Deltares

Energy Transition

Understanding the water-related challenges and opportunities of green hydrogen production

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Executive Summary

The role of green hydrogen (GH_2) in the energy transition is central in reducing greenhouse gas (GHG) emissions and mitigating the effects of climate change. It can serve as a bridging technology, facilitating the integration of renewable energy sources into the energy grid and promoting the decarbonization of hard-to-abate sectors like heavy industry, energy storage and long-haul transportation. However, the realization of these benefits must go hand in hand with responsible water use and management.

There is a lack of insight regarding the impact of GH_2 production on socio-economic, natural, and institutional systems. This is a problem as knowledge gaps and implementation challenges in the natural, socio-economic, and institutional systems are haltering progress in the scaling up of such solutions. Environmental uncertainties, associated to future water demands or societal challenges, including potential conflicts over water access and concerns for vulnerable groups, highlight the importance of public trust and awareness campaigns for this investment's success. Furthermore, institutional gaps reveal policy and regulatory vacuums, emphasizing the need for international collaboration, standards creation and clarity on stakeholder roles and responsibilities. Overcoming these challenges requires ongoing collaboration and adaptable frameworks to seamlessly integrate water governance into broader energy and environmental policies.

This paper recognizes the multidisciplinary nature of these challenges, and the need for a holistic feasibility assessment framework to surpass them. An approach that acknowledges the intricate interconnections among natural, socio-economic, and institutional systems and emphasizes integrated water-energy management is essential for achieving sustainable development in GH_2 projects.

Building on Deltares' expertise and knowledge, this paper advocates for a holistic understanding of water-related challenges in GH_2 development. The three-dimensional approach highlights the interconnected nature of GH_2 production investments to the natural, socio-economic, and institutional systems. Such approach is characterized as: water-focused, locally-led and future-proof.

The water-focused dimension highlights the need for efficient water and energy management, defining water-focused GH_2 investments. Software and tools like *Wflow*, *RIBASIM*, *iMOD*, and *WaterLOUPE*, can support policymakers in performing comprehensive assessments of water availability and scarcity risks in project areas. The second dimension, locally led, delves into vulnerability assessments and inclusive planning frameworks. This dimension addresses governance mechanisms through initiatives like the *EPIC Response framework* and the *Valuing Water Initiative*. The emphasis lies in fostering GH_2 growth while safeguarding resources, ensuring equitable distribution of benefits, and considering socio-economic impacts. Lastly, the future-proof dimension stresses the need for long-term planning under deep uncertainty and recommends methodologies like *Dynamic Adaptive Policy Pathways* (DAPP), emphasizing concepts such as adaptability, innovation, and scalability. This three-dimensional framework not only identifies critical aspects of GH_2 development but also provides actionable insights for a responsible and sustainable development of GH_2 investments. Overall, these illustrate that an inclusive, climate-resilient, and sustainable GH_2 production model is possible.

Finally, this paper concludes with the presentation of recommendations and next steps that seek to spark further discussion and research on the opportunities presented by these challenges. Recommendations span across the three-dimensional approach (water-focused GH_2, locally-led GH_2, and future-proof GH_2), as well as a general strategic planning category.

For water-focused GH_2, Deltares can contribute through assessments of water demands, suitability mapping for production hubs, integration into Delta scenarios, advice on water use efficiency, and evaluation of hydrodynamic infrastructure behaviour. Locally-led GH_2 efforts involve guiding water governance structures, facilitating stakeholder engagement, capacity building, and fostering partnerships. Future-proof GH_2 initiatives recommendations focus on developing climate-resilient frameworks, envisioning trends, and conducting risk and opportunity assessments. Finally, strategic planning recommendations include participating in national energy transition strategy development, advocating for GH_2 positioning, and establishing a GH_2 knowledge hub.

Acknowledgements

The completion of this report has been a collaborative effort that involved the contributions, guidance, and support of ten colleagues from Deltares. Their assistance and expertise have been invaluable throughout this report’s development.

Contents

Acronyms

CCUS	Carbon capture, utilisation, and storage
CINEA	European Climate, Infrastructure and Environment Executive Agency
CO_2	carbon dioxide
US-EIA	United States Energy Information Administration
GH_2	Green hydrogen
GHG	Greenhouse gases
DAPP	Dynamic Adaptive Policy Pathways
IEA	International Energy Agency
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
IWRM	Integrative Water Resources Management
R&D	Research and Development
RIBASIM	River Basin Simulation
USNOEP	United States National Oceans Economics Program
VWI	Valuing Water Initiative

1 Introduction

1.1 About this paper

This paper is part of Deltares' work on Sustainable Energy Transitions SO Program: "*Knowledge, systems and process innovations to accelerate the energy transition*" and is aligned with the organizations' Moonshot 4: "*In 2030, energy from water and subsurface will account for 75% of the energy required for sustainable collective energy systems*".

The paper's objective is to position Deltares as a knowledge partner in the energy transition by integrating knowledge on green hydrogen (GH_2) production, water management and governance. The document presents a multidimensional approach harnessed in the Blue Economy principles, focussing on GH_2 future-proof adaptability under deep uncertainties, water use efficiency in the production cycle, focusing on efficiency and resource conservation in water-scarce regions, and institutional aspects that need to be evaluated to guarantee log-term effective governance of the sector.

By harnessing Deltares' expertise from existing methodologies and initiatives, and incorporating lessons-learned from projects, this paper contributes to the Program's objectives as it will increase insight into the long-term impact of GH_2 investments, its link to other societal transitions[1], supporting the qualitatively assessment of large-scale GH_2 production's impacts on ecological and social systems, while considering existing institutional and governance frameworks, as well as identifying governance gaps[2].

The analysis and recommendations presented in this document, aim to inspire, and guide, not only the Deltares' community, but also Dutch and international policy officers, consultants, and organizations, involved in the feasibility phases of GH_2 projects, to explore these synergies.[3]

1.2 Hydrogen production: status and trends

Hydrogen, ammonia, and hydrogen-based fuels can be obtained from fossil fuels and biomass, from water, or from a combination of them (IEA, 2019). At present, hydrogen, and its derivatives, are primarily produced through fossil fuels-based thermochemical processes such as hydrocarbon reforming, coal gasification, hydrocarbon pyrolysis, and plasma reforming [4] (Abdin, et al., 2020). As a result, substantial carbon dioxide (CO_2) emissions, totalling around 830 million tons annually, are generated (IEA, 2019). Addressing this challenge implies shifting hydrogen production to renewable sources to reduce its carbon footprint and facilitate the transition to a more sustainable energy system (Megía, Vizcaíno, Calles, & Carrero, 2021).

Despite the fact that now less than 0,1% of produced hydrogen comes from water electrolysis (IEA, 2019), its sustainable potential to de-carbonize the energy sector has attracted considerable attention over the last decade (Hosseini & Abdul Wahid, 2016), as it can

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[1] This statement aligns with Program line 5: Spatial and ecological consequences and multifunctional use.

[2] This statement aligns with Program line 3: Integration of energy transition with other societal transitions.

[3] This peer-reviewed paper will be presented internally, and upon approval, a communication and dissemination strategy will be drafted in consultation with Deltares Communications Department for 2024.

[4] Currently, natural gas is the primary production source globally, through steam reforming process, contributing approximately 75% of the annual production (IEA, 2019).

significantly reduce energy-related CO_2 emissions (IEA, 2015). Depending on the energy sources to power the process, hydrogen products are known as: (i) “grey” or high-emission, when fossil fuels are employed; (ii) “blue”, when carbon capture, utilization, and storage (CCUS) methods are used; (iii) “green”, when renewable energy sources are utilized; and (iv) “pink” when nuclear energy is used (IEA, 2019). Blue and green hydrogen are also referred as low-emissions and are the focus of this paper [5].

In 2021, much of the increased hydrogen demand was met by fossil fuel-derived hydrogen, offering no climate change mitigation benefits. Low-emission hydrogen production (mainly blue) currently represented less than 1 million tons of hydrogen (Mt H_2). Despite this, there is a robust growth trajectory in the pipeline of projects dedicated to low-emission hydrogen production, particularly GH_2, aiming to reach 9-14 Mt H_2, leading to an installed electrolyser capacity 134-240 GW by 2030, as indicated in Figure 1 (IEA, 2022).

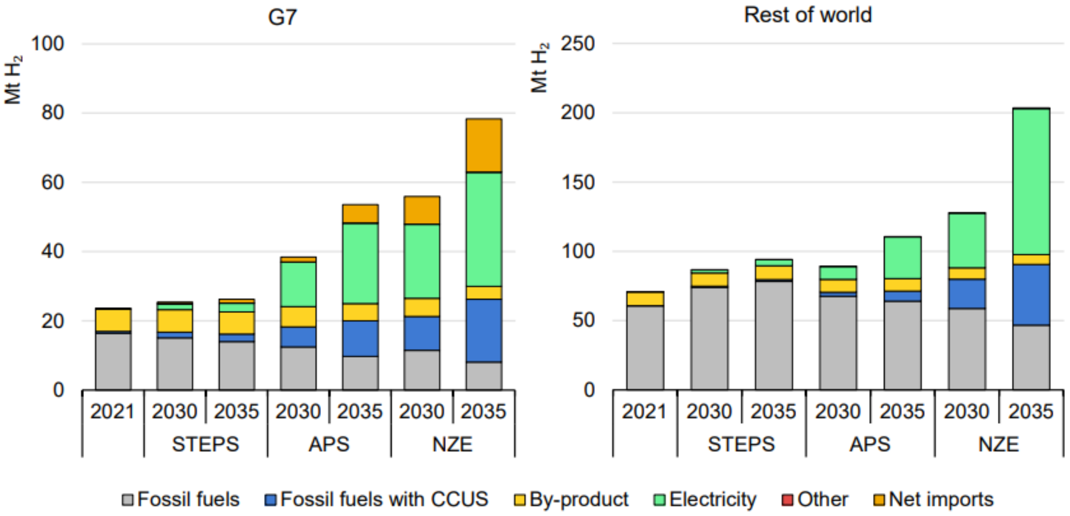

Figure 1. Global and G7 members’ hydrogen production by technology by scenario. Source IEA (2023, p. 19)

Note: APS = Announced Pledged Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emission by 2050 Scenario; Other includes hydrogen production from bioenergy.

Hydrogen, its derivatives and subproducts have diverse applications and the potential to decarbonize many sectors, such as energy systems, heavy industry, and long-distant transportation (IEA, 2023). Nevertheless, current demand is limited and concentrated in the chemical, iron, and steel production industries: 94 Mt H_2 demand were reached in 2021, representing around 2,5 % of the global final energy consumption (IEA, 2022).

Several countries are positioning themselves as key players in the future GH_2 scenario (see Figure 2 andFigure 3 for 2030 and 2050 scenarios). This emerging market creates opportunities throughout the GH_2 value chain, from production to transportation and end-use applications. Net exporters will need to ensure sustainable water use practices, while importers should be aware of the water footprint associated with their imports. GH_2’s potential as a cleaner energy carrier depends on its implementation capacity to simultaneously safeguard

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[5] GH_2 referred to as a carbon-free-fuel implies one where a life-cycle assessment of the production process is conducted, and where the boundaries for such assessment consider energy source types exclusively, given that many segments in its value chain (such as transportation) remain fossil-fuel dependent. This reference comes from the International Partnership for Hydrogen and Fuel Cells in the Economy’s (IPHE) methodology which assigns zero emission to solar PV, wind, and hydro- and geothermal power sources (IEA, 2023)

water resources, mitigate environmental impacts, and address social concerns within the broader context of the energy transition.

Large-scale projects aiming to produce low-emission hydrogen, ammonia, and hydrogen-based fuels encounter significant obstacles. Currently, only 4% of the announced projects, with a combined production capacity of nearly 1 Mt H_2, have confirmed implementation status (IEA, 2023). Key challenges include regulatory and certification uncertainties, insufficient infrastructure for hydrogen delivery to end users, and uncertainties surrounding future demand, all of which hinder the progress of these initiatives.

