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Dubious Promises of Hydrogen Energy in a Climate-Constrained World

Aviel Verbruggen [1,*], **Gulzhan Yermekova** [2] and **Kanat Baigarin** [3]

[1] Department Engineering Management, University of Antwerp, Prinsstraat 13, BE2000 Antwerp, Belgium
[2] Climate Change Coordination Centre, Abay av.20, Astana 010000, Kazakhstan
[3] Research and Innovation System, Nazarbayev University, Kabanbay batyr av.53, Astana 010000, Kazakhstan; kbaigarin@nu.edu.kz
* Correspondence: aviel.verbruggen@uantwerpen.be

Abstract: Vocal proponents claim that hydrogen will play a crucial role in the low-carbon energy future, a claim critics dismiss. Our approach to clarifying these disputes involves reviewing literature and policy documents, revisiting energy and hydrogen physics, and framing the hydrogen question within the context of failing climate and energy politics and actions aimed at reducing greenhouse gas emissions. Clarity about hydrogen's role begins with knowing its peculiar properties, followed by numerical data on energy conversions and related losses, which reveal intractable hurdles in deploying a hydrogen energy economy. Thus, hydrogen derivatives like ammonia and synthetic hydrocarbon fuels emerge, but they sink the green hydrogen ambitions advertised to the public. Their dubious environmental and financial performance is hidden by substantial subsidies. The announced EU megaproject for producing 11 Mtons of green ammonia at the Caspian Sea in Kazakhstan contrasts with the 20 ktons realized project in Norway. While the Kazakhstani project promises grand results, its practical and financial feasibility is questionable. The Norwegian project shows the reality of green ammonia production. The article concludes that hydrogen's economic and environmental feasibility remains challenging.

Keywords: H_2 embrittlement; H_2 flammability; H_2 climate impact; H_2 Hyrasia megaproject; H_2 Herøya Yara plant; squandering renewable electricity

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Academic Editor: Chukwuma Ogbonnaya

Received: 20 December 2024
Revised: 13 January 2025
Accepted: 18 January 2025
Published: 22 January 2025

Citation: Verbruggen, A.; Yermekova, G.; Baigarin, K. Dubious Promises of Hydrogen Energy in a Climate-Constrained World. *Energies* **2025**, *18*, 491. https://doi.org/10.3390/en18030491

1. Introduction

Earlier hydrogen publications were mostly technical [1]. Vocal proponents claim that hydrogen will play a crucial role in the low-carbon energy future [2–4], a claim critics dismiss [5–7]. This article explores both views, without offering a comprehensive evaluation of the economic, environmental, and technical feasibility of the many proposals emerging in the literature and in policymaking arenas. The article is a perspective article, with a lens on the actual and expected performance of the technology and of some proposed projects. Hydrogen as a chemical substance has a shorter lifespan than hydrogen as an energy carrier, an important difference. The irreversible loss of climate stability overarches all energy facts and choices. Hence, the role of hydrogen in avoiding climate collapse needs attention.

In the Universe, hydrogen represents about three-quarters of all matter. On Earth, the H-atom is part of many molecules, water and hydrocarbons being prominent examples. The H-molecule (gas H_2) is naturally scarce, so it needs manufacturing when humankind wants it for particular uses. The 95 million tons of H_2 produced in 2022 was extracted from hydrocarbons for use in industrial processes, like petroleum refining, ammonia for fertilizers, and steelmaking. The idea of using H_2 as an energy commodity is frequently proposed without result. Recently, it received renewed attention due to its property that its combustion is free of carbon emissions. The literature is abundant, and almost all aspects of the proposed hydrogen energy economy receive attention. Most salient is the use of hydrogen in transportation [5,8]. The production of H_2 from electrolysis powered by renewable electricity and from biomass [9] are also extensively researched topics.

An overview of the consecutive sections is as follows.

Section 2 reveals the ineffectiveness of policies and politics up to 2023 in stopping the rise of greenhouse gas emissions and concentrations in the atmosphere. This signals that *business-as-usual* thinking and acting fail to address climate change challenges. Sustainable energy systems that genuinely meet survival criteria are necessary beacons for proper energy decisions.

In Section 3, the worn-out solutions triptych of *renewable energy*, *nuclear power*, and *carbon capture and storage* is reviewed. Hydrogen has not been considered as a solution for GHG emissions reductions. Proponents assert its crucial role in low-carbon energy, often tying it to renewable energy, nuclear power, and CCS. They divert political focus and intellectual and financial resources away from small-scale distributed renewable electricity deployment. Hydrogen's failing record as an energy carrier is mostly silenced, having been overridden by academic and activist publications.

Because of their determining impact, the peculiar properties of hydrogen are revisited in Section 4. The energy performance of the proposed hydrogen energy economy is documented in Section 5. Section 6 sheds light on ammonia- and hydrogen-derived synthetic fuels, which play a central role in the 21st-century focus on hydrogen. The financial and environmental viability of the hydrogen energy economy is briefly assessed in Section 7. Section 8 describes the 11-million-ton hydrogen–ammonia Hyrasia One *announced* project in Kazakhstan, contrasted with the 550-times-smaller 20,000-ton *realized* project by Yara in Norway. Overall conclusions are summarized in Section 9.

2. Climate Change as Elephant in the Room

Global warming was the critical issue before the term climate change became more popular. It occurs by the accumulation of greenhouse gases (GHGs) in the Earth's atmosphere, which trap heat and lead to a rise in temperatures. To hold "*the increase in the global average temperature to well below 2 °C above pre-industrial levels*" and pursue efforts "*to limit the temperature increase to 1.5 °C above pre-industrial levels*" are the overarching policy goals adopted by political leaders of the largest countries at the 2009 COP15 in Copenhagen, reaffirmed at the 2015 COP21 in Paris.

The level of warming is directly influenced by the GHG concentration, steadily increasing due to annual gigaton emissions from human activities. Figure 1 illustrates the trends in greenhouse gas emissions and their atmospheric concentration over the past several decades. Since 1970, there have been four moments when the rise paused: in the mid-1970s due to the oil price increase; in the beginning of the 1980s due to the energy efficiency push; around 2008 due to the global financial crisis; and in 2020 due to the COVID lockdowns. The rising trend in emissions is driven by a *business-as-usual* approach to economic and industrial activities.

