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Viewpoint

Petroleum Sector-Driven Roadmap for Future Hydrogen Economy

Amir Safari [1,*,†], Joyashree Roy [2,3,‡] and Mohsen Assadi [4,§]

[1] Department of Science and Industry Systems, University of South-Eastern Norway (USN), 3616 Kongsberg, Norway
[2] Department of Energy, Environment and Climate Change, Asian Institute of Technology, Pathum Thani 12120, Thailand; joyashree@ait.asia
[3] Department of Economics, Jadavpur University, Kolkata 700032, India
[4] Department of Energy and Petroleum Engineering, University of Stavanger (UiS), 4036 Stavanger, Norway; mohsen.assadi@uis.no
* Correspondence: amir.safari@usn.no
† Associate Professor.
‡ Bangabandhu Chair Professor.
§ Professor.

Featured Application: This viewpoint article tries to come up with a proposal for an institutional arrangement which can enable and/or accelerate the actions towards hydrogen economy for the Persian Gulf region through international cooperation. Establishing a hydrogen hub (i.e., Gulf Cooperation Council Hydrogen Hub, GCCHH) as both a technology center and export core, based in a country nominated by the GCC, can initiate a regional process towards industrial developments for the future hydrogen society, given the technology prospect and unique position of each country.

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Abstract: In the climate change mitigation context based on the blue hydrogen concept, a narrative frame is presented in this paper to build the argument for solving the energy trilemma, which is the possibility of job loss and stranded asset accumulation with a sustainable energy solution in gas- and oil-rich regions, especially for the Persian Gulf region. To this aim, scientific evidence and multidimensional feasibility analysis have been employed for making the narrative around hydrogen clear in public and policy discourse so that choices towards acceleration of efforts can begin for paving the way for the future hydrogen economy and society. This can come from natural gas and petroleum-related skills, technologies, experience, and infrastructure. In this way, we present results using multidimensional feasibility analysis through STEEP and give examples of oil- and gas-producing countries to lead the transition action along the line of hydrogen-based economy in order to make quick moves towards cost effectiveness and sustainability through international cooperation. Lastly, this article presents a viewpoint for some regional geopolitical cooperation building but needs a more full-scale assessment.

Keywords: energy transition; energy hub; blue hydrogen; hydrogen economy; Gulf countries

1. Introduction

Energy transition is a continuous process. As decarbonization of the power sector and energy-intense industries are becoming an imperative global complexity and a large-scale investment, commitments for transformative change need serious consideration. COVID-19 has shown that by stopping economic activities emission can be reduced, but this disruptive path is also associated with large-scale hardships. Thus, any long-term transformative energy transition plan needs to start early by conceptualizing the new technology needs, innovation plans, and piloting, followed by full-scale demonstration projects to understand the socio-economic and technological challenges. The step from demonstration project to commercialization stage needs a feasibility check from other dimensions, with the most important being the business model and full supply chain in operation, as well as identification, policy readiness, finance, competitiveness, human capacity with new skills, and public education to enhance acceptance. Literature shows new technology penetration in society can experience many failures, such as being trapped in the valley of death in the innovation chain due to absence of a systems-approach, the absence of policy readiness, lack of a business model, competition from incumbents, etc. [1]. In the case of energy, which is open to international competition and has implication for global climate change investment, market knowledge sharing becomes even more complex. Under such circumstances, a transition path needs to be guided by national circumstances and international cooperation. Need for a fuel switch in the energy supply sector and end-use activities such as mobility of both people and freight are two major sectors which have been thrown open challenges for breakthrough innovation and accelerated implementation of changes on multiple tracks [2].

Previously, 2015 was considered a landmark year due to the adoption of the Paris Agreement at COP21 and endorsement of UN's Sustainable Development Goals (SDGs) framework by all the countries. In 2018, the Intergovernmental Panel on Climate Change (IPCC) special report on Global Warming of 1.5 °C presented their assessment based on available scientific literature that the net zero greenhouse gas (GHG) emissions goal by the mid-century is essential to be consistent with 1.5 °C warming compared to pre-industrial levels [3]. However, the same report also presented high agreement and robust evidence of risks in fast and deep mitigation strategies through the SDGs lens for countries currently dependent on hydrocarbon resources for revenue, economic development, and employment generation [3]. The same concerns are also presented in the literature on just transition, which represent arguments concerning possible job loss, loss of investment flow in new fossil fuel resource exploration, high risks of ending up with stranded assets, revenue fluctuations due to oil and gas price volatility, energy poverty, and dwindling resources [4].

Literature on solutions for fossil fuel-dependent countries is focused on enhancing resource diversification, and the discourse is mostly dominated by expansion of wind and solar energy sectors [5]. According to the United Nation Department of Economic and Social Affairs, the world population in 2050 will be about nine billion, meaning that the need for providing much more accessible, affordable, and secure energy for the people cannot be addressed by investment in solar and wind alone.

In the near term, natural gas and liquid natural gas (LNG) are being considered to provide immediate opportunities for reducing carbon emission from coal-fired plants via fuel switching and employing novel approaches in gas technology in many countries [4,6]. Natural gas is seen as the transition fuel since unconventional gas and new global abundance of natural gas (e.g., shale gas in the US) are already in place. It can be expected that natural gas will continue to be a critical component of energy transition and a reliable backup for intermittent renewables for a couple of decades [7,8]. On the other hand, all these discourses ignore perspectives of multiple challenges and realities in many small but fast emerging developing countries with their newly found oil and gas resources [9]. The discussion on countries at risk is dominated by Gulf Cooperation Council (GCC) countries [10].

