TASK 38
FINAL REPORT

POWER-TO-HYDROGEN AND HYDROGEN-TO-X:
SYSTEM ANALYSIS OF THE TECHNO-ECONOMIC, LEGAL
AND REGULATORY CONDITIONS

Report coordinated by
Olfa Tili, Sébastien de Rivaz, and Paul Lucches
CEA-Université-Paris-Saclay
September 2020
Task Members

Task 38
Final Report
Power-to-Hydrogen and Hydrogen-to-X: System Analysis of the Techno-Economic, Legal and Regulatory Conditions
# CONTENT

## INTRODUCTION

- General context ........................................... 17
- Part I: General framework for the development of the global hydrogen pathway ...... 18
- Part II: Literature and initiative review .................................................. 22
- Task 38 presentation ........................................... 23
- Task Objectives and Description .................................................. 24
- Framework .................................................. 24
- Participants .................................................. 24
- Work done and outline of the report .................................................. 24
- REFERENCES .................................................. 26

## CHAPTER I

Task force: Power-to-Hydrogen and Hydrogen-to-X pathways:

- Clearing the Definitions from ambiguities .................................................. 31
- Introduction .................................................. 31
- The limits of the power-to-gas concept .................................................. 32
- Screening the “power-to-hydrogen and hydrogen-to-X” pathways ............ 33
  - A. The common step: Power-to-Hydrogen .................................................. 33
  - B. Screening the Hydrogen-to-X pathways .................................................. 33
  - C. Expanding the value chain via the provision of ancillary services ........ 34
- Conclusions: PTH-HTX opportunities for the energy system and beyond ........ 37
- Acknowledgements .................................................. 37
- REFERENCES .................................................. 38

## CHAPTER II

Subtask 2: Mapping and review of existing demonstration projects ............... 41

- Introduction .................................................. 41
- Methodology .................................................. 43
- Results .................................................. 44
- General outlook .................................................. 44
- Pathway trends (“Hydrogen-to-X”) .................................................. 45
- Focus on Power-to-Hydrogen .................................................. 46
- Demonstration objectives .................................................. 53
- Conclusion .................................................. 53
- Acknowledgements .................................................. 54
- Appendix 1. list of the reviewed demonstration projects and location ........ 54
- REFERENCES .................................................. 59

## CHAPTER III

Subtask 3B: Review of the existing legal context and policy measures ............. 73

- Introduction .................................................. 74
- Incentives .................................................. 74
  - Promoting low-carbon hydrogen production (PTH) .................................................. 74
  - Incentives towards the use of hydrogen in the transport sector .................................................. 75
  - Incentives towards the use of low-carbon hydrogen in the industry and for electricity production .................................................. 77
  - Incentives towards blending with natural gas .................................................. 77
- Legal barriers .................................................. 78
  - Regarding hydrogen production .................................................. 78
  - Regarding hydrogen blending with natural gas .................................................. 78
  - Regarding hydrogen use for the transport sector .................................................. 78
- General outlook .................................................. 80
- Conclusion and policy recommendations .................................................. 80
- Acknowledgements .................................................. 82
- REFERENCES .................................................. 83
## CONTENT

### CHAPTER IV

**Part 1: Subtask 3A: Review and analysis of the existing techno-economic studies on PtH and HtX**

- Introduction: 89
- Methodology for a structured international and collaborative review: 92
- Detailed analysis of review Step 2: 94
- Electricity Supply: 94
- Electrolysis: 95
- Power-to-X pathways: 98
- Discussion: 100
- Conclusion: 101
- Acknowledgements: 101
- REFERENCES: 102

**Part 2: Task Force Electrolyser Data**

- Introduction: 113
- Results & discussion: 116
- Comparing CAPEX for electrolytic and SMR H2 production systems: 116
- Comparing CAPEX for PEM and alkaline electrolysers: 116
- Impact of CAPEX on electrolytic H2 price settings: 119
- Conclusions: 123
- Acknowledgements: 123
- REFERENCES: 124

**Part 3: Task Force Electrolyser Data**

- Introduction: 126
- Hydrogen production: 128
- Hydrogen production today: 128
- Green hydrogen production scale-up: 130
- Fossil parity for green hydrogen: 132
- The cost of electrolytic hydrogen: 132
- The scale of fossil parity for green hydrogen: 137
- Conclusion: 139
- Acknowledgements: 139
- REFERENCES: 140

**Part 4: Task Force Security Services**

- Introduction: 142
- Electrical energy commodity trading (EECT): 142
- Electricity system security markets (ESSM / Markets for ancillary services): 147
- Summary of potential roles for power to hydrogen: 151
- A more detailed review of key global market and non-market security mechanisms: 153
- 1. Definitions and technical requirements of ancillary services (focus on frequency regulation) in several electricity markets: 154
- 2. Definition of energy balancing services (focus on demand management): 160
- Electrolyser and fuel cell technical specifications: 165
- Economics and efficiency of power to gas systems: 167
- Previous studies pertaining to hydrogen participation in electricity markets and services to the grid: 169
- Demonstrations which have investigated aspects regarding services to the grid: 169
- Conclusions and remarks: 172
- REFERENCES: 173

### CHAPTER V

**1: Subtask 4 - Systemic approach - The curious case of the conflicting roles of hydrogen in global energy scenarios**

- Introduction: 178
- Global energy scenarios and the representation of hydrogen: 179
- Energy scenarios: 179
- Hydrogen representation in global energy scenarios: 181
- Conflicting roles of hydrogen in global scenario results: 183
- Discussion: what must scenarios do to represent hydrogen fairly?: 185
- Scenarios must use appropriate modelling tools: 185
- Models must capture sufficient temporal detail: 186
- Models must capture sufficient spatial detail: 186
- Models must appropriately represent technologies and inter-sectoral connectivity: 186
- Models must represent the complexity of consumer behaviour: 187
- Models must remain manageable and user-friendly: 187
- Model methodologies must be transparent: 187
- Challenges and pitfalls: 188
- Scenarios must be designed appropriately: 189
- Scenarios must include all relevant sectors: 189
- Scenarios must be technology-rich: a technology not included will not appear in the results: 189
- Scenarios must have an appropriate level of ambition: 190
- Scenarios must consider other objectives: 192
CONTENT

Scenarios must use consistent and substantiated data assumptions 192
Conclusions 193
Authors’ contribution 194
Conflicts of interest 194
Acknowledgements 194
REFERENCES 195

Part 2: Task Force – Data – The challenge of a collaborative database to support evolving modeling needs
Database – General considerations 202
Database in the IEA Hydrogen TCP Tasks 202
The need for an ad hoc effort around data management 202

CHAPTER VI
Subtask 5: Power to X Case studies
Introduction 205
Methodology 207
Specific Business Case 1. Power to Green Ammonia for Blasting Industry in Chile 208
Specific Business Case 2. Power to Green Ammonia Produced in Australia and Transport to Japan (to use as hydrogen) 212
Specific Business Case 3. Power to Green Hydrogen in Austria 219
Specific Business Case 4. Power to Green Hydrogen from Patagonia to Japan 222
Specific Business Case 5. Power to Hydrogen with Waste CO₂ from Green Methanol in China 230
Conclusions 235
REFERENCES 238

GENERAL CONCLUSIONS AND RECOMMENDATIONS
Techno-economic recommendations 241
Political recommendations 244
Pathway specific policy recommendations 245
Modelling related recommendations 247
1) Scenarios must use appropriate modelling tools 248
2) Scenarios must use consistent and substantiated data assumptions 249
REFERENCES 250

MAJOR TASK ACCOMPLISHMENTS
Workshop on demonstrations (ST2) in Aix-en-Provence 254
Workshop on hydrogen in energy models in Bath (ST4) 254
Workshop on Hydrogen in the Mediterranean region (STS) in Puertollano 255
Communication: 255
Papers 255
Participation in conferences (WHEC, P2G, EEM, IAEE) 255
Technology briefs 256
Award for the Operating Agent: Christine Mansilla 256

FORWARD LOOKING 259
Table of figures 262
Acknowledgments

This work is done in the framework of the Task 38 of the Hydrogen Technology Collaboration Programme, tackling Power to Hydrogen and Hydrogen to X systems and suggesting a system analysis of techno-economic, legal, and regulatory conditions related to Power to X deployment.

The Task 38 leadership team was composed of Paul Lucchese, working at CEA and chair of IEA Hydrogen TCP, creator and mentor of the task, Christine Mansilla and Olfa Tlili, from ITESE laboratory (laboratory on economic studies for energy systems) of French CEA, operating agent of the task.

The subtasks and task force leaders contribute a lot to the success of task 38: Joris Prost, Martin Robinius, Francesco Dolci, Sheila Samsatli, Jonathan Leaver, Rob Dickinson, Laurence Grand Clement and Carlos Fúnez.

This Task gathers more than 60 members coming from 39 organisations from 17 countries around the world.

We would like to thanks to all contributors to this final report, Sébastien de Rivaz for his help and also Samantha Hilliard from Clean Horizon Lmt.

We would like to also thank IEA Hydrogen TCP executive Committee for their task approval and support as well as Hydrogen TCP secretariat, former one Mary-Rose de Valladares of M.R.S. Enterprises, LLC, and the current secretariat Ariema.

We would like also to thank Capenergies, energy cluster in South of France and the secondee hired during 6 months, Zaher Chehade, who contribute a lot to establish the demo project database.

Last but not least, the CEA task management team was supported and partially funded by french energy agency Ademe. Special thanks for Ademe and Luc Bodineau for their help.
When I proposed in 2015 to Hydrogen TCP Executive Committee to create a new task on “Power To gas”, this expression, “Power to gas” was pretty new and covered different meanings and acceptations. The word “Power to gas” appeared in early 2010’s to make concrete a new idea aligned with the dramatic growth of variable renewables sources in some countries: “why shouldn’t we use the excess of electricity we can observe in some period of time now (leading to some abnormal economic trends like negative electricity price!) to produce hydrogen, taken into account electricity is quite for free?"

Of course, the idea, free electricity to produce low carbon, low-cost hydrogen, was not quite right but many new type of projects appeared compared to previous period (before 2010) when mainly mobility projects and stationary applications were in the forefront of hydrogen landscape.

The rationale behind the creation of the task was to clarify and understand what was under Power to Gas concept: Power to Hydrogen and Hydrogen to X, to analyse the multiple demonstration projects from technical, economical and reglementary point of view.

Understanding better leads to recommendations, both for policy makers and business developers.

And so, the task was created, numbered Task 38, structured and received a very positive feed back from the very beginning.
Executive Summary

During four years of work, the Task38 experts have addressed and analysed differed topics related to Power to X systems from techno-economic aspects to regulatory issues tackling the different hydrogen pathways. This report presents the results obtained from this collaborative exercise.

P2X pathway definitions has the aim to clarify terminologies that are often used but with different meanings or intentions which leads to misunderstanding and ambiguity. The Task Force Definitions have addressed this issue in the first chapter of this document, clarifying the terminologies adopted for the rest of the document. Once the hydrogen pathways from the production step to the application side are defined, the current hydrogen status is inspected. As numerous its energy applications are, hydrogen is mainly used today as a chemical component in industries like ammonia production and refineries. The energy related hydrogen pathways are currently mainly seen through demonstration projects. The Power to X demos around the world is reviewed and analysed within the framework of ST2. The results show that the investigated pathways are diversified with a recent trend towards hydrogen industrial applications attracting interest.

These demonstration projects aim at unlocking not only techno-economic but also regulatory and political bottlenecks.

In Chapter 3, a review of the incentives and regulatory barriers with regards to hydrogen deployment is proposed for twelve regions represented by Task38 experts (ST3B). This work has shown that the most acknowledged pathway, from a legal standpoint, is mobility applications. Only few countries are implementing legal frameworks for diverse H2 applications, although in the recent years many countries have announced hydrogen specific roadmaps with high targets.

Besides the regulatory aspects, this report adresses the techno-economic side of P2X pathways analysis, starting with a review of studies tackling this issue (ST3A), and then focusing on electrolyser cost projections (Task Force EL data) assessing their impact on renewable hydrogen price settings. The objective is to offer policy makers and industry the comprehensive trends and guidelines for further electrolyser cost reduction into the MW-scale, while providing objective technological & economic arguments for converging towards a realistic electrolytic (and renewable) H2 market price.

Addressing the electrolytic hydrogen could not be done without shedding light on the flexibility potential of its production process. Indeed, electrolyzers can provide the electricity system with security services and the third part of Chapter 4 details the services in question (Task Force Services to the Grid).

Regardless of the part of the supply chain to be tackled, three major kinds of stakeholders can influence the hydrogen deployment in a specific region:

1. Industries setting the hydrogen system price (that depends on its costs),
2. policy makers that show ambition or not in hydrogen deployment and that act accordingly to make sure the regulatory framework is suitable for it,
3. and last but not least, analysts, academics and organizations running models and publishing energy system scenarios, so often used to enlighten industries and policy makers.

Hence, chapter 5 presents a review on the role of hydrogen in the renowned global energy scenarios analyzing whether hydrogen is suitably presented or not, based on the available techno-economic data, but also conducting a deeper analysis to inspect whether hydrogen pathways are well presented in the models used to generate the scenarios. Some conclusions and best practices for scenarios development and hydrogen modelling are provided (ST4). For accurate modelling, accurate data is needed, a discussion on data is hence proposed based on the learning from Task Force Data.

The report then presents the results of the specific case studies that were chosen by Task38 experts participating to the ST5. This part addresses the profitability conditions of specific applications in different countries with different geographical and political contexts.

Finally, yet importantly, the final part of the report proposes a set of techno-economic and policy related recommendations regarding Power to X development based on the expertise of Task38 members.
Making the energy system more sustainable, with a significant reduction of CO\textsubscript{2} emissions in accordance with the Paris COP21 agreement\footnote{According to the 2017 OECD report \textit{Investing in Climate, Investing in Growth} \cite{OECD}, total investment needs for infrastructure are estimated to be around USD 6.3 trillion annually between 2016 and 2030.}, is the guiding principle of national energy policies. 175 of 197 Parties have ratified the COP21 agreement, with the following goals: to limit global warming within 2°C above pre-industrial levels and aim to limit it to 1.5 °C; set global emissions to collectively peak as soon as possible; and to reduce emissions in accordance with the best available science.

Within this general framework, three major challenges can be highlighted:

1. The main challenge is the limitation of the collective costs of the global warming effects, whose hulking forecasted scale has been outlined by the work of the IPCC. Due to the global and external nature of pollution in the production system, it is mainly from political action that depends decarbonisation of energy on. Given the need to involve huge investments needed to build new infrastructure, political action has a major role in meeting coordination needs and developing a strong and clear vision, allowing market players to position themselves in the market over the long term.

2. The emergence of technological solutions free of greenhouse gas emissions, which are presented as serious alternatives to carbon energies, in terms of costs and potential quantities, is the collateral challenge. These solutions give rise to a new market presenting an exceptional economic development opportunity for companies. The global potential turnover will be around trillions of dollars per year by 2030\footnote{shared between investments in infrastructures and equipment and final operations. Because of the high level of investments required, from upstream research to new infrastructure to be built downstream, it depends ultimately on the private sphere, and more specifically on the choices and flexibility of entrepreneurs, investors and consumers. In a transition phase, investments in infrastructures from local or national authorities \cite{Bennett} can be a major catalyst for starting a dynamic on new energies. Given the learning costs, policy facilitations will also play a major role in the dynamics of transition in terms of standardization and incentives.}, shared between investments in infrastructures and equipment and final operations. Because of the high level of investments required, from upstream research to new infrastructure to be built downstream, it depends ultimately on the private sphere, and more specifically on the choices and flexibility of entrepreneurs, investors and consumers. In a transition phase, investments in infrastructures from local or national authorities \cite{Bennett} can be a major catalyst for starting a dynamic on new energies. Given the learning costs, policy facilitations will also play a major role in the dynamics of transition in terms of standardization and incentives.

3. There is a third and equally crucial challenge, which could be described as the...
“overall acceptability” of the transition, and in particular, of the technical, economic and organizational solutions adopted. This growing acceptability includes the adherence, or even the demands, of citizens, but also of industries and States, including most of the countries currently exporting fossil fuels, which have an opportunity for effective prospects for the conversion of their economies, in accordance with their requirement to maintain energy income over time.

Part I: General framework for the development of the global hydrogen pathway

The zero-carbon horizon and its challenges

In line with the climate actions, targeting a zero carbon energy system (such as in Europe for the timeframe of 2050 (67) is characterized first of all by the achievement of a substantial overall gain in energy efficiency and energy sobriety. This gain must offset the energy needs linked to growth, particularly in developing countries, in order to stabilize or even reduce global primary energy consumption.

The Zero Carbon Horizon (ZCH) is also and above all characterized by the substitution of primary sources of fossil origin (oil, gas and coal) by non-carbon sources. This substitution is conditioned by the capacity of the world economic system to mobilize the investments necessary for the development of new production infrastructures. Among these alternative sources, focus is on developing solar photovoltaic and wind power, and, probably to a lesser extent, nuclear, bioenergy, hydroelectric and tidal power.