While emissions can be halted at any time, their accumulated concentration in the atmosphere is *irreversible for centuries*. Many damages caused to ecosystems, environmental amenities, and human habitats are *irreversible forever*. Despite its crucial importance, *irreversibility* is poorly understood and is overlooked by policymakers. In addition to irreversibility, the delayed and feedforward effects of increased GHG concentrations make climate change an utterly precarious problem. This all loads a heavy responsibility on past, present, and future policymakers related to energy and climate.

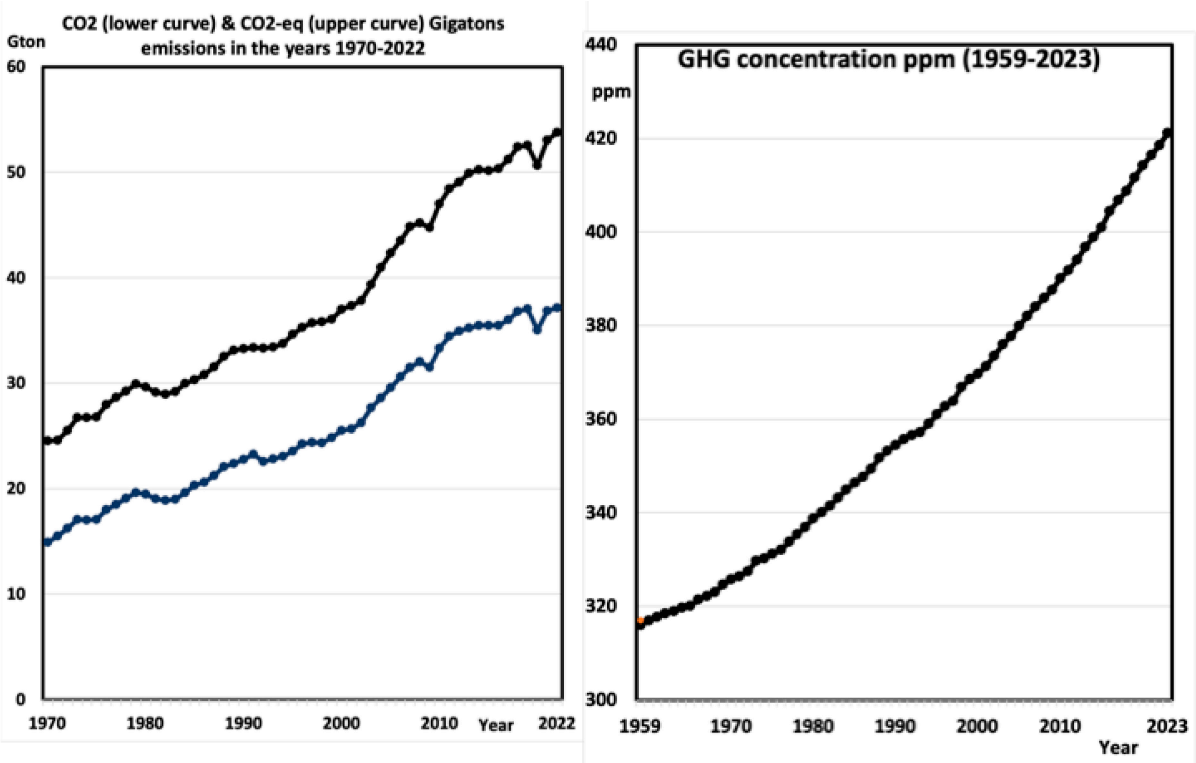

Figure 1. Rising greenhouse gas emissions and concentration reflect failing climate policies (data source: Statistica.com).

The curves in Figure 1 underscore the ineffectiveness of policies and political actions up to 2023 in halting the rise of GHG concentrations in the atmosphere. Despite the commissioning of many atomic power plants during the 1960s–1980s, numerous reports from the IPCC and UN agencies, series of international summits, high-level meetings, COPs, complicated emissions trading mechanisms, etc., from the 1990s to the 2020s, the climb in ppm concentration is not curbed. This uncurbed trend explains the unpredictable, shocking temperatures and weather irregularities occurring worldwide, worsening year by year. Although we observe and experience these changes firsthand, there remains a significant gap between our knowledge and our actions.

3. Attempts to Curb GHG Emissions

Official views on the future often frame scenarios that extrapolate current societal trends, believing that *business as usual* is the best practice, thereby precluding necessary transformations. In reality, *business as usual* is the worst possible practice in a world where continued adherence to present customs leads to the catastrophic and irreversible impacts of climate change.

Drastic reductions in carbon dioxide, methane, and nitrous oxide emissions are needed. With fossil fuel use alone accounting for over 80% of global emissions, decisions on energy are vital for the survival of human civilization. The energy sector stands as the foundation of industrial activity, commanding significant investments, employment, and profits. Annual super profits from fossil fuels amount to thousands of billions of US dollars, creating powerful incumbent interests that resist necessary change and transformations.

The pivotal role of *energy and technology* in reducing GHG emissions is reflected in the standard solution triptych *renewable energy (RE)*, *nuclear power (NP)*, and *carbon capture and storage (CCS)* [10] (pp. 12, 14, 20, 26, 27). This juxtaposition presents the three options as compatible and equivalent solutions. However, this discourse negates the big differences in contributions and the mutual technical and sustainability conflicts.

In 2005, the IPCC analyzed CCS in a Special Report [11]. Although the report was generally favorable toward CCS, it highlighted significant challenges:

> "*The available technology captures about 85–95% of the CO_2 processed in a capture plant. A pulverized coal power plant would need roughly 24–40% more energy than a plant of equivalent output without CCS, of which most is for capture and compression. Consequently, CCS would increase the cost of a kWh by 50% to 100%*" [11] (pp. 3, 9).

Nearly 20 years later, no commercial CCS projects have been successful in coal-fired power plants [12,13].

Eliminating thermal power generation, with its associated fuel cycle sources and waste, could reduce annual global CO_2 emissions by approximately 18 billion tons: half of the energy-related CO_2 emissions. This shift is also financially advantageous due to the low costs of wind and solar power.

Nuclear power (NP) was once (1950–1980s) believed to be the energy technology that could replace fossil fuels, at least in thermal power generation. Despite receiving substantial subsidies for over 70 years, nuclear power remains uncompetitive in any electricity market. Beyond financial challenges, nuclear power entails significant external costs, including the risk of accidents, management of high-level radioactive waste, and concerns over the proliferation of nuclear weapons.

Nuclear power disrupts the envisioned triptych because it is not compatible with variable renewable power from sunlight and wind. The first incompatibility arises in the generation merit order, as both nuclear and renewable sources claim priority to supply base-load power [14]. The development of electric grids reveals a second incompatibility: nuclear power requires a centralized, pyramidal grid structure, while sustainable renewable electricity thrives in local smart grids, which are horizontally interconnected.