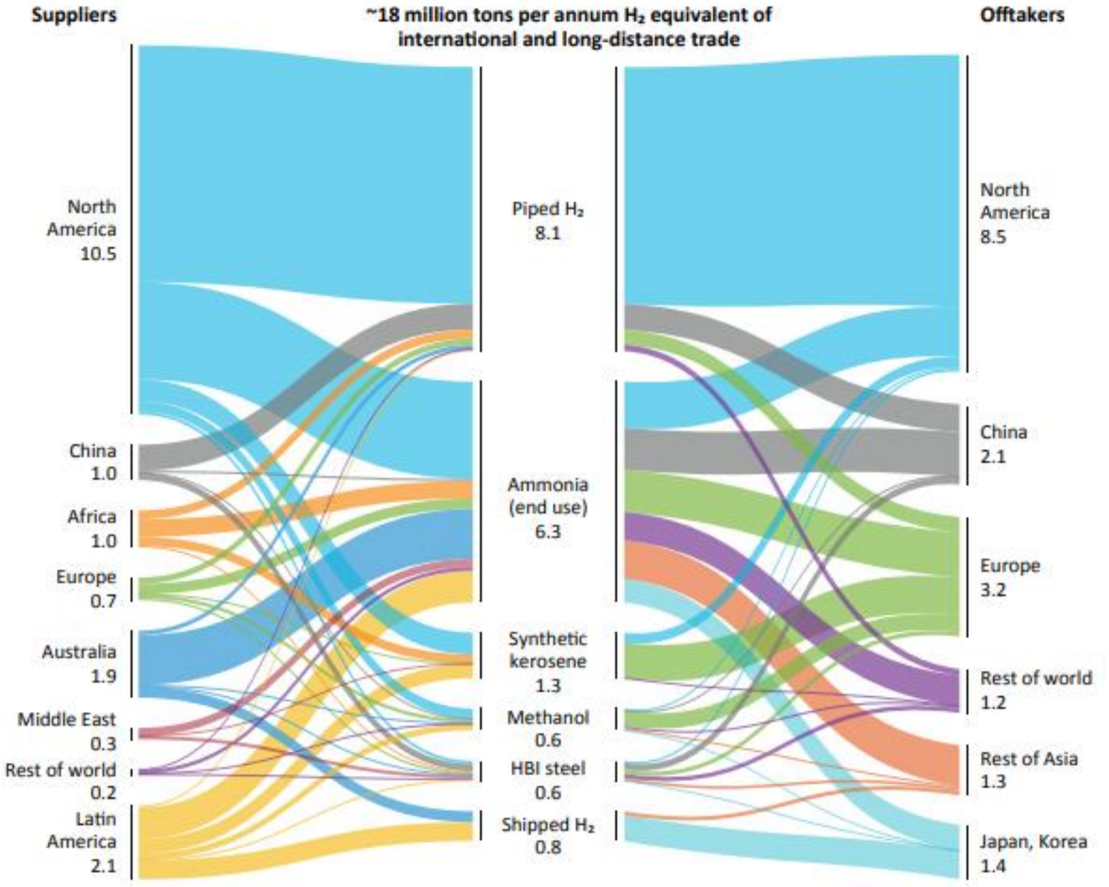

Figure 2. Global clean hydrogen long-distance flows[6] for 2030. Source: Hydrogen Council (2023, p. 14)

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[6] All international trade, including trade between split regions, most notably East and West China, including 65 percent of domestic production in Australia, Brazil, Canada, Russia, United States, and West China (Hydrogen Council, McKinsey & Company, 2023).

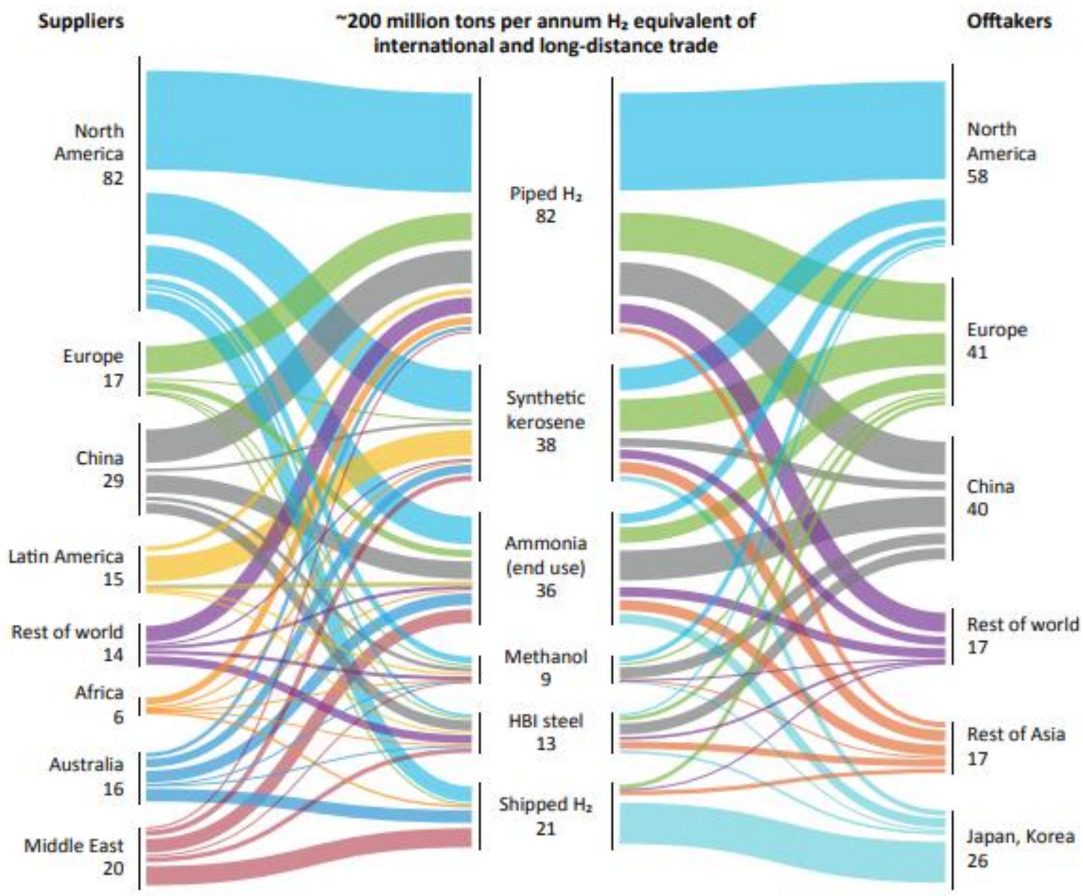

Figure 3. Global clean hydrogen long-distance flows[7] for 2050. Source: Hydrogen Council (2023, p. 16)

The landscape of hydrogen production as a vector to facilitate the energy transition is at a crossroad. Despite the current prevail of fossil-fuel derived hydrogen, there is a growing focus on low-emissions production models with blue and green at the forefront. Furthermore, the increasing number of pipelines of projects indicate a sectoral commitment to a more sustainable future. Nonetheless, several obstacles that can hinder progress need to be addressed. Infrastructure limitations, regulatory uncertainties are only few of the complexities involved in these large-scale productions that remain unanswered. As nations position themselves as key players in the emerging landscape, the potential of hydrogen as a cleaner energy carrier depends not only on innovations to tackle technology maturity, but also requires conscious water resources management, considerations over impacts on the natural and socio-economic, and institutional systems. The transformative impact of hydrogen depends on overcoming these challenges and achieving a seamless integration with existing systems.

1.3 Objectives and structure

This paper's objective is to identify the water-related key challenges and knowledge gaps in large-scale GH_2 production, emphasizing the need for a comprehensive approach that considers stakeholder engagement, new water demands, sustainability, and socio-

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[7] All international trade, including trade between split regions, most notably East and West China, including 65 percent of domestic production in Australia, Brazil, Canada, Russia, United States, and West China (Hydrogen Council, McKinsey & Company, 2023).

economic implications of the investments. Chapter 3 presents this analysis for three systems: (i) natural; (ii) socio-economic; and (iii) institutional.

Considering the natural, socio-economic, and institutional systems in GH_2 production is vital for a holistic and sustainable approach to this evolving energy technology. The socio-economic system includes job creation, community engagement, and social equity, while the natural system covers water and land usage. The institutional system involves regulatory and policy frameworks. Addressing the gaps in these systems enhances the resilience and adaptability of GH_2 projects amid changing social, environmental, and institutional conditions.

Additionally, this paper aims to build on Deltares' expertise and ambitions, by presenting recommendations for assessing such water-related challenges in the GH_2 production cycle. Under the Blue Economy (BE) principles, Chapter 4 introduces a three-dimensional approach to analyse GH_2 investments, highlighting key messages and transferable lessons learned based on Deltares' vast knowledge of water and subsurface:

1. **Water-focused hydrogen (section 4.2)**. This section highlights the significance of efficient water and energy management, defining water-focused GH_2 investments and assessing the utility of software tools to evaluate water availability such as *Wflow*, *RIBASIM* and *iMOD*; and water scarcity risk, such as *WaterLOUPE*.
2. **Locally-led hydrogen (section 4.3).** This section delves into vulnerability assessments and the application of frameworks and initiatives to promote inclusive GH_2 planning. It also addresses the governance of GH_2 water systems, stakeholder involvement, and effective governance mechanisms. We will examine institutional, legal, and regulatory frameworks, as well as the role of initiatives like the *EPIC Response Framework* and the *Valuing Water Initiative (VWI)*.
3. **Future-proof hydrogen (section 4.4).** This section defines the characteristics of a climate change-proof GH_2 investment and explores how long-term planning and decision-making under deep uncertainty methodologies like *Dynamic Adaptive Policy Pathways* (DAPP), or *DAPP-MRR* can facilitate it.

In summary, this paper enhances Deltares' standing by offering targeted recommendations for assessing water-related aspects within the GH_2 value chain. Within the BE framework, the three-dimensional approach explores water-focused, locally-led and future-proof GH_2 investments, building on the organization's expertise. By using existing tools and frameworks utilizing tools, the paper aims to guide GH_2 stakeholders in making informed and sustainable decisions, to mitigate risk and harness opportunities.

Box 1. Systems and dimensions: Definitions

Through this paper, the terms “*systems*” and “*dimensions*” are used.

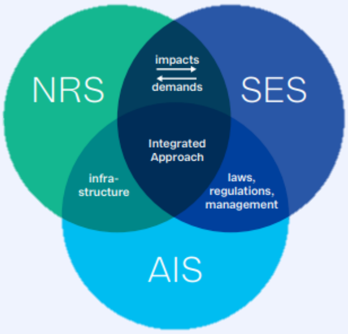

Figure 4 The 3 sub-systems and their interactions (Beek, et al., 2022, p. 11)

“*System*” refers to one of the three interconnected and interdependent structures governing the problem. Distinguishing between system components is an effective manner of dealing with high levels of complexity. Usually**, water systems can be seen as consisting of three sub-systems: (i) natural resources system (NRS), (ii) socio-economic system (SES); and (iii), institutional and administrative system (AIS).** The **natural system** consists of water bodies, their ecosystems, and associated infrastructure, including physical, biological, and chemical components, as well as facilities for water collection, treatment, transportation, and disaster protection. The **socio-economic system** involves human activities like fishing, tourism, and navigation, addressing the desires and challenges of stakeholders, including vulnerable groups, with a focus on the non-monetary benefits and power dynamics influencing outcomes related to water use. Lastly, the **institutional system** comprises institutions overseeing the administration, legislation, and regulation of both the supply (natural system) and demand (socio-economic system) components of the water system, delineating rules, roles, and responsibilities, including planning, building, and operating infrastructure to ensure optimal water placement, timing, and condition, with decision-making processes defining what is considered 'right' or 'beneficial' to society (Beek, et al., 2022).

On the other side, the approach’s “*dimension*” refers to the specific characteristics used for the analysis. **This paper presents a three-dimensional approach: water-focus, locally-led and future proof.** The **water-focused dimension** highlights the need for efficient water and energy management. **The locally led dimension** delves into vulnerability assessments and inclusive planning frameworks and addresses governance mechanisms. Finally, the **future-proof dimension** stresses the need for long-term planning under deep uncertainty emphasizing concepts such as adaptability, innovation, and scalability.

2 Approach

This paper adopts a dual approach. First, a comprehensive literature review was conducted to identify the current state of the problem and identify knowledge gaps. Scientific articles as well as reports from international organizations expert on the matter were consulted. Simultaneously, semi-structured interviews took place to collect insights and perspectives from Deltares' experts in the field. It is expected that this dual approach, integrating theoretical insights from the literature and qualitative aspects from interviews, allows for a comprehensive, in-depth, and robust analysis, as well as provide clear guidelines on Deltares' potential role in contributing to knowledge development in this emerging field.