As part of the energy transition and ZCH, it is expected that electricity will gain importance as an energy vector (56). The overall production structure of renewable energy (RES-E) will also be different from today’s system structure. Two new forms of production with relatively opposite profiles will in fact complement national productions, presenting opportunities for energy provision but also some challenges to overcome:

1. The first form of complementary production goes towards decentralization, on the scale of individual dwellings or, of local communities (village, isolated zone, urban district), whether in developed countries, for example like what was massively set up Germany (53), or in emerging countries. The motivations can be economic, social and environmental. In many scenarios, it is more rational to invest in decentralized local production than in new distribution and transport infrastructure. A typical illustration is found in photovoltaic household-production systems, but also in energetically efficient combined heat and power (CHP) systems (71). In addition, in this decentralized context, a certain number of complementary technical production solutions, rather marginal on a global scale, such as the energy treatment of biomass or waste for example (for electricity-heat cogeneration, hydrogen production, etc.), are of particular local and environmental importance.

The potential benefits of renewable energies for local ecosystems (public service mission, development of know-how, activities and jobs, public revenue returns, energy independence), legitimizes the mobilization of facilitation resources by public authorities. Their assistance is especially awaited on the development of the required infrastructures in organizational or financial (e.g., premium) forms. Although propitious to the development of regions and their independency, the decentralized structure may have some limits. Indeed, renewable resources do not have the same abundance everywhere, and some regions might be in excess of energy potential while others lack resources. Hence, there is still a need for transporting the energy from one region to the other to balance the system, and this will highly depend on the capacity of the electric system, for example, to cope with such new electricity flows.

2. The second form of energy production structure, on the contrary, looks like massive oligo-centric production, intended for international trade, a little like the structure of the current oil market. The motivations, economic, social and environmental, of this oligo-centric form are twofold:

> The national supply issues lead the first motivation of this global production structure, mainly linked to temporal and geographic global asymmetries between supply and demand. These asymmetries are manifested for certain nations by the expected deficit of domestic energy capacities with, for example, the closure of traditional power stations (fossil or nuclear thermal) or the local scarcity of renewable resources. It leads to the need for imports, for example in the form of hydrogen as Japan has planned (58) for its own demand.

> The need for economic efficiency leads the second motivation. It comes from the fact that there exists on the earth specific privileged sites for mass renewable energy production, meeting a double constraint: the cost minimization of energy production related to an attractive capacity factor (making systems already competitive in 2020), and the land availability that does not compete with vital areas like agricultural zones, forestry and inhabited areas. Among these sites, we can mention in a non-exhaustive manner, the Arabian Peninsula, the southernmost part of South America, the west of the US, Australia or North Africa. Although very attractive, these production centers can be far from the demand hubs, hence requiring energy transmission and distribution options. The latter must be economically feasible and environmentally friendly otherwise the low carbon and economic logic will be hard to keep.

Finally, beyond this triangular production structure (national centralized, national decentralized, internationally imported), another specificity of variable renewable production is its fatal and intermittent nature, which requires the development of techniques for smoothing/buffering the production/consumption differential and preserving the balance of the energy system.

For instance, different complementary competitive solutions can ensure the balance of the electricity system:

1. Large-scale real-time transport and distribution lines,
2. Storage options,
3. Power plants flexibility
4. Adaptation between final consumption and production, probably more marginally in terms of quantity, using so-called smart grid techniques and fine management of the supply/demand balance.

Accordingly, the mass development of renewable energies requires both temporal and geographic flexibility in order to be put in place in the most optimal way (technically, economically, environmentally and socially). Nonetheless, in order to reach a zero-carbon energy system, thinking beyond the electric system is required. Other sectors like transport which accounts for nearly 22.7% of
the total energy related CO2 emissions [9] will need to be considered in the decarbonisation strategy. Transportation is challenging, being so far highly dependent on fossil fuel combustion engines. However, governmental pledges have been set in several regions worldwide. The European Union (EU) has set CO2 reduction targets for the transport activity aiming to reach a 95 gCO2/km cap by 2020. These targets are ambitious compared to the ones announced by the United States (US), China and Japan (121, 117 and 105 gCO2/km respectively) [10]. Accordingly, new transport technologies have emerged aiming for a "cleaner" mobility provision. The same logic is applicable to the industrial and residential sectors. However, tackling each sector apart might not be the most efficient way, compared to adopting a multi-sectorial decarbonisation approach. Synergies between sectors can be created.

Understanding these challenges and projections concerning the development of the energy system, hydrogen can present a promising option allowing to contribute to fulfilling the ZCH target.

Opportunities for hydrogen in energy systems

Apart from small reserves of "natural" hydrogen [11], hydrogen is not a resource that can be extracted at scale in the same way as fossil fuels. Today, hydrogen is mainly produced via steam methane reforming (SMR) which is highly carbonized. However, it can be produced with minimal GHG emissions, for example through electrolysis powered by renewable electricity [12], or from bioenergy or fossil fuels with carbon capture and storage (CCS) [13]. Hydrogen has many possible energy applications, including for heating, transport, industry, and electricity generation [14], [15].

There are many possible pathways for hydrogen in energy systems and in some cases, they are already being realized in real projects. In this section, the main pathways are summarized; an overview is provided in Figure 1, whilst next chapter describes them in more detail.

Today, hydrogen is already a key chemical component in many industrial markets: the main applications include ammonia synthesis (55% of hydrogen demand), hydrocracking and hydrodesulphurization in refineries (25%), and methanol production (10%) [16]. However, hydrogen systems can also be key enablers to promote promising synergies between sectors, thanks to the hydrogen versatility [17]. The produced hydrogen can be used for both chemical purposes and energy applications: industry, transportation, heating, power generation, etc. [17], [18]. Accordingly, provided that hydrogen (H2) is produced via low carbon technologies such as electrolysis coupled with a decarbonized power mix, multi-sectorial decarbonisation can be achieved.

Once produced, hydrogen can be stored in quantities from MWh to TWh, for example in pressurized cylinders or underground in salt caverns, depleted oil and gas reservoirs and saline aquifers [19], [20]. Pressurized hydrogen storage has a volumetric energy density greater than 500 kWh m⁻³, far exceeding low-carbon energy storage alternatives (up to 1.5 kWh m⁻³ for pumped hydro storage (PHS) and 12 kW h m⁻³ for compressed air energy storage (CAES)) [21]. Hydrogen's high energy density makes it particularly interesting for system-wide energy balancing. Hydrogen could be manufactured from electricity at times of excess supply, stored, and later converted back to electricity or used for other purposes at times of high demand [12]. However, hydrogen storage round-trip efficiencies are around 30-56%, depending on the electrochemical technology used, which is low compared to alternatives (PHS: 70–85%; CAES: 65–80%; battery: 86–95%) [22]. Therefore, the value of hydrogen energy storage depends on the trade-off between the benefits of time-shifting bulk energy, and the costs of the efficiency losses.

Whilst hydrogen for electricity storage has not yet been deployed at large scale, already several projects have deployed electrolysers to absorb electricity from wind farms, to be stored and used at a later date in various applications (for example Energiepark Mainz [23] and Lam Takhong [24]). For the 2020 Olympics, postponed to 2021, Tokyo planned to power the Olympic village with hydrogen from solar-powered electrolysis [25].

As an attractive means of storage, but also transport and distribution of energy, hydrogen can present a fundamental complement to RES-E production, in a new global energy paradigm. The hydrogen trade, which could be one of the most promising solutions for energy exchanges, would follow the logic of international trade [26], [27]. The issue is linked to the choice of technologies and standards for conditioning, storage, and transport (CSTs), which will minimize both GHG emissions and the costs of long-distance exchanges. The economic maturity of CSTs is to be investigated more closely in the development of the international hydrogen trade.

1. For the international long-distance market, green hydrogen production from RES-E, according to the most current estimates by 2030, would be considered, in gaseous (CH4), liquid or synthetic form (N2H3, CH4, LOHC...), as a competitive technical transport and distribution solution to complement the direct electricity distribution infrastructure. Direct electric transport, in particular, can be very costly and less effective over very long distances (apart from social acceptance issues towards electricity lines installation nearby households).

**Figure 1** Overview of key hydrogen production and usage pathways. With multiple production options and applications, hydrogen could be valuable in providing flexibility and sector-coupling to energy systems.
Part II: Literature and initiative review

Facing its promising potential, the interest in hydrogen has increased drastically lately. Many reports have been published by renowned organizations, analyzing the potential of hydrogen in the context of the energy transition.

For instance, the IEA report "The Future of Hydrogen" (2019) [27] prepared for the G20 meeting addresses the whole hydrogen supply chain from the production step to final uses detailing the different pathways and involved technologies with a focus on the potential future volumes and costs for each pathway. A set of policy recommendations is then proposed.

Following this big report, the Hydrogen Council have recently published a study on hydrogen costs evolution [26], detailing the promising cost reduction potential in the years to come once the required volumes are reached. The report conveys the message that competitiveness is already reached for several applications and that industries are ready to upscale but there is still a need for a clearer political vision (clear strategies and adequate regulation ...) and support to trigger the markets.

The novelty about these reports compared to previous ones [38]-[41] on hydrogen is the opportunity to hydrogen energy towards final uses in a more connected, where electricity systems, transport (hydrogen for fuel cells, biofuels, synthetic methane for transport etc.), and the interesting potential of several regions in terms of renewable hydrogen generation at competitive costs.

Next to the multiplicity of publications, many initiatives have also been growing around hydrogen, on the international as well as the regional levels. The following is a selection of international hydrogen collaboration platforms:

- Mission Innovation 8th Challenge on Hydrogen
- Clean Energy Ministerial, Hydrogen Initiative
- World Economic Forum, Hydrogen task force
- Hydrogen Council
- International Energy Agency (IEA) Hydrogen Technology Collaboration Programme (TCP)
- International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)
- International Association for Hydrogen Energy (IAHE)
- Hydrogen Europe (European Hydrogen and Fuel Cell Association)
- U.S. Department of Energy’s (DOE’s) Fuel Cell Technologies Office
- Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

Among these initiatives, the IEA Hydrogen Technology Collaboration Programme (TCP) is an international global resource for expertise on hydrogen. For over 40 years, the hydrogen TCP of the IEA has provided unique management of coordinated hydrogen research, development, and demonstration activities on a global basis.

With over 40 tasks (annexes) created so far, the Hydrogen TCP addressed a comprehensive wide range of research fields. Task 38 is one of these tasks, tackling Power to Hydrogen and Hydrogen to X systems and suggesting a system analysis of techno-economic, legal, and regulatory conditions related to Power to X deployment.

Task 38 presentation

The “Power-to-hydrogen” concept means that hydrogen is produced via electrolysis. Electricity supply can be either from the grid, off-grid, or mixed systems. “Hydrogen-to-X” implies that the hydrogen supply concerns a large portfolio of uses:

- transport (hydrogen for fuel cells, biofuels, synthetic methane for transport etc.).
- natural gas grid (by blending hydrogen directly with natural gas or synthetizing methane and blending it into the natural gas grid).
- re-electrification through hydrogen turbines or fuel cells,
- general business of merchant hydrogen for energy or industry, especially refinery, steel industry, ammonia, etc.,
- ancillary services or grid services for the electricity grid, transport or distribution grid.

Hydrogen provides flexible energy storage and carrier option which could defer the need for new lines and would alleviate the transmission difficulties.
Task Objectives and Description

The general objectives of the Task are to:

1. Provide a comprehensive understanding of various technical and economic pathways for power-to-hydrogen applications in diverse settings.
2. Provide a comprehensive assessment of existing legal frameworks for hydrogen systems.
3. Present business developers and policy makers with general guidelines and recommendations which enhance hydrogen system deployment in energy markets.

The final objective is to develop hydrogen visibility as a key energy carrier for a sustainable smart energy system, within a two or three horizon time frame: e.g. 2020, 2030 and 2050.

Framework

The task is organized in subtasks (ST) and task forces (TF). Task forces aim at supplying the subtasks with data and methodology throughout the task duration. Subtask workshops are organized to advance the project as well as plenary meetings which are organized on a semi-annual basis.

The subtasks and task forces are presented below (Table 1).

Participants

Over 60 experts from 15 countries are involved in Task 38. The Task is coordinated by the French CEA/I tésé, supported by the French ADEME. Participating IEA Hydrogen TCP ExCo Members are Australia, Austria, Belgium, European Commission, France, Germany, Hychico, Japan, The Netherlands, New Zealand, Norway, Southern Company, Spain, Sweden, United Kingdom and the United States.

Work done and outline of the report

In what follows, the results of the Task38 will be presented, not necessarily in the chronological order they were conducted or in the order of the subtasks.

The document hence starts with work on P2X pathway definitions with the aim to clarify terminologies that are often used but with different meanings which leads to misunderstanding (Task Force Definitions). Once the hydrogen pathways from the production step to the application are defined, the second chapter tackles the current hydrogen status. As numerous its energy applications are, hydrogen is mainly used today as a chemical component in industries like ammonia production and refineries. The energy-related hydrogen pathways are currently mainly seen through demonstration projects. Hence, the second chapter of this document suggests a review of the P2X demos around the world. Within the framework of ST2, a workshop was organized, in which the organizations behind the reviewed demos-project expressed the challenges of P2X pathways deployment. These challenges are mainly related to cost and regulatory issues.

In Chapter 3, a review of the incentives and regulatory barriers with regards to hydrogen deployment is proposed for several regions represented by Task38 experts (ST3B). Chapter 4 addresses the techno-economic aspect of P2X pathways, starting with a review of studies tackling this issue (ST3A), and then focusing on electrolyser cost projections (Task Force EL data) assessing their impact on renewable hydrogen price settings. The fourth part of Chapter 4 also addresses the flexibility potential of electrolysis and the possibility to provide services to the grid, services that can help improve the profitability of hydrogen production (Task Force Services to the Grid).

Three kinds of stakeholders can influence hydrogen deployment in a specific region:

1) industries setting the hydrogen system price (that depends on its costs).
2) policy makers that show ambition or not in hydrogen deployment and that act accordingly to make sure the regulatory framework is suitable for it, and last but not least, academics and organizations running models and publishing energy system scenarios, so often used to enlighten industries and policy makers.

Chapter 5 presents a review on the role of hydrogen in the renowned global energy scenarios analyzing whether hydrogen is suitable presented or not, based on the available techno-economic data, but also conducting a deeper analysis to inspect whether hydrogen pathways are well presented in the models used to generate the scenarios. Some conclusions and best practices for scenarios development and hydrogen modelling are provided (ST4).

In Chapter 6, the ST5 case studies are conducted and analyzed.

Finally, yet importantly, the final chapter of the results part proposes a set of recommendations regarding P2X development based on the expertise of Task38 members.
REFERENCES

Hydrogen TCP- a Technology Collaboration Programme by IEA
[27] «Hydrogen TCP- a Technology Collaboration Programme by IEA” Task 38 Final Report - September 2020


Abstract

Energy systems are evolving rapidly around the world, driven mainly by CO2-e reduction targets. This has led to opportunities for integrated low carbon electricity-and-fuel systems founded on large scale "Power-to-Hydrogen, Hydrogen-to-X" (PtH-HtX). Power-to-Hydrogen (PtH) refers to large scale electrolysis. Hydrogen-to-X (HtX) refers to a range of high-value products and services. If these pathways start with low-carbon electricity, then the fuel consumed at the downstream end also low-carbon. Use of intermittently low valued power lowers all production costs. This paper specifically identifies the main pathways and interconnections in a way that overcomes the ambiguities inherent in the term “Power-to-Gas”. In turn, this provides solid and easier to understand foundations for building legal and regulatory frameworks for new business opportunities along the lengths of the numerous pathways from supply to consumption.

Key words

Energy markets
Low carbon fuels
Fuel cells
Hydrogen storage
Load management
Power-to-gas

Introduction

Energy systems are rapidly and substantially changing around the world due to a variety of factors [1-8]:

- Increasing demand for energy worldwide due to globalization and emerging and developing countries;
- Increasing share of renewable electricity production;
- GHG / Carbon dioxide equivalent (CO2-e) emissions reduction targets;
and technically attractive way to contribute to under many conditions. Accordingly, hydrogen once and for all is expected to have benefits renewable power out of the electricity grid PtStP just time-shifts the electricity grid relative to PtStP technologies is that whereas power consumption in the sub-second time-a few seconds [9]. They can also decrease full load operation within a few minutes, even consumption: electrolysers can indeed reach it possible to quickly adjust the power broader picture.

The “Power-to-hydrogen” (PtH) concept means that once hydrogen is produced from low carbon electricity, a potentially large portfolio of uses is possible. Applications across diverse sectors include transport, blending with natural gas, and PtStP. Additional products and services include the general business of merchant hydrogen for energy or industry, and provision of ancillary services to power networks. At large scales, PtH can also facilitate deferral of upgrades to distribution and transmission network components. Accordingly, the primary objective of this paper is to present the “Power to Hydrogen - Hydrogen to X” as broadly as space permits. The common component of all “PtH-HtX” pathways is the Power-to-Hydrogen step. This keeps “hydrogen” at the centre and thus emphasizes its flexibility as an energy carrier and an input industrial chemical production. It also ensures that the monetary value of “gas” does not dominate the perceived value of the processes being investigated. The next section presents an enumeration of pathways from intermittently low-value power to high-value products and services.

Screening the “power-to-hydrogen and hydrogen-to-x” pathways

A. The common step: Power-to-Hydrogen

The common component of all “PtH-HtX” pathways is the Power-to-Hydrogen step. Hydrogen from electrical power uses electrolysis: a process that until recently has been only deployed at small scales, but 100+ MW systems are now realistic and can be expected to be deployed within a few years. Electrical energy is used to split water into hydrogen and oxygen.

