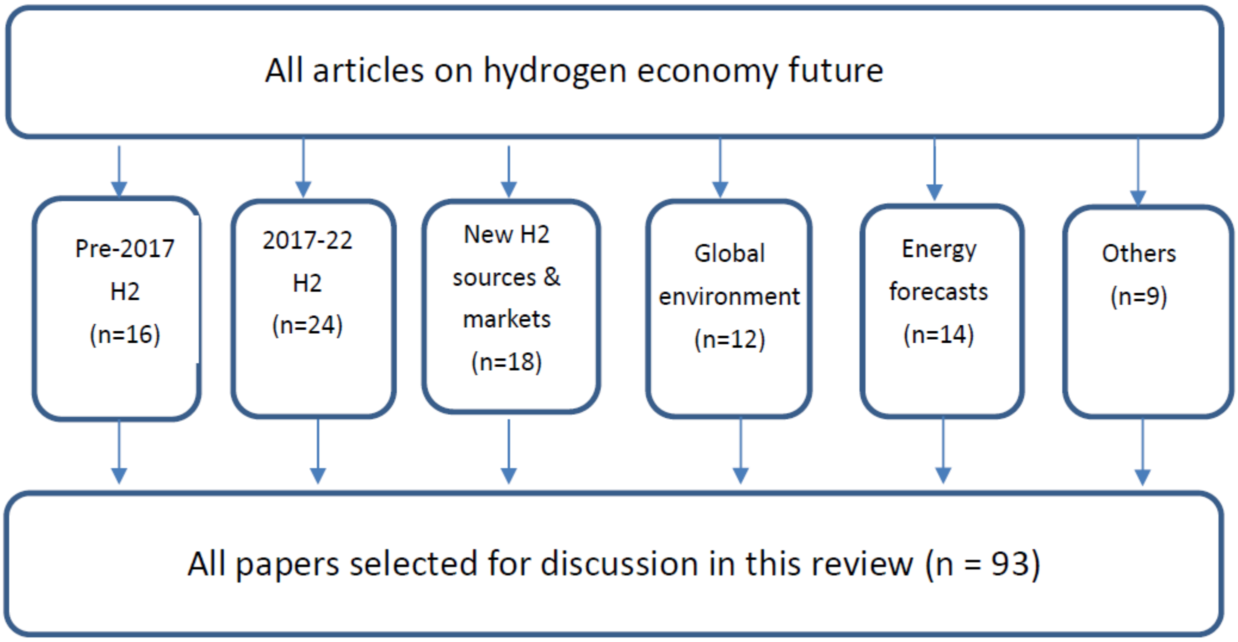

Figure 2. Flow chart for paper selection in this review.

3. H_2 research before rise of electric vehicles

This section examines forecasts and scenarios for the advent of the H_2 economy, i.e., before the largely unanticipated success of EVs, especially for passenger travel.

McDowall and Eames [9] provided a good review of research on the topic up to 2006. Many, if not most, H_2 researchers have, in the past, seen vehicular transport as spearheading the shift to a H_2 economy (e.g., [10]). Papers from the 1970s saw H_2-fueled aircraft as leading, but more recently, road transport has been favored, although interest in H_2-powered planes has not gone away [1]. However, in 2016, McDowall [11] found that forecasts for H_2 fleet numbers were optimistic compared with historical rates for other alternatively-fueled light-duty vehicles, such as diesel in France. (Nevertheless, since then, the introduction of EVs in Norway has been faster than even the maximum rates he reported.) In this section, only pre-2017 forecasts are reviewed. Forecasts made on or after 2017, when it became clear that EVs would be the leading replacement for internal combustion engine vehicles for light-duty vehicles, are considered in Section 4.

In a 1985 paper entitled "When will hydrogen come?" Marchetti [12] assessed the future for H_2 by using two different methods. Both his methods foresaw "sizeable amounts" of H_2 produced from non-fossil fuel (non-FF) sources as early as the year 2000. In a highly cited 2003 paper, Barreto et al. [13] produced a model for the global growth of H_2 use and output over the 21st century in a "sustainable development scenario", based on the SRES-B1 scenario of the Intergovernmental Panel on Climate Change (IPCC). H_2 production was forecast to reach about 32, 212 and 336 EJ in 2020, 2050 and 2080, respectively. Most H_2 was assumed to be produced from natural gas (NG) steam reforming, biomass gasification and, beginning in 2030, solar thermal.

In a 2007 paper, van Ruijven et al. [14] modeled H_2 production under three technology development scenarios (H_2-pessimistic, H_2-intermediate and H_2-optimistic) and two policy scenarios (climate policy and no climate policy). The H_2-pessimistic scenario saw no H_2 produced at all, regardless of climate policy. In the H_2-intermediate scenario, negligible H_2 production occurred before 2040, and slightly more with a climate policy. Both types of H_2-optimistic scenarios saw H_2 production of about 50 EJ by 2040. By 2060, the "no climate policy" produced about 120 EJ of H_2, but the climate policy case saw slightly less produced; by 2100, the difference was marked: 290 EJ compared with around 170 EJ. A similar result emerged with H_2-intermediate: H_2 production in 2010 was 3–4 times higher in the no climate policy case. The surprising conclusion from this model is that the adoption of strong climate policies will not help—and could hinder—the advent of the H_2 economy. This conclusion is at odds with almost all other H_2 future papers, which regard H_2 production as important for climate change mitigation [9].