Hydrogen has been in focus as an alternative fuel for quite some time [11]. This discourse started in 1968 in Stockholm during a scientific meeting [12,13]. Hydrogen as a new fuel can replace oil and gas eventually. In a changed landscape where net zero emission is the goal to be achieved in the next couple of decades, blue hydrogen can be thought of as an affordable and feasible solution to help the faster penetration of hydrogen in the socio-technical space. In methane reforming, if the CO_2 is captured and stored using relevant technologies, the produced hydrogen is called blue hydrogen. Blue hydrogen has the potential of solving downstream hydrogen challenges in power and transport sectors facilitating the transition towards green hydrogen in the future [14]. Critiques say that the decision towards petroleum-based development now will 'lock in' economies in high carbon futures without certainty about future level of development in carbon capture and storage (CCS) technology. Innovative technologies for hydrogen production from natural gas, where the carbon is separated as a solid carbon, can take away the need for CCS. However, the technology is currently under development and the costs and the capacities it can offer are not clear yet [15–17].

The research question of this article is how zero carbon energy transition in fossil fuel-rich and dependent countries can address the trilemma of jobs, stranded assets, and sustainability, and what can be the role of international cooperation in hydrogen-driven leapfrog technology. Oil- and gas-rich countries need to define their choice of pathway for achieving decarbonized energy systems, which is caught up in a complex combination of problems due to uncertainty and redundancy of human resources currently engaged in the oil and gas sector, huge energy supply infrastructure that will need to be retired early, and the need for finding substitutes for oil and gas as energy carriers.

In the sections below, the current study presents and discusses an indicative energy transition roadmap where the existing oil and gas infrastructures and resources are utilized for a faster and deeper cross-sectorial decarbonization plan through establishment of a hydrogen hub for the Persian Gulf region. According to previous studies by the authors, the analytical method (STEEP) can be used for assessing multidimensional feasibility by considering Social, Technological, Economic, Environmental, and Political dimensions [6,7]. Technological stimulus, enablers, and barriers will be addressed in Section 2. The social issue and a techno-economic cross-sectoral discussion will be briefly presented in Section 3 based on literature assessment. Finally, a geopolitical point of view for launching a hydrogen hub for the Persian Gulf region will be argued in Section 4. Obviously, the global environmental issue will stay a core concern for all the deliberations in different sections of the study.

2. Hydrogen Technology: How to Produce, Transport, and Store

The production, storage, and transport of blue hydrogen is presented in this section. The main five steps in the process include production via steam reforming, carbon capture and storage, transportation in pipelines, daily/seasonal storage, and industrial applications [14].

Researchers have discussed major hydrogen production methods including both the conventional and renewable approaches, along with the technical and economic aspects [18–22]. These official classifications are based on the production process of hydrogen [23]. Nikolaidis and Poullikkas provide an overview of the methods that produce hydrogen from fossil fuels as well as renewable energy sources [18]. Dincer and Acar have assessed them for environmental impact perspectives, including the social cost of carbon concept, economic factors, and energy and exergy efficiency [19]. Hosseini and Abdul Wahid [20] and Dincer [22] have specifically given an overview of the state-of-the-art hydrogen production technologies using renewable and sustainable energy resources, such as supercritical water gasification (SCWG) of biomass and nuclear energy and from energy recovery processes, respectively.

The main portion of hydrogen today is produced via methane (CH_4) reforming, so-called 'grey hydrogen' because of its natural gas origin and the release of CO_2 in the atmosphere. The cost range of this type of hydrogen is €1.5/kg which depends on the price of gas and carbon emissions [23]. According to the literature, steam conversion of one ton of CH_4 releases about four tons of carbon dioxide into the atmosphere. In case the CO_2 is captured and stored using CCS technology [21], the produced hydrogen is then labeled 'blue hydrogen'. Both steam methane reforming (SMR) and auto thermal reforming (ATR) have acceptable technology readiness levels (TRL) and have considerable market share potential for the production of blue hydrogen and have almost the same route in which natural gas reacts with hot steam leading to the production of syngas. The process consists of natural gas pre-treatment, pre-reforming, reforming, water-gas-shift reaction, and hydrogen separation [24,25]. The sizes of SMR and ATR plants vary in a range of 15,000–300,000 nm^3/h [14]. The process flow of blue hydrogen at the system level is briefly shown in Figure 1 [21]. Syngas production, separation technologies, advanced hydrogen production with CO_2 capture, and outlook on production and use of hydrogen in a CCS context have been particularly discussed by Voldsund et al. [21].

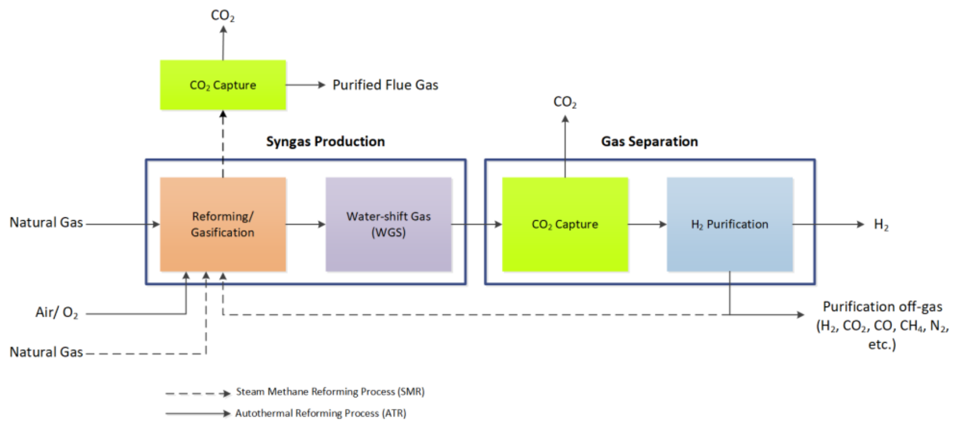

Figure 1. The blue hydrogen process flow: SMR and ATR.