Renewable energy (RE) has become the source of the cheapest electricity per kWh, starting in the 1880s, when electricity delivery started in the big cities of industrializing countries. Technologies for harvesting electricity from sunlight and wind are phenomenal and continually progressing. These technologies offer scalable decentralized solutions that are affordable and manageable by households, cooperatives, local communities, and local governments worldwide. Such disruptive energy transformation is both affordable and rewarding.

As of 2022, the average cost of electricity generated by new onshore wind turbines was USD ct.3.3 per kWh, and from new utility-scale photovoltaic (PV) fields, it was USD ct.4.9 per kWh [15]. These costs are expected to decrease further with ongoing advancements in science and technology. Innovations in quantum physics and nanoscience are driving progress in photovoltaics, power electronics, batteries, power-to-X technologies, and ICT [16]. These advancements strengthen and extend technical and economic superiority, pushing the boundaries of what a renewable electricity supply can achieve.

Given the predominant role of fossil fuels in causing climate change, energy experts outlined the only remaining feasible path for humanity, as follows: keep fossil fuels in the ground; enhance conservation and efficiency in using commercial energy; deliver nearly all energy services through electricity; ensure that all electricity is obtained from light, wind, water, or geothermal currents, with bioenergy reserved for fuel applications [7]. This path was once shaky, when renewable electricity was expensive. Today, this path is solid: possible, desirable for the majority of humanity, necessary, and sufficient to bring GHG emissions down. Energy experts are enthusiastic about this path because of the central role of electricity, with it being clean, versatile, top-quality energy, and for the first time in history, it is cheap, and experts are confident that it will stay cheap and become cheaper. Economics for the public good does not include other energy sources, given their inferiority to renewable electricity.

The heralding of hydrogen as the foundation of a new fuel economy confounds energy experts. For years, they had to argue and prove that renewable energy can meet the energy needs of the global population [17], countering claims like “Too little RE” and “Too expensive RE”.

The push toward a hydrogen economy holds a contradiction: hydrogen production is expected to be powered by renewable electricity. The hydrogen hype disrupts the positive momentum of the renewable energy transition by diverting massive RE resources and capital toward hydrogen production. Furthermore, this issue is complicated by the simultaneous promotion of CCS and NP as complementary solutions to RE in driving the hydrogen agenda. Essentially, the hype competes for the human and material capital required for renewable electricity serving direct energy needs. Does it make sense to allocate renewable electricity—already in high demand for direct use—to produce hydrogen? And how do CCS and NP fit into this equation?

The allure of *clean hydrogen* in power generation and transportation captivated governments and the public in the 1950s–1960s [18] and again in the 1970s [19], and it was relaunched by G.W. Bush in 2003 [20] as an early signal for today’s hydrogen hype. Most announcements about practical results did not materialize. Notably, hydrogen use in transport and other energy applications was less than 0.1% of global hydrogen use.

In 2022, the global industry utilized 95 Mt of hydrogen as a *chemical substance* in ammonia fertilizer production, oil refinement, and steel manufacturing [21]. Almost all this hydrogen came from natural gas or coal reforming processes, causing more than 1 billion tons of CO_2 emissions, along with additional methane and nitrous oxide emissions. Today, the literature splits into two strands: one follows the announcements of hydrogen being a crucial part of the energy future [2–4], and the other points to the danger of spoiling the opportunities of deploying the renewable electricity economy [5–7].

4. The Peculiar Properties of Hydrogen

Hydrogen (H) constitutes about 75% of all visible matter in the Universe. On Earth, pure hydrogen gas (H_2) is rare and scattered [22]. Due to its high chemical reactivity, hydrogen readily forms compounds with other elements, creating larger molecules like water (H_2O), hydrocarbons (C_xH_y), etc. Uncontained hydrogen quickly escapes from Earth into space.

4.1. Hydrogen Is a Fuel That Needs Manufacturing

All energy used by humans comes from natural flows or stocks, manufactured by nature on the spot or in the past. Such energies are available without manufacturing efforts or expenses for humans. They are a source of big economic profits. Hydrogen is the opposite; it has to be manufactured, a grave economic handicap compared to renewable currents and fossil fuels.

4.2. Energy Content

Among fuels, hydrogen has the highest energy value per weight, at 141.86 MJ/kg, which is advantageous for aerospace applications. However, its energy content per volume is low, at 11.88 MJ/m^3, three times less than natural gas. Little energy per m^3 is a handicap in the usual applications, because fuel tanks have a limited volume, and it is better for pipeline diameters to be small than large.

4.3. Storage Issues

As the lightest gaseous element, hydrogen’s condensing temperature is 20 °K or −252.9 °C. This poses significant challenges for storage. Storing hydrogen in a compressed state requires pressures beyond 800 bar and thick-walled high-pressure vessels. Currently, compressed storage of 1 kg of hydrogen requires cylinders weighing 33 kg, which may be lowered to 20 kg through advances in materials science [23] (p. 150). Liquefaction of hydrogen is highly energy-intensive, requiring approximately 40 MJ/kg H_2, which is 33% of hydrogen's lower heating value. Liquefied hydrogen has a low density: one liter contains only 71 g of hydrogen. Consequently, storing hydrogen in cryogenic form requires large volumes, leading to extra heat losses [24].

4.4. Hydrogen Embrittlement

Hydrogen's low viscosity, small size, and light weight enable it to penetrate almost any space, leading to leakages during all stages, from production to utilization. By being soluble in metals, hydrogen causes gas porosity and reduced strength, a phenomenon known as hydrogen embrittlement. This decreases the ductility of metals due to absorbed hydrogen. To mitigate this, special measures are required, such as selecting stainless steels and nickel-based alloys, using protective coatings with nickel, cadmium, or zinc, and using hydrogen removal techniques like baking and stress-relief annealing [25]. It is also important to limit exposure to hydrogen-rich or corrosive environments.

4.5. Hydrogen's Flammability

Hydrogen–air mixtures are highly flammable, due to hydrogen's broad flammability range: a 4–74% concentration in air and a 4–94% one in oxygen. A hydrogen–air mixture ignites with only 0.02 millijoules of energy, less than 7% of the energy needed to ignite natural gas [26].