In another highly cited 2007 paper, Marbán and Valdés-Solís [15] attempted an account of the future path toward the global H_2 economy. In their most favorable case, by 2050, "30% of the cars will be powered by hydrogen feed [fuel cells] and there will be a capacity of 200–300 GW in installed [fuel cells] to cogenerate heat and electricity in the residential sector". They also stressed two conditions that must be met: strong international action on climate change and cost reductions for H_2 "production, distribution, storage and utilization".

The findings of Sgobbi et al. in their 2016 paper [16] occupy an intermediate position on the prospects for the H_2 economy. For the European Union, their model results showed that, even in their long-term decarbonization scenario, "the share of hydrogen in the final energy consumption of the transport and industry sectors reaches 5% and 6% by 2050".

There were also some even more pessimistic forecasts for vehicular H_2 prospects, mainly because of perceived technical problems with fuel cells and on-board H_2 storage [17]. In the first decade of this century, two prominent critics of H_2, Joseph Romm from the US and Ulf Bossel from Germany, achieved widespread coverage of their views. In 2004, Romm published his book *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate* [18], which now has nearly 400 citations in Google Scholar. In this book and a later publication [19], Romm argued that "hydrogen cars are an exceedingly costly greenhouse gas strategy". Instead, he promoted hybrid-electric vehicles and fuel efficiency for the US. Bossel [20], likewise, saw H_2 as an expensive and energy-inefficient fuel for vehicles, writing that: “Electricity obtained from hydrogen fuel cells appears to be four times as expensive as electricity drawn from the electrical transmission grid.” These higher costs were in turn caused, he argued, by the much higher energy losses within an H_2 economy. Because of these losses, and the need for the plant to produce H_2, the cost of electricity produced from a hydrogen fuel cell must always remain higher than the electricity drawn from the grid to produce it, despite the large reductions in utility-level renewable energy (RE) system costs (photovoltaic system costs, for example, are reported to have fallen five-fold over 2010–2020 [21]).

Early advocates of the H_2 economy saw cheap nuclear power as providing zero-carbon, competitively priced H_2, as Peplow [22] pointed out. Further, battery technology was then under-developed. Even in 2005, Nobel laureate George Olah [23] advocated for large-scale H_2 production by the electrolysis of water, using nuclear electricity. But, because of his doubts about the storage and distribution of gaseous H_2, he argued for reacting H_2 with CO_2 to make methanol for use in a “methanol economy”. Later, Bockris [24], an early advocate of the H_2 economy, also advocated for a methanol economy, but with RE providing the electricity for H_2 production.

Robert Cherry, in 2004 [25], warned of adverse consequences of a shift to hydrogen fuel cell vehicles (HFCVs) in the USA, including “delayed development of other energy alternatives, hazards of catalyst or hydride metals, disruptive employment shifts, land usage conflicts, and increased vehicle usage”. These objections, however, would likely apply equally to EVs.

4. Rise of electric vehicles

EVs have dominated the light vehicle market for alternative propulsion systems in recent years. Although global fuel cell electric vehicles (HFCVs) totaled over 51,000, in 2021, which is an approximately 55% increase from the end of 2020, this needs to be put in context. As the IEA, which promotes both EVs and H_2 vehicles stated: “As a share of total hydrogen demand, however, transport represents only 0.03%, and as a share of total transport energy, hydrogen represents only 0.003%” [6].

Most research after 2016 had very modest H_2 forecasts (e.g., [26,27]), but some publications still saw significant production for H_2 as early as the year 2030. As expected, this optimism was particularly true for H_2 advocacy organizations. The Hydrogen Council (HC) [28] foresaw H_2 accounting for 18% of global final energy demand by 2050, and producing 6 Gt of annual CO_2 abatement. Their approach combined IEA [29] global energy forecasts for various sectors, along with “Hydrogen Council members’ input on the potential for hydrogen adoption in each sector” [28]. Their “vision statement” called for 10–15 million HFCV cars and 0.5 million trucks by 2030, and 400 million cars, 15–20 million trucks and five million buses by 2050. A later report from the HC and McKinsey [30] envisages an even more crucial role for H_2: “Hydrogen is central to reaching net zero emissions because it can abate 80 gigatons of CO_2 by 2050”.

Another 2017 report [31] was similarly optimistic, with a forecast for the global HFCV fleet of over 22 million by 2032. Nevertheless, 22 million vehicles would still only be a little over 1% of the forecast 2032 global vehicle fleet [32]. In Japan, a 2019 official report [33] aimed at realizing a national hydrogen society stated that: “Japan will try to introduce about 40,000 FCVs by 2020, 200,000 by 2025 and 800,000 by 2030”. But, IEA figures [6] for Japan show only 4,200 H_2 vehicles in 2020, ranked fourth after South Korea (10,000), the USA (9,200) and China (8,500—nearly all trucks and buses). A far more optimistic forecast made in 2022 [7] has seen “up to 400 million passenger vehicles running on hydrogen” globally by 2050.

Despite these optimistic H_2 forecasts, the recent astonishing rise to popularity of EVs has led most researchers to a scaling down in the medium-term prospects for H_2, especially for vehicles. Even in Japan, with its stated commitment to an H_2 economy, the EV fleet, at the end of 2020, numbered 334 thousand [34], which is almost two orders of magnitude larger than its HFCV fleet. By the end of 2021, there was a cumulative global fleet (excluding two & three wheelers) of over 16.5 million EVs, compared with only around 43 thousand HFCVs. The latest IEA forecast is for 200 million EVs by 2030 in their baseline "Stated Policies Scenario" and 350 million in their ambitious "Net Zero Emissions" scenario—again excluding two & three wheelers [35]. Bloomberg [36] has reported that the auto industry has a production target of "40 million per year by 2030".