'Green hydrogen', however, is produced via an electrolysis process by converting electricity generated from renewable energy (e.g., wind and solar) into hydrogen, which can be stored in large tanks and released when/if needed. The cost range of this type of hydrogen is €2.5–5.5/kg. No GHG is emitted during the process of green hydrogen [23]. As a matter of fact, it will contribute to coping with intermittent electrical power from wind, solar, and other renewable sources. The green hydrogen concept (i.e., Power to Gas, P2G) is shown in Figure 2 [26].

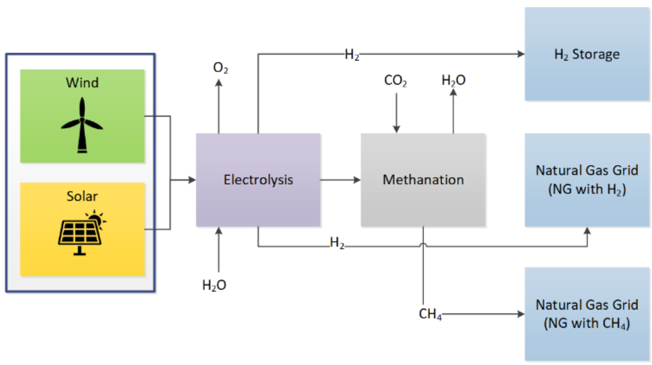

Figure 2. The green hydrogen schematic.

For a smooth transition to a hydrogen economy, an interconnection between hydrogen production units and industrial applications is needed. This downstream conversion enables hydrogen implementation, however parallel policy is also required to guarantee the integration of green hydrogen and the phasing out of blue hydrogen in the upcoming decades [14]. In addition, social acceptance for fossil fuel usage along with CCS and hydrogen transport is crucial for successful implementation of blue hydrogen projects.

As shown in Figure 1, CO_2 as a by-product of natural gas reforming can be captured and stored, and then the blue hydrogen chain can be climate-neutral despite relying on hydrocarbon. Based on that, CCS appears to be a vital part of the hydrogen economy, so its realization will lead to a superior focus on CCS in conjunction with hydrogen [27]. Because CCS is essential for blue hydrogen, an analysis on its feasibility in deferent regions is necessary [14]. The most important geological storage options are depleted oil and gas reservoirs, and offshore and onshore deep saline formation, where CO_2 can be used for enhanced oil and gas recovery (EOR), as well as coal mines, where CO_2 can be used for enhanced coal bed methane recovery. Alternative CCS and CCU (i.e., carbon capture and utilization) processes are illustrated in Figure 3 [28,29].

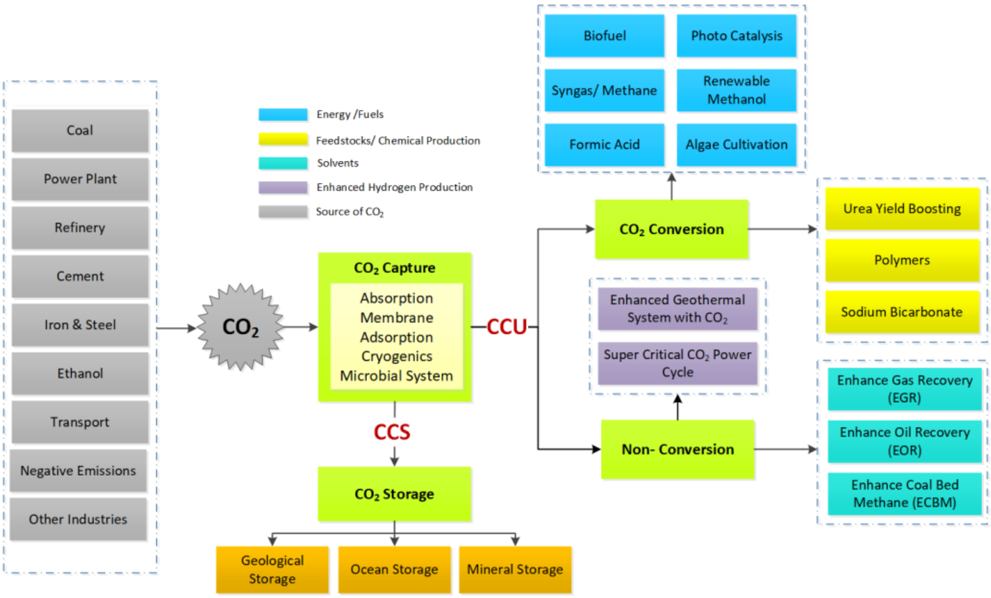

Figure 3. The CCUS schematic diagram.

A comprehensive feasibility study conducted in 2016–2017 concluded that CO_2 capture is technically feasible at three selected industrial sites in Norway: Norcem's cement factory in Brevik owned by Heidelberg Cement, Yara's ammonia factory in Porsgrunn, and the Fortum Oslo Varme's energy recovery plant in Oslo [30,31]. As the projects were based on transportation by ship, the storage site could also be accessible for other European countries. A successful demonstration could also be inspiring for the GCC countries.