Task 38 will review the roles of all electrolysis technologies, primarily: 1) alkaline and 2) proton exchange membrane (PEM), each of which is allocated a full chapter each in [8]. Co-electrolysis [14] refers to the co-production of both hydrogen and carbon monoxide from water and carbon dioxide, from which hydrocarbon fuels can be synthesized. High-temperature electrolysis uses cogenerated heat from power production to increase the efficiency of the electrochemical reaction. The key motivation for developing PtH-HtX pathways is to in turn develop cost-effective decarbonization of both the power and fuel sectors of the energy system. Accordingly, PtH needs to be economically and environmentally competitive with other low-carbon production processes, such as emerging solar hydrogen [15] and thermo-catalytic methane decomposition [16], also known as methane cracking, potentially co-producing high purity graphite [17]. In turn, a key to the economic competitiveness of PtH is the intermittent availability of low, zero, or negatively priced electricity. Diverse types of PtH systems can be considered, namely, off-grid, on-grid, and directly connected with a renewable power source with backup connection to the grid.

B. Screening the Hydrogen-to-X pathways

With the aim of decarbonization of a complete integrated energy system covering both power and fuel, all the sectors can be targeted. The three main pathways are the transport sector, the industry sector, and the energy sector (power, gas and heating/cooling).

For the transport sector, hydrogen offers diverse pathways for decarbonization. Hydrogen can be used in fuel cells in vehicles, as either the only source of electricity to the electric drive train and any onboard batteries for regenerative braking, or as range extension to plugin battery electric vehicles [18]. Low-carbon hydrogen can also be an input to synthetic liquid fuel production. Similarly, synthetic and biomass sourced low carbon fuel production can be enhanced by using low carbon hydrogen [19,20,21]. Low carbon
synthetic fuels are particularly attractive for aviation. Another pathway for the transport sector is the production of synthetic gas fuels, where hydrogen is reacted with carbon dioxide to generate synthetic methane. Again, given that decarbonisation is the key motivation, the life-cycle balance of these systems needs to review with due diligence.

Industrial chemical technologies use hydrogen across many segments. The two major examples are hydrocarbon refineries and ammonia for fertilizers. Together they represent over three-quarters of global hydrogen demand [22]. Most hydrogen consumed to date by these industries has been produced using emissions-intensive steam methane reforming. Other carbon-intensive production methods include coal gasification and oil cracking. Clearly, providing low carbon hydrogen with PtH would decrease the carbon footprint of these industries.

Finally, the versatility of low carbon hydrogen can make it a unique energy carrier for contributing to the decarbonisation of the entire energy sector: in the broadest sense: power, fuel, and heating/cooling.

After having been generated from low carbon power, hydrogen can be used to regenerate clean electricity through fuel cells or gas turbines. Power production from hydrogen is particularly promising for off-grid applications (e.g., supply of remote communities and back-up power). But for grid-connected applications, a very large difference in power buy/sell price is required for PtH to be competitive.

Low carbon hydrogen can contribute to decarbonizing gas supply through blending. Two options are open. The first option is to directly blend hydrogen with natural gas in the natural gas grid. The amount of hydrogen that can be directly injected is limited. The second option is to inject synthetic methane produced from methanation, in which low carbon hydrogen is reacted with carbon dioxide (or also in principle, carbon monoxide). The scale of this second option is unbounded with respect to proportions injected.

Finally, hydrogen can also be used for heating and cooling, and combined heat and power (CHP) applications.

A visualization of the main PtH-HtX pathways with interconnections from low carbon intermittently low valued electricity to (potentially) high valued products and services, is presented in Figure 2 and Figure 3.

C. Expanding the value chain via the provision of ancillary services

As also presented in Figure 2 and Figure 3, extra revenues from PtH could potentially be obtained by providing system support services to the grid, in particular, “Frequency Control Ancillary Services” (FCAS) (see for instance [23]) concurrently with hydrogen production. Depending on the specific power system and market, different types of ancillary services may be required which can potentially be provided by PtH. These include primary and secondary frequency response (usually) with a collection of event-response times in the order of seconds, tens of seconds, and minutes), as well as different types of reserves with event-response times in the order of minutes, and tens of minutes. Recently, new fast frequency response services are also emerging (see for example [24,25]). The event-response times for these are in the sub-second time scale, particularly to address a loss of system inertia in the presence of high instantaneous penetration of renewable electricity output, which exacerbates the frequency balance challenge. These services could be provided by electrolyzers that represent the initial step in all PtH pathways.

By providing FCAS, PtH could thus enable both the productive consumption of excess renewable power when demand is low, and grid security and reliability services that overcome the resistance by some to the ongoing deployment of increasingly high proportions of renewable power capacity.

Figure 2

**Figure 2**

**PTH-HtX: Enumeration of the main pathways from low carbon, intermittently low valued power to high-value products and services**

---

**Choice of supply of product or service or energy transformation technology depends on market price**

---

**Low carbon products/services at every stage from the source to the consumer**

---

**Power to Hydrogen, (PtH)**

- **Intermittent electricity (market price [2]) driven** hydrogen production, co-located with Hydrogen to X infrastructure

- The market (spot) price of electricity will increasingly become a function of both demand (normal load) and zero-resource cost supply + Some current electrolysis hardware already provides frequency control services

**Low carbon hydrogen**

- storage
- transmission
- distribution at a sufficient scale to reliably provide demand following supply despite power price intermittency, including “just in time” delivery services.

**Other low carbon hydrogen production technologies**

- “Conventional” power market technologies (during periods of no risk of curtailment)

**Transport**

- Hydrogen to Fuelled Energy Consuming Services (HtF)

**Energy System**

- Hydrogen to Energy System Products, (HtE)

---

**Hydrogen TCP - a Technology Collaboration Programme by IEA**
Conclusions: PTH-HTX opportunities for the energy system and beyond

The main drivers for Power-to-Hydrogen and Hydrogen-toX are decarbonizing the energy system and productively enabling ongoing increases proportions of renewable power capacity. This paper discussed the potential role of hydrogen systems to decarbonize the transport, industry and energy sectors (power, gas, and heating/cooling). Assessing the hydrogen potential on each of the identified sector, as well as the feasibility for hydrogen to enter the identified markets was beyond the scope of this paper. The aim was rather to highlight the potential of hydrogen of being a key enabler towards a low-carbon economy.

In this context, this paper has begun to precisely identify the main PtH-HtX pathways that can be considered, to overcome the ambiguities related to the phrase “Power-to-Gas”. Each pathway has been defined to examine the associated opportunity for the energy system. Specific attention is given to the definitions of the words and the interconnections along the main pathways, to prepare for providing inputs to future Codes and Standards committees, and to provide solid foundations for building legal and regulatory frameworks for new business opportunities. This is an ongoing work of Task 38, through the collaboration with the standardization organizations CEN (the European Committee for Standardization) and CENELEC (the European Committee for Electrotechnical Standardization).

Acknowledgements

The present work was carried out in the framework of the Task 38 of the Hydrogen Implementing Agreement of the International Energy Agency. The task is coordinated by Institute for techno-economics of energy systems (I-tésé) of the CEA, supported by the ADEME. Hydricity Systems receives support in part from the ATO/AusIndustry’s Research and Development Tax Incentive program. Pierluigi Mancarella would like to acknowledge the partial support by the UK EPSRC through the MY-STORE project (EP/N001974/1).
REFERENCES


Abstract

Demonstration is a key first step towards large-scale market introduction. This chapter presents the results of a review of 249 Power-to-X demo projects in 33 countries until the year 2020. Results show that the features of demonstrations have evolved significantly over the years: electrolysis capacity has increased, both for PEM and alkaline systems, and the potential for balancing and ancillary services is increasingly investigated via grid-connected demos. The scope of Hydrogen-to-X pathways has also evolved over the years, mainly to include industry applications.

Key words

- Power-to-hydrogen
- Hydrogen-to-X
- Power-to-gas
- Renewable energy
- Demonstration
- Pilot plant

Introduction

Hydrogen systems are included in the global discussion on energy system progression [1], [2]. The application of Power-to-Hydrogen concepts for managing demand, providing seasonal storage, and the linking element between different sectors (electricity generation, gas grids, transport and industry), has attracted significant interest during the last decade [2].

Further down the value chain, hydrogen can be deployed in a large portfolio of applications.
Figure 4
Power-to-X pathways

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>ACRONYM</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-to-Hydrogen</td>
<td>$H_2$</td>
<td>Hydrogen production (and storage when requested) from low-carbon electricity either from the grid or off-grid</td>
</tr>
<tr>
<td>Hydrogen-to-Power</td>
<td>$H_{tp}$</td>
<td>Supply of electricity to the grid from hydrogen with a fuel cell or a gas turbine</td>
</tr>
<tr>
<td>Hydrogen-to-Gas</td>
<td>$H_{tq}$</td>
<td>Hydrogen injection in natural gas grid</td>
</tr>
<tr>
<td>Hydrogen-to-Fuel</td>
<td>$H_{tF}$</td>
<td>Synthetic methane injection in natural gas grid, synthetic methane is obtained from Hydrogen from $H_{tq}$ through methanation processes</td>
</tr>
<tr>
<td>Hydrogen-to-Industry</td>
<td>$H_{tI}$</td>
<td>Hydrogen in a vehicle to be injected in a fuel cell</td>
</tr>
<tr>
<td>Hydrogen-to-Heat</td>
<td>$H_{tQ}$</td>
<td>Hydrogen for liquid synfuel applications: liquid biofuels, synthetic liquid fuels, methanol</td>
</tr>
<tr>
<td>Hydrogen-to-Chemical</td>
<td>$H_{tCh}$</td>
<td>Hydrogen for mobility through gas fuels (Hythane©, biogas, synthetic methane)</td>
</tr>
</tbody>
</table>

Other pathways to industrial chemical intermediates from hydrogen which we may want to include explicitly:
1. $H_2$ to methanol to $C_2$, $C_3$ olefins
2. $H_2$ to syngas to $C_2$, $C_3$ olefins
3. Methanol/syngas to $>C1$, hydrocarbons and $>C1$ alcohols
4. $H_2$ to ammonia and formic acid (which could also be used as alternative renewable energy storage)

- termed as “Hydrogen-to-X” (HtX). Possible applications for hydrogen are fuel cells in transport (HtF-H2), other transport pathways include using hydrogen to produce syngas such as methanol or biofuels (HtF-S), or gas fuels for transport (HtF-G). “green” gas through methanation (PtG-M) or direct blending of hydrogen with natural gas (PtG-H2) [3], in the industry e.g. refineries (HtI), heat generation (HtQ), production of chemicals (HtCh), and for re-electrification into the electricity grid or remote areas (HtP). Thereby, hydrogen interlinks the power sector to other energy-intensive sectors (heat, transport, industry). This leads to consider an integrated energy system with interconnections between the energy carriers [4].

The total value chain from power generation to the usage of hydrogen in diverse applications is commonly termed “Power-to-X”. Figure 4 summarizes the different Power-to-X pathways and the respective nomenclature used in this chapter. 6 categories and 9 sub-categories are identified as downstream hydrogen production (“Hydrogen-to-X” part).

In this context, Power-to-X demonstrations are developed throughout the world to explore the potential of Power-to-X by identifying previously established knowledge and remaining concepts which should be further developed, before reaching the market.

This work carried out under the umbrella of Task 38 of the International Energy Agency’s Hydrogen Technology Collaboration Programme [5], aims at reviewing all the $H_{tq}$ and $H_{tp}$ demonstrations that have been implemented around the world, to analyse the general trends and coverage, and remaining unknowns. The focus is put on the existing demonstrations, i.e. projects having a purpose of learning about the technology or system. Investigating commercial plants is beyond the scope of this chapter. So is a prospective study on planned projects. Indeed, the ultimate goal is to propose a roadmap depicting the needs for future projects based on what was demonstrated so far (be it in technical, economic or other terms such as regulation), which will be done in collaboration with the IEA.

The following section briefly describes the methodology and selected parameters for a review of 249 demonstration projects in 33 regions (see Appendix 1). Section Results then provides the analysis of the results, focussing first on the Hydrogen-to-X part, and then on the electrolysis system (Power-to-Hydrogen). The aim is to provide insights about the general trends and not an in-depth analysis of each demonstration project.

Methodology

This section describes the methodology and selected parameters for a review of 249 demonstration projects in 33 regions (see Appendix). As stated in the introduction, 249 demonstration projects were reviewed using a methodology developed in several steps. These 249 identified references target all demonstrators around the world, the date of which is characterized by their effective commissioning, until 2020.

The demonstration projects were first identified, using the expertise of the Task 38 members. Over 40 parameters characterizing the demonstrations were identified:

- **Overview**: Project location, start date, duration of demonstration, investigated pathways, consideration of services to the grid;
- **Technical specifications**: Type of electrolysis system, installed capacity of electrolyser, power supply scheme (on-grid, off-grid, on-grid + connection to a renewable energy source (RES)), in case of renewable connection: type of power supply (e.g. all-in, excess power) and RES capacity, type of hydrogen storage (CHG, MH, CNG, salt cavern, etc.), capacity of hydrogen storage, hydrogen production mode (baseload, flexible), load factor and efficiency;
- **Objectives**: overall scope and demonstration objective(s); for example, technical, economic, other, and more specifically, when relevant: focus of technical objective (component, system, pathway), type of technical objective (operation validation, efficiency improvement, upscaling, etc.), type of economic objective (e.g. hydrogen production cost optimisation), type of regulatory objective;
- **Results and maturity**: Major technical results of the demonstrations; major economic results, technology readiness level (TRL), and market readiness level (MRL);
- **Legal aspects**: Specific regulations taken into account, certification scheme considered, green labelling for hydrogen production, policy support scheme, avoidance of grid fees, the maximum hydrogen concentration in the natural gas grid, and incentives if any.
Future plans: Planned future demonstrations, connection with other demonstrations, links to a roadmap, steps towards the market and messages to policy makers.

To collect the data for all the demonstrations, the demonstration coordinators were contacted directly using a template questionnaire. Also, data were collected from the literature. Over 200 references were consulted, including scientific papers, specific studies on Power-to-Gas projects, articles and news, dedicated platforms (European Power to Gas, DOE global energy storage database, EASE, Dena, etc.) [6]-[229].

The results are detailed and discussed in the following section. Note that the information regarding each demonstration project is not always available; therefore, the demonstration numbers may not always sum up to 249. Moreover, multiple nominations may be allowed on certain indicators (such as the investigated pathways), which explains that, on the contrary, totals higher than 249 may be noticed.

Results

General outlook

249 demonstration projects were examined in 33 different countries, the HYSOLAR project being the first demonstration being identified in 1985, designed by the German Aerospace Center (DLR) and the University of Stuttgart, and implemented in two different countries (Saudi Arabia and Germany). Demonstration projects are implemented in each continent (cf. Figure 5). Europe leading the way with 202 projects, and more specifically Germany being far from the other countries with 74 demonstration plants. Demonstration projects have been installed for over twenty years, and we can notice a considerable increase from 2010 onwards.

Pathway trends (“Hydrogen-to-X”)

Hydrogen is versatile. To investigate which pathways are more explored, Figure 6 shows the number of demonstrations for each of the Hydrogen-to-X (HtX) pathways being identified in Figure 5. Since each demonstration project can address more than one pathway, multiple nominations in different categories have been taken into account. Overall, the pathways that have been addressed most extensively are Hydrogen-to-Power (HtP) and Hydrogen-to-Fuel (HtF). As to the first, this is even more so if we take into account that 85% of the Hydrogen-to-heat (HtQ) projects are related to HtP as well through Combined Heat and Power (CHP) concepts. At first glance, hydrogen use for industry or chemical applications seems less investigated, with only 9% of demonstrations covering this pathway.

If we look at the temporal progression of the different pathways (cf. Figure 7), HtP and HtF have also been the pathways that have raised interest first, which contributes to explain that they appear more often among the demonstrations: they have been investigated since the beginning and still are. Hydrogen-to-Gas (HtG) applications have emerged in the early 2000s and had a boom ten years later. Most recently, the number of demonstrations on Hydrogen-to-Industry (HtI) and Hydrogen-to-Chemicals (HtCh) have risen significantly, and are now close in number to the other pathways. Since they raised interest later, it is quite logical that, overall, there are fewer of them. Since 2010, there has therefore been a marked increase in mobility applications, gas injection into networks and industrial applications.

When we consider more specifically the role of H2 as a fuel (HtF) or a gas (HtG), it can be seen in Figure 8 that pure hydrogen as a fuel is the most investigated pathway, rather than H2-based mixtures. It should be noted however that demonstrations on liquid synfuels only started in 2010, along with the interest in

Figure 5
Geographical spread (left) and temporal evolution (right) of the number of demonstration projects

Figure 6
Share of each HtX application of the demonstration projects (multiple nomination allowed)

Hydrogen-to-Industry and Hydrogen-to-Chemicals as in the literature [229], making them as of today a viable alternative to pure H2 gas for fuelling applications. Concerning Hydrogen-to-Gas, Figure 8 indicates that the injection of synthetic methane is more investigated than the direct injection and blending of pure hydrogen into the natural gas grid. This may be explained by the regulation challenges regarding the latter pathway (the allowed hydrogen concentration in the natural gas network may vary significantly from one place to another).
Focus on Power-to-Hydrogen

In this section, the focus is put on the demonstration upstream: the Power-to-Hydrogen part, i.e. the production (and storage when requested) of hydrogen from low-carbon electricity, either from the grid or off-grid. As the power supply scheme is a crucial topic for the production of “green” or low-carbon hydrogen, the power source of the projects was identified and classified in three main categories: on-grid supply (connected to the power grid), off-grid supply (only powered by renewable energy installed nearby or micro-grids isolated from the public power grid), and “on-grid + RES”, meaning that two connections co-exist: a direct connection with a renewable capacity, as well as a grid connection.