An important reason for the less-than-hoped-for growth of HFCVs in Japan, as elsewhere, is the relative lack of refueling infrastructure, compared with electric vehicles. This infrastructure gives EVs in the short- and medium-term an enormous advantage, which is being translated into EV sales. Globally, publicly accessible slow and fast public EV chargers numbered 1.3 million in 2020, a seven-fold rise over five years [35]. In contrast, H_2 refueling stations totaled only around 530 globally in 2020. The ratio of H_2 vehicles to refueling stations is increasing, a further obstacle to their uptake [6]. Since home-based HFCV refueling is unlikely, the ability to charge EVs at home provides them with a significant advantage over HFCVs.

Figure 3 demonstrates that, ever since the early 1960s, research interest in EVs has been higher than for HFCVs, and the share of all vehicle-related articles is now about nine times higher. Figure 4 shows the global fleets for both HFCVs and EVs over the years, beginning in 2010. By year 2020, EV paper numbers were 2–3 orders of magnitude higher.

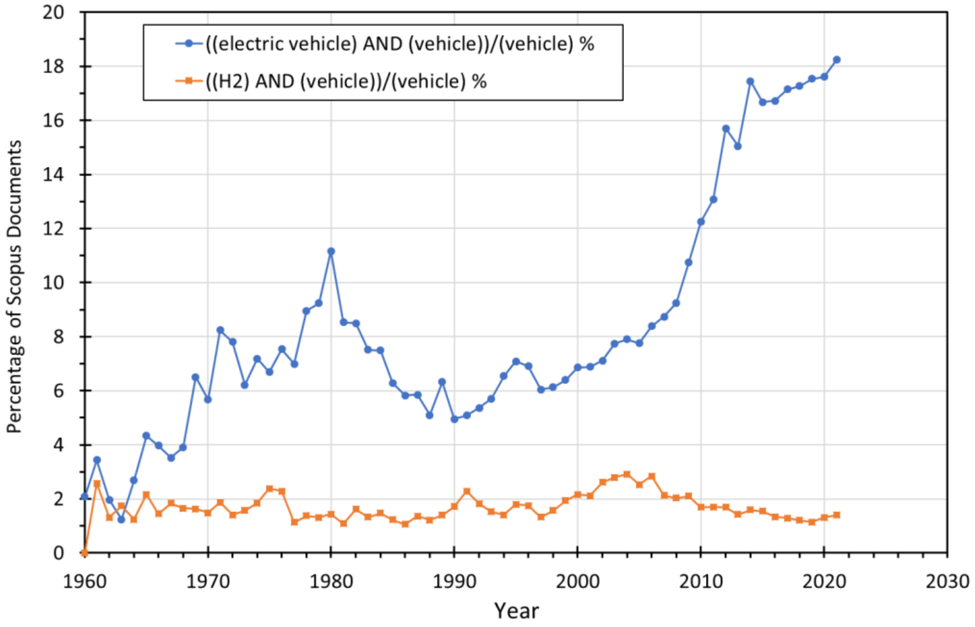

Figure 3. Comparison of annual Scopus database papers on EVs and HFCVs, normalized by all vehicle articles between 1960 and 2021.

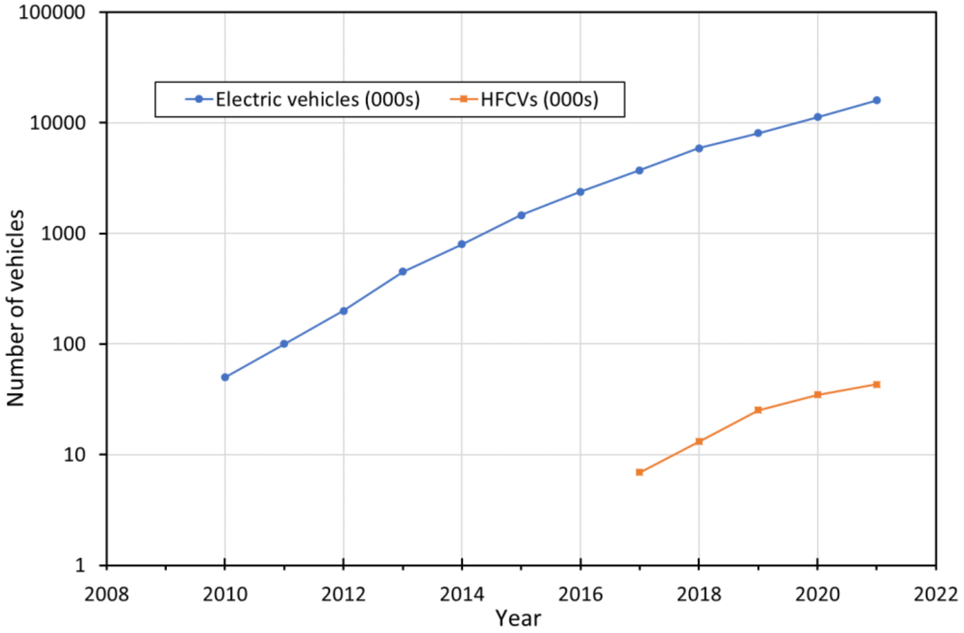

Figure 4. Cumulative sales of EVs and HFCVs by year. Note the y-axis logarithmic scale. References: [6,35,37].