2.1 Literature Review

The materialization of a hydrogen economy[8] faces two main challenges: (i) the economic viability of hydrogen production and (ii) the security of the energy supply. These challenges have prompted the inclusion of the hydrogen issue in political programs (IEA, 2019) (Dawood, Anda, & Shafiullah, 2020), such as the European policy, emphasizing hydrogen as a key fuel to achieve climate action targets for a carbon-neutral scenario by 2050 (EC, 2019). Moreover, within the framework of the *Hydrogen Strategy for a Climate Neutral Europe*, hydrogen is seen as a significant driver for recovering from the socio-economic impacts of the recent COVID-19 pandemic, fostering sustainable growth and job creation (EC, 2020). Nonetheless, the establishment of a hydrogen economy requires addressing production, storage, transportation, and distribution concurrently, as well as supporting strategic policies (Brandon & Kurban, 2017).

Despite considerable focus GH_2 in research, its production remains economically non-competitive, when compared to fossil fuels, and several technical challenges persist (Megía, Vizcaíno, Calles, & Carrero, 2021). Innovative production methods to reduce energy consumption and enable large-scale production, efficient methods to reduce and manage hydrogen volume for storage and transportation, safety concerns, end-use energy applications and cost considerations are at the forefront of these analysis. Furthermore, scaling up GH_2 production, conversion, storage, and transport cost are considerably higher compared to fossil fuels, primarily due to the nascent state of GH_2 technologies and the lack of economies of scale. Technological maturity remains low, with many components yet to be proven at scale. Efficiency is also a concern, as there are significant energy losses at each stage of the GH_2 value chain, as it takes more energy to produce hydrogen than what it can provide when transformed (US-EIA, 2023). Moreover, the availability of sufficient renewable electricity, essential for GH_2 production, can be a potential bottleneck (IEA, 2019).

Scaling up GH_2 production is not just about overcoming technological and economic challenges; it also entails a comprehensive consideration of water, environmental, and social aspects, emphasizing the need for assessments. As previously indicated, GH_2 production processes can significantly impact water resources, leading to competition and potential conflicts with other water-dependent sectors, such as agriculture and ecosystem preservation. The water-dependent nature of GH_2 production raises concerns about water availability,

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[8] The term *"hydrogen economy"* envisions a system where hydrogen serves as the primary energy carrier, where the overarching goal is to scale up hydrogen production using readily available energy sources, replacing the current fossil fuel-based power economy (Bockris, 2013).

especially in regions facing water scarcity. Rinawati et al. (2022) highlight the need for a comprehensive life-cycle assessment to quantify the environmental impacts and ensure that GH_2 truly aligns with sustainability goals, yet these are not at the core of current GH_2 development Programs.

Socio-economic impacts, social acceptance, influenced by safety, social conflicts derived from new water demands and environmental impacts, also threaten the advance of large-scale investment in areas lacking hydrogen infrastructure (Valente, Iribarren, & Dufour, 2021). Nevertheless, social dimensions, specifically quantifiable sustainability criteria for GH_2 generation have not received adequate attention (Blohm & Dettner, 2023). Some publications present multicriteria assessment for various production processes (Ren, Li, Ding, & Dong, 2020) (Ren & Toniolo, 2018) or focus on identifying knowledge gaps in the socio-environmental systems (Wijayasekera, Hewage, Siddiqui, Hettiaratchi, & Sadiq, 2022).

On the other hand, in the context of hydrogen production, long-term access to water is essential. Water electrolysis for GH_2 stands out with the smallest water footprint, requiring approximately 9 kilogram of water per kilogram of hydrogen (kgH_2O/kgH_2). Alternative production methods impact water usage differently. For instance, blue hydrogen production (natural gas with CCUS) increases water use to 13-18 kgH_2O/kgH_2, pink hydrogen to 270 kgH_2O/kgH_2 due to the cooling water needed in the nuclear reactions, and water consumption for grey hydrogen ranges from 40-85 kgH_2O/kgH_2 (Hydrogen Council, 2021).

Though the overall water demand for hydrogen production remains relatively low [9], individual large-scale production plants can significantly strain local freshwater resources, especially in water-stressed regions (IEA, 2021). Some of these regions, which also benefit from high renewable energy potential, like Australia or Chile, project alternative approaches involving seawater. Despite the electricity-intensive nature of reverse osmosis for desalination (3-4 kWh/m^3, costing USD 0,70-2,50 per m^3), its impact on total water electrolysis costs is minor—increasing total hydrogen production costs by just USD 0.01-0.02 /kgH_2 (IEA, 2021).

Research indicates that GH_2 production in water-scarce regions can create additional pressure on already stressed local and regional water systems by triggering new demands or affecting resources quality and quantity. Furthermore, the competition for water between hydrogen production and other sectors may lead to conflicts, specifically during periods of scarcity. Conflict and uncertainty do not scape regions planning to implement desalinization of seawater for electrolysis, as are topics such as corrosion, chlorine production and waste treatment are subjects of ongoing research aiming to facilitate future seawater utilization in electrolysis.

Overall, the scientific community has identified knowledge gaps and implementation challenges for the scalability of GH_2 production centres. Succinctly, these can be grouped in four categories: technological readiness, environmental, social, and institutional. The three latter are the focus of analysis of this document and are expanded in Chapter 3

2.2 Semi-structured interviews

To support the desk research, this paper is enriched by the insights gathered from a semi-structured interviews conducted as part of the research methodology. These interviews serve as a crucial component in shaping the narrative and content of the paper. By engaging with experts in the several fields, a comprehensive and well-informed analysis, enriched by the valuable insights gleaned from these interviews can be presented.

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[9] In the Net Zero Emissions Scenario, global water demand for hydrogen production is projected to be 5.800 million cubic meters (12% of the current water consumption of the energy sector) (IEA, 2021)

The interviews were tailored to the area of expertise of the interviewees, as indicated the list of consulted experts is presented in Table 1.

Name	Expertise	Department, Unit
Andrew Warren	Decision-making under deep uncertainty, and climate adaptation strategies	Advisor/Researcher. CAD, ZWS
Anoek van Tilburg	Climate adaptation strategies and well-fare	PhD Graduate CAD, ZWS
Bas Bolman	Sustainable Blue Economy (SBE), Integrated Coastal Zone Management (ICZM), Marine Spatial Planning (MSP), climate change, and multi-use.	Sr. Advisor/Researcher RAP, ZKS
Bonne van der Veen	Energy transition and subsoil and water management	Expert Advisor SWB, BGS
Didrik Meijer	(Urban) water management, flood risk assessment, climate adaptation strategies, modelling and monitoring, water-sensitive urban design	Specialist HYD, ZWS
Reinaldo Penailillo Burgos	Water resources and environmental management, climate change adaptation, water-energy-agriculture nexus	Department Head Freshwater Ecology and Water Quality EWQ, ZWS
Ronald Roosjen	(Ground)water in the energy transition, and water management	Sr. Advisor/Researcher SWB, BGS
Rutger van der Brugge	Systems innovations and transitions, governance of transformation of climate change adaptation and sustainability, water management and regional planning.	Specialist SWB, BGS
Sharon Tatman	Interdisciplinary applied research, integrated coastal zone management, marine spatial planning, science-policy interaction	Expert Advisor RAP, ZKS
Umit Taner	Climate Stress Toolbox and climate adaptation strategies.	Advisor/Researcher CAD, ZWS

Table 1 List of interviewees.

Note: the order of names is for organizational purposes and not indicative of any specific hierarchy of acknowledgement.

3 Knowledge gaps and implementation challenges for large-scale GH$_2$ projects

From the literature review and interviews, outlined in Chapter 2, four core aspects concerning scalability of large-scale GH$_2$ projects have been identified. The natural, socio-economic, and institutional systems stand out as highly influential and commonly unattended elements and are consequently the focus of this paper. Their interconnection highlights the complexity of the GH$_2$ based energy transition.

3.1 Natural System

Hydrogen production has been traditionally approached from the energy perspective, and research has focused on energy availability or technology readiness as the critical pathway to scale investments. In GH$_2$ production, water and energy will become codependent and solely rely on each other, showing a new interlinkage in the water-energy nexus that has not been explored before. Yet, policies for water and energy have only recently started to be developed in an integrated manner (Woods, Bustamante, & Aguey-Zinsou, 2022).

The impact on water demands for hydrogen production remains unclear and is highly dependent on the employed technology and landscape. Additionally, electrolysis' efficiency is variable, indicating that a substantial amount of the input energy may be lost during the conversion process (Shiva Kumar & Himabindu, 2019). Moreover, most of the identified hotspots for development, are projected in areas with a high solar or wind energy potential (see Figure 5), usually coinciding with water-scarce areas. These issues highlight the importance of understanding the pressures that new demands can put on the water ecosystem.

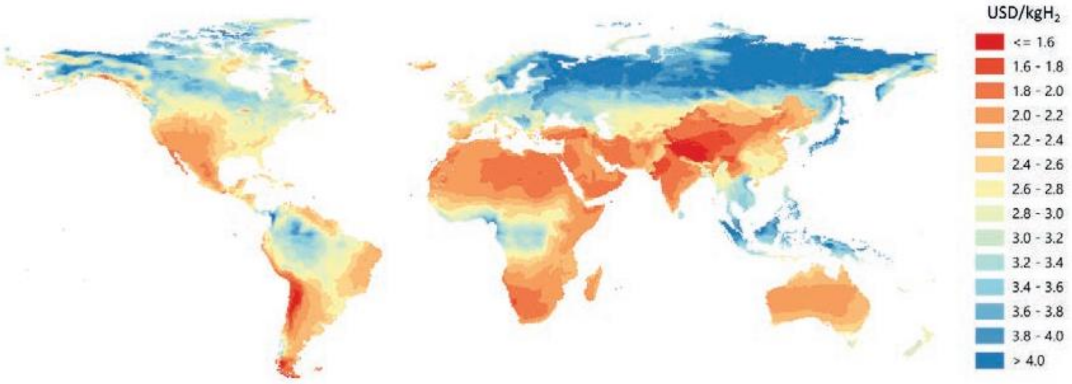

Figure 5. Hydrogen costs from hybrid solar PV and onshore wind in the long term. Source: IEA (2019, p. 49) based on wind data from Rife et al. (2014) and solar data from Proost (2018).

Note: Electrolyser CAPEX = USD 450/kWe, efficiency (LHV) = 74%; solar PV CAPEX and onshore wind CAPEX = between USD 400–1 000/kW and USD 900–2 500/kW depending on the region; discount rate = 8%

Hydrogen's rising prominence in Africa, the Middle East, and Latin America is attributed to the region's abundant renewable energy potential. Multiple countries have either released or are in the process of developing national hydrogen strategies and roadmaps[10] (IRENA, 2022).

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[10] Annex A presents the details of several hydrogen national strategies and ambitions across the globe.

Limited research has been done in this domain, yet the topics of freshwater and land availability were identified as critical elements from an environmental and socio-economic perspective for the sustainable development of GH_2 projects (Cremonese, Mbungu, & Quitzow, 2023). Some efforts have been conducted to develop sustainability criteria, including benchmarks for land tenure, water scarcity and energy source efficiency to determine the viability of investments from a multicriteria and sustainable point of view (Blohm & Dettner, 2023). But these do not appear to have been incorporated as standard practises for pre-feasibility assessments, and hence remain strictly theorical.

3.2 Socio-economic System

The challenges faced by large-scale GH_2 investment projects are not only in the water realm. Large-scale GH_2 projects can have significant socio-economic impacts on local communities, as the new water demand for its production may affect access to clean water for households and agriculture, potentially leading to conflicts between different users and sectors (IRENA, 2020). Tensions are expected to arise among stakeholders regarding the evolution of an energy transition led by GH_2 (IEA, 2023). GH_2 production facilities (and dependent infrastructure, such as photovoltaic or wind parks) environmental impacts may limit support from local communities. There is evidence of project's failure due to the lack of support of local communities (The Guardian, 2023), (The Guardian, 2023), (CBC, 2023), (Andreasen & Sovacool, 2014). Earning public trust for new technologies, requires robust education and awareness campaigns (Carr-Cornish, Lamb, Rodriguez, & & Gardner, 2019)).