As shown in Figure 11 (left), the majority of demonstrations have focused so far on off-grid systems (53% vs. 28% for on-grid demonstrations and 19% for on-grid + RES). Moreover, almost all of the renewables considered were coming from wind power (cf. Figure 11 right). In recent years, however, on-grid systems start to prevail (cf. Figure 12). This may be due to the fact that the pathways may be investigated with a more holistic approach (what could be the contribution of hydrogen to the energy system), including the potential input to help balancing the electric system. Indeed, 41% of the demonstration projects that started after 2015 include grid balancing services, while only 22% in the period 2011-2015, 8% between 2001 and 2015, and zero before 2001.

Regarding the electrolyser technology, it can
**Figure 10**
Time evolution of the versatility (number of HtX applications) of demonstrations

![Graph showing the time evolution of the versatility of demonstrations.](image)

**Figure 11**
Power supply schemes (left) and origin of green power (right) for the P2H part of the demonstrations

![Graph showing power supply schemes and green power origins.](image)

**Figure 12**
Evolution of the power supply schemes as a function of time

![Graph showing the evolution of power supply schemes over time.](image)

**Figure 13**
Number of demos (left) and total installed capacity (right) for the 3 types of electrolyser technologies

![Graph showing the number of demonstrations and total installed capacity for different electrolyser technologies.](image)

**Figure 14**
Total aggregated installed electrolyser capacity per year

![Graph showing the total aggregated installed electrolyser capacity per year.](image)
**Figure 15**
Comparison between the cumulative capacity of the Alkaline, PEM and SOEC technologies

**Figure 16**
Total installed electrolyser capacity per demonstration project per year

**Figure 17**
Installed electrolyser capacity (in MW) vs. H₂ output (in Nm³/hr) for each demo project.

**Figure 18**
Evolution of Alkaline and PEM efficiencies as a function of time, as calculated from Figure 17
be seen in Figure 13 that alkaline and PEM (Proton Exchange Membrane) electrolysers are almost as often selected (47% of the demonstrations assess alkaline electrolysers; 46% PEM). On the other hand, the total capacity installed over the years is still significantly higher for alkaline electrolysis with 184 MW installed vs 81 MW for PEM. The situation differs greatly for SOEC (Solid Oxide Electrolysis Cell) electrolysers. This technology, even though promising, is much less mature. As a result, demonstrations are still at a different scale: SOEC are investigated in 8% of the demonstration projects, with a mere 3 MW being installed. Figure 14 and Figure 15 consider in more detail the installed Pth electrolyser capacity as a function of starting date, both on a year-to-year basis (Figure 14) and cumulatively (Figure 15). Although alkaline is a more mature technology that was also installed first, very similar trends can be observed with a 5-year interval. Moreover, an upscaling phenomenon can be seen, the installed capacity per demonstration reaching several MW in years 2018 and 2019 and up to more than 10 MW in 2020 (Figure 16). The installed demo electrolysis capacity on each of the two technologies more than doubled in 2020. The electrolysis system efficiency was also assessed from the available data. To this end, the total installed electrolyser capacity (in MW) was plotted as a function of H2 output (in Nm3/hr), whenever available. The slope of a linear fit through such data is then inversely proportional to the system efficiency. The results are shown in Figure 17. It appears that contrary to what is often being claimed in the literature, no significant difference can be observed between alkaline and PEM systems. For ≤2 MW systems, the slopes are even identical, resulting in an average efficiency of 73%, based on a slope of 4.9 kWh/Nm3 and a HHV value of 3.54 kWh/Nm3. Moreover, when looking at the temporal evolution in Figure 18, the efficiency values are quite scattered, and no obvious trend can be observed. Also, in the framework of Task 38 of IEA Hydrogen, an international network of experts assessed the techno-economic potential of Power-to-Hydrogen pathways. From their review of 230 internationally published studies [231], two-thirds of the studies assume an average electricity consumption of 45 to 50 kWh/kgH2. Finally, regarding storage, 79% of the demonstration projects that provide information on this matter, include a storage option. Most of these projects considered a compressed hydrogen gas technology to store the produced hydrogen (cf. Figure 19).

**Demonstration objectives**

184 demonstration projects out of 249 have explicitly mentioned their objectives. In what follows, the percentages are based on these 184 projects. 100 % of demonstrations have technical objectives, with 91% of these projects testing the operational validation, 88% evaluating the efficiency, and a mere 27% considering an upscaling plan. Since 2010, the interest in only the technical aspects of the demonstrations has been decreasing. Economic assessments are included in the demonstration objectives as well (cf. Table 2). 43% of the projects have an economic objective, of which only 14% consider the H2 production cost though.

When studying the other targets of the projects, it appeared that most of the direct feedbacks received indicated a regulatory objective, while in the reviewed literature only 2% of the projects highlighted the regulatory aspect. This shows that the regulatory objectives are rather implicit subjects, yet crucial ones.

**Conclusion**

'Low-carbon' hydrogen (i.e. H2 produced through low-carbon pathways) can be used by many energy-consuming services. It has a potential role to play in the electric, gas, transport, and industrial sectors. Demonstrations are a key step towards reaching the market. A review of the Power-to-X projects in the world was carried out, identifying 249 demonstrations in 33 countries until 2020. Results show that the features of

**Table 2**

<table>
<thead>
<tr>
<th>Demonstration start date</th>
<th>Share of demonstrations with technical objective(s) only</th>
<th>Share of demonstrations with economic objective(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 2001</td>
<td>83%</td>
<td>17%</td>
</tr>
<tr>
<td>2001-2005</td>
<td>57%</td>
<td>43%</td>
</tr>
<tr>
<td>2006-2010</td>
<td>64%</td>
<td>36%</td>
</tr>
<tr>
<td>2011-2015</td>
<td>65%</td>
<td>35%</td>
</tr>
<tr>
<td>2016-2020</td>
<td>45%</td>
<td>55%</td>
</tr>
<tr>
<td>Total</td>
<td>57% (105 demos out of 184)</td>
<td>43% (79 demos out of 184)</td>
</tr>
</tbody>
</table>
demonstrations evolved significantly in recent years. The investigated pathways diversified, with a recent interest in industrial applications. This is happening in the context of a recent and general momentum for industry applications, both at national and international levels [2], [229],[232],[233],[234]. Also, recent studies showed that only approaches favouring synergies between sectors and acknowledging sector coupling can reveal the full potential of hydrogen to decarbonize the energy system [233],[234],[235],[236],[237]. Accordingly, demonstrations consider several applications simultaneously, together with an increase of on-grid systems investigating the potential of providing system balancing to the electric grid.

This reviewing work is the first step towards an international roadmap, to be designed with the IEA, to better identify what are the demonstrations that are required and focus the effort on the most relevant topics, in order to reach the different markets in the near term. The increasing installed capacities of electrolysers show that we are on the way.

Acknowledgements

The present work was carried out within the framework of Task 38 of the Hydrogen Technology Collaboration Programme of the International Energy Agency. The task is coordinated by the Institute for techno-economics of energy systems (I-tésé) of the CEA, supported by the ADEME. We would also like to acknowledge the support of Capenergies for this work. One of the authors (JP) wishes to acknowledge financial support from the Public Service of Wallonia – Dept. of Energy and Sustainable Building. Special thanks to Ito Hiroshi, Yuki Ishimoto, and Federico Zenith for providing information on demo projects.

Appendix 1. list of the reviewed demonstration projects and location

<table>
<thead>
<tr>
<th>Demonstration Project</th>
<th>Country</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abalone Energie Nantes</td>
<td>France</td>
<td>Aberdeen, Hydrogen bus project</td>
</tr>
<tr>
<td>Adelaide Hydrogen Park South Australia (HyP SA)</td>
<td>Australia</td>
<td>Aeropila</td>
</tr>
<tr>
<td>Air Fuel Synthesis pilot plant</td>
<td>UK</td>
<td>AirLiquid Becancour</td>
</tr>
<tr>
<td>Alzey, Exytron Null-E</td>
<td>DE</td>
<td>Ameland</td>
</tr>
<tr>
<td>Baglan Energy Park Wales</td>
<td>UK</td>
<td>Balance</td>
</tr>
<tr>
<td>Big HIT UK</td>
<td>UK</td>
<td>BioHyMe</td>
</tr>
<tr>
<td>BioPower2Gas, Allendorf, Eder</td>
<td>DE</td>
<td>BOEING (rSOC Demonstrator)</td>
</tr>
<tr>
<td>Carbazol pilot plant, University of Erlangen-Nürnberg</td>
<td>DE</td>
<td>Carbon2Chem</td>
</tr>
<tr>
<td>CEC Denizli Turkey</td>
<td>TR</td>
<td>CELBICON</td>
</tr>
<tr>
<td>CEOG</td>
<td>FR</td>
<td>Cerro Pabellón Microgrid 450 kWh Hydrogen ESS - Enel S.p.A.</td>
</tr>
<tr>
<td>CHOHC0</td>
<td>FR</td>
<td>CO2Exide</td>
</tr>
<tr>
<td>CO2RECT-Niederaussem</td>
<td>DE</td>
<td>Commercial Plant Svartsengi/George Olah plant</td>
</tr>
<tr>
<td>CoSine: Synthetic Natural Gas from Sewage, Barcelona</td>
<td>ES</td>
<td>CUTE and HyFLEET:CUTE, Barcelona</td>
</tr>
<tr>
<td>CUTE, Stockholm</td>
<td>SE</td>
<td>DEMETER</td>
</tr>
<tr>
<td>Demo Plant Agricultural University Athens</td>
<td>GR</td>
<td>Demonstration of bio-CO2 products, Bio economy</td>
</tr>
<tr>
<td>Demonstration plant Kuala Terengganu, Malaysia</td>
<td>MY</td>
<td>Dietikon Hybrid Power-to-Gas Plant</td>
</tr>
<tr>
<td>Direktmethylisierun von Biogas im Technikum Wallenau</td>
<td>DE</td>
<td>DNV Kema/DNV GL</td>
</tr>
<tr>
<td>Don Quichote</td>
<td>BE</td>
<td>DRI CO2 recycling</td>
</tr>
<tr>
<td>DTE Energy Hydrogen Technology Park, Southfield Michigan</td>
<td>US</td>
<td>Dubai Green Hydrogen Demonstration</td>
</tr>
<tr>
<td>DVGW-EBI KIT - Demo-SNG</td>
<td>DE</td>
<td>ECTOS</td>
</tr>
<tr>
<td>EE-Methan aus CO2</td>
<td>AT</td>
<td>Eichhof - 1st step</td>
</tr>
<tr>
<td>Eichhof - 2nd step</td>
<td>DE</td>
<td>EkoLyser (R&amp;D)</td>
</tr>
<tr>
<td>El Tubo</td>
<td>ES</td>
<td>ElectroHgna</td>
</tr>
<tr>
<td>ELECTROHYPEM</td>
<td>EU</td>
<td>ELY4OFF</td>
</tr>
<tr>
<td>ELYGRID (R&amp;D)</td>
<td>EU</td>
<td>Emden I Biogas upgrading</td>
</tr>
<tr>
<td>Enbridge P2G toronto</td>
<td>CA</td>
<td>EmBW H2 station, Stuttgart</td>
</tr>
<tr>
<td>Energiepark Mainz</td>
<td>DE</td>
<td>Energy Park BAD LAUCHSTADT</td>
</tr>
<tr>
<td>Energy Valley, Delfzijl</td>
<td>NL</td>
<td>ENGIE-Anglo American project</td>
</tr>
<tr>
<td>EON PtG plant Falkenhagen</td>
<td>DE</td>
<td>EON PtG plant Hamburg-Reitbrook</td>
</tr>
<tr>
<td>E-THOR</td>
<td>NL</td>
<td>ETOGAS, Solar Fuel Alpha-plant 250 kW, ZSW</td>
</tr>
<tr>
<td>ETOGAS, Solar Fuel Alpha-plant mobile device, ZSW</td>
<td>DE</td>
<td>ETOGAS, Solar Fuel Beta-plant AUDI, Werlte (Audi e-gas)</td>
</tr>
<tr>
<td>Etzel, Salt caverns</td>
<td>DE</td>
<td>Eucolino Schwandorf</td>
</tr>
<tr>
<td>Falyence</td>
<td>FR</td>
<td>Fife, Levenmouth Community Energy Project</td>
</tr>
<tr>
<td>FIRST - Showcase II</td>
<td>ES</td>
<td>FIRST project, INTA facility</td>
</tr>
<tr>
<td>Foulum Demonstration plant</td>
<td>DK</td>
<td>Freiburg solar house</td>
</tr>
<tr>
<td>FrE5Me</td>
<td>SE</td>
<td>Foro Energy Cell, self-sufficient house</td>
</tr>
<tr>
<td>Fronius HyLOG-Fleet (Hydrogen powered Logistic System)</td>
<td>AT</td>
<td>GenHyPEM (R&amp;D)</td>
</tr>
<tr>
<td>Gösgen hydropower plant</td>
<td>CH</td>
<td>Green Ammonia Hanwell in Oxford &amp; Fukushima</td>
</tr>
<tr>
<td>Green Natural Gas</td>
<td>DK</td>
<td>Greenhouse heating, solar-H2</td>
</tr>
<tr>
<td>Grenzach-Wyhlen ZSW (Zentrum für Sonnenenergie- und Wasserstoff- Forschung Baden-Württemberg)</td>
<td>DE</td>
<td>GRHYD (Hythane)</td>
</tr>
<tr>
<td>Project Name</td>
<td>Country</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>GRHYD (inj in NG grid)</td>
<td>FR</td>
<td>Grimsstad Renewable Energy Park</td>
</tr>
<tr>
<td>GrInHy</td>
<td>DE</td>
<td>H&amp;R electrolys to refinery</td>
</tr>
<tr>
<td>H2 from the sun, Brunate</td>
<td>IT</td>
<td>H2 research center BTU Cottbus</td>
</tr>
<tr>
<td>H2BER (Berlin airport)</td>
<td>DE</td>
<td>H2FUTURE</td>
</tr>
<tr>
<td>H2Herten</td>
<td>DE</td>
<td>H2IT - Hydrogen Energy Storage in Nuuk</td>
</tr>
<tr>
<td>H2SusBuild / RES-H2</td>
<td>GR</td>
<td>Halcyon Power in Mokal</td>
</tr>
<tr>
<td>Halvor Topsoe - El-Opgraderet Biogas</td>
<td>DK</td>
<td>Halvor Topsoe - El-Opgraderet Biogas II</td>
</tr>
<tr>
<td>Hamburg - Schnackenburgallee</td>
<td>DE</td>
<td>Hamburg Hafen City, CEP</td>
</tr>
<tr>
<td>Hanau, Wolfgang Industrial Park</td>
<td>DE</td>
<td>HARI project, West Beacon Farm</td>
</tr>
<tr>
<td>HARP System, Bella Coola</td>
<td>CA</td>
<td>Hassfurt</td>
</tr>
<tr>
<td>Hawaii Hydrogen Power Park (phase 2)</td>
<td>US</td>
<td>Hebeif - China</td>
</tr>
<tr>
<td>Hebei Jiantou Yanshan (Guyuan) Wind</td>
<td>CN</td>
<td>Wind Energy</td>
</tr>
<tr>
<td>Hitodrica, Tahvila</td>
<td>ES</td>
<td>Hitachi Zosent/C02 Conversion to Methane Project</td>
</tr>
<tr>
<td>HPEM2GAS (R&amp;D)</td>
<td>DE</td>
<td>HRS CMB</td>
</tr>
<tr>
<td>HRS Wuppertal</td>
<td>DE</td>
<td>Hydrogen Power Plant Enertrag, Prenzlau</td>
</tr>
<tr>
<td>Hybrid energy storage system NFCRC, California</td>
<td>US</td>
<td>Hychico, Comodoro Rivadavia</td>
</tr>
<tr>
<td>Hycycle - Center for renewable H2 (R&amp;D)</td>
<td>DK</td>
<td>Hydepark</td>
</tr>
<tr>
<td>HyCycle</td>
<td>DK</td>
<td>Hydepark</td>
</tr>
<tr>
<td>HyHydro</td>
<td>UK</td>
<td>Hydrogen Island Bozcaada</td>
</tr>
<tr>
<td>Hydrogen mini grid system Yorkshire (Rotherham)</td>
<td>UK</td>
<td>Hydrogen village Burgenland</td>
</tr>
<tr>
<td>Hydrogen Wind Farm Sotavento</td>
<td>ES</td>
<td>HYFLEET:CUTE, Amsterdam</td>
</tr>
<tr>
<td>HyFLEET:CUTE, Hamburg</td>
<td>DE</td>
<td>Hygreen Provenz</td>
</tr>
<tr>
<td>HYLINK, Totara Valley</td>
<td>NZ</td>
<td>HyNor Lillestræm, Akershus Energy Park</td>
</tr>
<tr>
<td>HYPOS (Leipzig)</td>
<td>DE</td>
<td>HYRES</td>
</tr>
<tr>
<td>HySeas III</td>
<td>UK</td>
<td>HySolar in Nieuwegein</td>
</tr>
<tr>
<td>HySolar test bed Riyadh (R&amp;D)</td>
<td>SA</td>
<td>HYSSOLAR, Stuttgart</td>
</tr>
<tr>
<td>HyStock</td>
<td>NL</td>
<td>HyWindBalance, Oldenburg</td>
</tr>
<tr>
<td>Infinity-1</td>
<td>DE</td>
<td>INGRID</td>
</tr>
<tr>
<td>IRENE System</td>
<td>CA</td>
<td>IETHER</td>
</tr>
<tr>
<td>Jupiter 1000</td>
<td>FR</td>
<td>KEROSyN100</td>
</tr>
<tr>
<td>Kopernikus Project</td>
<td>DE</td>
<td>Laboratory Plant HRI Quebec</td>
</tr>
<tr>
<td>Laboratory Plant Stralsund</td>
<td>DE</td>
<td>Laboratory System at IFE Kjeller</td>
</tr>
<tr>
<td>Lam Takhong Wind Hydrogen Hybrid Project- EGAT</td>
<td>TH</td>
<td>LastEUs (R&amp;D)</td>
</tr>
<tr>
<td>Laufenburg e-fuel plant</td>
<td>CH</td>
<td>Leuchtturnprojekt Power-to-Gas Baden- Württemberg</td>
</tr>
<tr>
<td>Lingen refinery</td>
<td>DE</td>
<td>MEDYS, Medium temperature water electrolysis (R&amp;D)</td>
</tr>
<tr>
<td>MECOC2</td>
<td>DE</td>
<td>MEGASTACK</td>
</tr>
<tr>
<td>MeGa-stoRE</td>
<td>DK</td>
<td>MeGa-stoRE Optimising and Upscaling</td>
</tr>
<tr>
<td>Meth Quest</td>
<td>DE</td>
<td>METHCENTRE</td>
</tr>
<tr>
<td>Mhyrabel Project</td>
<td>FR</td>
<td>MicroEnergy GmbH, Schwandorf</td>
</tr>
<tr>
<td>MicroPyros</td>
<td>DE</td>
<td>Minerve, Nantes</td>
</tr>
<tr>
<td>Morbach</td>
<td>DE</td>
<td>MULTIPHY</td>
</tr>
<tr>
<td>MYRTE</td>
<td>FR</td>
<td>NOED kouf city, Yamanashi Prefecture</td>
</tr>
<tr>
<td>NEMO</td>
<td>FI</td>
<td>New zealand Matiu/Somes Island</td>
</tr>
<tr>
<td>NEXPEL (R&amp;D)</td>
<td>NO</td>
<td>NOVEL</td>
</tr>
<tr>
<td>Optifuel</td>
<td>AT</td>
<td>P2G-Biocat</td>
</tr>
<tr>
<td>PHOEBUS</td>
<td>DE</td>
<td>Pilot &amp; Demo PM HSR, Rapperswil</td>
</tr>
<tr>
<td>Ports of Auckland</td>
<td>NZ</td>
<td>PostBus Hydrogen bus, Brugg, aargau</td>
</tr>
<tr>
<td>Power to flex</td>
<td>DE</td>
<td>Primolyzer (R&amp;D)</td>
</tr>
<tr>
<td>PIG-Elektroyse im MW-Maßstab (R&amp;D)</td>
<td>DE</td>
<td>PURE Project, Unst</td>
</tr>
<tr>
<td>PUSHY (LASYH)</td>
<td>FR</td>
<td>PUSHY (OSSHY)</td>
</tr>
<tr>
<td>PVFCSYs Agrate</td>
<td>IT</td>
<td>PVFCSYs Sophia Antipolis</td>
</tr>
<tr>
<td>RABH2</td>
<td>UK</td>
<td>Raglan Nickel mine</td>
</tr>
<tr>
<td>Ramea Wind-Hydrogen-Diesel Project</td>
<td>CA</td>
<td>Redlands Renewable Hydrogen Plant</td>
</tr>
<tr>
<td>REHYNE</td>
<td>DE</td>
<td>REFLEX</td>
</tr>
<tr>
<td>Regenerativer Energipark Ostfalia/ hybrid renewable energy park (HREP)</td>
<td>DE</td>
<td>RegEnKibo, Kirchheimbolanden</td>
</tr>
<tr>
<td>Region Energie Solothurn/Aarmat hybrid plant</td>
<td>CH</td>
<td>Remote Agkristo Greece</td>
</tr>
<tr>
<td>Remote Ambornetti Italy</td>
<td>IT</td>
<td>Remote Froan Islands Norway</td>
</tr>
</tbody>
</table>
REFERENCES