What other factors account for the market success of EVs? First, like HFCVs, EVs have made great progress over the past two decades or so, particularly with battery technology and costs. Like H_2, electricity is an energy carrier that can be made from a variety of energy sources, thus enhancing energy security; EVs can also potentially reduce urban air pollution. More importantly, EVs are presently cheaper to own and operate than HFCVs, partly because of the already extensive electricity grids. Ajanovic and Haas [38] have shown that, in 2016, the total costs for HFCVs (in Euros per 100 km) were far greater than those for EVs, mainly because of much higher capital costs.

Nevertheless, the path to present EV dominance has not been a straightforward one. Bakker et al. [39] analyzed the competition between battery electric and hydrogen vehicles between 1990 and 2009 over three time intervals: 1990–1997, 1998–2005 and 2006–2009. They found that, while industry interest in EVs, as represented by the number of vehicle prototype models presented to the public (and mentioned in the journal *Autoweek*), heavily favored EVs in the earliest period, the reverse was true for the 1998–2005 period. In the 2006–2009 period, EV models once more outnumbered hydrogen car models 34 to 23. This EV dominance has continued ever since 2009: the number of light duty models available for purchase in 2020 was around 370 for EVs (with most of the models being sports utility vehicles), against only three for HFCVs. However, 12 bus and five truck HFCV models were also available [6,35].

Although H_2 may never be significant for private road vehicles, other applications of H_2 are possible. The IEA [6] has promoted the idea of repurposing NG pipelines, and even liquefied NG terminals at ports, for H_2. H_2 is also used (34 Mt) to produce ammonia, with 70% of ammonia used for fertilizers. However, in the future, ammonia may also be used to fuel freight ships. Oldenbroek et al. [40] examined, in a European context, how parked and grid-connected HFCVs could contribute to a zero-emissions future.

Two other papers also examined how parked HFCVs could bring sustainability benefits. Liu et al. [41], looking at Hong Kong, studied energy management and optimization for "renewable energy systems integrated with energy storage of hydrogen and battery vehicles for power supply to a diversified net-zero energy community". They found that peer-to peer was superior to peer-to-grid energy trading for reducing carbon emissions, grid imports and energy bills. Further, HFCVs were superior to EVs in some aspects, but not in others. He et al. [42] modeled a hybrid electricity-hydrogen sharing system in a Californian setting. They concluded that their proposal could provide guidelines for "carbon-neutral transition with district peer-to-peer energy sharing, zero-energy buildings, hydrogen-based transportations together with smart strategies for high energy flexibility".

5. Possible future global energy trajectories

Future hydrogen production will depend on future energy production, both total primary energy and the energy sources used [43]. Table 1 gives data from the IEA [8] for their global energy scenarios for the year 2050: Stated Policies Scenario (STEPS); Announced Pledges Scenario (APS); Sustainable Development Scenario (SDS); Net-Zero Emissions by 2050 (NZE). Even the APS is optimistic, as such pledges given in the past were seldom met. The NZE scenario is really a back-casting exercise to give one possible energy mix (the lowest-cost solution) which would give zero CO_2 emissions by the year 2050. Carbon capture, utilization and storage (CCUS) is used with much of the FF in NZE, and bioenergy with carbon capture and storage (BECCS) is used to offset the remaining FF emissions. Only this scenario gives some reduction in global primary energy (about 8%) in 2050 compared with 2020.

Table 1. Global primary energy (EJ) in 2050 under four IEA scenarios.

Energy source	2020 Actual	STEPS 2050	APS 2050	SDS 2050	NZE 2050
Total[1] (EJ)	589.1	743.9	674.4	577.9	543.0
Wind/solar (EJ)	10.4	74.8	115.6	149.2	198.0
Other RE[2] (EJ)	82.3	134.9	149.9	167.2	164.4
Nuclear (EJ)	29.4	40.5	48.5	51.4	60.6
Fossil fuels (EJ)	466.3	491.6	359.1	209.2	120.1
CO_2 emissions (Gt)	34.2	33.9	20.7	8.2	0.0
Wind/solar elec. (%)	9.1	40.2	53.3	62.8	69.7
FF elec. with CCUS (%)	0.0	0.8	16.1.	45.2	83.7

Source: IEA [8]

[1] Energy sources do not sum to total due to rounding.

[2] Includes traditional biomass (estimated at 24.1 EJ in 2020, and declining thereafter in all scenarios).

In this section, we examine two idealized possible futures for global energy:

- continued dominance of FFs, as in the IEA STEPS and APS options;
- non-FF energy sources becoming dominant, as in the IEA SDS and NZE options.

Just as is the case for today, the actual energy mix for some decades to come will likely include all energy groups, as shown in Table 1.

Other organizations have made global energy forecasts for the 2040–2050 period. The Organization of the Petroleum Exporting Countries (OPEC) [32] latest single-value forecasts for 2045 most closely align with the IEA STEPS option. The BP [44] "New Momentum" scenario is close to the IEA base-case STEPS, while BP's "Net Zero" scenario is a little below the IEA's APS case. Shell [45] also has three scenarios for 2050 global energy: Waves ("wealth first"), Islands ("security first") and Sky 1.5 ("health first"). All Shell scenarios have large increases in overall energy, but unlike the IEA and BP, the Sky 1.5 scenario only achieves the 1.5 °C temperature limit by 2100; FF use is accordingly higher (at 45% of the total) in 2050.