From a techno-economic perspective, 50–70% CO_2 capture with around 0.135–0.146 Euros/m^3 levelled production cost of H_2 could be seen in the SMR technique without capturing flue gas (which means about 0.037–0.060 Euros/Kg CO_2 tax reduction), while these amounts for ATR technology are 90%, 0.143 Euros/m^3, and 0.048 Euros/Kg, respectively [14]. A new SMR scenario with capture from flue gas or hydrogen as combustion fuel for heating offers up to 90% CO_2 capture and 0.165 Euros/m^3 levelled cost of H_2 [24].

After hydrogen production, its transport via the existing natural gas infrastructure and/or a new hydrogen grid can be considered as two feasible scenarios. For the first option, different chemical properties between CH_4 and H_2, the regulation and safety, the integrity of the pipelines, and the availability of capacity are among the important challenges to be addressed. Other important parameters are number of compression stations, characteristics of measurement instruments, replacement of critical components, and degradation of existing pipelines/grid. For instance, a feasible implementation strategy can determine the impurities and process parameters based on the largest consumers' need, and then on-site purification and compression can be implemented if needed [14]. More studies are required to determine which parts of the existing infrastructure are applicable to the hydrogen transport and which ones must be replaced. The related social concerns and economic issues are discussed in the next section of the paper.

At the same time, one major key to wholly developing a hydrogen economy is safe, compact, light and cost-efficient hydrogen storage [32]. Storage of hydrogen is needed to compensate for a mismatch between supply and demand on timescales from minutes to seasons in a way that flexibility and security in delivery and purchase can be ensured [14].

Various hydrogen storage methods and their challenges are presented and briefly discussed by several researchers, for example in [33,34]. For the blue hydrogen case, it will be vital to determine the cumulative demand flexibility and the related storage volume/pattern, which will determine the selection of the storage method [14]. The most important identified methods for blue hydrogen storage are [35]: (a) Line packing (daily storage in the gas network), (b) tanks for compressed gas (daily small-scale storage in cylinders), (c) liquid hydrogen (daily small- and large-scale storage in tanks of LNG), (d) salt caverns (daily and seasonal large-scale storage), and (e) depleted gas fields (seasonal very large-scale storage). According to the literature, hydrogen storage will only be limited on a system level and would be feasible in cryogenic tanks or salt caverns [14]. A summary of H_2 storage options is illustrated in Figure 4. For more details, readers are referred to [14,35,36].

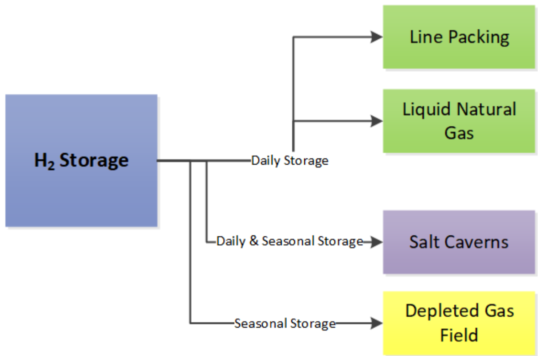

Figure 4. The hydrogen storage alternatives.

The industrial applications of hydrogen include feedstock and fuel in burners/fuel cells/turbines that will be briefly discussed in the next section, i.e., a hydrogen economy.

3. Hydrogen Economy: A Pathway for Society with a Sustainable Future

This section focuses on possible users of hydrogen, which application types can be assumed, when and where hydrogen usage will be considered and why. Full-scale demonstration and commercialization of blue hydrogen technology is the key factor for promoting hydrogen society and utilization in the future energy world. For this purpose, focus on four cornerstones of resilience engineering, including ability to learn, to anticipate, to monitor, and to respond, would be fruitful.

For the energy system transformation globally, two time periods are crucial: 2030 and 2050. The year 2030 is a milestone when the emission curve should bend if the temperature stabilization goal is 2 °C above the pre-industrial level and 2050 is the time when globally a net zero emission level should be achieved. All modelled pathways show fossil fuel-based emission to be declining at an unprecedented rate and there will be need for carbon capture and storage and utilization (CCS/U) and carbon dioxide removal (CDR) for achieving net zero emissions. This would imply new demonstration projects for CCS and new innovations for carbon utilization. Technically these are feasible, but scale-up and investment need are uncertain. However, if this route is not pursued, there is need for alternative economic activities to mining/drilling and refining and transportation infrastructure should be abandoned, and manpower should be retrained for some alternative skills which need to be decided at a national level. All these need to be included in a comparative cost estimation, but a reliable account of which is almost absent now, and this study also does not intend to go in that direction except for highlighting the need. For coal production, CCS/U with CDR is more reasonable if coal abandoning is not an option. For oil and gas, the situation can be different if combined with parallel scientific innovation happening alongside hydrogen production technology innovation and combining with renewables. As mentioned earlier, once produced, hydrogen can be stored using the existing gas infrastructure and used for power generation and for the transport sector as and when needed. It can be imagined as the gas economy replacing natural gas by hydrogen but continuing with the same infrastructure. Therefore, the cost of system shift from gas to hydrogen will be much less for gas resource-rich/consuming countries compared to those that are not. This can be even better than lithium battery storage technology if raw material procurement and recycling costs of batteries are included. Intermittent renewables like solar and wind are prescribed with battery storage. For countries with gas infrastructure, hydrogen can be a more cost competitive (for both job and infrastructure assets) storage option and sustainable than lithium battery storage technology. Based on that, our argument is that for oil- and gas-producing countries, transition to a hydrogen-based economy can be more cost effective and sustainable if the long-term goal is energy transition without near term job loss, loss of assets, and to find a sustainable substitute solution.