Preventing hydrogen from mixing with air or oxygen in confined spaces is crucial. Even an invisible spark or static electricity discharge from a human body may trigger ignition. Moreover, hydrogen's low electro-conductivity can create electrostatic charges during flow or agitation of hydrogen gas, potentially causing sparks. Therefore, all hydrogen-conveying equipment must be thoroughly grounded [27] (p. 28).

The NASA, being a pioneer in using hydrogen as fuel, derived clear lessons from past accidents [26]. A report from UK gas distributor SGN highlights the substantial explosion risks of hydrogen gas, with the devastating consequences, and the need for stringent safety measures has been long suppressed [28]. A society-wide use of hydrogen would require an encompassing safety apparatus with a multitude of equipment, prescribed practices, rules, and enforcement measures. Even a very costly apparatus cannot reduce the likelihood of significant accidents to zero.

Hydrogen's peculiar properties imply technical, environmental, and safety challenges in its logistics and utilization, with a significant impact on its socio-economic viability.

4.6. Hydrogen as Unexpected Climate Culprit

Leaked hydrogen not only poses fire hazards; it also extends GHGs' lifetime in the atmosphere. While a hydrogen molecule itself does not trap heat, it indirectly contributes to global warming by prolonging the life of GHGs like methane, CH_4, tropospheric ozone, O_3, and water vapor. These GHGs are gradually neutralized in the atmosphere by reacting with hydroxide radicals, OH, which are important oxidants. When leaked H_2 reacts with OH radicals, it depletes atmospheric OH, delaying the neutralization of GHGs and effectively increasing their lifetime.

Four main climate impacts are associated with increased hydrogen levels: a longer methane lifetime, leading to increased methane concentrations; enhanced production of ozone in the troposphere, causing photochemical smog; increase in stratospheric water vapor; and changes in the occurrence of particular aerosols.

IEA [2] (p. 158) and IRENA [29] (p. 73) reference the study of Warwick et al. [30], which found that hydrogen's global warming potential was 11 ± 5. This number significantly exceeds previous calculations, highlighting the critical need to consider the broader atmospheric impacts of hydrogen in the announced growth scenarios.

5. Energy Performance of Hydrogen as Energy Commodity

Testing the energy performance of an acclaimed *new* energy commodity requires evaluating the standards for *production*, *logistics* (handling, transport and distribution, transfer and storage), and *use* [1]. The standards may encompass various technical processes, as exemplified by the multicolor labeling of hydrogen (Table 1).

Table 1. Multicolor labeling of hydrogen.

Color	Description
Gold	Few natural H_2 sources available on Earth, not requiring manufacturing
Green	H_2 produced via electrolysis with renewable electricity
Gray	H_2 extracted from hydrocarbons *without* capturing emitted CO_2
Blue	Gray version with methane as hydrocarbon, *with* capturing part of emitted CO_2
Brown	Gray version with coal as hydrocarbon, *with* capturing part of emitted CO_2
Pink	H_2 obtained via electrolysis or via thermochemical processes with atomic energy

5.1. Production Standard

Electrolysis transforms water into hydrogen and oxygen gases. At 71% efficiency, producing 1 kg H_2 with a 39.4 kWh energy content requires 55.5 kWh of electricity: an energy loss of 16.1 kWh. The average electricity input is 59.7 kWh, accounting for a 5% decrease in electrolysis efficiency during 10 to 15 years of operation [31] (p. 23). The hydrogen gas is delivered at atmospheric pressure (alkaline electrolysis) or at 35 bar (PEM electrolysis). Electrolysis consumes 9 L of ultrapure water per kg H_2 [32]. When saline water is used, a multiple of the water input is needed, resulting in significant brine pollution contaminated with chemicals and metals used as catalysts in desalination [31] (pp. 28–29). Hydrogen from electrolysis powered by renewable electricity is labeled with green, and pink when powered by nuclear energy.

Hydrogen production via natural gas reforming has a maximum efficiency of 70%, further reduced by fugitive gas losses. The process emits 10 kg CO_2 per kg of H_2 produced, and 22 kg CO_2-eq when adding fugitive methane emissions [6]. Gas-based hydrogen is labeled with gray, and blue when the CO_2 emissions are captured.

5.2. Logistics Standard

The simplest *handling* of H_2 occurs when it is used immediately—without pressurizing and without storage—near the place of production. This happens when H_2 serves as a chemical substance.

- *Compression*: As an energy commodity, manufactured H_2 gas usually requires compression. For pipeline transport, an intermediate pressure of 140 to 350 bar is suitable. When hydrogen is used in vehicles, compression beyond 800 bar is typically necessary. The overall compressor work from electrolysis to fill a car tank would take approximately 7.87 kWh/kgH_2 [33] (Figure 11, p. 118).
- *Transport*: Energy use in *pipeline transport* varies widely, depending on the diameter and length, pressure levels, and compressor technologies. Gas flowing over longer distances (e.g., 4000 MJ/s hydrogen rate over 2000 km) requires consecutive compressions. Transport over a distance of 500 km consumes about 3.97 kWh/kg of conveyed H_2, while 13.37 kWh/kg is consumed over 3000 km.
- *Liquefaction*: As an alternative to compression, hydrogen can be liquefied at −253 °C for transport and storage. The theoretical minimum energy loss of hydrogen liquefaction is 18%; in practice it ranges from 25% to 45%, depending on plant size [33] (p. 116), or 7

to 13.4 kWh/kg H_2 [34]. Over long distances, shipping could consume one-third of the liquefied hydrogen. Since ammonia (NH_3) liquefies at −33 °C while at atmospheric pressure, or at ambient temperature at 10-bar pressure, it is proposed as the best hydrogen energy carrier. However, the energy penalty of converting hydrogen to ammonia and back is roughly equivalent to chilling hydrogen [35].

- *Distribution over the hinterland*: This standard would be needed when hydrogen would become a widely applied fuel from international imports. A 200-bar distribution network for hydrogen would require about 3.93 kWh/kg H_2 for delivery at a 150 km distance, and 9.83 kWh/kg H_2 over 400 km [1] (pp. 97–100). A 100-bar distribution would reduce these numbers by 1 kWh/kg H_2. Transport over 100 km (a radius of 50 km around an intermediate transfer/storage depot) would take 1.39 kWh/kg H_2 [36] (p. 113).
- *End use of hydrogen in transport*: Currently, hydrogen as an energy commodity is only used in fuel cell-powered vehicles or internal combustion engines running on hydrogen. From the electricity generated, battery electric vehicles deliver 69% to the wheels and hydrogen fuel cell vehicles around 23% [5]. Internal combustion engines on hydrogen show efficiencies of 20–30%, whereas hydrogen fuel cells driving electric motors would attain efficiencies of 40–50%. Figure 2 provides an example.