5.1. Continued fossil fuel dominance

Strong forces are at work to continue high levels of FF use. Hence, it is possible—for some time at least—that an energy system dominated by FF use, as at present, will continue. If FF production is curtailed for climate change reasons, most FF proved reserves will become stranded assets with zero worth [46]. Most OPEC nations are heavily reliant on oil exports; if these fell to zero in the extreme case, the effect on their economies would be severe. A very different concern is the sulphate aerosols produced from FF combustion, which act to reduce climate forcing and thus promote global warming. Were these aerosols to be suddenly removed (by either emissions control or a cessation of FF use), the air quality would be improved and the global temperature could rebound by 0.5 °C, or even more [47]. Yet another concern is the growing need for energy independence to counterbalance geopolitical instability. While renewable energy can provide some independence, securing large-scale long-term energy storage without the use of FF (or perhaps nuclear energy) remains a significant challenge.

For these reasons, we can expect cuts in FF to be resisted, particularly in both presently low-energy-use countries and in FF exporting countries. In 2021, according to the IEA [8], FF use rebounded strongly. FF advocates can hold out the theoretical promise of technologies for CDR by either mechanical or biological methods, or via solar geoengineering, and especially the use of SRM, by injecting millions of tonnes of sulphate aerosols into the lower stratosphere.

The most discussed CDR methods, i.e., carbon capture and storage (CCS), which is CO_2 removal from power plant exhaust stacks followed either by utilization or storage deep underground, and BECCS, would both allow continued FF use, as would biological carbon storage in plants and soils [48]. Simbeck [49] even saw CCS as "the essential bridge to the H_2 economy". However, both are largely unproved technologies [46], are energy intensive and would take decades to implement on a large scale. One much-discussed approach for mitigating climate change, i.e., mechanical negative emissions technology (see e.g., [44]), would, however, advance the rate of FF depletion. The reason is that commercially unproven technologies such as direct air capture (and also mineral weathering) are projected to not only be costly, but also very energy-intensive [50–52].

In contrast, supporters claim SRM could be implemented quickly and cheaply to offset climate forcing from rising greenhouse gas (GHG) atmospheric concentrations, and that, if the world continues on the present course, the climate changes could be so severe that, in a decade or two, all regions would be better off with SRM implementation [53,54]. Political objections would then be muted. However, even if SRM could produce the desired global average temperatures and precipitation, regional values could vary greatly from those desired. Further, ocean acidification will continue unabated, and, given that this problem requires urgent attention, ocean alkalinity enhancement will be needed, which will be expensive and carries its own set of risks [55]. Given the uncertainties, SRM—if used at all—will probably only be used for regional climate amelioration, such as changing the albedo of crops or urban surfaces [56]. If so, more conventional approaches will still be needed to mitigate most of the risks from carbon capture (CC). Biermann et al. [57] have argued that, even if SRM delivered on its promises, its political risks are too high in the present strained international climate.

What are the implications for H_2 in this high FF scenario? In this scenario, it makes little sense, for example, to undertake large-scale steam reformation of NG to produce H_2 for the partial replacement of NG in the gas grid. In general, if H_2 were to be produced mainly from NG or coal, without coupling this to CCS, GHG emissions, and thus global warming, could be worsened, since further energy losses would occur from conversion to H_2; and, a new H_2 infrastructure would be need to be built. In summary, an energy future still dominated by FF would seem to have little need for H_2 beyond existing uses [43].

In the long run, however, continued heavy use of FF will eventually lead to depletion. This depletion would be hastened if energy-intensive mechanical CDR was heavily deployed. The present mainstream thinking is that concerns about peak oil production are now misplaced; instead, peak oil consumption is more likely, driven by the urgent need for climate change mitigation. However, Delannoy et al. [58] have argued that this idea of pure consumption limits to oil production changes when a net energy analysis is performed. They found that oil production—including both conventional and unconventional sources such as shale oil—today has an energy return on investment (EROI) value of 6.5 when all direct and indirect energy costs are included; but, by 2050, this value would have fallen to only 2.0. They also envisaged oil production to peak as early as 2035. Since coal and NG can also expect some declines in EROI, the conclusion is that an FF-dominated future beyond the next decade or so is most unlikely for both climate change mitigation and depletion considerations. This conclusion is further strengthened by increased interest in energy security following the Russian invasion of Ukraine [59,60].

5.2. Low carbon energy dominant

In the IEA scenarios, only the SDS and NZE scenarios have low carbon energy sources, accounting for more than half of all global primary energy. Here, dispatchable and intermittent sources will be considered separately.

Dispatchable low carbon energy. These sources include hydro, geothermal and bioenergy, as well as nuclear power. None of the IEA scenarios in Table 1 see nuclear energy as supplying much more than its present share of global electricity; other scenarios even suggest a declining share [4]. Even in the NZE scenario, which is the most favorable for nuclear power, it only provides 7.7% of global electricity. The RE sources, i.e., bioenergy and hydropower, both face environmental and resource constraints on their expansion; geothermal energy for power production has limited potential, although considerable potential to provide low-grade heat [61,62]. All these low-carbon dispatchable sources together are forecast to provide only between 18% and 30% of global primary energy in 2050 in the four IEA scenarios, which is less than twice their present share [8].

Intermittent RE. The intermittent RE sources, i.e., wind and solar, will be the major future electricity source in all four IEA scenarios, and they are forecast to supply around two-thirds in the SDS and NZE scenarios by 2050 (Table 1). In contrast to the low-carbon dispatchable sources, which are forecast to grow only by a factor of two from 2020 to 2050, wind/solar output is anticipated to expand 10- to 20-fold in all except the baseline STEPS scenario. Even in the two higher wind/solar scenarios, CCUS and BECCS technologies—both untried at large scales—are needed to cut emissions.