[23] Thorsten Liese Dr. Experiences and results from the RWEpower-to-gas-Projekt at Niederaußem site. RWE Power AG, München; November 11, 2013. Presentation.


[33] Dr Luis Correas. Elgygrid project. Foundation for the development of new hydrogen technologies in Aragon(Spain). [Presentation].


[51] Dr Luis Correas. Elgygrid project. Foundation for the development of new hydrogen technologies in Aragon(Spain). [Presentation].


[73] Franca Barbir. UNIDO-ICHE'Ts Hydrogen islands initiative, Projects Update. [Presentation]

European Union Sustainable Energy Week 22-26 March 2010.


[92] Tauron group. CCS/CCU in Tauron group. [Presentation].


[95] Torgeir Nakken et al. Tauron group. CCS/CCU in Tauron group. [Presentation].


[130] OECD. Task 38 Final Report - September 2020


[132] Jürgen Stremegy, MHC. Methycentre: Unité de Power-to-Gas (hydrogène et méthane de synthèse) couplée à une unité de méthanisation. [Brochure].


[189] European Commission. The Hydrogen Fuelling Station, Ecological City Transport System. Demonstration, Evaluation and

[202] Aujhara Weerawong. CO2 Conversion to Methane Project. PTT Exploration and Production PCL.


Low-carbon H₂ can play a role in the electric, gas, transport, and industry sectors

This chapter provides a snapshot of the legal context for PtH in 12 countries.

CHAPTER III
Subtask 3B: Review of the existing legal context and policy measures

The most acknowledged pathway, from a legal standpoint, is mobility applications

Only a few countries are implementing legal frameworks for diverse H₂ applications

As shown in the last section, the demonstration projects allow learning what challenges PtX pathways are facing. These challenges are not only cost-related. They also include an inadequate regulatory framework often presenting a barrier to hydrogen deployment projects. The next chapter addresses the regulatory bottlenecks but also the required incentives concerning PtX developments.

Abstract
Rendering the energy system more sustainable can only be achieved through a combination of low-carbon energy production, energy efficiency, and coupling of energy sectors. In this context, Power-to-Hydrogen concepts for managing supply and demand, providing seasonal storage, and being the linking element between different sectors (electricity generation, gas grids, transport, and industry), has attracted significant interest during the last decade. However, the deployment of technology is subject to legal barriers, which may differ from one region to another. On the contrary, there may be incentives to facilitate market introduction of a new technology.

In this paper, an international network of experts under the umbrella of Task 38 of the International Energy Agency’s Hydrogen Technology Collaboration Programme assesses the legal framework in ten countries regarding power-to-hydrogen applications. The most frequently considered pathway, from a legal standpoint, is using hydrogen for mobility applications. Only a few countries are implementing legal frameworks for diverse hydrogen applications.

Key words
Power-to-Hydrogen
Hydrogen-to-X
Power-to-Gas
Incentives
Legal
Sector Coupling

AUTHORS
Francesco Dolci¹, Denis Thomas², Samantha Hilliard², Carlos Fúnez Guerra², Ragnhild Hancke⁴, Hiroshi Ito⁶, Mathilde Jegou², Gijs Kreeft⁴, Jonathan Leaver⁵, Marcus Newborough⁴, Joris Proost⁴¹, Martin Robinus²⁵, Eveline Weidner⁰, Darja Markova⁸, Ezequiel Serwatka¹⁴, Ricardo Ariel Perez¹⁴, Christine Mandillia¹⁴, Olfa Tlili¹⁵, Paul Lucchese¹⁵.

AFFILIATIONS
Introduction

In the last couple of years, several countries worldwide have issued hydrogen visions documents, with the aim of exploring the decarbonisation possibilities offered by hydrogen technologies and hydrogen deployment across several sectors. These visions are integrated with the framework of a larger scope on climate goals.

In Europe for instance, the climate goals are threefold [1]:

1. At least 20% (2020), 55% (2030) and 80% (2050) cut in greenhouse gas emissions should be achieved compared to 1990 levels;
2. At least 20% (2020) and 27% (2030) of total energy consumption from renewable energy should be reached (the new Renewable Energy Directive set a 32% target for renewable energy by 2030), and
3. At least 20% (2020) and 27% (2030) increase in energy efficiency attained (the new Renewable Energy Efficiency Directive set a 32.5% target for energy savings by 2030).

These objectives have been updated and brought even further (achievement of carbon neutrality by 2050) with the issuing of the European Green Deal [2].

Such a transformation is demanding, and all possible means need to be leveraged, i.e. a combination of low-carbon energy, energy efficiency, and the coupling of energy sectors [3]. The application of Power-to-Hydrogen concepts for managing demand, providing seasonal storage, and linking element between different sectors (electricity generation, gas grids, transport and industry), has attracted significant interest during the last decade.

In the last years, an ever-increasing number of demo projects associated with power-to-hydrogen applications are being carried out through the globe and several Task 38 members reporting initiatives in their home countries. These offer opportunities for gaining field experience and gaining important insight into how legislation can impact the deployment of hydrogen technologies.

In this chapter, an international network of experts under the umbrella of Task 38 of the International Energy Agency’s Hydrogen Technology Collaboration Programme (H2) carries out an assessment of the legal framework related to Power-to-Hydrogen pathways in twelve countries: Argentina, Austria, Belgium, France, Germany, Italy, Japan, New Zealand, Norway, Spain, The Netherlands, and the United Kingdom. Only national legislation is considered, as the review does not examine at a regional scale.

The following section focuses on the incentives. When none are mentioned, it means that none currently exist. Section 3 then provides an overview of the legal barriers.

Incentives

Promoting low-carbon hydrogen production (PH) Power-to-Hydrogen pathways can contribute to the transition towards a low-carbon energy system, provided of course that hydrogen is produced sustainably. Indeed, today 96% of hydrogen is produced from fossil fuels [5].

To ensure the low-carbon origin of hydrogen, some renewable or green hydrogen certification mechanism should be defined and established. In Europe, there are some on-going initiatives regarding certification. The project CERTHY aims at establishing a first Green Hydrogen Guarantee of Origins (GOs) that will be available for sale EU-wide [6]. The work distinguishes between renewable and low-carbon origins. Under the new EU Renewable Energy Directive, the role of renewable hydrogen is now explicitly acknowledged [7].

A standardisation effort is also ongoing. At the European level, the European Committee for Electrotechnical Standardization (of the European Committee for Standardization, CEN – CENELEC) [8] is developing a standard on Guarantee of Origin for production of hydrogen.

Since 2006, Argentina has put in place incentive for promoting the production, use and applications of hydrogen through the National Law Nº 26.123 [9].

In Austria, a regulation providing for the certification and labelling of gas has been adopted and is in force since January 2020 (so-called Gaskanzenzeichnungsverordnung) [10].

The situation varies for supporting policies for hydrogen production from electrolysis (PtH). In Austria, according to its 111 (3) EWOG 2010, facilities converting electricity into hydrogen or synthetic natural gas, which are commissioned for the first time after 7 August 2013 until the end of 2020, do not have to pay any of the system utilization charges and charges for system losses prescribed for the purchase of electrical energy until the end of 2020 [11]. In Norway, hydrogen produced through electrolysis is exempt from electricity consumption taxes (not from grid tariffs though) [12]. Specific subsidies are available in the Netherlands as the Ministry of Economic Affairs established a subsidy programme for energy projects, including a specific subsidy for hydrogen-related projects (not limited to production). The maximum allowable funding is 750,000 € per project [13].

Incentives towards the use of hydrogen in the transport sector

Regarding the downstream uses of hydrogen production, the incentives vary drastically from one pathway to the other. The most favourable pathway (and the most incentivized) is the use of hydrogen in fuel cell vehicles (HtF-H2).

- **Incentivizing the vehicle purchase**
  Still, regarding the HtF-H2 pathway, there are several incentives regarding fuel cell electric vehicles. In some cases, these incentives are binding regulations. In the Netherlands, from 2035 onwards, all new passenger vehicles must be able to drive with a carbon-neutral footprint [19].
  Most often, the incentives consist of subsidies for vehicle purchase. Several grants are possible for electric or fuel cell electric cars. The order of magnitude is usually several thousand euros.

- **Incentivizing the infrastructure deployment**
  First, incentives to foster the deployment of a hydrogen infrastructure (to address the well-known chicken and egg problem) are deployed by several nations.
  In Italy, public incentives (EU and national) are expected to reach 47 million € in 2020 and 419 million € for 2021-2025, 40% of them being national funds [14].
  In Germany, the eMobility funding programme includes a 300 million € for infrastructure [15].

  The Alternative Fuel Infrastructure Directive (AFID) EU 2014/94 implementation involves the construction of 400 hydrogen refuelling stations by 2023 in Germany [15]. In Japan, half of the construction costs of the HRS are subsidized regardless of the origin of the hydrogen [16]. In Norway, a national investment support program for the establishment of hydrogen refuelling stations was launched in spring 2017, where up to 40% of project costs can be covered. Technical requirements of this programme demand a minimum capacity of 200 kg H2/day and a minimum of two fueling nozzles, in which one should deliver at 700 bar [17]. In the Netherlands, subsidies for the deployment of hydrogen refuelling stations are provided for under the Hydrogen subsidy programme of the Ministry of Economic Affairs [15]. Finally, in Belgium, an excise tax is not paid on the sale of hydrogen as a transport fuel. Another indirect European incentive is the possibility to account for renewable liquids or gaseous fuels of non-biological origin used in the transport sector as contributing to the required targets as defined in European legislation (e.g.: RED II).

- **Incentivizing the hydrogen production pathways**
  Incentivizing the hydrogen production pathways

  Incentives towards the use of hydrogen in the transport sector

  Incentives towards the use of hydrogen in the transport sector
Subsidies for private battery electric and fuel cell electric vehicles amount to 3,000 € per vehicle. “Electric cars and light electric utility vehicles” together with “Electric Minibuses” and “Electric Light Vehicles” used by companies, local authorities, associations also benefit of subsidies depending on their class and ranging from 1,000 to 20,000 € per vehicle. Electric cars are input tax-deductible (vorsteuererabzugsfähigkeit) if they are purchased as company cars. Electric drivetrains (excluded from the IG-Er (Immissionsschutzgesetz Luft) speed limit. In some communities, EVs are already allowed to park for free - in a next step, bus lanes for EV will be opened and free parking for electric cars will be promoted [20].

In Belgium, a 4,000 euro grant is available in Flanders for all electric cars, but it is not applicable for companies/leasing [21]. In Germany, for electric cars (including fuel cell ones), there is a grant of 4,000 €. For hybrid cars, it amounts to 3,000 €. Rewards are only for cars with a list price of maximum 60,000 € (base model). The promotion lasts for a maximum total of 400,000 cars. The federal government contributes a total of 600 million €, and this cost is shared equally between the federal government and the automakers. Overall, the funding reaches 1.2 billion €. This promotion will end in 2020 [22]. In Japan, the national subsidy for fuel cell hydrogen electric vehicles is of 2.02 million JPY (i.e. 15,000 €/vehicle) [23]. It ranges from 0.1 to 0.4 million JPY for other kinds of electric cars. In France, 27% of the price of the vehicle (taxes and batteries included) is subsidised, not exceeding a maximum of 6,000 €. This is granted for the acquisition of a new vehicle which emits less than 20gCO2/km (except for hybrid vehicles which use diesel). For vehicles emitting between 21 and 60 g CO2/km, the premium is 1,000 €. There is also a diesel scrappage scheme: switching from a 1.1-year-old or older - diesel car for a new electric car grants an extra 4,000 € (or 2,500 € in case it is a plug-in hybrid electric vehicle). The “L” category (Quadricycles, Motorbikes, Scooters...) has a 250 € per kWh purchase subsidy (lead battery vehicles excluded), with a limit of 1,000 € or 27% of the purchase price [24, 25]. In Spain, electric vehicles can benefit from incentives ranging between 1,100 and 15,000 €, with a limit of 5,500 € for fuel cell electric vehicles [26]. In the Netherlands, for lease/company cars, the fiscal costs for the private use of zero-emission lease cars, including fuel cell electric vehicles, are limited to 4%. Petrol cars pay 22% [27, 28]. In the UK, there is a government grant of £4,500 (approximately 5,000 €) for buyers of fuel cell electric vehicles [29].

Additionally, several countries grant an exemption (partial or total) of registration tax to electric and fuel cell electric vehicles. In Belgium, electric and plug-in hybrid vehicles are exempt from registration tax (in Flanders only) [21]. In France, there are road tax exemption and reduction of matriculation certificate fees (French “carte grise”). The reduction of a clean engine vehicle depends on the region [30]. In Spain and Norway, there is a purchase tax exemption [31, 32]. In the Netherlands, zero-emission cars are exempt from paying the registration tax. For the other kinds of cars, the system is progressive, with five levels of CO2 emissions which pay different amounts of registration tax. Plug-in hybrid cars go to level 1 (1-79 gCO2/km) and pay 6 € per gram. For level 2 (80-106 gCO2/km), the tariff is 69 € per gram CO2. The final level is 476 € per gram for cars emitting 174 gCO2/km or over [28].