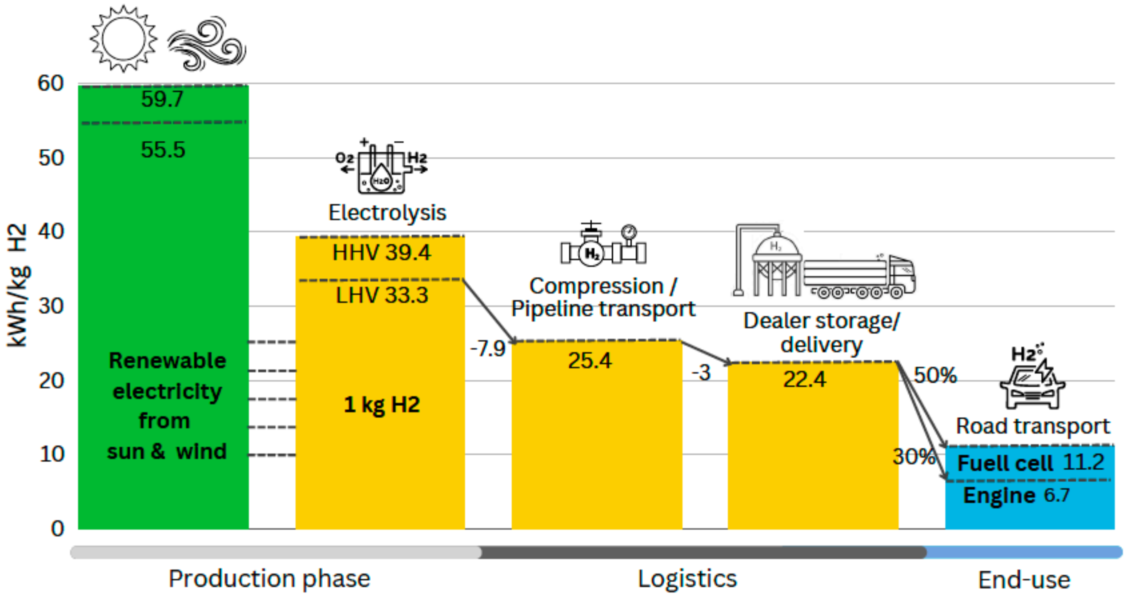

Figure 2. Hydrogen for road transport, assuming *minimum-loss conversions*. The figure's fixed point is 1 kg H_2. The 39.4 kWh HHV is delivered by renewable electricity via electrolysis at η 71% in a new unit, viz. η 66% over 15 years of functioning [31] (pp. 22–23). The 33.3 kWh LHV is for use. When electrolysis occurs in areas with ample sun, wind, and water resources, 140-bar pressurized pipeline transport over 2000 km is a *minimum* need [33]. Dealer storage and delivery within a 50 km radius requires 5 kWh/kg H_2 [36] (pp. 73–92). Road transport by fuel cell (η 50%) or internal combustion engine (η 30%).

The option of using excess renewable electricity for hydrogen production through electrolysis, subsequently *stored at home* for later conversion back to electricity with a fuel cell, has an efficiency of 33.5%, assuming optimal operation without any hitches.

The energy losses associated with a hydrogen-based economy are excessive and directly related to hydrogen's molecular structure and inherent properties. Consequently, these losses cannot be significantly reduced by any amount of research and development efforts, rendering the concept of a pure hydrogen energy economy unrealistic [1] (p. 107).

6. Hydrogen-Derived Products and Fuels

By now, hydrogen primarily functions as a substance in industrial activities: oil refineries, fertilizer production, and steel plants. *Ammonia* is a key raw material for chemical fertilizers, while *hydrogen-derived synthetic fuels* are presented as climate-valid substitutes for fossil fuels.

6.1. Ammonia

Ammonia, NH_3, consists of 82.35% nitrogen and 17.65% hydrogen. The lower heating value of liquidized/pressurized ammonia is 18.6 MJ/kg [2]. Most ammonia is used in the nitrogen fertilizer industry. Annually, about 265 Mt of atmospheric nitrogen are fixated on land: 55 Mt natural and 210 Mt anthropogenic. The latter consists of 52 Mt fixated biologically and 32 Mt from the combustion of fossil fuels; via the Haber–Bosch synthesis process, 126 Mt nitrogen is combined with hydrogen to manufacture ammonia. In 2020, the global ammonia production capacity was around 243 Mt, with a demand of 183 Mt. Approximately 90% of the produced ammonia is consumed on-site. Ammonia was generated from natural gas and naphtha (75%), coal, and heavy fuel oil (25%) [3] (p. 22).

Ammonia (NH_3) is a corrosive and toxic gas that can severely pollute air and water, posing a grave threat to ecosystems and to human health. Despite existing infrastructure and regulations, satellite observations reveal industrial NH_3 plants as major emission hotspots, greatly underestimated in inventories by a median factor of 50 [37] (Figure 4, pp. 4–5). In an ammonia-driven economy, the risk escalates dramatically, with potential emissions from pipelines, distribution, storage systems, fuel stations, and combustion sources. Losses and inefficiencies across the value chain result in reactive nitrogen emissions of NH_3, NOx, and N_2O, with negative impacts on air quality, nature, human health, and the climate.

In industrial and agriculturally intensive areas of the EU, critical nitrogen loads are surpassed [38], as they are globally [39]. There is now *a full stop on the licensing of additional nitrogen-emitting activities* in many regions of the EU, like Flanders (Belgium), the Netherlands, and German counties. Licensing more ammonia production in satiated markets is unlikely. This situation increases the eagerness of multinational companies to produce ammonia overseas.

A spectacular growth of the ammonia industry has been announced, pending its ample use as an alternative fuel: "…a decade or two after 2050, ammonia energy will have reached 30 EJ/y, or 1600 Mt NH_3/y. Hydrogen will become 150 EJ/y and 20% of it will be transported as ammonia" [37] (p. 3). Today, shipped ammonia amounts to around 20 Mt/year.

There is no carbon in NH_3, and the stochiometric conversions are attractive:

> "Most of the nitrogen in ammonia is converted back to atmospheric N_2 during ammonia combustion ($4\ NH_3 + 3\ O_2 \Rightarrow 2\ N_2 + 6\ H_2O$) or ammonia cracking ($2\ NH_3 \Rightarrow N_2 + 3\ H_2$). Practically, however, leakages across the ammonia value chain and undesired reactions during ammonia use would keep the nitrogen cycle partially open, releasing reactive nitrogen compounds like NH_3, NO_x, and N_2O" [37] (pp. 2–3).