5.3. Discussion

In Table 1, combined wind and solar energy supply only 25.8% of total primary energy in SDS, and 36.5% in the NZE scenario, even with their high growth rates. In previous work, the authors have cast doubt on the ability of other sources of RE to supply more than a minor share of future energy [61,62]. Similarly, as already discussed, nuclear energy may never rise to twice its present output, as in the NZE scenario. Further, CDR and SRM may well continue to have marginal impacts on the need for emissions reduction. The implication is that, in a sustainable future, intermittent RE, chiefly wind and solar, will need to supply most of the energy.

FF use today is heavily subsidized. Including an estimate for climate change costs from GHG emissions, the World Bank estimated a subsidy of USD 5300 billion for the year 2017 [63]. (Nuclear energy and RE are also subsidized, but to a lesser extent than FFs.) But, as large-scale demonstrations in France in 2017–18, and in Kazakhstan in early 2022 showed, raising FF prices are likely to meet strong popular resistance.

The removal of subsidies, whether from FFs or low-carbon sources, would tend to reduce energy use overall. Although there is clearly overlap with subsidy removal, the favored method for climate change mitigation that could be expected to heavily impact energy choice is the general imposition of a significant carbon tax [64]. Such a tax would have two effects: first, it would shift energy supply over time to non-carbon sources (RE and, perhaps, nuclear); second, by raising energy prices. it would tend to lower energy use overall, with the timing and magnitude of the shift itself depending on the timing and size of the carbon taxes. Regardless of the approach used, if effective climate change action is taken soon to greatly cut FF use, FF depletion, urban air pollution and energy security problems would be greatly ameliorated. Reduced energy use and emissions would largely come from FF reductions; there would thus be substantial spare capacity, particularly in the Organization for Economic Cooperation and Development (OECD) countries. Construction of new wind and solar plants would likely be scaled back, reducing surplus intermittent electricity. Eventually, however, closures of obsolete nuclear and FF plants would necessitate construction of new (presumably low-carbon) power plants.

One problem with RE sources, in general, is that their material needs per TWh of electrical energy produced are far higher than that for FFs [65,66]. This is particularly the case for materials in short supply, which are often mined in non-OECD countries, providing a supply security problem for RE. (In contrast, most non-hydro RE is installed in the OECD countries [67].) Such non-OECD countries often have low or poorly enforced environmental standards, resulting in hidden substantial environmental costs. Avoiding environmental damage would entail energy expenditure for what the authors have earlier termed ecosystem maintenance energy (ESME) costs. An example would be properly constructed tailings dams, as tailings dams fail all too frequently, with often devastating environmental damage [61]. It is because such ESME costs are rarely included in either EROI calculations or costs for RE [68] that caution must be exercised in using such published cost figures.

6. Implications of future energy choices for the H_2 economy

An important recent document on the future of H_2 is the *Global Hydrogen Review 2022* from the IEA [6], which uses the IEA energy scenarios discussed above. H_2 production in 2020 was reported as 90 Mt, with most of this used for oil refining and industrial applications (global ammonia production is currently almost twice this). As the report summarized: “In the Net Zero Emissions Scenario, hydrogen demand multiplies almost six-fold to reach 530 Mt H2 by 2050, with half of this demand in industry and transport”. The 2050 figure of 530 Mt corresponds to around 64 EJ, compared with present global primary energy use of roughly 600 EJ [67,69]. Consequently, over the years 2021–2050, this shift to H_2 would only produce 6.5% of the cumulative total CO_2 reductions needed in the NZE scenario. Alternatively, even in the NZE scenario, which is the most favorable for a H_2 economy, H_2 provides little more than 10% of present-level energy use by 2050.

Overall, other reports since 2019 have predicted only modest growth rates in global H_2 production and use out to 2050. The World Energy Council [27] has recently presented projections of global H_2 production and consumption out to 2050 from a number of recent studies, including the IEA study discussed above. The minimum forecast value is about 150 Mt, and the maximum just under 700 Mt. The Chapman et al. [26] figure of 450 Mt by 2050 fits in with this range. The modeled results in the latter paper showed that H_2 could potentially account for approximately 3% of global energy consumption by the year 2050, mainly from HFCVs and H_2 for city gas. IRENA [70], in contrast, envisage H_2 accounting for 12% of final energy demand, or 614 Mt in 2050.

In summary, these studies, while mainly supportive of H_2, only see H_2 as having a minor role in energy in 2050. In contrast, as already discussed, the much earlier Barreto et al. scenario [13] forecast for 2050 was for a sizable 212 EJ (or 1760 Mt). Clearly, in an era of EV ascendancy, any chance for a medium-term H_2 economy will need to come from novel sources of H_2, or strong and consistent government support, as discussed in the following section.

7. Possible novel pathways to the H_2 economy

As argued in Section 3, neither an energy future dominated by FFs nor by low-carbon sources appear to offer much scope for H_2 production. However, there are other technological possible paths to significant H_2 production and large-scale adoption [71], as discussed in Section 7.1. An important consideration, of course, is the probability of their introduction. Further, H_2 introduction will not be uniform across energy sectors or countries; this topic is explored in Section 7.2.