Lack of understanding on benefits' co-sharing is a risk that can hinder GH_2 production expansion. Ensuring that social equity demands are met through detailed planning and policies prioritizing vulnerable groups can help in closing this gap and guaranteeing that benefits are equitably distributed (Sharma, Verma, Taheri, Chopra, & Parihar, 2023) (Falconi, Hiete, & Sapio, 2021). Moreover, in other to avoid burdening the most vulnerable groups, GH_2 production development should consider equitable job creation and opportunities for local communities. An approach to stakeholder engagement and benefit sharing, as well as a comprehensive life-cycle assessment to quantify the socio-economic and environmental impacts, ensuring that GH_2 truly aligns with sustainability goals is fundamental for these investments' success (Rinawati, Keeley, Takeda, & Managi, 2022). Yet, these topics are not explicitly addressed in existing feasibility studies.

On the other hand, scaling GH_2 production might displace jobs in traditional energy sectors like coal, oil and gas while creating opportunities in renewable energy. Retraining and reskilling the workforce are crucial for this transition. These educational efforts should consider not only technical aspects of GH_2 production but also go into socio-economic dimensions, including international trade's relevance to regional industries. The government of Ceara (Brazil) is undergoing efforts in this direction to understand local community's preferences and opinions on the up-coming production sites in the Port of Pecém (CIPP, 2023).

3.3 Institutional System

Policy and regulatory uncertainty can also hinder GH_2 up-scaling. The "chicken-and-egg" problem in the GH_2 market complicates the matter. Without sufficient demand, investments in GH_2 infrastructure remains too risky, hindering economies of scale and cost reduction. Policymakers are often hesitant to support GH_2 without a clear understanding of its costs, benefits, business models, and socio-environmental trade-offs. Addressing these barriers is crucial for the widespread adoption of GH_2 as a sustainable energy carrier (Rasul, Hazrat, Sattar, Jahirul, & Shearer, 2022). Despite the sectoral value chain that governments seek to explore, policy efforts for institutional clarity are needed to support demand creation, mitigate investment risk, promote research, development (R&D) and knowledge sharing and create standards to remove transaction barriers (IEA, 2019).

Implementation challenges and gaps associated to the institutional dimension of GH_2 appear as (i) an absence of targets, long-term policy signals and lack of common standards, (ii) limited R&D initiatives and strategic pilots to facilitate knowledge sharing, and (iii) multisectoral competences and a fragmented decision-making processes; and (iv) limited community involvement leading to lack of support of initiatives (IEA, 2019). At the same time, some studies warn against the risks of over regulation and delay implementation times (Jesse, Kramer, Koning, Vögele, & Kuckshinrichs, 2024). Policy interventions in these domains are crucial to establish public and private commitments embedded in a comprehensive energy, environment, and socio-economic policy framework.

Inter- (and intra-) national collaboration to establish consistent standards for GH_2 production and distribution are the cornerstone for GH_2 sustainable growth, particularly in countries with higher yield potentials and riskier scenarios. Harmonizing standards can facilitate cross-border trade and ensure the transparency, safety, and efficiency across the value chain. These regulatory efforts must be conducted on multiple institutional levels. From the supranational dimension, with emissions' reduction commitments, like the Nationally Determined Contributions (NDCs), the Sustainable Development Goals (SDGs) targets, or the European Commission Climate-Neutral Strategy for 2050; to national efforts in the forms of hydrogen roadmaps and legislation; to sectoral transformation strategies; all contribute to creating a conducive institutional framework for up-scaling GH_2.

The global community has seen some efforts in addressing these gaps. The certification of CO_2 intensity and supplies origin, alongside international frameworks like the Clean Hydrogen Partnership[11], the Hydrogen Technology Collaboration Programme (Hydrogen TCP)[12], International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)[13], and organizations like International Organization for Standardization (ISO) TC197, CEN-CENELEC Sector Forum Energy Management[14], or EU CertifHy[15], have contributed to overcoming these challenges (IEA, 2019). The international community ought to collaborate to define roles, standards, and institutions in the GH_2 energy transition. Another example of the international collaboration is the case of the Hydrogen Innovation Platform resulting from the ambitions of the city of Den Helder (the Netherlands), the Port of Rotterdam (the Netherlands), the port of

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[11] Succeeding the Fuel Cells & Hydrogen Joint Undertaking, this partnership aims to implement the EU Green Deal and the EU Hydrogen Strategy by accelerating the production, distribution, and storage of clean hydrogen in the EU, especially within hard-to-abate sectors, through optimised funding of research and innovation activities (EC, 2024)

[12] Stablished in 1977 under the IEA, previously known as Hydrogen Implementing Agreement, the Hydrogen TCP supports collaborative R&D, information exchange among its member countries (Hydrogen TCP, 2020).

[13] IPHE, formed in 2003, is an international governmental partnership, formed by 23 member countries and the European Commission. It aims to facilitate and accelerate the transition to sustainable energy and mobility systems using hydrogen and fuel cell technologies across sectors. IPHE informs stakeholders, including policymakers and communities on the implementation of hydrogen and its technologies (IPHE, 2023).

[14] CEN is the European Committee for Standardization, an association that consolidates the National Standardization Bodies of 34 European countries. And provides a platform for the development of European standards. The European Committee for Electrotechnical Standardization (CENELEC) is an association that brings together the National Electrotechnical Committees of 34 European countries. It prepares voluntary standards in the electrotechnical field (CEN-CENELEC, 2024).

[15] CertiHy seeks to advance and facilitate the production, procurement, and use of non-renewable, renewable, and low carbon hydrogen, fulfilling ambitious environmental criteria as well as decarbonization objectives. The organization is currently developing an EU Voluntary Scheme for the certification of hydrogen as Renewable Fuel of Non-Biological Origin (RFNBO) according to the European Renewable Energy Directive (CertifHy, 2022).

Newcastle (UK), the Port of Sines (Portugal) and the Pecém Port Complex (Brazil), which seek to establish themselves as a crucial GH_2 import-conversion-storage hubs and export centres, respectively (Platform Zero, 2024) (RVO, FME & TKI New Gas, 2023).

Nonetheless, little attention has been given to the implications of water-related institutional aspects. The water sector is intrinsically fragmented and consequently overly sensitive and dependent on effective multilevel governance for success (OECD, 2015). The integration of water governance into broader energy and environmental policies is still lacking and will require ongoing collaboration between different government agencies and stakeholders. Addressing governance gaps and inconsistencies is crucial for a coherent and supportive regulatory environment in the water-energy nexus. Moreover, amidst the increasing complexity and the systems' interconnectivity concerning the energy transition, institutional frameworks must be flexible and adaptable to reflect regional contexts, considering variations in water availability, climate conditions, and competing demands. Water governance principles remain high-level or sectoral specific. Contextualizing governance approaches requires further understanding and research.

Finally, knowledge sharing, and R&D also play a key role, particularly for early-stage high-risk projects, not only in setting the agenda, but also can be a means to foster collaborations, facilitating multisectoral and stakeholder involvement in innovation in GH_2's value chain. Furthermore, investing in innovation is vital to ensure the economic viability and competitiveness of GH_2 compared to other energy forms (Qazi, 2022) (Sharma, Verma, Taheri, Chopra, & Parihar, 2023). Initiatives such as the United States Department of Energy Hydrogen and Fuel Cells Program, EU Horizon 2020, and national programs in Germany, France, and Japan are successful examples of effective strategies (IEA, 2019). Yet, there are unexplored opportunities, specifically in regions seeking to be net exporters, like Latin America, Middle East, and Africa.

Box 2. Key messages: Knowledge gaps and implementation challenges for GH_2 up-scaling.

Large-scale GH2 projects face knowledge gaps and implementation challenges across multiple dimensions. From an environmental perspective uncertainties surrounding future water demands of hydrogen production, emphasize the need for integrated water and energy policies. Socio-economic challenges, such as potential conflicts over water access, uneven burdens on vulnerable groups or local communities, may further complicate project implementation and highlight the importance of public trust and awareness campaigns. Institutional challenges reveal policy and regulatory uncertainties, a lack of clear targets, and the need for international collaboration and standards creation. While the international community has made progress in addressing some institutional gaps, insufficient attention has been given to water-related institutional aspects. Overcoming these gaps requires fostering ongoing collaboration and adaptable frameworks to seamlessly integrate water governance into broader energy and environmental policies. Given the multidisciplinary nature of these challenges, a holistic feasibility assessment framework is needed. An approach recognizing the intricate interconnections among natural, socio-economic, and institutional systems, and emphasizing integrated water-energy management, is consequently crucial for achieving sustainable development in GH_2 projects.

4 Closing the gap with Deltares' expertise

Chapter 3 illustrated how current knowledge gaps and implementation challenges can hinder the scalability of GH_2 projects. This chapter presents an approach, anchored in the Blue Economy (BE) principles, the Integrated Water Resources Management (IWRM) Framework, and Deltares' expertise and tools.

4.1 BE and IWRM Frameworks

Understanding the implications of scaling up GH_2 investments, requires an integrated approach that connects the natural, socio-economic, and institutional systems, as an integrative water resource planning and management, stakeholder participation, and multisectoral governance and policies are needed for its success.

Blue Economy (BE) has been redefined over the years and is a widely used term to highlight the contribution of oceans and coasts for economic growth, improved livelihoods, and ecosystem health (USNOEP, 2023). It comprises all economic activities related to water bodies, including fisheries, aquaculture, maritime transport and off-shore renewable energy, and covers a wide range of interlinked established and emerging sectors, which rely on common skills and shared infrastructure and resources, increasing the interdependency. The framework's guiding principles focus on providing social and economic benefits for current and future generations, in an inclusive, cross-sectoral, innovative, and proactive manner (WWF, 2015). Its three-dimensional approach, (i) socio-economic, (ii) environmental and (iii) institutional, depicted in Figure 6 emphasizes an ongoing engagement with local communities and stakeholders (investors, NGOs, private, research and governmental), aiming to harness multi-sectoral social and economic benefits.

In the context of GH_2 production's upscaling, the principles of innovation and adaptability, inherent in the BE framework, can encourage the exploration of cutting-edge technologies and practices, driving the sector towards greater efficiency and reduced environmental impact.

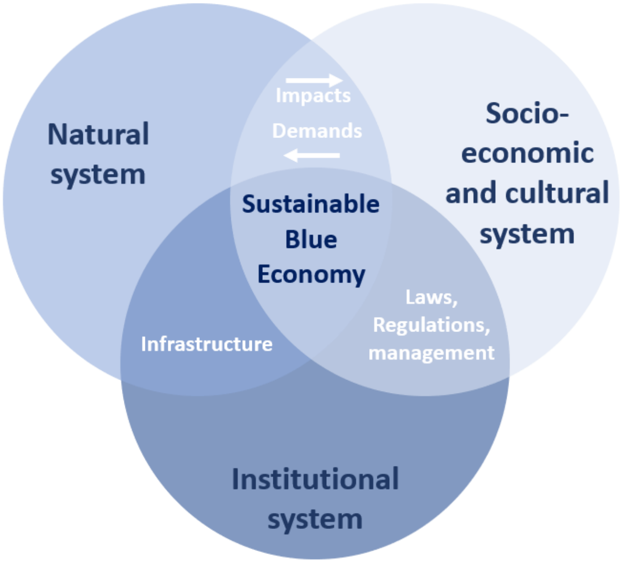


Figure 6. Framework for Sustainable Blue Economy: Interrelationship between sustainability systems of the Blue Economy sectors. The inner part identifies the space where sustainable Blue Economy sectors should operate. Source: Deltares.

On the other hand, the IWRM framework recognizes the uniqueness of each system and the need for customized strategies, providing a systematic logical sequence that supports the integrated planning processes (Beek, et al., 2022). Consequently, BE and IWRM framework are closely related. Both emphasize the sustainable use and management of water resources but approach it from different perspectives. The BE Framework often incorporates principles of IWRM to ensure that economic activities related to water are carried out in a way that aligns with broader sustainability objectives, including those related to water quality, availability, and equitable access (WWF, 2015) (SIWI, 2020).

The planning process depicted in Figure 7, rooted in the IWRM framework, aims to facilitate stakeholder engagement through a structured five-step approach. The framework begins with an *Inception phase*, defining clear multisectoral goals (social, environmental, economic, institutional, etc.). The next step requires a *Situational Analysis*, which includes a comprehensive evaluation of existing water resources, their current use, and potential challenges or threats. Once the analysis is complete, the focus shifts to *Strategy Building*. This phase involves the development of plans and strategies based on the assessment findings and established objectives. Subsequently, the *Implementation phase* starts when the identified strategies are put into action. The final step is *Monitoring and Adaptation*, an ongoing process involving continuously supervision of the implemented strategies and their adaptation based on feedback and changing environment to ensure optimal outcomes. Throughout the processes, stakeholder engagement and capacity building are fundamental as it supports ownership of robust strategies.