A significant stumbling block to the efficacy of ammonia as a climate change mitigation solution is the potential emissions of nitrous oxide (N_2O). N_2O is a potent and long-living greenhouse gas with a lifespan of ~120 years. Its global warming potential is 265 times that of CO_2.

Leakages occur during ammonia synthesis, as well as during combustion and cracking. Total leakages and combustion emissions are assessed to range from 0.5% to 5% [37] (Figure 1, p. 2), referring to experience with natural gas shipments and conversions, and to imperfections in the practical use of devices deviating from theoretically perfect combustion in ideal conditions.

IRENA [3] reflects the vision and interests of the ammonia industry by including "discussions on the direct use of ammonia as a fuel for electric power generation or maritime transport, as well as its indirect use as a hydrogen carrier and a carbon-free energy commodity". The report is titled "Renewable Ammonia: How Can Ammonia Be Renewable? Is a Car Using Electricity from Solar Panels a Renewable Car?"

> "Ammonia production accounts for around 45% of global hydrogen consumption, or around 33 Mt of hydrogen in 2020. Replacing conventional ammonia with renewable ammonia produced from renewable hydrogen presents an early opportunity to decarbonize the chemical sector (. . .) In 2021, less than 0.02 Mt of renewable ammonia was produced, but 15 Mt by 2030 is announced, notably in Australia, Mauritania and Oman (. . .) an electricity price below US$ct.2/kWh is required for renewable ammonia to be competitive with fossil-based ammonia" [3] (pp. 10–12).

This quote underscores the ammonia industry's reliance on fossil fuels, ignoring the immense societal costs of climate change. Accurate financial appraisals that include these costs would mandate immediate use of hydrogen from renewable sources. Western investors, however, expect electricity prices below USD ct.2/kWh for their announced hydrogen–ammonia projects in the Global South, exclusive locations, unrestricted access to all natural resources, and likely subsidies and tax exemptions. The language is "de-risk early investment projects" [3] (p. 20), meaning that the public treasury pays for the capital and operational expenses of ammonia projects.

The energy efficiency of the best available technology using low-temperature electrolysis (alkaline or PEM) is 50% [3] (p. 65). This means that producing one ton of ammonia, which has an energy content of 18.6 GJ, requires 37.2 GJ of energy.

6.2. Hydrogen-Derived Synthetic Fuels

Some energy activities are not grid-connected and require large quantities of storable fuels, making them challenging to power with batteries. Examples include long-distance aviation, ocean-borne shipping, military aircraft, vessels, and rolling equipment. They rely heavily on *liquid hydrocarbon* fuels, and they claim unlimited supplies. *Without a ban* on petroleum extraction, oil products will continue to meet their expanding demand. Pressures inspired by the growing awareness among destitute communities, young activists, concerned citizens, and scientists spur fossil fuel interests to propose *solutions* for the continued use of fossil fuels. One such solution is said to be blue hydrogen based on fossil gas [6]. By capturing (part of) the emitted CO_2, it becomes the carbon source for fabricating syngas, a mixture of CO and H_2. Although carbon capture is technically feasible, it is financially expensive and not practical on a small scale.

At the bottom of Table 2, it is shown that CO_2 emission during H_2 fabrication exceeds the CO_2 input for synthetic fuel fabrication. It is unclear how this surplus is managed.

With a stringent ban on any use of fossil fuels, green hydrogen is seen as a solution for making hydrocarbons without full dependency on fossil fuels. Table 2 documents energy and material flows, and efficiencies of Fischer–Tropsch Syncrude and methanol. The inputs of green electricity and of green hydrogen are significant, when fossil fuels are completely excluded.

The blue hydrogen pathway expands the use of natural gas and requires significant investments in installations and equipment. In this context, the role of hydrogen is more a disguise than a solution. Natural gas is used at the beginning of the process, and liquid hydrocarbons are the outcome at the end. Without complete CCS, the CO_2 created for producing H_2 will be emitted. When synthetic hydrocarbons are used in aviation, shipping, and the military, CCS is impossible, resulting in the emission of all the created CO_2.

Table 2. Green electricity to liquid synthetic fuels based on theoretical maximum efficiencies. For lost H_2 and CO_2 mass, minimum–maximum ranges are shown [31].

	Fischer–Tropsch Syncrude	**Methanol**
Composition	15% H_2 + 85% C	12.5% H_2 + 37.5% C + 50% O_2
Heating value	11.94 kWh/kg	6.29 kWh/kg
Heat surplus of synthesis	3.94 kWh/kg	0.82 kWh/kg
Heat input for syngas	2.27 kWh/kg	1.01 kWh/kg
Synthesis efficiency	67%	83%
Input electricity	25.4–29.0 kWh	10.9–12.5 kWh
Input H_2	0.44–0.46 kg	0.19–0.20 kg
Input H_2O	4.0–4.1 kg	1.7–1.8 kg
Input CO_2	3.2–3.3 kg	1.4–1.5 kg
Output	1 kg C_xH_y hydrocarbon	1 kg methanol CH_3OH
Overall efficiency	41–47%	50–58%
Averages about CO_2:		
CO_2 production for input H_2	4.83 kg	2.09 kg
Surplus CO_2	1.58 kg	0.64 kg

7. Is the Hydrogen Energy Economy Financially and Environmentally Affordable?

An energy economic sector is characterized by infrastructures and equipment for handling the energy stocks and flows, and by energy losses during conversion and transfer processes.

Before committing to significant investments in research, development and demonstration, machinery, and infrastructures for a hydrogen-based energy economy, gaining clarity is crucial. Public policymakers should evaluate key physical, technical, financial, and environmental issues from a public interest perspective.

The inherent properties of hydrogen (Section 4) are the fundamental hindrances to a successful hydrogen energy economy. Section 5 documents the poor energy efficiencies of proposed hydrogen applications (Figure 2). Electric battery cars are three times more efficient than hydrogen fuel cell-driven cars. In addition, fuel cell vehicles require about double the capital expenditure and at least triple the operation expenses of battery-powered electric vehicles [5].