7.1. Novel pathways for H_2 production

Pasquali and Mesters [72], in their article *We can use carbon to decarbonize—and get hydrogen for free*, have a novel approach to CCUS. Instead of finding uses for CO_2, they propose using the pyrolysis of methane (CH_4) to produce carbon and H_2. Ideally, one tonne of pyrolyzed CH_4 can produce 0.25 tonnes of H_2 alongside the carbon. The reaction is slightly endothermic, and the net H_2 energy (lower heating value) is 25.3 GJ. The authors argue that the produced carbon can now find extensive use in carbon nanotubes. As they explain: “Because of this material’s potential use in cars, heavy vehicles, and aircrafts, mass-scale production of carbon nanomaterials from methane could cogenerate significant amounts of hydrogen (tens to hundreds of Mt per year), providing additional economic value as well as clean energy”. As an additional benefit, lightweight carbon nanomaterials could reduce the mass of transport vehicles, potentially providing energy savings.

The cost of H_2 production cannot be directly compared with more conventional methods, since there are joint products. As the paper title suggests, H_2 could be a free by-product of carbon production. But, what is the global scope for carbon nanotubes? In 2013, carbon nanotube production “exceeded several thousand tons per year" [73], and applications already included structural applications such as boat hulls and automotive parts [74]. It is difficult to see a market for the many millions of tonnes of nanotubes that the large-scale production of H_2 by this approach would produce.

H_2 can also be produced from microalgae. Use of microalgae for fuel is seen as averting the competition between food and fuel production which occurs with land-based bioenergy production. Options include both direct and indirect bio-photolysis, and dark and photo-fermentation [75]. Kumar et al. [76] have reviewed various H_2 production methods, both conventional (e.g., steam reforming of methane) and unconventional (e.g., biological techniques). They found only a factor of two variations for the costs of H_2 produced, with overlap between the costs of H_2 produced from methane and microalgae. In fact, H_2 from indirect photolysis was the cheapest of all options, at a low price of USD 1.42 per kilogram. However, all four options discussed for H_2 from algae are reported as suffering from various forms of low efficiency [76].

Fernández et al. [77] reported far higher costs for current microalgae production systems, "ranging from minimum values of 5 €/kg for raceway reactors to 50 €/kg for tubular photobioreactors". Further, these costs—USD 5.7/kg and USD 57/kg, respectively—for dried microalgae only, before conversion to H_2, are far higher than those suggested by Kumar et al. [76]. A further indication of the difficulties facing this route to H_2 production is the low reported EROI values for dried microalgae biomass. Ketzer et al. [78], in their review of earlier studies, found reported EROI values to be very low, with only four EROI values of the 23 processes studied being >1.0, and the highest reported value was 3.72.

Direct H_2 production by photolysis would remove the need for electrolysis plants, which have associated embodied energy costs and conversion losses; in theory, the process only needs sunlight, water and a catalyst. But, the method suffers from a conversion efficiency of only 0.5%, which is better than photo-fermentation (0.1%), but two orders of magnitude lower than the other novel H_2 production methods given above [79]. Because this efficiency will always remain below the 10% benchmark, Ng et al. [80] concluded that "the H_2 production from solar-driven photocatalytic water splitting is an industrially impractical pathway for solar energy harnessing, despite technically feasible".

7.2. H_2 fast-tracking in selected countries and/or sectors

A second possibility for widespread H_2 introduction is in countries in a similar position to Japan and South Korea. These two countries lack FF reserves, face stagnating development of nuclear energy and have limited technical potential for local RE, including hydropower. Figure 5 displays the trend in both nuclear and hydro electricity production in recent decades. Given these circumstances, the two countries are at the forefront of plans to introduce a H_2 economy possibly using imported liquid H_2 developed from RE sources in Australia and elsewhere [81–84]. These countries are also leaders in advancing plans to replace FF use in power generation by co-firing with ammonia. Despite the added energy and financial costs of producing ammonia from H_2 (and the enhanced health and safety concerns), the relative ease of large-scale transport and storage provides advantages over H_2 [85]. Large-scale production of ammonia from renewable H_2 also has the advantage of providing a feedstock for the production of a green fertilizer.

In their 2019 report on H_2, the IEA [85] identified four key areas for scaling up H_2 production and use by 2030:

1. Promote H_2 in coastal industrial clusters (see also Point 4).

2. Use existing NG infrastructure for transporting H_2 and blending H_2 with NG.
3. Develop vehicle fleets, freight and corridors for H_2 use.
4. Establish the first shipping routes for shipping liquid H_2 internationally.

As the IEA report details, opportunities for such H_2 introduction will vary from country to country, and even for different cities/regions within a given country. Japan and South Korea should be among the most favorable locations. (However, even with strong government support, Iida and Sakata [86] forecast that, by 2050, only 13% of Japanese primary energy would be from H_2.) Ajanovic and Haas [38] and Elmanakhly et al. [87] have also argued that the best prospects for H_2 are in the heavy vehicle sector, and they stressed, as have others, that a stable and long-term policy framework is needed for H_2 success. Finally, the challenge posed to the development of a large-scale H_2 export market by the difficulties of large-scale shipment of liquid H_2 should not be underestimated [85,88].

The four points listed above indicate sectors where H_2 may be advantageously used. But, as discussed in Section 5, intermittent RE is likely to be the fastest-growing energy source if we get serious about CC mitigation. As FF use falls, energy storage will be increasingly needed for the wind and solar energy produced that is surplus to immediate demand. Hydrogen storage has the advantage that the H_2 can be used directly for transport and as a supplement in NG pipelines, without the need to reconvert back to electricity. Hence, the ability of H_2 to be used to replace both electricity and heat gives it an advantage over competitors in a high wind/solar energy future.