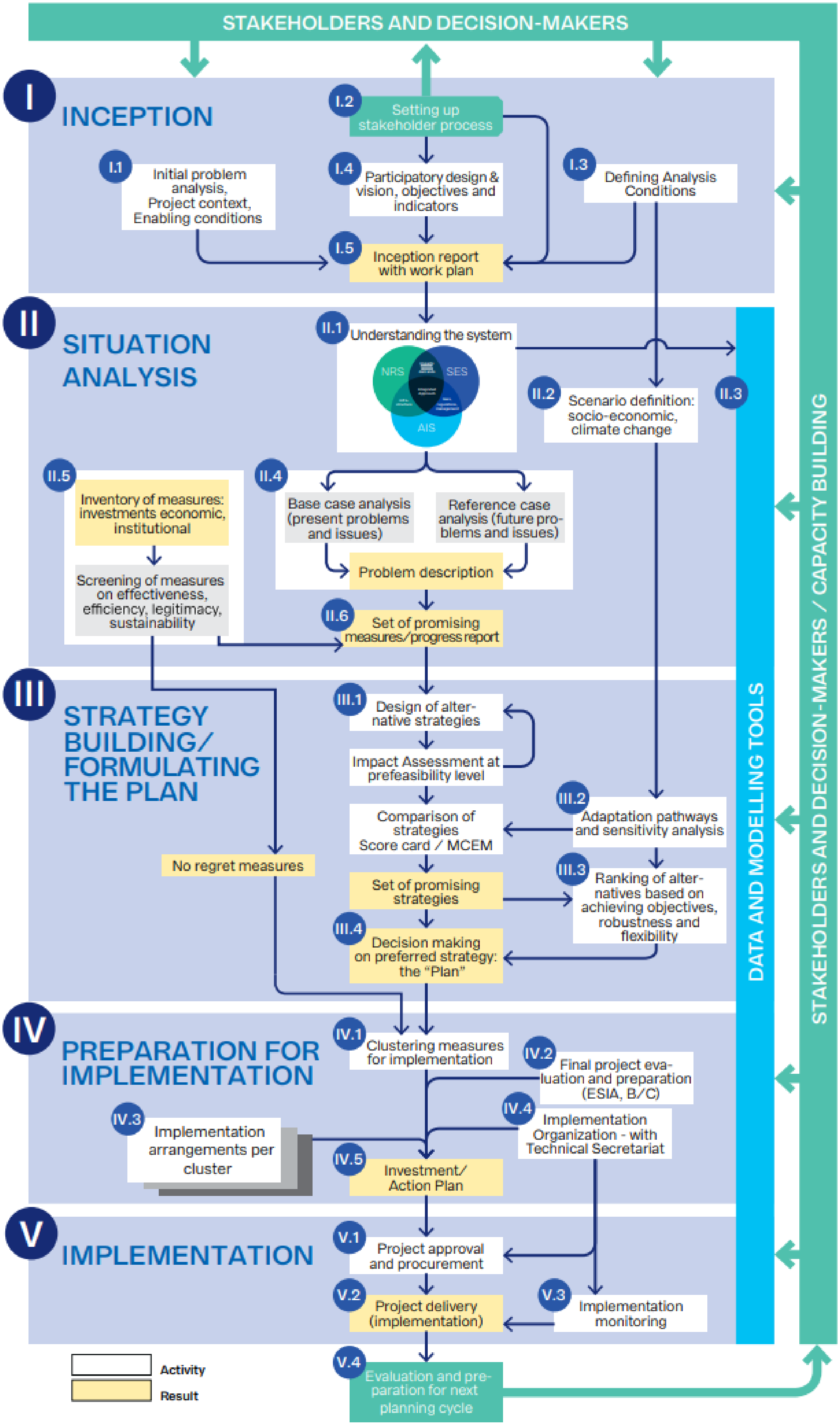


Figure 7 IWRM framework for analysis and implementation of water resources projects. Source: Beek et al. (2022, p. 37)

When reflecting on the synergies between the BE framework, the IWRM approach and the knowledge and implementation gaps and challenges associated to the up-scaling of GH_2, three sectoral dimensions emerge: water-focused, locally-led and future-proof. Firstly, the water-focused GH_2 dimension emphasizes optimal water management and seeks to close the environmental knowledge and implementation gap. Tools like *Wflow*, *RIBASIM, iMOD*, or *WaterLOUPE* can support decision-makers in understanding the investments' impacts on the natural system. Furthermore, they can assist policy-makers in creating strategies aligned with diverse climate scenarios and their impact on multiple sectors. Secondly, the locally-led GH_2 dimension goes deep into governance mechanisms and vulnerability, and stakeholder assessments. This dimension addresses the challenges and gaps presented in Section 3.2 and 3.3, by introducing methodologies and tools an like the *EPIC Response Framework* and *Valuing Water Principles*, prominently featured in the situational analysis phase. Lastly, the future-proof GH_2 dimension focuses on the long-term feasibility of GH_2 investments, by highlighting the need to address and uncertainties. The application of methods such as *Dynamic Adaptive Policy Pathways (DAPP)* aids in defining actions to ensure a resilient GH_2 production. Tools, methods and approaches previously mentioned and their applicability are presented in following sections.

4.2 Water-focused GH_2

A water-focused GH_2 considers current and future climate change impact on the water cycle, the new demand and competition for resources generated, and acknowledges the importance of an inclusive water management process that considers that visions of the different stakeholders play a role. A GH_2 focused on water is based upon three main concepts: (i) Water availability; (ii) Water scarcity risk; and (iii) Socio-economic impacts, as illustrated in Figure 8. These are correlated, as the quantitative aspects of water accounting and water risk assessment must receive input from the socio-economical component.

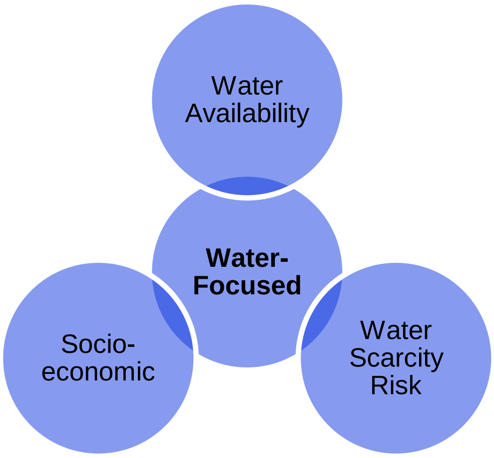


Figure 8. Water-focussed framework's dimensions. Source: made by authors.

These three aspects are interdependent. The more quantitative aspects of water accounting and water risk assessment should receive input from the social approach, while the first two will also consider the social component. This can be done, for example, either by creating simulation scenarios based on the results of stakeholder workshops, or by having discussions in workshops supported by the results of such simulations. The following subsections will expand on water availability (4.2.1) and water risk (4.2.2) assessments. Socio-economic aspects are expanded in Section 4.3.1.

4.2.1 Water Availability Assessment

The main knowledge gap identified for the expansion of GH_2 production is water demand. It is fundamental for investors, governments, and society to understand the volumes involved in the GH_2 production process, how this new demand can impact the current and future natural system status, as well as what it means for water availability for other current and future uses. Deltares has tools, software and digital services that can support policymakers in assessing water availability in such scenarios.

4.2.1.1 Wflow – Catchment Hydrology

Wflow is a free and open-source hydrological software that allows to simulate catchment hydrological processes even in data-scarce environments in the short and long term. It facilitates comprehensive source-to-sea hydrological analysis, utilizing gridded topography, soil, land use, and climate data. Designed for flexibility, *Wflow* supports complex modelling by coupling with other software applications, including *Delft-FEWS* for drought and flood forecasting and *MODFLOW 6* for groundwater modelling. With features like a reservoir, kinematic wave, and local inertial modules, *Wflow* accurately represents river discharges, making it a versatile tool for water allocation, emissions modelling, and various hydrological processes. The software's user-friendly nature and compatibility with open earth observation data contribute to its effectiveness in enhancing water management and planning. (Deltares, 2023).

With this input, software like *RIBASIM* can be later used to calculate the water balance of the basin or area in evaluation. Here, the water needed for GH_2 can be simulated as an extra demand interacting with other demands, such as agriculture, and industry, among others. This allows for the development of different scenarios of climate or water use, which can help to find different alternatives to maintain the sustainability of the water resources in the area. Both these tools can be jointly used to conduct a climate stress evaluation, where the uncertainties in climate and non-climate factors are taken into consideration. *Wflow* can also be coupled with decision-support system tools. *Wflow* has been used in several areas of the world, such as the Meuse and Rhine basins, Australia, and Thailand, among others.

Figure 9. Wflow and its coupling with other software. Source: Deltares.

4.2.1.2 RIBASIM (RIver BAsin SIMulation)

RIBASIM is an open-source river basin planning and management software that can be connected to *Wflow* to calculate the water balance of the basin or area in evaluation. This free software aids policy officers in visualizing, evaluating, and prioritizing water allocation strategies, providing insights that facilitate consensus-building among water users and informed decision-making for optimal water resource management. Developed to support basin stakeholders in planning and discussing alternative water allocation strategies, *RIBASIM* features a user-friendly interface with case management tools for exploring and visualizing future scenarios. It has been instrumental in transboundary water allocations and rights negotiations globally, either deployed independently or interoperating with Deltares' hydrological and hydrogeological software for detailed surface and groundwater resource analysis (Deltares, 2023). This tool was used to assess the possible impact of water consumption in various socio-economic sectors on low flows in the Rhine basin.

4.2.1.3 iMOD Suite – Groundwater modelling

Given that groundwater constitutes around 99% of global freshwater reserves and a sizeable portion of daily water supplies, it is critical to understand its evolution and impact as new extraction demands are introduced. The *iMOD Suite* is a free and open-source modelling software that addresses groundwater distribution and quality, delivering reliable, evidence-based advice to policymakers on sustainable groundwater resource management (Deltares, 2023). The *iMOD Suite* has been used around the world to assess challenges related to groundwater availability and groundwater quality under different stresses such as sea level rise, storm surges, droughts, saltwater intrusion, and land subsidence.

Box 3. Deltares tools for water availability assessment

Software like *Wflow*, *RIBASIM,* and *iMOD* can support the assessment of water availability for GH_2 production. New water demands can be simulated and the interaction with others, such as agriculture, and industry, can be evaluated. These tools allow for the development of different scenarios of climate and water use, which can help to find different alternatives to maintain the sustainability of the water resources in the area. Furthermore, these can be jointly used to perform a climate stress evaluation, where the uncertainties in climate and non-climate factors are taken into consideration. By incorporating mass balance models, hydrologic routing methods, and diverse indicators to assess ecological, environmental, and socio-economic aspects of water management strategies, and due to their graphical user-friendly interfaces, they facilitate visualization, and collaborative evaluation in workshops, making it an invaluable asset for long-term water resource planning and analysis.

4.2.1.4 Climate Stress Toolbox (CST)

The CST is an online, open-source toolbox for rapid bottom-up climate risk assessment. A conventional approach to use this tool is to predict future systems responses under uncertainty. It “stress tests” the limits of a system considering an array of vulnerabilities and future climate scenarios, and helps user understand the natural system’s coping capacity. It can be used to explore hydrological outputs across a wide range of futures, while interactively assessing vulnerabilities and risks added as input by stakeholders. It can generate weather series and explore natural variability and climate change revealing conditions that lead to vulnerabilities and critical thresholds.

This tool also supports decision-making under uncertainty considering future climate projections and vulnerability perspectives and is hence also related to the future-proof dimension. Climate vulnerabilities are considered in this tool not only by looking at a broader range of trends and correlations between climate and social impact but also by considering stakeholders' perspectives. Before analysing long-term climate, projections and limiting factors, stakeholders can define what they perceive as a risk in the specific project implementation and what are the critical thresholds they would like decision-makers to consider. The same reasoning can be used to assess new investments and new project implementation.

The CST has been used in the Chancay Lambayeque basin located in northern Peru. Its implementation helped to determine the reliability of the water supply system to meet different demands and whether it is sensitive to future changes, both climatic and anthropogenic. Its implementation is an important complement to the water availability analysis provided by *Wflow*, *RIBASIM* or *iMOD Suite*, as the water demand required for GH_2 production will compete with other uses. Moreover, in areas where droughts are expected to occur more frequently, the reliability of water systems under these scenarios could be analysed to determine the feasibility of a GH_2 project.