For the *long-distance transport* of hydrogen, two main methods are proposed: pipelines for hauling pressurized gas and ships for carrying liquefied gas. Both methods are so capital- and energy-intensive that imports from overseas to Europe are not economical; domestically produced e-hydrogen with renewable electricity is invariably cheaper [40]. Despite this, large-scale hydrogen-producing projects in distant countries (Australia, Chili, Kazakhstan, Morocco, Namibia, Oman), requiring cross-continental transport mains, are an essential part of the envisaged hydrogen energy economy.

The feasibility of hydrogen energy projects depends entirely on subsidies from the treasury. The EU Commission and some national states provide lavish subsidies, without a guarantee on returns. The rationale for the subsidies is the development and demonstration of new technologies for mitigating climate change. This rationale is not based on facts.

First, green hydrogen can substitute for gray hydrogen in the ongoing manufacturing of about 95 Mt hydrogen for industrial purposes. The technologies are known, and the benefits of substitution are too: the avoidance of more than 1Gt of CO_2 emissions. According to standard rules of economics, the industrial sectors using hydrogen should include the costs of green hydrogen in the price of their products (chemical fertilizers, refined petroleum products, steel, ammunition, etc.).

Second, the *new* solutions proposed so far do not guarantee reductions in GHG emissions. Hydrogen-derived synthetic fuels are hydrocarbons whose combustion will emit CO_2, while their production will consume massive amounts of renewable electricity (Table 2). The associated environmental impacts of ammonia could be excessive for nitrogen and GHG emissions. N_2O formation is the most dangerous, because of its global warming potential of 265 and its potential to deplete stratospheric ozone. *"The ammonia economy would have the same climate impact as the fossil-fuel energy system in case if 0.4% of nitrogen converted from* NH_3 *to* N_2O*"* [37] (p. 3), considering that the overall loss range is likely 0.5 to 5%. *"*CO_2 *emissions from ammonia production amount to 500Mt annually, or 1.4% of the global energy-related 36Gt* CO_2 *emissions"* [3] (p. 11).

In addition to the noxious atmospheric emissions caused by hydrogen production, escaped or released hydrogen extends the lifetime of GHGs (Section 4). Electrolysis for manufacturing hydrogen absorbs significant clean water resources (Section 8). Megalomanic parks of wind turbines and PV panels disturb wildlife, biotopes, and human settlements. Renewable electricity production belongs where people need electricity for their daily use.

8. Hyrasia One, Announced Megaproject of Ammonia Export from Kazakhstan's Caspian Sea Shore

This European project plans to produce 2 million tons of hydrogen for 11 million tons of ammonia annually, utilizing water from the Caspian Sea [41]. The project developers have received permission from the local government to install PV and wind farms over 20,000 km^2 territory at the shore of the Caspian Sea. Figure 3 illustrates the land area that would be occupied by Hyrasia One.

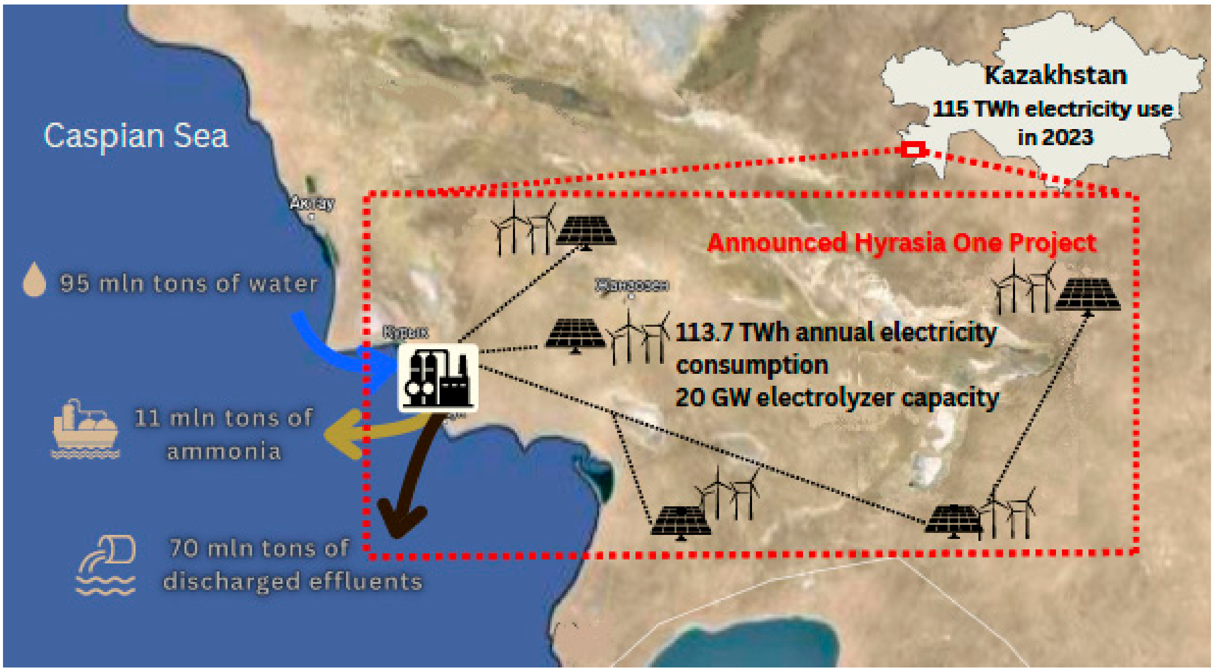

Figure 3. Overview of the announced Hyrasia One project in Kazakhstan.

It is planned to abstract around 95 million tons of seawater annually, or 255,000 m^3 per day. Hyrasia promotors state that the project will not harm the local environment, as the amount of pumped water is *only* 0.03% of the average annual inflow from the main five rivers of the sea's basin. As compensation, they foresee a discharge to the region's water cycle of 70 million tons of effluents after processing hydrogen and ammonia. Discharging such effluents will harm the marine ecosystem, because they include desalination residues, process water, and electrolyzers' cooling water. They contain higher concentrations of minerals, metals, and other industrial contaminants compared to the abstracted Caspian Sea water. Moreover, 25 million tons of abstracted water will be absorbed in the production of 2 million tons of hydrogen and 11 million tons of ammonia, which will be exported and permanently cut out from the local hydrological cycle. Such losses will repeat year by year; essentially, they will be exporting water from a closed basin without return. These cumulative impacts pose significant risks to the Caspian region, located in an arid zone and already scarce of clean water resources.