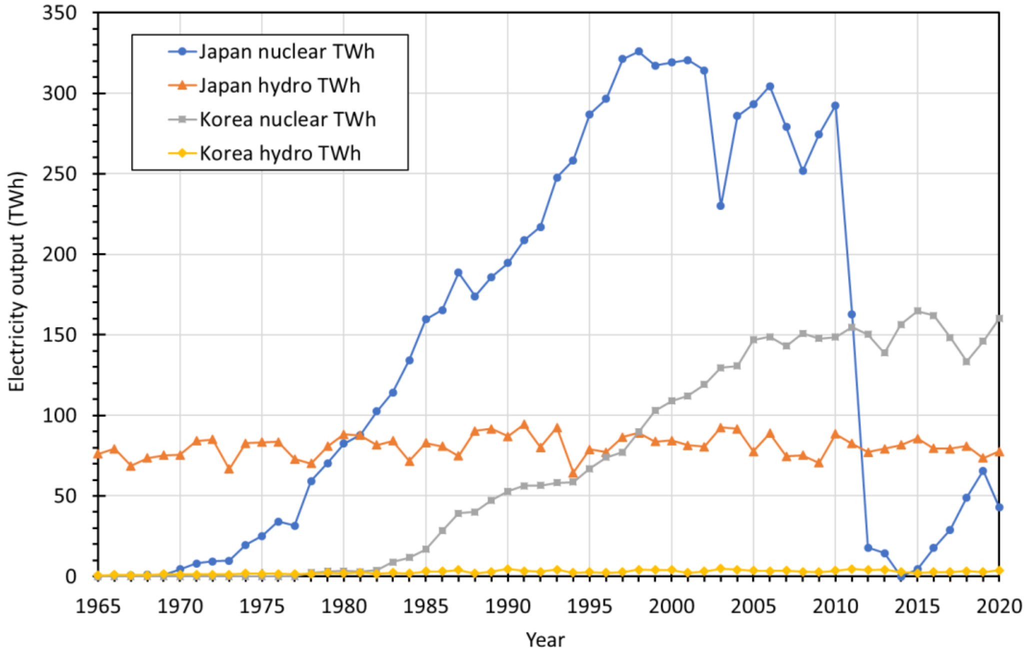

Figure 5. Nuclear and hydro output (TWh) for Japan and South Korea, 1965–2020. Source: [67].

8. Research limitations

We really have little idea what total energy use will be in 2050. As an example of this uncertainty, a study from 2015 even suggested that "by 2040 computing will necessitate more energy than the world currently produces" [89]. We also do not know the likely relative contributions of different energy sources. Most earlier studies on the future prospects for H_2 have assumed that it will have an important role in mitigating climate change. On the one hand, the recent IPCC reports [47,48], and others (e.g., [90,91]), have made clear the urgency of immediate and strong climate action, but, on the other, three decades of IPCC warnings have seen large rises in global emissions. There is no guarantee that the future will be different. The future promise of technical fixes such as CDR and SRM could well be used by governments as an excuse for inaction, as they potentially enable continuation of the existing energy system—at least for a decade or two.

Comparative costs are important for technology selection. But, any comparisons between even conventionally measured energy costs for different energy sources or vehicle propulsion types can only be for a snapshot in time. Further, published energy costs do not give a good indication of even present costs [61,62,68,92] since some ESME costs are usually omitted, as discussed in Section 5.3. Future true costs are even more uncertain. Because of such uncertainties, Wanitschke and Hoffmann [93], in a German context, have even advocated keeping open all three existing options for private road passenger transport: EVs, HFCVs and internal combustion engine vehicles.

9. Conclusions: H_2 in an uncertain energy future

The global energy picture is rapidly changing, and it will continue to change. Recent decades have witnessed major advances in solar cells, battery technology and H_2 storage, for example, as well as a host of less spectacular technological improvements. Some of the technological advances in areas other than H_2 could conceivably help the introduction of the H_2 economy, but others will act to delay it, or, possibly, even render H_2 irrelevant as a significant energy carrier.

Section 3 showed that most H_2 researchers, until recently, believed that road transport, and particularly, light duty passenger vehicles, would lead the way to an H_2 economy, but EVs now dominate alternatively fueled vehicles. It is even possible that private cars of all propulsion types will only account for a minor share of transport energy by 2050 [16]. In 2019, before the current pandemic, light-duty passenger vehicles accounted for 39.5% of all final transport energy. By 2050, in the two IEA scenarios with strong climate change mitigation policies (SDS and NZE), the modeled share had fallen to only 21–22% [8]. Freight transport appears set to dominate future energy use (see Section 7.2); and, here, HFCVs have a range advantage over EVs; also, a lack of public H_2 stations is less of a problem for fleet vehicles.

Technological progress will continue for H_2 energy, but, as indicated in Section 7.1, major breakthroughs seem unlikely. Further technological progress can also be expected in competitor energy systems. Instead, the best chance for a H_2 economy is likely in areas such as heavy freight transport, especially in countries that are running out of conventional energy options, such as Japan and South Korea. It could be objected that implementation in the short term will not help climate change mitigation. But, much the same could be said of EVs, which are also advocated on the promise of future GHG emission savings, when low-carbon energy dominates electricity production.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, P.M. and D.H.; methodology, P.M. and D.H.; writing—original draft preparation, P.M.; writing—review and editing, D.H. All authors have read and agreed to the published version of the manuscript.

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