Society today is struggling to find 'fit for purpose' solutions while facing a number of critical interrelated problems which should be addressed within a hydrogen economy [4]: (a) global climate change goals, (b) depletion of fossil fuel resources, (c) energy poverty in many fossil resource-rich countries, and (d) job and economic growth in the face of rising global population. Hydrogen society is expected to deliver great benefits for the environment, energy security, the economy, jobs, and end-users [13,32]. The value of the hydrogen-driven energy system lies in its flexibility because hydrogen can connect different energy domains, from electricity generation to heat production to transport in future smart cities with multi-energy carriers [37]. Utilization of hydrogen as an energy carrier includes use as fuel in the transport sector, especially in shipping, as fuel for heating buildings or in heat-intensive industries, and as a medium for energy storage from renewable power generation. An assessment by Marchenko and Solomin [38] demonstrates that the electricity economy proves more desirable in the case of short-term energy storage, while the use of hydrogen is more advantageous in the case of long-term storage.

Considering the future of transport, it is estimated that about 6 EJ/year (20%) of air transportation and 20 EJ/year (30%) of road-freight transport will be covered by hydrogen [39]. A main portion of the world trade is done by shipping which needs to make the fuel switch, and hydrogen can play an important role in that. In Norway, for example, electrification and use of hydrogen in transport are the central policy actions, but biofuels and biogas are also promoted [40]. In addition, blue hydrogen is a strong clean complementary to the renewables because [41]: (i) converted gas turbines running on hydrogen provide a solution if dispatchable carbon-neutral sources of power need to be available in case of intermittency of renewables, (ii) both blue and green hydrogen could be combined to provide the necessary volumes to achieve bulk emission reductions where renewables alone will not be sufficient, and (iii) sustainable hydrogen can be gradually mixed into the existing natural gas network, with a full switch capability to green hydrogen when available in the future [42].

Some best practices and considerable blue hydrogen case studies are the H-vision, Hydrogen to Magnum, NATURALHY, and ELEGANCY projects. H-vision was the first potential blue hydrogen project [43]. A feasibility study on the business case, technological challenges, hydrogen markets, and CCS has been proposed to realize four steam-reforming plants, at a total capacity of 150,000–200,000 Nm^3 hydrogen per hour, which store the CO_2 under the North Sea via the Porthos backbone. The project will determine how the industry can lower the CO_2 impact of its energy use by replacing natural gas and coal with blue hydrogen [43]. Another project, Hydrogen to Magnum or H2M, is a collaboration between Vattenfall (power plant owner with three combined cycle gas turbines (CCGTs) and approximately four million tons of CO_2 emission per year), Equinor (ATR plant developer), and Gasunie (gas grid infrastructure proprietor). The H2M offers a wide field of applications of hydrogen and would be the first blue hydrogen project of its kind in the world (as the only real case) [44]. Designing a large-scale value chain where production of hydrogen from natural gas is combined with carbon capture, transport, and storage (CCT/S) can open up new business opportunities [44]. Apart from the H2M project, the Norwegian company Equinor also has a hydrogen portfolio as follows: H21 North of

England, Maritime Transport (in Norway), Clean Hydrogen Pilot (in Norway), Ammonia to Power (in Japan), Power and Industry (in France), Heat and Power (in Germany), Hydrogen CCU (in the UK), Power and Industry (in Netherlands). As another one of the first projects in this field, the main objective of NATURALHY is preparing for the hydrogen economy by identifying and removing the potential barriers regarding the introduction of hydrogen into the society using the existing natural gas system as a catalyst [45]. The other important project that is worth mentioning is the ELEGANCY project. The main aim of the project is to accelerate the deployment of CCS technologies in Europe through H_2-CCS chain networks [36]. This includes large-scale carbon dioxide transport/storage infrastructure for use by other sectors and infrastructure for the rapid introduction of green hydrogen as an energy carrier for the future [36].

From the carbon footprint analysis point of view, different production routes mentioned in Section 2 have their own sustainability impact so that the future hydrogen production mix should be optimized to this aim. Multiple studies show that where CCS is applied, the carbon footprint per kilogram hydrogen for SMR, ATR, and electrolysis methods are in the same range [14]. Nonetheless, for the GCC countries, both SMR and ATR technologies with CCS combining all the possible scenarios for electricity supply should be studied against cost, efficiency, and potential for CO_2 reduction. The future of CCS lies largely in the hands of policymakers setting a higher carbon price than the cost of the technology [46]. Nevertheless, the industrial sector can still play a role in encouraging quicker adoption to reduce the cost of CCS technology [47]. On the other hand, blue hydrogen may still face public opposition or at least some debate from those who disagree with the idea of any use of fossil fuels, even if the use is carbon neutral. This implies that a narrative around hydrogen needs to be created carefully to avoid miscommunication. Social support is a very exigent parameter in deployment of any mega-projects in the energy sector.

Taking a perspective from the GCC region as well as Iran (mostly oil- or gas-rich countries), in the near term, the blue hydrogen option can sustain simultaneously their economy, jobs and assets, and market presence while addressing the long-term global climate goals. For this purpose, however, there are many cross-sectoral challenges that should be addressed. For GCC, two major utilizations of blue hydrogen can are foreseen: (i) so-called sector coupling, in which domestic electricity generation (use hydrogen as a sustainable fuel), ammonia production (as the most important industrial application in the region), and transport are integrated; and (ii) export markets. For domestic purposes, hydrogen can be used for fuel cell vehicles and/or heavy-duty transportation among the region's countries. Benefits and deficiencies of hydrogen in transportation and its hazard and safety issues have been discussed in the literature [33]. Hydrogen-based domestic power plants could be also an option for electricity generation, but there needs to be large pilots to achieve the scale and competitive price point. Besides power and transport, the steel sector as well as the ammonia industry would be other potential markets for hydrogen in the GCC. At the same time, the blue hydrogen produced in the GCC might be exported in liquid form, like LNG. Some international companies such as Kawasaki and Shell are currently working on building their own liquid hydrogen vessels [35,39]. Transportation of bulk hydrogen to the international markets in form of clean ammonia (NH3) as one of the most traded chemicals worldwide is another well-designed and affordable way.