The project plans to construct fields of 13 GW Photovoltaic panels, and 27 GW wind turbine farms, which together represent twice Kazakhstan's electricity production capacity of 20.4 GW [42]. In 2023, Kazakhstan consumed 115 TWh of electricity, around 87% from coal and gas. The country will not benefit from the renewable electricity production capacity of the Hyrasia project to decarbonize the country's energy economy, as the planned 113.7 TWh electricity generation is intended solely to power hydrogen production and its derivative, ammonia.

On top of the water and electric power issues, Hyrasia raises significant environmental and safety concerns. There will be irreversible habitat loss for local wildlife and migratory birds due to the vast areas occupied by the megalomanic PV and wind turbine constructions. Hydrogen storage and transportation facilities pose fire hazards and risks of atmospheric releases. Ammonia implies contamination risks for water currents and lakes, and for land. Ammonia is known for its toxicity and deleterious impacts on biodiversity, and its nitrogen component is one of the major environmental challenges [39].

Visiting an existing plant for green ammonia production is highly instructive for assessing the Hyrasia megaproject. In June 2024, the second largest ammonia producer in the world, Yara, opened its first 20 kt/year ammonia plant. It produces up to 3.6 kt/year of green hydrogen. The 24 MW PEM electrolysis is driven by hydropower, whose annual consumption we assess at 0.207 TWh. The PEM delivers 10 tons H_2/day for immediate use, avoiding costly H_2 compression and storage. The layout of the plant shows there is a combination with gray ammonia production from liquid petroleum gas, increasing the reliability of the continuous feedstock for ammonia synthesis while avoiding H_2 storage. For a picture of the layout of the Yara project, please consult [43].

Fresh water is abstracted from Lake NorsjØ. For cooling cycles, it seems directly applicable. For the PEM treatment, ultrapure water is needed. Several treatment steps are needed to obtain ultrapure water for green ammonia production.

Remarkable in the layout is the addition of a cold hydrogen venting stack, likely built for safety reasons; however, it releases hydrogen into the atmosphere, with a negative impact on its GHG concentration (Section 4). This real-life project highlights the predominant role of renewable electricity inputs and the critical importance of water for the electrolysis process. Innovation subsidies cover up to 40% or EUR 25 million of the investment.

The announced Hyrasia One project would produce 550 times the output of the Yara plant in Norway. Such upscaling is unseen in sound industrial practices.

9. Conclusions

Hydrogen has been known about for a long time [44]. It is used as a chemical substance in industry. Its use as an energy commodity was promoted several times but remains negligible. Because natural hydrogen sources on Earth are few, most hydrogen is generated from energy sources, predominantly natural gas and coal. Consequently, manufacturing 95 Mt hydrogen for industrial use in 2022 caused more than a billion tons of carbon dioxide, methane, and nitrous oxide emissions. Such emissions need elimination for humankind to avoid climate collapse. Applying green hydrogen in present industrial processes would be a responsible start. However, only small steps have been noticed, like Yara, which, in 2024, started a 10-ton-per-day production of green hydrogen for synthesizing ammonia.

Announcements of megaprojects abound. Hydrogen is advertised as a pivotal component of the future low-carbon energy economy. We grant the *irrefutable physical truth* that combusting hydrogen with oxygen produces heat and clear water as a residual output. Nonetheless, such truth functions as a *delusion* when nonrealistic sequels are built upon it. A famous historical case is the delusion of Archimedes lifting the Earth, which was based on the observed truth of the lever mechanism.

Producing one energy unit of green hydrogen needs a minimum of 1.4 units of renewable electricity. Giant electrolysis projects exhaust the water resources of countries without ocean coasts. Handling and using hydrogen require expensive infrastructure, appliances, equipment, and control systems for leakages and safety. Transport and storage of hydrogen are energy-intensive handlings on top of the wasteful generation process. The hydrogen energy economy is no sane energy economic option. It unravels in the covered-up continuation of fossil fuel use via blue hydrogen's delivery of synthetic hydrocarbons for aviation, shipping, and the military.

Ammonia production is dislocated from industrialized and intensively cultivated regions because of excess nitrogen emissions. Hydrogen-related activities cause various emissions and impacts, making their claim of being a crucial component of effective climate policy baseless. The only climate-friendly hydrogen activity is replacing hydrocarbon-based hydrogen in industrial processes (refineries, fertilizer chemistry, steelmaking) with on-site electrolysis using renewable electricity. It is puzzling why this substitution has not occurred after the 1994 ratification of the UNFCCC, and still is yet to start in 2024.

The green label of green hydrogen depends on green electricity from sunlight and wind currents, which since 2018 have also been the cheapest electricity ever seen in history. The announced giant projects in developing countries for green hydrogen and ammonia production claim a kWh price below EUR 0.02 and hint at Giga-Watt wind turbine and solar PV parks. Such parks are a biased concentration of essentially small-scale and even micro-generation technologies. Some even suggest producing electricity from hydrogen, likely at a cost price above EUR 0.20 per kWh.

A crucial choice for politicians in every country in the Global South is how to use their solar and wind resources. The simplest way is to build solar and wind generation units all over each country, and to electrify as many energy services as possible, such as battery-powered electric cars. Doing so is following Einstein's advice: *make things as simple as possible, but not simpler*. Distributed community renewable electricity is the proper energy fundament for escaping climate collapse, while strengthening democracy, equity, and welfare. The appropriate solutions are negated and obstructed by concentrations of money and power, as showcased by the 2014 putsch of the EU's energy conglomerates.

Embarking on megalomanic hydrogen generation projects is a waste of energy, money, and time. In that case, top-quality energy, electricity, is converted into a really problematic fuel, hydrogen. The argument that such conversion is needed for addressing climate change is false. The contrary is true: a hydrogen energy economy prolongs the use of fossil fuels and distracts societies from deploying the beneficial distributed renewable electricity economy.

While common sense may suffice for denouncing the utopian hydrogen tales, involved interests are often strong and widespread in keeping up deceiving delusions, and obtaining political and financial support for realizing their costly utopia. In the end, it is the citizenry of a region, country, or locality that is submitted to the pernicious impacts of ineluctable utopia failures.

Author Contributions: Conceptualization, A.V. and G.Y.; Investigation, A.V. and G.Y.; Project administration, K.B.; Supervision, K.B.; Validation, K.B.; Visualization, G.Y.; Writing—original draft, A.V.; Writing—review and editing, G.Y. and K.B. All authors have read and agreed to the published version of the manuscript.

Funding: University of Antwerp AK/WD351300.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Glossary

CCS	carbon capture and storage
H/H_2	hydrogen atom/molecule
NH_3	ammonia
PEM	Proton Exchange Membrane

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