There are also ownership tax exemptions (partial or total) in several countries. In Belgium, electric vehicles pay the lowest rate of tax under the annual circulation tax in all three regions, (74 € instead of 1,900 €) [21]. In Italy, electric vehicles are exempted from the annual circulation tax (ownership tax) for five years from the date of their first registration. After this five-year period, in many regions, they benefit from a 75% reduction of the tax rate applied to equivalent petrol vehicles [33]. In Germany, the exemption is for the first ten years for cars registered until Dec 31, 2015, then five years afterwards until Dec 31, 2020 [22]. In Norway and Spain, tax reductions also exist. In the Netherlands, exemption from motor vehicle taxes and road tax is granted for fuel cell electric vehicles [34]. Finally, in New Zealand, there is a 385 €/road user charge exemption and a 44 € reduction in compulsory personal injury insurance.

**Incentives towards the use of low-carbon hydrogen in the industry and for electricity production**

There are few supporting policies for the use of green hydrogen in industry (HI).

In France and the Netherlands replacement of fossil-fuel derived hydrogen is encouraged by tax exemptions. In France, the use of renewable hydrogen in industry has an impact on avoiding the carbon tax (“Contribution Climat-Energie”) which was 30.5 €/tCO2 in 2017, and should reach a level of 100 €/tCO2 by 2030 [35]. In the Netherlands, investments which result in the replacement of fossil fuels by hydrogen are deductible from the profit before being taxed up to 41.5% [36].

In Austria, hydrogen cannot take advantage of specific feed-in tariffs dedicated to green electricity obtained from biogas, since synthetic natural gas and hydrogen from power-to-gas plants, according to Austrian legislation do not fall into the definition of biogas. Thus, there are no supporting policies for re-electrification of hydrogen [37].

Argentina does not yet have dedicated legislation, but the projectHychico is using renewable hydrogen production from wind turbines to power a genset where it is combusted together with natural gas [38].

In Austria, according to the exemptions for production of hydrogen previously mentioned, it can be surmised that the electricity input necessary for the production and feeding of hydrogen or synthetic natural gas is exempt from the electricity levy (so-called “Elektrizitätsabgabe”) and that these applications are exempted from the obligation to pay further charges such as the renewables contribution, flat-rate renewables charge, and the CHP flat-rate. Hydrogen based on renewable energy (and synthetic gas produced from renewable hydrogen) is tax-exempt concerning the payment of the natural gas levy (the so-called “Erdgasabgabe”) [40].

In Germany, bio-methane utilisation is eligible for feed-in tariffs only when being used for CHP [41]. In France, bio-methane feed-in tariffs were fixed in 2016 for 15 years [42]. The producer will benefit from a feed-in-tariff between 46 and 139 €/MWh. In the Netherlands, for the production of energy products from biomass, operators can request a subsidy. The amount of subsidy is awarded for every kWh injected into the gas grid and covers the difference between the price of bio-methane and natural gas, with a maximum amount of 6 million € per project and a period of 12 years [43, 44]. In the Netherlands, the bio-methane feed-in tariffs is 3.6 €c/kWh for first 40 GWh injected, falling to 2.1 €c/kWh for next 40 GWh, and to 1.6 €c/kWh for any remainder from sites injecting >80 GWh [45].

However, some questions arise: is synthetic methane produced through the methanation pathway (H2-M) eligible for similar feed-in tariffs? And what about direct blending of hydrogen (H2-H2) and tariffs that respect the blend concentration? Today, none of these schemes recognize synthetic gas or hydrogen as a green gas eligible for a green gas feed-in tariff. What is more, concerning the latter, there is the additional issue of the maximum concentration of hydrogen in the hydrogen-natural gas blend. This is addressed in the following section on legal barriers.
Legal barriers
Regarding hydrogen production

For the production of hydrogen, regulations (especially regarding safety) are being implemented. In Europe, the reference European directives are the “Seveso” and “ATEX” ones, which can be implemented differently in each Member State. In France, for instance, special permitting is required for hydrogen production and storage [46, 47]. Hydrogen production sites “making industrial quantities” are subject to ICPE authorisation (ICPE, Installation Classée pour la Protection de l’Environnement in French, facilities classified for environmental protection), which is a binding regime. This case is under negotiation for a less constraining administrative regime for hydrogen obtained via water electrolysis. Hydrogen sites storing strictly less than 100 kg of hydrogen are not subject to administrative constraints. An ICPE declaration needs to be made if the stored quantity ranges from 100 kg to 1000 kg. An ICPE authorisation is compulsory for quantities beyond 1000 kg. In Spain, regardless of the amount of hydrogen produced, it is necessary to process and obtain the environmental impact assessment [48] and integrated environmental authorization [49]. The Spanish legislation does not differentiate the sources of hydrogen production; they must comply with all the same environmental requirements. These permitting regimes in France, Spain and other EU countries are to a large extent prescribed under the EU Industrial Emissions Directive under which Power-to—Hydrogen is considered an activity for the production of inorganic chemicals” [50]. The permitting regime for such installations does not differentiate between different hydrogen production pathways such as Power-to-Hydrogen and methane steam reforming.

Regarding hydrogen blending with natural gas

Regarding the direct injection of hydrogen in the natural gas grid, the authorized concentrations vary significantly from country to country because historically, when the existing regulations were introduced, there was no consideration of the possibility of gas grids conveying hydrogen admixtures (see Table 3). In Germany for example, there are no national legislative restrictions regarding the hydrogen content in natural gas. The limitations vary from 10 vol.% as an admixture to below 2 vol.% if a CNG filling station is connected, and if no calibrated hydrogen measurement system is installed, the hydrogen content shall not exceed 0.2 vol.% [51]. A similar conflict exists in Austria, where the permitted hydrogen concentration in the grid is 4 vol.%, but it is restricted to 2 vol.% for natural gas-powered vehicles [40].

Argentina has no regulation that explicitly mandates a maximum hydrogen percentage. The gas HHV is the only parameter which has to be monitored [52].

When assuming perfect gases, molar and volume percentages are equivalent. As a result, the values taken from the regulatory frameworks can be ranged to catch the rate of diversity (see Figure 20). This is a major bottleneck to develop this pathway since even when allowed, the maximum concentration of hydrogen is low. Projects like GRHYD [53] and HyDeploy [54], which have local exemptions to inject up to 20% hydrogen, are pushing the boundary and may lead to new regulations and greater harmonisation across Europe.

Regarding hydrogen use for the transport sector

There are also legal barriers related to the use of hydrogen in fuel cell vehicles. Accuracy in hydrogen dispensing is a significant issue in several European countries, as well as homogeneously standardised connectors. In Belgium, measurement accuracy in fuel distribution must meet specific accuracy criteria (metrology, based mainly on liquid fuels). Current technologies do not meet these criteria and therefore intermediate regulations need to be adapted to provide for payment terminals accepting bank card payments. In Germany, the allowable dispensing tolerance of 1% to 1.5% is prescribed. Unfortunately, it is not possible to reach the required accuracy, therefore a derogation has been requested for the existing hydrogen refuelling stations to allow for higher tolerances [52]. In France, a decree is in preparation, for stations with storage capacities lower than 1 tonne H₂ (declaration with periodic control). Hydrogen vehicle refuelling points, or renewed refuelling points, across the EU are currently unable to meet the AFID [63] requirement concerning the deployment of ISO 17268 compliant nozzles, because such technology is not yet available commercially. The transposition of AFID Article 5, clause 2, has been implemented inconsistently across the EU with some countries requiring the use of ISO 17268 compliant nozzles (e.g. Sweden, Spain, Netherlands, UK) while others do not (e.g. France, Denmark and Germany).

Additionally, permitting procedures are required for hydrogen refuelling stations, concerning safety considerations.

### Table 3

<table>
<thead>
<tr>
<th>Country</th>
<th>Maximum H₂ concentration allowed in the gas grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>&lt; 4% vol by 2030, the hydrogen tolerance in the gas network should be &lt; 1% mol</td>
</tr>
<tr>
<td>Belgium</td>
<td>&lt; 0.1% mol (injection up to 2% vol could be considered)</td>
</tr>
<tr>
<td>Italy</td>
<td>&lt; 2.3% vol (0.5% vol for biomethane)</td>
</tr>
<tr>
<td>Germany</td>
<td>&lt; 10% mol (for 2 mol% of CNG tanks)</td>
</tr>
<tr>
<td>France</td>
<td>6% mol</td>
</tr>
<tr>
<td>Japan</td>
<td>0% mol</td>
</tr>
<tr>
<td>Spain</td>
<td>5% mol</td>
</tr>
<tr>
<td>Netherlands</td>
<td>0.02% mol (There are plans to raise this to 0.5% mol)</td>
</tr>
<tr>
<td>UK</td>
<td>0.1% mol</td>
</tr>
</tbody>
</table>

#### Figure 20

Hydrogen blending rates range
General outlook

Considering the legal barriers and incentives that were identified in this article, an attempt to characterise the legal framework for each pathway and country is carried out in Table 4. It is worth noting that the European HyLAW project [64] is investigating the specific details of the existing legal barriers pushing back against the development of hydrogen systems in Europe.

From this table, it clearly appears that the most acknowledged pathway, from a legal standpoint, is the use of hydrogen as a fuel for fuel-cell vehicles since it benefits from general incentives for electric or low-emission vehicles. Hydrogen blending in the natural gas grids is trickier under the current regulation. Specific regulations seem to be lacking for several pathways. Some frameworks are in place, such as the one for bio-methane, but at this time it remains unclear whether this will be an opportunity for PtH pathways in the future. Incentives begin appearing for the industrial sector, which is recently gaining momentum [65].

Compared to other countries, the Netherlands seem to be implementing a global legal framework, encompassing the variety of hydrogen applications as shown in recent works and scenarios [66-70]. France seems to be on the same pathway, but industry uses do not appear on the agenda of most examined countries.

Conclusion and policy recommendations

Low-carbon hydrogen (i.e. that produced through low-carbon pathways, such as water electrolysis powered with low-carbon electricity) can be used by different energy-consuming services. It has a potential role to play in the electric, gas, transport, and industrial sectors. This paper presents a review of the incentives and legal barriers in twelve countries, concerning Power-to-Hydrogen and Hydrogen-to-X pathways, as communicated by Task 38 members.

The main application specific to hydrogen for which countries have already started to develop explicit regulations is the use of hydrogen in fuel cell vehicles. A number of incentives were implemented, either for low-emission vehicles in general or specifically for hydrogen vehicles. For the pathways involving the natural gas grid, there are still barriers. Allowed injection limits for hydrogen are low, and feed-in tariffs are only implemented for bio-methane. On the other hand, incentives are beginning to appear in the industrial sector.

However, the specificity of hydrogen being a versatile energy carrier seems to be often disregarded. Only a few countries are implementing legal frameworks facilitating diverse hydrogen applications. Also, the potential benefits of hydrogen production via water electrolysis in contributing to the electric system stability and greater integration of variable renewables seem neglected as well. Power-to-Hydrogen production via electrolysis is rarely promoted directly. Among the countries covered, only Norway has implemented an electricity tax exemption for hydrogen production.

From the review that was carried out, some policy recommendations can be identified: Promote hydrogen use with a holistic approach, by encompassing all the possible pathways (PtX):

- Develop incentives in the transport sector beyond the sole light passenger duty vehicles (i.e. by including trucks, trains, maritime use), and incentivize the infrastructure development jointly with the vehicle purchase;
- Remove the legal barriers for the blending of hydrogen with natural gas by harmonizing the blending concentrations, and set thresholds based on physical constraints [71]; acknowledge the actual greenhouse gas mitigation for gas applications by also accounting the contribution of methane leakages during processing and transport of natural gas (and implement the relevant incentives/penalties accordingly); implement support schemes as it is done for bio-methane injection;
- Promote the use of low-carbon hydrogen in industry by implementing adequate certificates and/or penalties; ensure a “level playing field” for products obtained with low-carbon hydrogen;
- Promote the production of low-carbon hydrogen;
- Implement adequate regulations on polluting activities (e.g. carbon taxation);
- Acknowledge the contribution of hydrogen systems to the development of renewables (develop certificates, tax exemption for the power consumed by electrolyzers (especially when hydrogen is meant to produce power, grid tariff exemption could also be considered); allow participation to ancillary services and capacity mechanisms).

Even if favourable economic conditions are met, Power-to-Hydrogen pathways will only develop provided that appropriate regulations make it possible. The attention of stakeholders must be raised on this topic. At present, there is a lack of regulations or penalties being applied to conventional polluting methods of hydrogen production to make them more expensive and ease the transition to low-carbon hydrogen.

Investigating the incentives and legal barriers for hydrogen system deployment is an on-going task. This paper provides a short, high-level, snapshot. Future research will develop the current analysis to cover a number of additional countries.

Table 4

<table>
<thead>
<tr>
<th>Country</th>
<th>AR</th>
<th>AT</th>
<th>BE</th>
<th>FR</th>
<th>DE</th>
<th>IT</th>
<th>JP</th>
<th>NZ</th>
<th>NO</th>
<th>ES</th>
<th>NL</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>PtH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HiP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HtF-H2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HtF-S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HtF-G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HtG-H2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HtG-M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HtI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HtCh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HtQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Country AR AT BE FR DE IT JP NZ NO ES NL UK

PtH Power-to-Hydrogen
HiP Hydrogen-to-Power
HtG-H2 Hydrogen-to-Gas (feed-in H2)
HtG-M Hydrogen-to-Gas (feed-in of synthetic methane)
HtF-S Hydrogen-to-Fuel (hydrogen)
HtF-S Hydrogen-to-Fuel (liquid synfuels)
HtF-G Hydrogen-to-Fuel (gaseous synfuels)
HtI Hydrogen-to-Industry
HtQ Hydrogen-to-Heat
HtCh Hydrogen-to-Chemicals

- Favourable context
- Somewhat favourable
- Somewhat difficult
- No information
Acknowledgements

The present work was carried out within the framework of Task 38 of the Hydrogen Technology Collaboration Programme of the International Energy Agency. The task is coordinated by the Institute for techno-economics of energy systems (I-tésé) of the CEA, supported by the ADEME. Special thanks to Rob Dickinson for his precious help with the references of this chapter.

REFERENCES


[25] République Française, “Bonus écologique pour un véhicule électrique ou hybride (vélo, etc.). [ Ecological bonus for an electric or hybrid vehicle (car, bicycle, etc.) ]” 2020.


[54] HyDeploy project. “Hydrogen is vital to tackling climate change,” https://hydeploy.co.uk/.


[57] European Biogas Association (EBA). “[*** to be confirmed ***],” https://www.europeanbiogas.eu/ [*** to be confirmed ***].


[70] O. Tlili, “Rethinking the way to decarbonize the energy system: prospective study of hydrogen market attractiveness,” 2017.

Low-carbon H₂ can play a role in the electric, gas, transport, and industry sectors

The review identified clear cost reduction trends for hydrogen production by electrolysis

Authors
Jochen Linssen1, Christine Mansilla2, Abhilash Bandam3, Mihai Balan4, Francesco Dolci5, Robert R Dickinson6, Carlos Fúnez Guerra7, Henrik Iskov8, Jonathan Leaver9, Emilio Nieto Gallego10, Andre Pereira11, Joris Proost12, Christopher Quarton13, Sheila Samsati14, Olfa Tili15, Solène Valentin16, Dietlef Stolten17, Paul Lucchese18, Martin Robinus19.

Affiliations
1. Forschungszentrum Jülich GmbH, Techno-economic Systems Analysis (IEK-3), Germany;
2. CEA, Université Paris Saclay, France;
3. Institute for Cryogenics and Isotopic Technologies ICSI, Romania;
4. Joint Research Centre of the European Union;
5. Hydricity Systems and University of Adelaide, Centre for Energy Technology, Australia;
6. Centro Nacional del Hidrógeno, Spain;
7. De Montfort University, UK;
8. PertE, France;
9. Danish Gastechnology Centre A/S, Denmark;
10. Unitec Institute of Technology, New Zealand;
11. Department of Chemical Engineering, University of Bath, UK;
12. Université Catholique de Louvain, Division of Materials and Process Engineering, Belgium;
13. Air Liquide, France.

*corresponding author: Jochen Linssen, Forschungszentrum Jülich, Wilhelm-Johnen-Straße 1, D-52428 Jülich, Phone: +49 2461 61-3581, email: J.linssen@fz-juelich.de

CHAPTER IV

Part 1: Subtask 3A: Review and analysis of the existing techno-economic studies on PtH and HtX

This chapter presents an approach for a collaborative review of Power-to-X pathways available in literature, considering policy papers and studies from national and international agencies, industry and NGOs.

This chapter presents an approach for a collaborative review of Power-to-X pathways available in literature, considering policy papers and studies from national and international agencies, industry and NGOs.

The cost-reduction potential for PEM electrolysis appears more promising than AEL

Abstract

The application of Power-to-Hydrogen Hydrogen-to-X (or Power-to-X Ptx) concepts for managing demand, providing seasonal storage, and linking the end-use sectors to low-carbon electricity generation has attracted significant interest during the last decade. This chapter presents an approach for a collaborative review of Power-to-X pathways available in literature, considering policy papers and studies from national and international agencies, industry, and NGOs, published before 2017. The review is based on over 220 national and internationally published studies and reports.

This collaborative review process was performed by an international team of experts as a two-step approach. The identified publications are first evaluated, and then the selected publications are analyzed in depth.