In terms of industrial applications, natural gas has been used for decades in the Persian Gulf countries' industries as both fuel and as feedstock. There is no significant difficulty in replacing natural gas with hydrogen for feedstock usage. However, since hydrogen as fuel should be burned with burners, in furnaces or turbines, there would be some technical and safety challenges here to address. Hydrogen can be used in fuel cells, which could be additional use compared to natural gas. Due to the importance of such adaptive applications of blue hydrogen in today's industry, their feasibility is briefly analyzed. Different flame properties (temperature, length, stability, etc.) can be seen as showstoppers in industrial burners to use hydrogen instead of natural gas. Some

3–50 MW state-of-the-art technologies for new H_2-based burners/furnaces have been successfully tested up [27]. The key challenge is about operational regulations such as NOx emissions for the redesigned H_2-based burners and their surrounding furnaces. Exhaust gas recirculation and using particular (but expensive) catalysts could be some feasible solutions to this problem, reducing the NOx emission levels [14]. At the same time, there are several substantial R&D activities on carbon-free firing of gas turbines nowadays. Using existing gas turbines with hydrogen as fuel is not possible, since hydrogen has a lower heating value than that of natural gas, therefore, the fuel flow needs to be increased to maintain the power out of the gas turbine. Another issue to be considered in this regard is the increased steam content of the exhaust gas due to oxidation of the hydrogen, which has a negative impact on the thermal barrier coating of the gas turbine blades. For instance, Mitsubishi's focus is on thermal power generation that does not emit CO_2, which means the development of hydrogen gas turbines [48]. To do that, it is necessary to understand the combustion characteristics, control pressure fluctuation, and the air mixing and its behavior. On the other hand, fuel cells have been the promising technology around the corner for decades, but their large-scale implementation as energy conversion technology has been delayed by various factors and challenges. Fuel cell technologies are usually classified after their operational temperature and principles. Access to pure hydrogen would definitely be advantageous to pave the way for large-scale introduction of fuel cells as an energy conversion technology for distributed generation in combined heat and power (CHP) applications. The potential for hydrogen demand and utilization are discussed in [34] and summarized in Figure 5 [49].

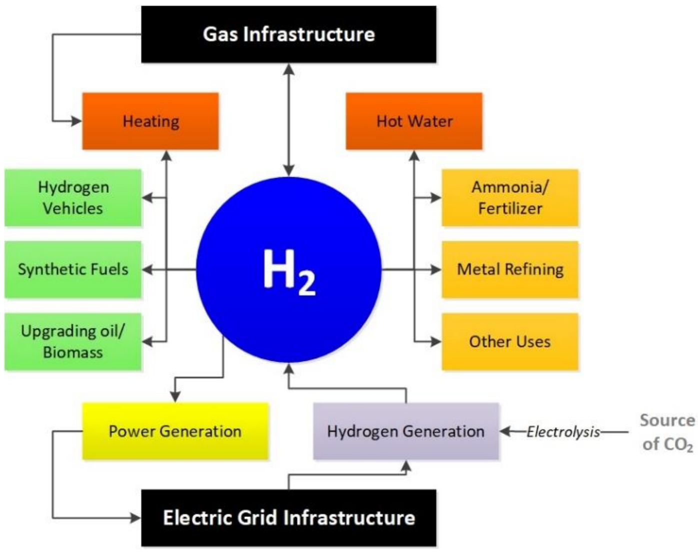

Figure 5. The hydrogen utilization options.

4. Geopolitical Vision: Proposal for a Persian Gulf Countries' Hydrogen Hub

Given the technology prospect and unique position of GCC, this section tries to come up with a proposal for an institutional arrangement which can enable and accelerate the actions towards a hydrogen economy through international cooperation in the region. Establishing a hydrogen hub for the Persian Gulf region (i.e., Gulf Cooperation Council Hydrogen Hub, GCCHH) as both a technology center and export core, based in a country selected by the GCC, can initiate regional processes towards industrial developments for the future hydrogen society. As the share of (green and blue) hydrogen in the GCC's energy sector is predicted to increase dramatically in the future, there would be an emerging need for an efficient hydrogen market, pricing benchmark, and trading platform. Having such a platform is exigent for any new energy carrier with a new market prospect [50,51].

The proposed centralized hub can enable sharing of resources, technologies, and infrastructure from different countries in the GCC in which a number of hydrogen-based energy solutions both in supply and demand sides could be integrated. The hub can put its primary focus on regional collaboration and create capacity among municipalities, citizens, and local industries to kick-start such a transformation from a variety of social actors. This can generate demand and matching supply of services from various actors. All these need to be facilitated by a well-defined policy at GCC and nationally keeping the long-term strategy to guarantee effective, affordable integration of the new approaches for (both blue and green) hydrogen into the existing gas and electricity grids. The final GCCHH roadmap should also include an investigation for mapping the CO_2 storage capacity in the region through niche experiments to enhance learning and advance innovation and transition, for example in depleted gas fields in Qatar (ranked 3rd in natural gas proven reserves in the world), Iran (in 2nd place), Oman (in 28th place), and UAE (in 7th place). Such an offshore (and likely onshore) storage of CO_2 offers the lowest cost and technological risks, the cleanest value chain, the largest scale, and the most robust infrastructure. Moreover, the roadmap will take the geopolitical situations of this particular region and its role in future energy market into account.