4.2.2 Water Scarcity Risk Assessment supported by WaterLOUPE.

The *WaterLOUPE* initiative, founded by Deltares with the support of Kimberly-Clark, maps local water scarcity challenges faced by diverse types of water users in various metropolitan regions. The aim is to evaluate the level of water scarcity risk for the areas in evaluation, measuring how vulnerable they would be based on their availability to supply their water demands based on the water available. The analysis is based on the comparison between the water availability and water demands of the different sectors for the region in evaluation, for current conditions and various climatic and socioeconomic future scenarios. In addition, vulnerability factors, such as poverty levels, are included, providing an extra dimension to the analysis by exploring how water scarcity affects different users. This evaluation provides water scarcity risk indicators to have an overview of which areas could be facing more water challenges in the future not only based on the hydrological cycle but also considering the social aspect. This approach can be used together with the CST explained in the previous section. The *WaterLOUPE* assessment has been applied in areas around the world such as Lima (Peru), Johannesburg (South Africa), Chennai (India), Cali (Colombia), Sao Pablo (Brazil), Bahrain, Israel, Johannesburg (South Africa), among many others (Deltares, 2023).

The *WaterLOUPE* initiative emerges as a crucial asset in the context of water risk assessment for hydrogen production. In the realm of green hydrogen production, where water is a vital resource, the ability of *WaterLOUPE* to distinguish between different water-use sectors and stakeholder groups becomes particularly relevant. By providing a risk assessment tailored to the specific impacts on various stakeholders, including those involved in agriculture, industry, and energy production, *WaterLOUPE* can contribute invaluable insights for sustainable water stewardship. The subsequent version, *WaterLOUPE 2.0*, takes it a step further by enabling the development of strategies to mitigate water scarcity risks, aligning perfectly with the considerations essential for green hydrogen initiatives. This tool equips stakeholders with a shared knowledge base, allowing them to evaluate the physical, environmental, economic, and social suitability of measures aimed at reducing water scarcity risks. The quantification of risk reduction levels for each sector and user group becomes instrumental in making informed decisions, ensuring that hydrogen production aligns with sustainable water management practices.

Box 4. Key messages for a water-focused GH_2,

The comprehensive assessment of water-related challenges and opportunities in the GH_2 value chain is fundamental for sustainable and responsible development. The examination of water availability, facilitated by tools like *Wflow, RIBASIM*, and *iMOD*, provides invaluable insights into the natural system's capacity to meet the demands of GH_2 production. These allow for scenario development, collaborative decision-making, and climate stress evaluation, enhancing water resource planning. Additionally, the *Climate Stress Toolbox* aids in a bottom-up climate risk assessment, stressing the system's limits and evaluating coping capacities under various scenarios. The *WaterLOUPE initiative* further contributes by mapping water scarcity risks, considering the interconnection of hydrological, social, and economic factors, facilitating the development of strategies to mitigate water scarcity, and aligning perfectly with the needs of GH_2 initiatives.

4.3 Locally-led GH_2.

Institutional aspects concerning the energy transition's particularly in emerging and unregulated sectors and technologies, such as GH_2, are inherently complex and require a comprehensive understanding of stakeholders involved, their roles, interests and responsibilities. A locally-led GH_2 approach should consider aspects of IWRM institutional frameworks, agency mandates and responsibilities, and stress critical questions about equity, inclusion, and socio-economic impacts. Consequently, such approach needs to be understood from three different angles: (i) socio-economic impacts; (ii) community values and visions; and (iii) institutions. The next sections will delve into these topics and put forward Deltares' expertise in the field.

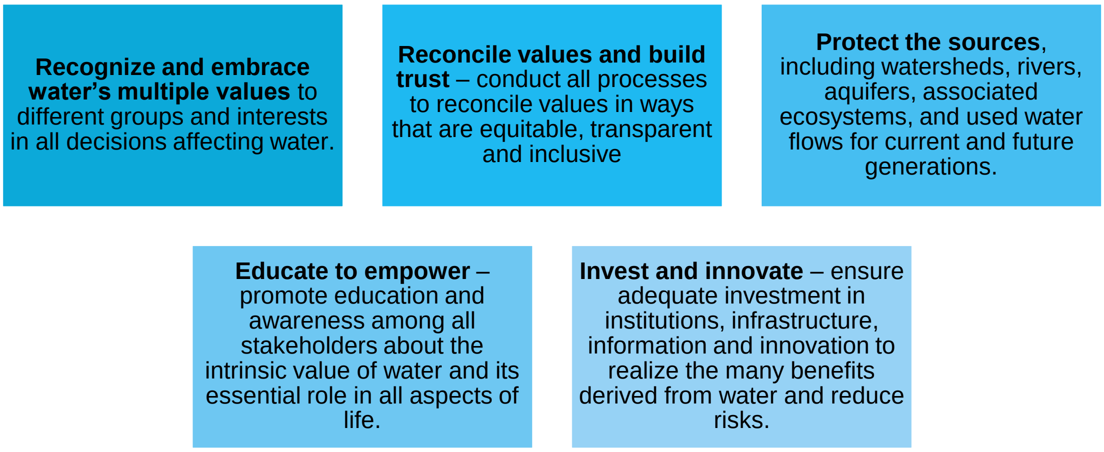
4.3.1 Socio-economic Assessment

Among the socio-economic knowledge gaps and implementation challenges mentioned in Section 3.2, socio-economic assessments play a critical role in the development of GH_2 projects, ensuring that the transition to a hydrogen-based economy is not only environmentally sustainable but also socially and economically just. For instance, tools such as the *WaterLOUPE* can help identify the risk of water scarcity for the different socio-economic groups within a basin. Moreover, when developing GH_2 projects, it is crucial to engage with distinct groups involved in and affected by the project. Groups may be impacted differently over time, so a distributional impact assessment should be done across various time frames (Basco-Carrera, Warren, van Beek, & Giardino, 2017). Literature shows that the social welfare values of risks are relatively high for vulnerable low-income households when impacts from water scarcity and floods occur (Kind, Botzen, & W.J.W., 2019; Basco-Carrera, Warren, van Beek, & Giardino, 2017). Hence, it is fundamental for the affected people to understand, acknowledge, and accept the quantified impacts, and that their perspectives are represented (Kind, Botzen, & W.J.W., 2019).

4.3.2 Incorporating Community Values

It has been extensively mentioned that stakeholder engagement and transparency on benefit sharing, through an understanding of socio-economic and environmental impacts of GH_2 production and associated value chain, are fundamental for these investments' community acceptance and for their long-term success. However, these actions are lagging. Approaches like *Valuing Water Initiative* (VWI) can support policy makers in addressing these gaps.

The VWI, initiated in 2019 by the Government of the Netherlands, is dedicated to implementing the five United Nations' Valuing Water Principles (see Figure 10). These principles aim to drive a systemic shift in how water is valued in practice, finance, and policy, accounting for cultural and behavioural dimensions. It represents a comprehensive framework to foster inclusive and collaborative water resources management (Government of The Netherlands, 2019).



Recognize and embrace water's multiple values to different groups and interests in all decisions affecting water.

Reconcile values and build trust – conduct all processes to reconcile values in ways that are equitable, transparent and inclusive

Protect the sources, including watersheds, rivers, aquifers, associated ecosystems, and used water flows for current and future generations.

Educate to empower – promote education and awareness among all stakeholders about the intrinsic value of water and its essential role in all aspects of life.

Invest and innovate – ensure adequate investment in institutions, infrastructure, information and innovation to realize the many benefits derived from water and reduce risks.

Figure 10. UN Valuing Water Principles. Made by authors, based on VWI (Government of The Netherlands, 2019)

The initiative aims to raise awareness about the multiple values of water and to impart lessons on recognizing its value across diverse uses and sectors, transcending boundaries between communities, cities, and countries. Its goal is to tackle the fundamental core of major water challenges.

Though the VWI cannot replace IWRM or Water Security frameworks it strengthens them by emphasizing the relevance of understanding water's value within an IWRM process and in achieving water security. This method is applied through a strong stakeholder engagement process, which is based on the development of surveys and local workshops to gather information and promote discussion between actors. This exchange of ideas will lead to a “values reconciliation” where a common consensus between parties would be sought. This would be a starting point to define future water security strategies or policies by considering the different interests of the stakeholders in the area. This methodology is currently being applied in a basin in the northern part of Peru, as well as in Colombia and Chile.

Applying the VWI principles to GH_2 up-scaling is pivotal to ensure all stakeholders' voices are heard and their perspectives incorporated. This will not only harmonize the values of actors concerned by GH_2 production but will also help in closing implementation gap by increasing communities support of such initiatives. Moreover, it would be crucial for the enduring effectiveness of hydrogen produced and distributed.

4.3.3 Untangling Institutional Complexities

Building effective governance mechanisms in the context of GH_2 demands a multifaceted and integrated approach, which considers not only institutional, legal, or regulatory frameworks, but also offers clarity on inter- and intra-agency coordination. These elements have been identified as key institutional gaps in Section 3.3. Frameworks like *EPIC Response*[16] offer valuable insight into innovative governance for hydro-climatic risks.

Developed in collaboration between Deltares and the World Bank, with the support of the Global Water Partnership, and the World Meteorological Organization, the *EPIC Response* framework represents a paradigm shift in understanding floods and droughts, not as isolated events but as interconnected components of the hydroclimatic spectrum, emphasizing

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[16] EPIC Response stands for: Enable, Plan, Invest, Control, and Respond.

collaboration among various government agencies (Voegele & van der Heijden, 2021). By identifying roles, promoting collaboration, and offering a comprehensive guide to flood and drought management, the framework presents a valuable model for addressing complex water-related challenges. Analysing the evolution of key elements, such as policies, laws, agencies, strategic plans, information, planning, investment, and control measures, the framework provides a roadmap for governments at various levels to enhance their water-management systems (Browder, et al., 2021).

The *EPIC Response* brings awareness of this enormous challenge and the potential solutions to a broad audience, as well as offering a practical and detailed guide to help governments improve their flood and drought management systems. This is done by analysing the evolution of five basic elements and their respective program areas, as shown in Figure 11. First, the enabling environment of policies, laws, agencies and strategic plans, and information. Secondly, the planning at all levels to prioritize risk mitigation measures; followed by investing in watersheds and water resources infrastructure; controlling the use of land and water resources to reduce exposure and vulnerabilities; and concluding with responding better to extreme events (Browder, et al., 2021).

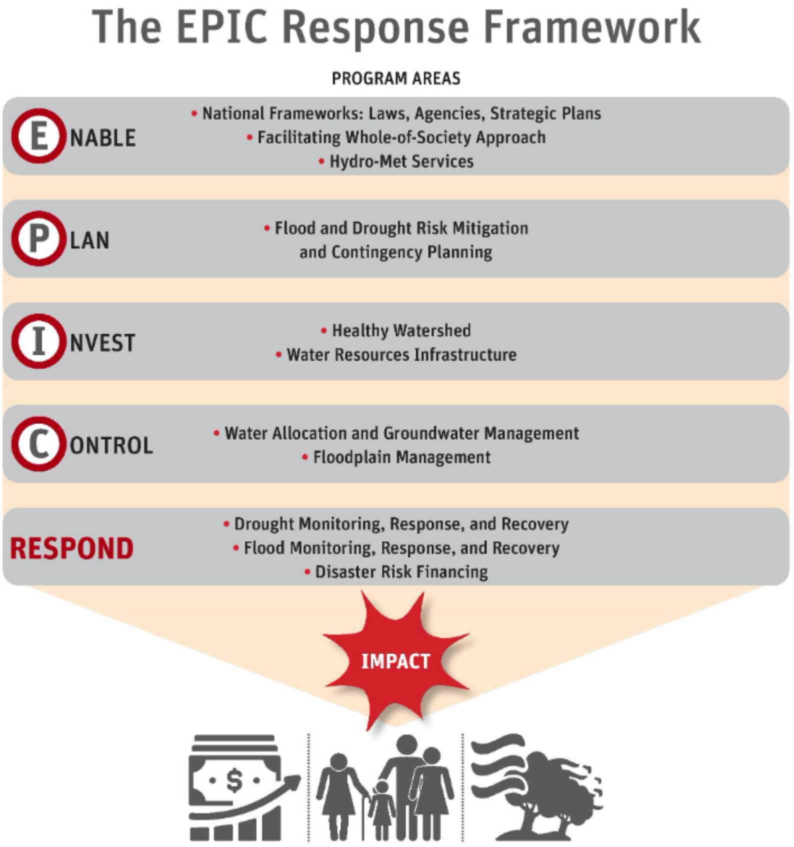

Figure 11. The EPIC Response Framework cascading graph and program areas. Source: Browder et al. (2021).