Notwithstanding assumed rising electricity costs of up to 50% from today to the period 2030 to 2050, the review identified clear cost reduction trends for hydrogen production by electrolysis, starting with an average at...
over 10€/kg H₂ for the period before 2020, the production costs estimate decrease to 3.2€/kg H₂ in the period 2030 to 2050. The decrease in hydrogen production costs can be explained by increasing efficiencies in combination with significantly lower costs for all electrolysis technologies. The assumed efficiencies for alkaline electrolysis (AEL) and proton exchange membrane (PEM) electrolysis improve reaching an average value of 60% for the period 2030 to 2050. The specific investment for AEL and PEM goes down to 640€/kWel and 440€/kWel respectively. The cost-reduction potential for PEM electrolysis appears more promising than AEL.

The review of applied pathways identifies Hydrogen-to-Gas by synthetic methane, Hydrogen-to-Gas by direct use of hydrogen, Hydrogen-to-Fuel by hydrogen conversion to transport fuels and Hydrogen-to-Power by re-electrification of hydrogen. PtX for industrial use of hydrogen and Power-to-Liquids are not the focus since there are no available reviewed publications before the 2017 cut-off date.

**Key words**

- **Power-to-Hydrogen**
- **Hydrogen-to-X**
- **Power-to-Gas**
- **Hydrogen Markets**
- **Collaborative review**

**Introduction**

The application of Power-to-Hydrogen (PtH) concepts for managing demand, providing seasonal storage and supplying transport, industry, households, and small consumers with carbon-free energy carriers have attracted significant interest during the last decade. This concept supports the integration of Variable Renewable Energy Sources (VRES) by converting electricity to hydrogen in times of high VRES electricity generation to make that energy storable and tradeable. In addition, chemical energy carriers such as hydrogen can also facilitate large-scale and long-term storage due to their high energy density, very high storage capacities due to the possible use of geological storage sites, and comparatively low storage costs [1]. Further down the value chain, hydrogen can be deployed in a large portfolio of applications – referred to here as “Hydrogen-to-X” (HtX) [2]. Figure 21 summarizes the different options and the generation, conversion, and infrastructure parts of the pathways.

In the broadest sense, all the pathways from Power-to-Hydrogen Hydrogen-to-X, where X refers to the many and diverse end-point applications, are commonly shortened to simply Power-to-X (PtX). Note that Power-to-Gas (PtG) can be used in the literature to refer to PtH systems or both HtG-M and HtG-H2 pathways. A categorization of many but not all of these pathways is presented by Dickinson et al. (2017) [3].

There is a considerable amount of literature analyzing future energy systems, including the future potential of PtX concepts. For example, Saba et al. have undertaken a review of electrolysis [4] and Ghab et al. of methanation [5]. Detailed reviews of PtX demonstration projects have been prepared by Chehade et al. on a worldwide level [6] and by Wulf et al. for Europe [7]. However, despite the vast literature available, a systematic overview and a comprehensive understanding of the various technical and economic pathways for PtH and HtX applications, under the diverse scenarios and policy schemes, is still lacking.

The novelty of this study lies in the collaborative review involving several experts and the integration of policy papers and studies coming from industry and NGOs written in languages other than English. The approach allows for consideration of national and international policy strategies in the implementation of PtX. This goes beyond scientific papers and incorporates publications of national and international agencies, governments, NGOs and industries.

In this chapter, an international network of experts under the umbrella of Task 38 “Power-to-Hydrogen and Hydrogen-to-X” of the International Energy Agency’s Hydrogen Technology Collaboration Program [8] assesses the techno-economic potential of Power-to-Hydrogen pathways as available in the literature for the period 1999 to 2017. The review of 220 national and internationally published studies was carried out by over 15 international hydrogen experts, based on a consistent and transparent assessment process. The review undertaken for this work does not seek to examine an exhaustive list of all hydrogen studies. Rather, the aim has been to capture the diversity of the current state of studies undertaken so far.

The paper is structured by the description of the designed methodology for task sharing and the cooperative review process (Methodology for a structured international and collaborative review). This includes a two-step approach for selecting scenario studies for a detailed review. Following this, Detailed analysis of review Step 2, provides an analysis of the general and techno-economic parameters of the reviewed scenario studies in the literature. Based on this analysis, general trends and possible technical and economic pathways to markets are identified. A special focus of the review was given to Power-to-X pathways in future scenarios and their associated costs for hydrogen production, including electricity and electrolyzer costs.
Methodology for a structured international and collaborative review

A shared literature review performed by a variety of discipline experts from different countries requires a general understanding of the topic and a clear definition of the objective and used terms. A structured representation of data input and a precise definition of analyzed parameters for such a process is mandatory.

The process of gathering literature was based on inputs from the international review team. The international composition of the panel of experts allowing a wide range of literature review is the strength of this exercise. Approximately 15% of the reviewed literature is published in languages other than English (e.g. Dutch, German, Danish and French). Twelve were not captured due to a lack of translation.

The review process is a two-step approach. Given the large number of identified documents, the first review step evaluates the publications according to key criteria, including:

- the context of the study and general issues: date, type of document, geographical scope and time horizon;
- the crucial issues and bottlenecks in publications identified concerning Power-to-X pathways.

This approach allows the screening of publications that do not fit the objective of the review: which revolves around the previously listed PtX and HtX pathways. The review process was centrally organized and controlled by a single lead reviewer. Step 1 of the review process was performed by completing structured fact sheets to capture general data of the publication and its applicability to PtH – HtX pathways.

Out of 220 publications, 166 publications were selected to be eligible for further analysis. A fundamental part of the in-depth analysis of step2 is a common understanding of the review goals and a detailed definition of parameters and common reading scheme.

The second review step involved the in-depth analysis of suitable publications from step1. The challenge is to make different data comparable irrespective of different
Electricity Supply

The PtH step implies the use of electricity to produce hydrogen. This process (water electrolysis) is based on the electrochemical splitting of water using electricity as the energy input. Therefore, the generation of electricity and the system integration of electrolysis are essential for the efficiency and costs of all PtX pathways. The concept for electrolysis integration derives from a variety of electricity sourcing strategies, from coupling a full portfolio of generation technologies, including fossil, nuclear and Renewable Energy Sources (RES), to off-grid applications with high regard to dynamic behaviour.

The left chart of Figure 25 shows the histogram of the assumed concepts for electrolysis integration for all 79 scenarios that include the relevant information. More than 70% of the eligible scenarios imply a full grid integration of electrolysis without direct coupling to RES. Only 15% of the analyzed scenarios take a direct coupling of RES and surplus electricity into account.

The analysis of the assumed specific electricity costs (right chart of Figure 25) illustrates a large bandwidth. The average electricity costs in eligible PtX scenarios begins in the period 2012 to 2019 with 63€/MWh, rising to approximately 82€/MWh and rises to 95€/MWh in the periods 2020–2030 and 2031–2050, respectively. In the majority of scenarios, this trend is explained by the rising share of RES electricity generation.

Electrolysis

The central part of all PtX pathways is the electrolysis to produce hydrogen from electricity. A detailed description of the status quo of the technology and expected trends is, for instance, prepared by Carmo et al. [12] but is not within the focus of this paper. This section analyzes the types, costs, and efficiencies of electrolysis in the analyzed scenarios. The applied type of electrolysis (i.e. AEL, PEM, solid oxide electrolysis cells (SOEC)) is summarized in Figure 26. The histogram reveals a slight tendency towards AEL in all periods. Prior to 2030, SOEC is of minor importance. For the period 2031–2050, the application of SOEC is seen as more viable and reaches the same range as AEL and PEM. This fact reflects the lower degree of maturity of this technology. The type of electrolysis is not specified in a large number of studies, probably since AEL and PEM characteristics (CAPEX, electricity consumption) are expected to converge in the medium term [13]. Regarding the specific cost for electrolyzers, Figure 27 shows a clear cost trend for the AEL and PEM technologies. Starting from a large distribution of specific cost between 750 €/kWel up to over 2000 €/kWel for AEL and 1000 up to over 2000 €/kWel for PEM, costs decrease for AEL to an average value of 640 €/kWel and to 440 €/kWel for PEM, respectively, in the period 2031 to 2050. The cost reduction potential of PEM is seen to be more promising in the reviewed scenarios than AEL, but it starts at a higher level. It should be noted that the number of eligible scenarios, especially for PEM deployment, is low, and average values are influenced by high range within these scenarios. The cost trends for SOEC cannot be derived due to the lack of data. Regardless of the type of electrolysis considered, 95% of scenarios foresee a specific cost for electrolysis below 750 €/kWel.

Figure 28 shows the histogram of the average electricity demand for hydrogen production. All technologies start with a high variability of specific electricity demand (between 45 and 65 kWhel/kgH2), but there is a clear trend towards higher efficiencies. The review reveals a similar efficiency range for AEL and PEM in
The right histogram of Figure 28 shows the trend in hydrogen production costs in different periods. The review of eligible scenarios reveals a large spread in the resulting hydrogen production costs. The cost range is from under 2 €/kgH₂ to over 10 €/kgH₂ depending on assumed electricity costs, electrolyzer capital costs, etc. The average hydrogen production costs of all eligible scenarios show a clear decrease over the time horizon (Table 5). Average production costs in the period 2031-2050 are 3.2 €/kgH₂.

The trend histogram of Figure 28 shows the spread in load factors in the various studies. Our review reveals a high range of assumed load factors in the scenarios depending on the configuration (e.g., on-grid, off-grid, RES coupled). No clear trend in time can be identified for this important operation criterion. The low number of eligible scenarios shows the lack of temporal resolution of production/generation data over the year in many scenario studies.
Table 5
Average hydrogen production costs by period

<table>
<thead>
<tr>
<th>Period</th>
<th>Average hydrogen production costs of eligible scenarios (€/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today - 2020</td>
<td>7.8</td>
</tr>
<tr>
<td>2020-2030</td>
<td>4.7</td>
</tr>
<tr>
<td>2030-2050</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Power-to-X pathways

Of the 166 publications, more than 85% see P2X as a possible option for conversion, storage or sector coupling. Hydrogen has the potential to be used in various applications in the conversion and final consumption in the electricity, gas, transportation, residential and industrial sectors [14]. The distribution of H2 downstream pathways in the publications are shown in Figure 30.

Drawing conclusions from the studies is not a straightforward task, since the technoeconomic analyses of the different scenarios are tightly linked to specific local contexts, as highlighted in Decourt et al. [2014] [15].

However, three major potential markets emerge out of the analyzed literature:


- **Hydrogen-to-Fuel**: pure hydrogen as transportation fuel in various modes, *IEA* Hydrogen TCP: a Technology Collaboration Programme by IEA.

- **Hydrogen-to-Power**: re-electrification of hydrogen in thermal power plants or fuel cells.

The need for decarbonization of the transport sector provides a very strong incentive for producing low-carbon fuel, as can be seen by the inclusion of H2F pathways in almost 30% of the studies reviewed (around 65% of which corresponding to the direct use of hydrogen as a fuel, H2F-H2). Switching to hydrogen and electricity for transportation can improve air quality and reduce greenhouse gas emissions over the long term [16].

According to the UK *H2 Mobility* report [17], the CO2 emissions of hydrogen-fueled vehicles could be 75% lower than for equivalent diesel vehicles and facilitate a trajectory to zero CO2 emissions by 2050. In the short term, the use of “green hydrogen” (i.e. hydrogen produced by low-carbon pathways) in refineries is also a promising option for reducing the greenhouse gas intensity of established transport fuels [16].

Apart from the transport sector applications, blending hydrogen from PtH pathways with natural gas (in its pure form or as synthetic natural gas via methanation) is another popular pathway, being considered in 37% of the review studies. The overall potential, economic feasibility, and limitations still need to be examined closely, despite the work carried out so far [16].

The production and injection of synthetic natural gas (PtG) is more expensive than injecting pure hydrogen to form a blend (HCNG) [18] [19] [20]. PtG can utilize existing infrastructure with almost no modification. In contrast, HCNG is currently limited to values (depending on various factors) between 2-10% by volume [21] [16].

Industrial users are especially sensitive to variable hydrogen injection rates. However, the available estimations reviewed conclude that commercial competition is out of reach for synthetic methane blending, in particular in comparison with potential low-carbon options such as biomethane [19]. To become market competitive, direct injection of hydrogen from electrolysis would need low power prices along with tax exemption in order to foresee this pathway becoming economically attractive by 2050 [19]. Thus, in the mid-term, profitability is only possible with the support of government subsidies and/or premiums. Additionally, ENEA [19] and Thomas et al. [20] conclude that the electricity price and natural gas price have the most significant impact on the possible competitiveness of these business cases. To improve profitability, a multimodal operation is frequently suggested. For example, participation in the heat market would improve the business case [21], selling oxygen and providing ancillary grid services would improve economics [20]. Another proposed option is the use of an integral “smart gas” system [22].

The smart gas systems, which are designed in a style similar to electrical smart grids, profit from increased flexibility and efficiency through multiple fuels and outputs. In particular, the option to deploy hydrogen or synthetic natural gas, as alternative energy carriers to electricity transmission, is often emphasized [20] [16]. Hydrogen can also enhance renewable energy integration [23]. H2F pathways were included in 17% of the studies in this review. Re-conversion of hydrogen to grid electricity is generally seen as a potentially viable option in the context of premium back-up or seasonal storage for systems with very high shares of renewables [23]. Particularly in instances exhibiting a very high share of renewable generation in addition to a shortage of conventional storage capacities (like pumped-hydro storage), hydrogen is expected to become the key solution for long-term storage [15]. For remote locations or energy supply systems strongly dominated by renewable energy sources, and therefore require long-term energy storage (potentially displacing the need for fossil fuel to power during peak load periods concurrent with low VRE production), re-electrification of hydrogen is also likely to prove viable [16]. However, in the near-term, re-electrification schemes are expected to be economically challenging, primarily due to low round-trip efficiencies [16]. As such, re-conversion is projected to be last in the merit order of hydrogen end-uses [15]. Nevertheless, the path from water electrolysis to salt caverns and then to turbine is anticipated to be the most cost-efficient technology for long-term storage [24]. In this case, the low cost of energy storage partially compensates for the round-trip losses [25]. Flexible operation of electrolyzers makes them a controllable load.

Figure 30
Addressed H-t-X pathways in the reviewed scenarios (multiple nominations possible)
However, providing flexible-load services to the grid competes with many other competitive options [18]. Business cases are only possible by using all system services markets, and all market regimes need to be adapted. In all cases, the use of heat recovery can significantly improve overall system efficiencies [15]. Even if the economics prove difficult in the short term, the deployment of PH-HX pathways could be encouraged by policies (power tax exemption, feed-in tariffs for the gas grid, etc.) [26]. Regulations in support of such policies could be developed to limit the carbon intensity of energy services and products, thereby favoring low-carbon pathways within the electricity, transport, and heat sectors. Previous work tackled the incentives and legal barriers to power-to-hydrogen pathways [27]. In our review, around 8% of the publications address hydrogen industrial use (Hi). However, no scenario was identified to quantify this use in the period 1999 – 2017. It is thus worth highlighting that momentum for industrial applications has been observed recently, both at national [28] and international levels [29-30]. At the international level, the IEA recently issued a report on the use of renewable electricity in different industry branches with a variety of applications [29]. This report emphasizes the potential role of ammonia produced by green hydrogen, either as a chemical feedstock, a process agent or as fuel [29]. Another recent trend addressed in techno-economic studies on hydrogen pathways (e.g. in [31]), is large-scale production of “green ammonia (which is easier” than hydrogen globally transported in existing shipping infrastructure. Other industrial routes include substituting natural gas with renewable-based hydrogen for direct iron reduction, or manufacturing methanol from renewable-based water electrolysis and recycled CO2 [29]. Ultimately CO2-free iron and steelmaking, and CO2-free cement manufacturing, could be achieved. The use of recycled CO2 for methanol production could even achieve carbon neutrality [29].

## Discussion

The proposed two-step approach for a collaborative literature review has many advantages including task sharing, using broad language expertise and exploiting a large and diverse shared knowledge base. A drawback of this process is the time-intensive discussion process to arrive at a consensus on goals of the review, on definitions of terms used and on the design of a structure for the review process and resulting database. A lesson learned from the collaborative and task-sharing review is that a common understanding of the analyzed criteria and parameters, including interpretation, is deemed essential for success. In turn, a robust planning process is paramount. The two-step approach for identifying the most valuable reports is highly recommended for focusing on aspects to be analyzed. Once the analysis aspects are identified, one major challenge of the review was to be able to compare data coming from different documents.

In some cases, documentation of assumptions and quality of data was seen as an issue due to a lack of transparency in the process used in some publications. To address this problem, the experts decided applying a score for data quality for all analyzed publications. Figure 31 shows the histogram of the score of data quality. It is defined by a level of trust that was guided by a short description of quality standards. The average level of trust quantified by the experts is approximately 70% and the spread is high. Most of the publications have a confidence level higher than 50%. However, quality issues were noticed with some publications addressing the economic assessment of hydrogen systems. The comparison of cost data on an internal level is always combined with an evaluation of currencies having variable exchange rates, different financial risks resulting in different WACCs (weighted-average cost of capital) for costs, and financing of technologies in different periods. Most of the analyzed scenarios do not give any information about the mentioned criteria and weaken the basis for a transparent comparison of cost parameters.

## Conclusion

Low-carbon hydrogen (i.e. produced through low-carbon pathways) can be used by many energy-consuming services. It has a potential role in the electricity, gas, transport, and industrial sectors. This paper presents an international and collaborative literature review of Power-to-Hydrogen and Hydrogen-to-X techno-economic studies. The aim is to capture the broad diversity within the current literature and draw some major conclusions from it. Over 220 documents were reviewed with a methodology developed to analyze a wide variety of studies. The two-step approach developed allows for a collaborative review by experts and the integration of policy papers and studies for industry and NGOs written in different languages.