The innovation part of the hub could be based on the complex concept of energy hub, which should be re-defined and tailor-made for the blue hydrogen production, storage, transport, and usage [37]. There is definitely a need for an in-depth scientific comprehensive research study to develop the blueprint to manage 'just transitions' in GCC in the period up to 2040. There is a Norwegian model in this regard which could be considered as a good starting point [52]. The current study is a rapid assessment of the possible vision for the region. The final aim is to undertake and present a hydrogen strategy for the entire region, which could also include green hydrogen. Lastly, a roadmap of CO_2 reduction in the region is also targeted. It is important to note that to recognize how much Mton of CO_2 per year can be stored in this region, based on the emissions as well as total available capacity for storage both offshore in the Persian Gulf/Oman Sea and onshore on the countries' land, needs scientific assessment. For example, available capacity for the Netherlands is 1400 Mton offshore while some territory countries like Norway are interested in storing CO_2 (according to the atlas prepared by the Norwegian Petroleum Directorate, the total storage capacity is about 70 billion tons). Therefore, the required gas infrastructure for this purpose as well as the GCC governments' policy and regulations for CO_2 storage underground needs to be developed. Such a storage potential could also be used for storing hydrogen itself when/if technically and economically feasible. Since the scalability is a significant criterion for the feasible CCS, a close cooperation among the GCC countries to have several clusters of CO_2 resources with larger volumes may be a way forward. On the other hand, because the GCC countries have no direct experience with real and/or full-scale CCS projects, common pilots in cooperation with experienced and knowledgeable countries like Norway are also suggested. Their extensive knowledge and know-how can be transferred in terms of the technical, economic, and commercial aspects of the RD&D projects as well as invaluable evidence-based recommendations.

A blue hydrogen plant can be theoretically part of any large CCS project [14]. Thus, it would be wise to centralize such a CCS plant near the natural gas processing industrial fields in the region, enabling efficient carbon capture and transport. For this particular purpose, an overview per country and sector is presented in Figure 6 [53–56]. The largest potential for CCS would mean the feasibility for hosting blue hydrogen plants. Unfortunately, some vital information is missing for now including precise information about where and how natural gas is produced and processed and consumed, data on depleted NG reservoirs in the region (exactly where and how much), and information about the suitable locations for CO_2 storage and utilization (industries, EOR needed oil and gas fields, etc.). For a comprehensive study and detailed roadmap in the future, however, all these data should be collected, mapped with georeferencing and analyzed.

	Proved Reserves (tcm)- At end 2018	Gas Production (bcm)- 2018	Gas Consumption (bcm)- 2018	Gas Fields			LNG Import (bcm) 2018	LNG Export (bcm) 2018	Gas Export 2018	LNG Export to:	Pipeline Export to:
				Name	Location	In-Place Gas Reserve					
Bahrain	0.2	14.8	…	Awali	Center of Kingdom of Bahrain	20 tcf (570 km3)	…	…	…	…	…
Kuwait	1.7	17.5	21.8	…	…	…	4.3	…	…	…	…
Oman	0.7	36	24.9	…	…	…	…	13.6	LNG	China, India, Japan, Pakistan, South Korea, Taiwan, Thailand	…
Qatar	24.7	175.5	41.9	North Dome Field	Persian Gulf	900 tcf (25000 km3)	…	104.8	LNG - Pipeline	Argentina, Brazil, Belgium, France, Italy, Spain, Turkey, UK, Egypt, Kuwait, China, India, Japan, Pakistan, Singapore, South Korea, Taiwan, Thailand	UAE, Middle East
Saudi Arabia	5.9	112.1	112.1	Ghawar Field	Al Ahsa	57 tcf (1600 km3)	…	…	…	…	…
UAE	5.9	64.7	76.6	Rub Al Khali Province	…	426 tcf (12100 km3)	1	7.4	LNG	India, Japan, Taiwan, Thailand	…

Figure 6. The GCC countries' natural gas data in brief.

A business model of the GCCHH could be affected by some design parameters including market/demand for both CO_2 and H_2, capacity of storage (both CO_2 and H_2), available infrastructure for distribution and transport, ETS CO_2 price, TRL, subsidies from government, social acceptance, and so on. On the demand side, for instance, the final goal is to sustainably meet the needs for electrical/thermal power, transport, and industrial/chemical applications. As another example, from a market point of view, an innovative restructuring of the Organization of Petroleum Exporting Countries (OPEC) might be required where a smooth transition to a hydrogen economy without involvement of these countries in the most effective hydrogen plan (i.e., the blue concept) seems to be impossible. In this way, natural gas-rich countries in Middle East and North Africa (MENA) can continue to supply the Europe's (and the world's) 'clean' energy demand in a long-term perspective using existing pipelines and/or by tankers (for liquid form of hydrogen) [57]. The Persian Gulf countries, in turn, can provide this exporting system with their green hydrogen because of considerably inexpensive electricity that comes from their (future) solar farms. The existing GCC's gas grid/pipelines and map of distribution/compression points should also be included in the business model. Depending on the usage of existing networks for import/export or distribution purposes over the region, it could be considered for blue hydrogen transport if there is adequate capacity. To realize this, a strong science-based, top-down governmental policy and involvement of large industries and infrastructure/plants owners are required. To this aim, the focus should be on reduction of the carbon footprint, not of the source of energy carrier itself. Figure 7 demonstrates all the possible alternatives for the blue/green hydrogen economy [58]. It could be applicable to the GCC region for its future 'glocalized energy system'.