A central concept of the *EPIC Response* framework is the cascading effect among these main elements. This means that without an enabling environment, it is challenging to advance in specific elements of hydro-climatic risk management. Furthermore, planning supports decision makers in prioritizing investments that mitigate risks, while effective water and land management help reduce exposure to hazards and is usually linked to enhanced response actions to accelerate recovery. Such downscaling of the different institutional layers reflects the various implementation challenges as well as institutional regulatory gaps that need to be considered for a successful GH_2 up-scaling.

To date, *EPIC Response* has been applied in more than ten different contexts, and assessments have been carried out at national, regional, and local levels (Nunez Sanchez, 2022). Recognizing the cascading effect among these elements, the *EPIC Response* becomes particularly relevant in the GH_2 context, emphasizing the need for an enabling environment, strategic planning, and effective water and land management to ensure sustainable and resilient water systems. This approach aligns with the goals of managing stakeholder demands and interests in the dynamic landscape of GH_2 planning, offering a comprehensive and adaptable governance framework for the evolving challenges at the intersection of water resources and GH_2 production.

Box 5. Key messages for a locally-led GH_2.

A locally-led GH_2 approach must intricately consider water resource management, institutional frameworks, and socio-economic impacts, a delicate balance between fostering the sector's growth while safeguarding resources and guaranteeing equitable distribution of the benefits among users. Hence, socio-economic implications and governance challenges in the emerging hydrogen sector need to be approached in a comprehensive manner. It must consider water management, institutional frameworks, and socio-economic impacts alike. Socio-economic assessments are pivotal in understanding the broader impact of GH_2 production at various levels. Engaging with local communities through surveys and consultations ensures project alignment with their needs and expectations. Understanding the social and economic dimensions of GH_2 is crucial, and employing frameworks like the *Valuing Water* Principles and the *EPIC Response* framework can assist in addressing impact concerns and fostering inclusive GH_2 production that is environmentally, socially, and economically just.

4.4 Future-proof GH_2

The final dimension that is key to understanding the feasibility of large-scale GH_2 investments requires looking into the future. However, the future is uncertain, and no expert can predict it with absolute certainty. Uncertainties for hydrogen's growth in the energy market have been thoroughly discussed, especially when concerning technological developments, demand creation, or other long-term policy signals (IEA, 2019). Therefore, future-proofing GH_2 production requires various potential scenarios and developing strategies that can adapt to different outcomes. This might involve flexibility in technology choices, continuous innovation, and the ability to scale operations based on market demands and advancements in renewable energy sources. Emphasizing robust research and development while remaining agile in response to evolving economic, environmental, and policy landscapes will be crucial in ensuring the long-term viability and success of initiatives. Furthermore, future-proofing GH_2 investments require reflections concerning the evolution of water resources availability in the context of climate uncertainty.

In this context, the *Dynamic Adaptive Policy Pathways (DAPP)* is a forward-thinking approach to policy and decision-making that has gained prominence in the face of escalating climate change challenges. It offers a framework for planning and executing long-term strategies, particularly in sectors prone to climate-related impacts, such as water resource management, infrastructure development, and energy production. In the next sections, the paper delves into the principles of DAPP, exploring its key components and how it can be applied to the pressing challenge of developing climate-resilient GH_2 investments.

4.4.1 Decision-Making under Deep Uncertainty

DAPP is a methodology that recognizes the dynamic nature of climate change and the inherent uncertainties associated with it (Lawrence, et al., 2019). Unlike traditional decision-making processes, which often rely on static, single-pathway strategies, DAPP embraces the concept of adaptation in the face of change. At its core, DAPP entails the continuous evaluation and adjustment of policies and strategies in response to evolving conditions, be it environmental, societal, or economic. It is a flexible, iterative, and forward-looking approach that empowers decision-makers to navigate an uncertain future confidently (Haasnoot, Kwakkel, Walker, & ter Maat, 2013). DAPP consists of key components:

1. **Scenario Development**: The process begins by envisioning a range of possible future scenarios, considering various climate and socio-economic variables. These scenarios represent diverse paths the future could take, acknowledging the inherent unpredictability of climate impacts.
2. **Decision Pathways**: Rather than committing to a single, unalterable strategy, DAPP creates multiple decision pathways. Each pathway outlines a distinct set of policies and actions to be taken under different conditions or scenarios.
3. **Monitoring and Triggers**: Continuous monitoring of conditions and triggers are established to signal when it is appropriate to transition from one decision pathway to another. Triggers are typically based on predefined thresholds and the evolving understanding of climate impacts.
4. **Adaptation and Learning**: DAPP promotes a culture of learning and adaptation. Decision-makers continually update and refine policies based on emerging data and experiences. This iterative process ensures that strategies remain relevant and effective over time.

4.4.2 Pathways to Overcome Uncertainty.

Applying the principles of DAPP to GH_2 investments can support in making these investments future-resilient. GH_2 production is intimately tied to water resources, making it susceptible to shifts in water availability and extreme weather events. As such, the GH_2 sector must be prepared to address the uncertainties associated with climate change, among others. DAPP can facilitate this preparation by:

1. **Adaptive infrastructure**. Incorporating DAPP in GH_2 infrastructure planning allows for the development of adaptive facilities that can withstand extreme conditions and changing water resource dynamics.
2. **Continuous evaluation**. GH_2 projects can benefit from ongoing assessments that consider the effects of climate change on water resources and adjust operations accordingly.
3. **Flexible policies**. DAPP can support stakeholders in the design of policies that can adapt to varying climate scenarios, ensuring the long-term viability of GH_2 production, and the sustainability of the overall water-demands of the region.
4. **Collaborative decision-making**. By embracing DAPP, GH_2 projects can involve multiple stakeholders in decision-making processes, fostering a collective effort to build climate-resilient infrastructure and policies. This can create further synergies with the locally-led dimension, by facilitating an actively stakeholder inclusive process.
5. **Multi-risk assessment.** Finally, leveraging DAPP for GH_2 investments assessments extends beyond climate resilience, as the methodology could be potentially used as a multi-risk assessment approach. Recent research, exemplified by Schlumberger, Haasnoot, Aerts, & Ruiter (2022), shows the evolving nature of DAPP as a framework. Integrating multi-risk assessment within DAPP which could allow GH_2 projects to systematically evaluate and address a spectrum of potential risks associated not only with climate change but also with other hazards.

DAPP has been applied in several case studies and is recently one of the key components of the MYRIAD-EU project to handle interconnected risks by developing a unified framework for managing multi-hazard, multi-sector risks, collaborating across sectors (such as energy, shipping, nature) to understand their interactions, using a qualitative storyline approach for assessment and engaging stakeholders to devise joint strategies. Moreover, the framework is used in addressing challenges in spatial planning by promoting data sharing and recommendations for coastal areas like the North Sea. By adopting DAPP, MYRIAD-EU aims to revolutionize risk assessment by acknowledging the interconnected nature of risks and fostering collaboration among various sectors and stakeholders.

Box 6. Key messages for a future-proof GH_2.

Future-proofing GH_2 production is crucial given uncertainties in its energy market growth. Adaptable strategies, flexible technology choices, continuous innovation, and scalability are essential for success. Robust research, agility in response to evolving landscapes, and considering resource availability amidst climate uncertainty are key. *DAPP* offers a flexible, iterative, and forward-looking approach to decision-making under deep uncertainty, that when applied to GH_2, *can* support decision-making process that are climate-resilience-focussed, through adaptive infrastructure, continuous evaluation, flexible policies, collaborative decision-making, and a multi-risk assessment. Finally, embracing *DAPP* principles would allow the hydrogen-production sector to navigate uncertainties, enhance resilience, and contribute to a sustainable and climate-proof energy future.

5 Conclusions

This paper’s objective was to identify the key implementation and knowledge gaps inherent in large-scale GH_2 production to facilitate an integrated approach which considers stakeholder engagement, water demands, socio-economic implications, and institutional dimensions. The analysis in Chapter 3 focused on identifying gaps in three systems: natural, socio-economic, and institutional. Then, building on Deltares' expertise and ambitions, Chapter 4 introduced a three-dimensional approach under the BE principles and IWRM framework, offering valuable insights and transferable lessons for analysing the up-scaling GH_2 and addressing such gaps and challenges.

Chapter 3 has identified core gaps in the natural, socio-economic, and institutional systems, that significantly impact the scalability of large-scale GH_2 projects. The analysis of the natural system revealed the emerging synergies in the water-food-energy nexus, emphasizing the co-dependency of water and energy in GH_2 production. Uncertainties surrounding current and future water demands, especially in regions with high renewable energy potential and coinciding water scarcity, are one of the main deterrents for advancing project, as they create opposition among local communities. Although GH_2 has gained relevance in the scientific community, limited research has addressed critical environmental and socio-economic elements, such as freshwater and land availability. Furthermore, despite efforts to develop sustainability criteria to evaluate investments, their incorporation into standard pre-feasibility assessments remains theoretical.

The socio-economic system’s gaps highlight the potential impacts of large-scale GH_2 projects on local communities. The need for inclusive planning, governance mechanisms, and stakeholder involvement to address conflicts arising from increased water demand and potential displacement of jobs in traditional energy sectors was identified as a main impediment for progress. The absence of detailed planning and policies prioritizing vulnerable groups also pose a risk to social equity and public trust, essential for the success of GH_2 investments.

Lastly, the institutional system’s challenges explored in Chapter 3 illustrate the barriers to the up-scaling of GH_2 projects. Policy and regulatory uncertainties, hinder investments, and demand efforts for institutional clarity. The absence of targets, long-term policy signals, and common standards, along with limited R&D initiatives, also contribute to gaps in the institutional dimension. As a result, the paper stresses the need for inter- and intra-national collaboration to establish consistent standards for GH_2 production, highlighting global efforts and initiatives to overcome regulatory challenges. However, it also emphasizes the lack of attention to water-related institutional aspects, stressing the need for effective multilevel governance and integration of water governance into broader energy and environmental policies.

Challenges tied to existing freshwater limitations, seawater desalination, and potential water stress require the formulation of integrated policies to ensure sustainability amidst climate and anthropogenic changes. Building on the identified research needs of Chapter 3, Chapter 4 advocated for a comprehensive approach to materialize the multidimensional synergies of GH_2 production across the natural, socio-economic and institutional systems. Consequently, a three-dimensional approach was introduced, and Deltares’ tools and expertise are brought forward to support the policy-making process. As such it is recommended that GH_2 investments become water-focused, locally-led and future-proof. These pillars appear as interconnected elements, addressing critical aspects like water management, governance, socio-economic impacts, and uncertainty management. Within the water-focused GH_2 dimension, the paper emphasized the importance of addressing critical aspects such as water availability, risk assessment, and social inputs in enriching quantitative assessments. Modelling, mapping, and social engagement emerge as vital contributors to understanding GH_2's impact on water resources. The locally-led dimension acknowledges governance complexities, stressing the need for a delicate balance between socio-economic growth and environmental concerns. Workforce transition and the equitable distribution of GH_2 benefits require thorough planning and incentives, which can be guided by frameworks such as the *UN Valuing Water Principles* and the *EPIC Response*. The *Valuing Water Principles* emphasize inclusive water resources management and stakeholder engagement by increasing awareness of the water values, whereas *EPIC Response* offers insights into effective governance for hydro-climatic risks. Lastly, the future-proof dimension of GH_2 production, recommends the implementation of decision-making under deep uncertainty methodologies and tools to ensure climate-resilient investments by adapting to changing scenarios.

By supporting the application of these frameworks, this paper aimed to pave the way for an inclusive, climate-resilient, and sustainable GH_2 production model aligned with social, environmental, and institutional considerations. Moreover, it hopes to stimulate further research to address current and emerging gaps in understanding the water-related impacts and opportunities associated with hydrogen production.

6 Where can Deltares play a role in the GH_2 energy transition?

Considering the research conducted during the development of this document and Deltares' Moonshot 4 (*In 2030, energy from water and subsurface will account for 75% of the energy required for sustainable collective energy systems*), several key areas have been identified where Deltares can play a pivotal role in supporting the GH_2 energy transition in an integrated manner. These recommendations aim to build on Deltares' expertise and bridge existing internal and external knowledge gaps. Topic suggestions where Deltares can support are presented for each of the three-dimensional approaches previously presented (water-focused GH_2, locally-led GH_2 and future-proof GH_2) as well as for a general strategic planning dimension.