The proposed blue hydrogen hub is an institutional arrangement which can act as an enabler to foster the development and use of blue hydrogen in the GCC. It facilitates interactions between supply chain stakeholders (including natural gas explorers/producers, equipment suppliers, research institutions, investors, and national authorities) and customers/end-users (such as relevant industries, energy companies, and hydrogen exporters) to share assets and products and to learn from each other, creating economies of scale around some specific blue hydrogen projects.

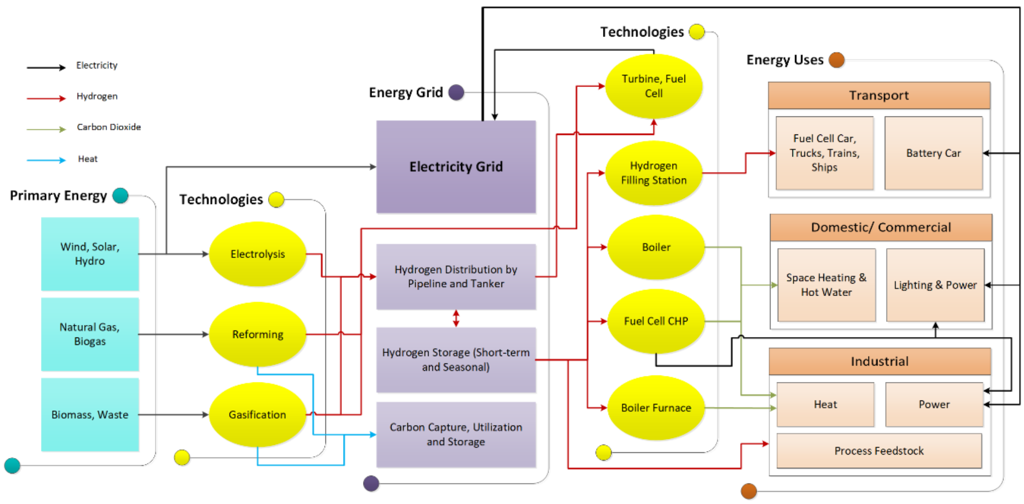

Figure 7. The hydrogen in future energy system.

5. Conclusions

In this perspective paper, a narrative frame has been presented using scientific evidence and multidimensional feasibility analysis to build the argument to solve an energy trilemma: the possibility of job loss, stranded asset accumulation, and sustainable energy solution in gas- and oil-rich regions, especially in GCC countries, in a climate change mitigation context based on the blue hydrogen concept. In other words, by learning from case studies and best practices in other experienced countries like Norway, this paper is an initial vision to highlight the necessity of thinking of transition management with a long-term goal but by accelerating actions in near term. Large-scale hydrogen production can follow a strategic transition plan starting from conversion of existing technologies for grey hydrogen with cost of ~€1.5/kg, hydrogen from natural gas without carbon capture and storage, to blue hydrogen, hydrogen from natural gas with carbon capture and storage, to create a functioning market and support development of future green hydrogen with a cost of ~€2.5–5.5/kg for hydrogen from renewable energy sources.

There are multiple attempts towards this transition happening at project scale which GCC can take part of to learn and lead in the region. We show that the short primitive proposal for the blue hydrogen chain in the GCC region is feasible such that it can assure economically attractive industrial volume decades before green hydrogen. To maximize the impact and determine the optimum scenario, not only must all stakeholders in the field at national and regional levels must work together, but also all different applications should be somehow coupled in the proposed institutional arrangement proposed as 'hub'. The authors would recommend that more organized bilateral and/or multilateral research and development cooperation between the Persian Gulf countries and Europe and Norway in particular is clearly required to discover all the opportunities and to pave the road to a hydrogen economy. Here, the role of Qatar as owner of the third biggest natural gas proven reserves and one of the world's largest exporters can play a leadership role in establishment of such a hydrogen hub in the region. This is a rapid assessment-based vision document and there is immense possibility of developing a full scientific document to manage hydrogen transition in GCC countries.

We understand there is a wide variety of scope for widening this research field. Some such areas are likely safety aspects involved in the transition to a hydrogen-fueled society and how they differ from the current oil and gas infrastructure. Another area with scope of new research is hydrogen storage technologies, which is also emerging using advanced materials with the ability to efficiently store/confine hydrogen into their porous or crystal structure. This article presents a viewpoint for some regional geopolitical cooperation building but needs a more full-scale assessment. This paper does not solve the question raised but identifies scope for future research. As we realize, this is a very fast-emerging field and there are multiple angles which need to be scientifically analyzed to make the transition sustainable.

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Abbreviations

ATR	Auto Thermal Reforming
CCGTs	Combined Cycle Gas Turbines
CCS	Carbon Capture and Storage
CCS/U	Carbon Capture, Storage, and Utilization
CCT/S	Carbon Capture, Transport, and Storage
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
COP21	21st Conference of the Parties
EOR	Enhanced Oil (and Gas) Recovery
ETS	Emissions Trading System
GCC	Gulf Cooperation Council
GCCHH	Gulf Cooperation Council Hydrogen Hub
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquid Natural Gas
MENA	Middle East and North Africa
OPEC	Organization of Petroleum Exporting Countries
P2G	Power to Gas
SCWG	Supercritical Water Gasification
SDGs	Sustainable Development Goals
SMR	Steam Methane Reforming
STEEP	Social, Technological, Economic, Environmental, and Political
TRL	Technology Readiness Level

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