6.1 Recommendations for water-focused GH_2.

Creating and sharing knowledge in the field of water and subsurface is at the core of Deltares' mission. To support a water-focused GH_2 implementation the organization has a clear role to play in the following aspects.

1. **Assessment of current and future water demands**. Deltares has the capacity to perform in-depth analysis to assess potential competition between sectors for freshwater use in GH_2 production. It can also support policy-makers in the development of alternative scenarios and tailored solutions, including the use of seawater and salinization to fuel such process, through the development of impact assessments and risk studies for these alternative water sources.
2. **Mapping of GH_2 production hubs suitability**. Deltares can support the strategic agenda on GH_2 by creating suitability maps for new GH_2 production hubs, based on multisectoral indicators, such as water availability, socio-economic impacts, renewable energy availability, infrastructure and logistic needs and climate uncertainty. This mapping initiative could provide valuable insights for decision-makers and investors by highlighting the most suitable locations with an environmental, social-economic, and institutional perspective.
3. **Integration of GH_2 in Delta Scenarios.** Integrate the water use influence of GH_2 production in the Delta scenarios, specifically assessing its implications for water systems in potential GH_2 hub areas. This exercise could offer insights into the broader environmental implications and potential risks associated with large-scale GH_2 production in identified hubs, facilitating informed “no-regret” decision-making.
4. **Advise on water use efficiency**. Research on water use efficiency throughout the GH_2 production cycle, emphasize technological advancements, or proposing effective water pricing mechanisms, and recommend supportive regulatory frameworks, can support the feasibility of GH_2. This action aims can support minimizing water consumption in the production cycle, optimize resource utilization, and promote sustainable practices within the GH_2 industry.
5. **Hydrodynamic infrastructure behaviour evaluation**. Deltares can also play a role in supporting infrastructure re-design and repurposing for GH_2 and its derivatives storage and transport. Evaluating the hydrodynamic behaviour pipeline systems using tools such as *WANDA* can create insights into flow dynamics, pressure variations and overall performance of infrastructure.

6.2 Recommendations for locally-led GH_2.

Supporting policy-makers overcome institutional implementation challenges in the context of IWRM projects is at the core of Deltares. In the GH_2 energy-transition, the institute can play a key role advocating for the development of sustainable and inclusive processes, based on the lessons-learned from experience. The following topics are highlighted:

6 **Water-energy governance best practices**. Guide water governance structures and frameworks, drawing on best practices and lessons learned from advanced GH_2 initiatives worldwide, including legal, institutional, and policy instruments. This can provide actionable insights into improving water governance in the context of large-scale GH_2 projects.

7 **Facilitation of stakeholder engagement processes**. Deltares has experience in facilitate stakeholder engagement processes, promoting participation, transparency, and accountability in IWRM projects world-wide. The lessons learned from applying this on competing water demands, can support policy-makers in guaranteeing the development of inclusive and collaborative GH_2 projects. Activities under this category include stakeholder mapping, capacity building, multi-sectoral dialogue facilitation and value reconciliation to avoid conflicts.

8 **Capacity building and community ownership.** Knowledge sharing has been identified in previous sections as a fundamental action towards community acceptance and ownership of project. By supporting project developments in the design and implementation of training sessions, and masterclasses, to share experiences among the GH_2 implementing community, it can be expected that current gaps and challenges will become smaller.

9 **Building multi-sectoral and locally-led partnerships.** As stated through the document, the up-scaling of GH_2 is a multisectoral effort, and consequently building partnerships that leverage diverse expertise and experience is fundamental. By identifying international and regional partners Deltares can support efforts for locally-led investments. This includes partnerships with entities such as TNO, Port of Rotterdam, as well as local knowledge institutes and consultancy firms specializing in other aspect of the GH_2 value chain.

6.3 Recommendations for future-proof GH_2.

As identified in Chapter 4, the anticipation and preparedness for facing climate uncertainties and technological developments can support the transition to a GH_2 economy. The following actions stand out as logical steps:

10 **Development of an integrated climate-resilient GH_2 production framework.** Combines climate change adaptation strategies with the integration of DAPP or DAPP-MRR and continuous monitoring and scenario planning for assessing GH_2 future feasibility. This approach could address the potential impacts of climate change on GH_2 production, identifying emerging challenges and opportunities, and consequent contingency measures as issues arise.

11 **Envisioning future trends and technological developments**. Analysing future trends and technological developments while simultaneously performing a techno-economic assessment for future-proof GH_2 production, can provide insights into the emerging technologies that can enhance the sustainability and efficiency of GH_2 production or that may hinder its progress. This can guide decision-makers in adopting strategies that align

with the evolving landscape of the hydrogen economy while ensuring economic viability in the medium term.[17]

12 **Risk and opportunity assessments for future-proof investments.** A comprehensive risk and opportunity analysis framework specific to future-proof GH_2 investments can help identify potential risks associated with climate change, market dynamics, and technological uncertainties, while simultaneously, highlight opportunities for innovation, collaboration, and competitive advantage in the evolving landscape of the hydrogen economy. This element is strongly tied to recommendations 10 and 11.

6.4 Strategic Planning of GH_2.

Final recommendations consider a series of next steps to assure the relevance of Deltares in the energy transition discussions.

13 **National energy transition strategy development and water-energy nexus integration**. Participate in the development of the national long-term strategy for the energy transition, focusing on the relationship between the water and energy nexus, particularly connected to GH_2 generation. This action aims to contribute specialized insights that align water considerations with broader energy transition goals, ensuring a holistic and integrated approach.

14 **Strategic position as knowledge advisor in national and regional (EU) GH_2 policy**. Actively engage in discussions and policy forums to strategically position GH_2, emphasizing its significant role in national energy agendas. Simultaneously, facilitate collaboration between the Ministry of Economic Affairs and the Ministry of Infrastructure and Water Management. This aims to ensure not only the prioritization of GH_2 in national discussions but also a cohesive approach to its development by aligning energy policies with water management strategies.

15 **Creation of a GH_2 knowledge hub.** Establish a GH_2 knowledge hub by building local partnerships with other research institutes, leveraging each other's expertise, and collaborating with local and international partners. Engage in partnerships at both local and international levels to create a collaborative platform for GH_2 research, development, and innovation.

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[17] Due to the multisectoral nature of this recommendation, and the limited expertise on the technological advances within the organization it is advised that it is carried out in closed partnership with a technology specialist partner, such as TNO. As a result, Deltares can strongly advise on the methodological aspect of scenario planning while the sectoral expert can illustrate on the future trends and technological dimension.

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Annex A - National hydrogen strategies overview

A.1 Argentina’s Hydrogen Strategy

One of Argentina's key goals is to capitalize on its green hydrogen production by exploring international trade opportunities. With plans for exporting this clean energy source, Argentina seeks to establish itself as a reliable global supplier, tapping into the increasing global demand for sustainable energy solutions.

The Economic and Social Council promotes a debate to create a National Hydrogen Strategy for 2030. This strategy seeks to unite the public and the private, promote dialogue between industries and science, and boost the hydrogen economy in line with the vast potential of the country in this sector (Gobierno de Argentina, 2023).

A.2 Australia’s Green and Blue Hydrogen Goals

Australia seeks to become a significant global player in clean hydrogen production and trade by 2030, positioning hydrogen as its next major export. The country aspires to secure a position among the top three global hydrogen exporters to Asian markets by the specified year (Government of Australia, 2019). The Australian government has committed a substantial investment exceeding USD 1 billion and has actively participated in co-sponsoring seven hydrogen hubs. Australia is currently developing 9GW-scale green hydrogen projects, while remaining open to the possibility of blue hydrogen production (Government of Australia, 2020).

A.3 Brazil and Port of Pecém

The Port of Pecém and Rotterdam have partnered since 2018, aiming to leverage their strengths in renewable energy and trade. This collaboration involves a 30% government partnership and focuses on port development, logistics, and energy projects between Ceará and the Netherlands.

Around thirty memorandums have been signed for investments in Ceará's Green Hydrogen Hub, with three companies planning a collective investment of US$ 8 billion. Additionally, Pecém intends to invest R$ 2.2 billion in infrastructure.

Both sides are committed to promoting green initiatives and economic growth, foreseeing this partnership transforming Ceará into a clean energy hub while strengthening bilateral ties (Governo do Ceará, 2023).

A.4 Chile’s GH_2 strategy and associated socio-economic challenges.

Chile initiated a green hydrogen strategy in 2020 with ambitious targets. The plan aims to achieve 5 GW of electrolyser capacity by 2025 and escalate to 25 GW by 2030. The goal is to produce the most cost-effective hydrogen globally by 2030 and position Chile among the top three hydrogen fuel exporters by 2040 (Gobierno de Chile, 2020). Projections suggest that by 2030, the country could be exporting green hydrogen and its derivatives valued at USD 30 billion. Chile’s green hydrogen strategy is to be sustained by desalinization.

Chile has ambitious climate goals, aiming to phase out coal-fired power plants by 2030 and generate 80% of electricity from renewables by 2030. The overarching goal is to achieve a 100% emission-free energy matrix by 2050. The country adopted a national green hydrogen strategy, intending to be a leading producer and exporter of green hydrogen from wind and solar sources (World Bank, 2023). It plans to invest approximately $5 billion USD in green hydrogen by 2025. The mining industry sees its potential, aiming to operate zero-emission fleets and power mining with at least 90% renewables by 2030 (Losada, 2022; World Bank, 2023).

Future investments are focused not only on the necessary infrastructure to build the facilities, but also consider the capacity building issues that comes with the transition by developing skills in the job market (World Bank, 2023).

However, Chile faces water scarcity issues, impacting green hydrogen production, which requires significant water for electrolysis, necessitating desalination. In addition, social acceptance is a growing concern, especially regarding the installation of wind and solar farms which can feed into land conflicts. Therefore, active community participation and government engagement are emphasized, especially after past policies marginalized local populations (Losada, 2022).

The government's role is crucial, requiring reforms addressing regulatory frameworks, sanctions for violations, and long-term economic, environmental, territorial, and social issues. Additionally, acknowledging and addressing past injustices and disparities are vital for a fair transition.

A.5 Namibia’s Green Hydrogen and Ammonia Ambitions

Investors have been drawn to Namibia's extensive solar and wind energy resources. The government has identified emerging export opportunities in the form of green hydrogen and green ammonia (Government of Namibia, 2021). A national Green Hydrogen Council has been established, and a dedicated green hydrogen commissioner has been appointed. The scale of these proposed projects is notably substantial relative to Namibia's economy, underscoring the transformative potential of green hydrogen for the national economy (Geingob, 2021).

A.6 Oman’s National Hydrogen Strategy

Oman has formulated a national hydrogen strategy with the goal of creating a hydrogen-centric society by 2040. Additionally, the country intends to emerge as a substantial exporter of green hydrogen and green ammonia.

Numerous gigawatt-scale projects have been unveiled, leveraging the ample solar and wind resources in the al Wusta governorate and targeting the Arabian Sea port of Duqm for export activities. The largest among these initiatives is set to be fuelled by 25 GW of solar and wind power (Argus, 2021).

A.7 United Arab Emirates (UAE)’s Hydrogen Roadmap

The hydrogen roadmap unveiled by the UAE in November 2021 is geared towards positioning the country as a key player in the global markets for both blue and green hydrogen exports. The overarching goal is to secure 25% of the worldwide low-carbon hydrogen market by 2030. Over seven projects are currently in progress, driven by major stakeholders such as the Abu Dhabi Hydrogen Alliance, Notably, Abu Dhabi National Oil Company has already completed transactions involving four trial shipments of blue ammonia (Emirates News Agency, 2021)

A.8 Uruguay’s Green Hydrogen Roadmap

Uruguay is strategically positioned to play a pivotal role in the global green hydrogen landscape. With a remarkable 97% share of renewable energies in its electricity matrix from 2017 to 2020, Uruguay’s synergistic wind and solar resources are poised to enable competitive hydrogen production, with projected costs of 1.2-1.4 USD/kg by 2030 and a total capacity exceeding 90 GW of power from renewable sources. Beyond energy. (Gobierno de Uruguay, 2022)

Uruguay's advantages extend to the production of synthetic fuels, facilitated by hydroelectric power plants, a resilient electricity transmission grid, and access to biomass. The strategic location of the port of Montevideo, provide favourable conditions for infrastructure development.