The literature analysis revealed that the PH – HX topic is not only addressed through academic work, but also by regional studies undertaken by institutions or firms that investigate related business opportunities. The regional coverage is broad, and the timeframes varied from present to the medium and long term. Although business cases are tightly linked with local circumstances, three major applications emerge from the literature: transportation, hydrogen-to-gas routes, and power generation. A momentum for industry applications has been observed only very recently, both at national and international levels. Overall, even if specific techno-economic studies are required to investigate business opportunities for diverse regional contexts, only approaches favoring synergies between sectors and acknowledging sector coupling can reveal the full potential of hydrogen to decarbonize the energy system.

## Acknowledgements

The present work was carried out within the framework of Task 38 of the Hydrogen Technology Collaboration Program of the International Energy Agency. The task is coordinated by the Institute for techno-economics of energy systems (I-IKEA) of the CEA, France supported by the ADEME. The literature review process was coordinated by Forschungszentrum Jülich GmbH, Techno-economic Systems Analysis (IEK-3), Germany.
REFERENCES

analyse af power-togas i energisystemet. 2015. Geografisk scope: Denmark.


Within this framework, a specific task force was set-up for the compilation of state-of-the-art technical and economical data on large-scale water electrolyser systems, both based on PEM and alkaline technology. The objectives set forward have been twofold. Firstly, to offer policy makers and industry with comprehensive trends and guidelines for further electrolyser cost reduction (CAPEX, in Euro/kW) into the MW-scale. Secondly, to provide objective technological & economic arguments for converging towards a realistic electrolytic (and hence renewable) H₂ market price (in Euro/kg). This should help water electrolysis to become competitive with SMR technology for (local) H₂ production, and hence to start making H₂ a competitive fuel.
the P2G concept, based on running or past large-scale demonstration projects, especially in Europa [3], [4], [5]. Independent of its recognised potential for storage purposes of electricity "upstream", there is still a vast range of opportunities to be explored "downstream" concerning the use of such electrolytic (and hence renewable) H2. Indeed, with the concern concerning the use of such electrolytic electricity "upstream", there is still a vast range of opportunities to be explored "downstream" of the different H2 technologies in some cases exceed the total investment cost. In our current paper, essentially because of the lack of reliable OPEX data on operating large-scale electrolyser systems, we will only concentrate on their CAPEX. Moreover, the projected production cost of electrolytic H2 today is dominated by the cost of electricity [9], which can therefore still be considered to be the dominant OPEX parameter.

Rather recently, literature studies have been dedicated to summarizing both historical trends [10] and short- and long-term projections [11] of investment cost (CAPEX) and performance data for two of the most common water electrolyser technologies being used today, namely alkaline and Proton Exchange Membrane (PEM) systems. However, such literature reports are often only able to generate a relatively wide range of CAPEX data, depending on the exact performance (e.g. input power) of the system being considered. For instance, Figure 32 summarizes CAPEX data from the available literature reports reviewed in Ref. [10]. It can be observed that the spread of the CAPEX estimations in the 1990s was in the range 870–2350 Euro/kW and 310–4750 Euro/kW for alkaline and PEM technology, respectively. At the same time, estimations for the future investment costs by the year 2030 are reported to be in the range 790–910 Euro/kW and 400–960 Euro/kW, respectively.

When it comes to the short- and long-term projections reported in the expert elicitation study on future cost and performance of water electrolyser systems, the difference in production costs of the different H2 technologies can in some cases exceed the total investment cost. In our current paper, essentially because of the lack of reliable OPEX data on operating large-scale electrolyser systems, we will only concentrate on their CAPEX. Moreover, the projected production cost of electrolytic H2 today is dominated by the cost of electricity [9], which can therefore still be considered to be the dominant OPEX parameter.

Rather recently, literature studies have been dedicated to summarizing both historical trends [10] and short- and long-term projections [11] of investment cost (CAPEX) and performance data for two of the most common water electrolyser technologies being used today, namely alkaline and Proton Exchange Membrane (PEM) systems. However, such literature reports are often only able to generate a relatively wide range of CAPEX data, depending on the exact performance (e.g. input power) of the system being considered. For instance, Figure 32 summarizes CAPEX data from the available literature reports reviewed in Ref. [10]. It can be observed that the spread of the CAPEX estimations in the 1990s was in the range 870–2350 Euro/kW and 310–4750 Euro/kW for alkaline and PEM technology, respectively. At the same time, estimations for the future investment costs by the year 2030 are reported to be in the range 790–910 Euro/kW and 400–960 Euro/kW, respectively.
specific task force was asked to collect techno-economical data on commercially available water electrolyser systems directly from the major electrolyser manufacturers involved in the Task 38 effort.

Results & discussion

Comparing CAPEX for electrolytic and SMR H₂ production systems:

As a starting point, Figure 33 (re-)considers published data [12], [13] already available from the previous IEA/HIA Task 33 on Local hydrogen production for energy applications (2013–2015), this task being itself a continuation of both Task 23 on Small scale reformers for on-site hydrogen supply (2006–2011) and Annex 16 Subtask C on Small stationary reformers for distributed hydrogen production (2002–2005). Figure 33 shows the actual CAPEX evolution of PEM electrolyser systems, both as a function of H₂ production capacity (in Nm³/hr, Figure 33a) and as a function of the equivalent electrolyser power input (in kW, Figure 33b). The latter graph was derived from the first one, based on data collected separately from the PEM electrolyser manufacturers on the specific electrical energy consumption (in kWh/Nm³ H₂). The latter is today still considered to be the most mature and durable technology, especially for large-scale and long-term renewable H₂ production [1]. Such a comparison of CAPEX data for both PEM and alkaline electrolysers is shown in Figure 34, again as a function of the overall energy consumption of the hydrogen plant. The latter was explicitly verified with the electrolyser manufacturers to include the following components:

Figures 33

CAPEX data for PEM electrolysers, collected from Task 33 [12], [13], as a function of H₂ production capacity (a) and replotted as a function of equivalent power input (b). The conversion factor corresponds to specific electrical energy consumption of 5.2 kWh/Nm³ (c). The latter figure also represents the number of cells/stack needed to comply with a given input power in the range 7–700 kW.
On the other hand, it should be noted that in the above CAPEX estimations, life cycle issues of electrolysers and electrodes have not been taken into account. Clearly, with the durability aspect of alkaline stacks currently still very much in favour in current state-of-the-art alkaline vs. PEM technologies, including such lifetime (and hence OPEX) aspects in the calculation can be expected to somewhat flatten out the projected difference in CAPEX reduction between alkaline and PEM for multi-stack systems.

Moreover, in absolute terms, CAPEX values as low as 400 Euro/kW are currently projected by NEL for alkaline systems when scaling up to 100 MW. The latter is based on an intelligent engineering design of a 40-stack system. Moreover, the manufacturer also claims that it would be very feasible to deliver hydrogen at 100 bar for more or less the same CAPEX value as the hydrogen pressure of 15 bar considered as default for alkaline systems in Figure 34, Figure 35. This would significantly improve their Power-to-Gas and energy storage business cases, where high pressures are indeed required.

**Impact of CAPEX on electrolytic H2 price settings**

Apart from the intrinsic quantitative merit of the above alkaline and PEM electrolyser CAPEX data as such, a major additional asset is that they also allow for a better fine-tuning of projections and simulations regarding price settings for electrolytic (i.e. renewable) H2. In this respect, some simulations from the literature have been reproduced from Ref. [15] in Table 6, representing a number of relevant production scenario’s. This Table, dating back from 2015 and therefore overestimating currenty available CAPEX...
values, can still be taken as a useful relative starting point to identify the main additional operational parameters for setting a realistic H₂ price. These include, besides electrolyser CAPEX, also electrolyser efficiency, annual operating hours and (renewable) electricity cost. Despite the discrete character of the simulations and the lack of elementary definitions and explanations in Ref. [15], some general relative trends can still be distinguished from the at first sight rather arbitrary parameter combinations. First of all, considering scenario’s 5 and 2, it appears that, at a fixed (overestimated) CAPEX of 800 Euro/kW and for a renewable electricity cost on the order of 60–70 Euro/MWh, an electrolytic H₂ production cost on the order of 4 Euro/kg is obtained. However, this still requires that the electrolyser can be kept operational for a sufficient amount of time (assumed 7000/8760 = 80% on a yearly basis in scenario 5), which seems as of today not very feasible in view of the relatively weak penetration of H₂ for P2G storage purposes. When the electrolyser "up-time" further decreases to 20% (or 2000 hrs/year, cfr. scenario 2), the electrolytic H₂ production cost goes up to about 6 Euro/kg. This is clearly not sufficiently competitive, except maybe for H₂ mobility applications [16]. Moreover, if at about the same conditions as scenario 2 the electricity price would double to 140 Euro/MWh (cfr. scenario 3), the electrolytic H₂ production cost reaches totally unacceptable levels of more than 12 Euro/kg. It appears that in this range of relatively low operational time (<2000 hrs/year), even a zero renewable electricity cost would still result in unacceptable H₂ prices > 10 Euro/kg (cfr. scenario 4).

From Table 6, it is obvious that the expected annual operating hours clearly is a critical parameter to consider for electrolytic H₂ cost projections. Therefore, it makes much more sense to represent its effect on a continuous rather than a discrete scale. Recent examples from the literature are given in Figure 36 [17, 18] and Figure 37 [19] for different CAPEX and renewable electricity prices, respectively. For these simulations, the electrolyser efficiency was kept constant at about 70–80%, which appears to be the limiting value that is being accepted for future electrolyser generations as well [11]. As to the effect of electrolyser CAPEX, both Figure 36 [17] and Figure 37 [19] quantitatively confirm one of the major conclusions from Table 6, namely that for an insufficient electrolyser up-time (<2000 hrs/year), the cost of electrolytic H₂ increases very steeply. Moreover, for an assumed renewable electricity price of 70 Euro/MWh, Figure 36 a and Table 6 also appear to be quantitatively coherent in terms of H₂ price for a CAPEX of 2000 Euro/kW (scenario 1) and 1000 Euro/kW (scenario 2), respectively. In Figure 36 b, reproduced from a more recent study [18], a further refinement of price simulations is provided for CAPEX values closer to today’s technological reality. This particular study also takes into account more refined assumptions for the (average) electricity price, based on so-called power price duration curves. The latter have been included between brackets.
Figure 37
Electrolytic H₂ production cost (in USD/kg) as a function of electrolyser operational time (FLH = full load hours) for different renewable electricity costs (in USD/MWh), reproduced from Ref. [19]. Further assumptions are an electrolyser CAPEX of 450 USD/kW, a lifetime 30 years, and a system efficiency of 70%. The cost of hydrogen from SMR (purple area) was estimated at 1–3 USD/kg, depending on regional variations in natural gas prices. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

For this combination of onshore wind power and solar PV electricity, the associated load factor will hardly be above 4500 full load hours (FLH), which brings the average electrolytic H₂ production cost to 3–4 USD/kg.

Secondly, at times of excess electricity production from renewables, the market price of electricity can become very low. Assuming a zero renewable electricity price (cfr. blue line in Figure 37), it can be seen that the cost of electrolytic hydrogen becomes very dependent on the electrolyser load factor. For instance, if the relevant load factor which may take benefit from such free (“dumped”) electricity is in the range of 1000 FLH, electrolytic hydrogen can still become very competitive, at a production cost of less than 2 USD/kg. However, since such small load factors generally also entail a smaller scale electrolyser, its CAPEX will be significantly higher than the 450 USD/kW assumed in Figure 37. In that case, as already shown in Table 1 (cfr. scenario 4), load factor uncertainties can make such an investment quite risky.

Thirdly, a combination of high load factors under the CAPEX values corresponding to the different curves. These results indicate that already at current CAPEX values of 700 Euro/kW (considered to be realistic as of today for a 2 MW alkaline electrolyser, cfr. Figure 34), an electrolytic H₂ production cost below 4 Euro/kg can be obtained once an electrolyser uptime >20% can be guaranteed. Moreover, this cost further decreases to 3 Euro/kg upon a further decrease in CAPEX towards 400 Euro/kW.

Finally, results from a relatively recent IEA study [19], reproduced in Figure 37, allow to anticipate a further evolution in H₂ production cost as a function of the available renewable electricity price, assuming the most favourable (but still realistic) CAPEX value of 450 USD/kW. Note that in Ref. [19], the default currency was USD, which still entails some uncertainty when comparing to the above CAPEX or H₂ prices expressed in Euro. Three different cases have been considered. Firstly, in countries with good but not excellent solar and wind resources, the cost of electricity can be assumed to be about USD 60 per MWh (cfr. red line in Figure 37).

For PEM, such CAPEX values come within reach for 5 MW systems, requiring multi-stack systems;

a CAPEX values on the order of 400 Euro/kW have been projected for alkaline systems, but this will require further upscaling up to 100 MW;

from the state-of-the-art CAPEX data collected, an electrolytic H₂ production cost on the order of 3 Euro/kg is very realistic by 2020, very much comparable to SMR H₂.

Acknowledgements
Participation of J.P. to the IEA/HIA Task 38 and the IEA/HIA ExCo is supported by the Public Service of Wallonia – Dept. of Energy and Sustainable Building. We would also like to cordially thank Eric Dabe from NEL and Lucas Bertrand and Marcus Newborough from ITM Power for sharing their CAPEX data within the Task 38 effort.

Conclusions
At this stage of the IEA/HIA Task 38 effort, the following major conclusions have been reached:

for PEM, such CAPEX values come within reach for 5 MW systems, requiring multi-stack systems;

a CAPEX values on the order of 400 Euro/kW have been projected for alkaline systems, but this will require further upscaling up to 100 MW;

from the state-of-the-art CAPEX data collected, an electrolytic H₂ production cost on the order of 3 Euro/kg is very realistic by 2020, very much comparable to SMR H₂.

(REFERENCE)
REFERENCES


CHAPTER IV
Part 3: Task Force Electrolyser Data
Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen

AUTHOR
Joris Proost.
AFFILIATION
Université catholique de Louvain, Louvain-la-Neuve, Belgium

Abstract
Hydrogen produced from renewable electricity through Power-to-Hydrogen can facilitate the integration of high levels of variable renewable electricity into the energy system. An electrolyser is a device that splits water into hydrogen and oxygen using electricity. When electricity is produced from renewable energy sources, electrolytic hydrogen can be considered to be green. At the same time, electrolysers can help integrate renewable electricity into power systems, as their electricity consumption can be adjusted to follow wind and solar power generation. Green hydrogen then also becomes a carrier for renewable electricity. Key green hydrogen production technologies, mostly PEM and alkaline electrolysers, are still further maturing, both in technical efficiency, economical (CAPEX) and durability (lifetime) performance. Nonetheless, we will show in this contribution how fossil parity for green hydrogen, i.e. a Total Cost of Ownership (TCO) similar to grey H2 coming from today's CO2 intensive SMR processes, can already be achieved today. Moreover, this can be realised at a scale which corresponds to the basic units of renewable electricity generation, i.e. a few MW.

Keywords
Power-to-hydrogen
Electrolyser
Renewable electricity
Fossil parity

Introduction
The global energy system has to undergo a profound transformation to achieve the targets of the Paris Agreement. In this context, low-carbon electricity from renewables may become the preferred energy carrier. The share of renewable electricity in all of the energy consumed by end-users worldwide would need to increase to 40% in 2050 (from about 4% in 2015) to achieve the decarbonisation energy world envisaged by the agreement [1]. In absolute terms, this implies that the total installed renewable power capacity should increase from about 1.500 GW in 2015 to more than 15.000 GW in 2050, i.e. a 10-fold increase [2]. However, the total decarbonisation of certain sectors, such as transport, industry and applications that require high-grade heat, may be difficult purely by means of electrification. This challenge could be addressed by green hydrogen produced electrochemically from renewables (so-called Power-to-Hydrogen or P2H [3]), allowing large amounts of renewable electricity to be channelled from the power sector into these end-use sectors [4]. Renewable electricity can be used to produce green hydrogen via water electrolysis, a well-known process splitting acidified or alkalised water into ultrapure (up to 99.998%) H2 and O2 [5]. Such electrolytic H2 can then further be used downstream as a green and clean chemical feedstock material in sectors otherwise difficult to decarbonise through electrification. The latter includes both the chemical industry itself, as well as new applications in the transport sector [6]. As to the first, hydrogen is currently already widely used in several industrial sectors (refineries, ammonia production, bulk chemicals, etc.), with the majority of it being produced from natural gas by means of steam methane reforming (SMR), a vast CO2-intensive process [7]. Green hydrogen from renewables could replace such fossil fuel-based feedstocks in high-emission applications. For the transport sector, fuel cell electric vehicles (mainly cars and buses) provide already today an attractive low-carbon mobility option when the hydrogen is produced from renewable energy sources and offer driving performances comparable to conventional vehicles. On the longer run, H2-based electrofuels, i.e. liquid fuels produced from renewable power, can also replace fossil fuels in the freight sector (including aviation and heavy-duty rail and trucks), without the need to change end-use technologies [8].

Although water electrolysis is already a well-established H2 production technology for almost a century [9], its large-scale implementation for the production of green H2 has been hampered mainly by cost issues. In a recent review [10], the production cost of hydrogen from electrolysis has been extracted from a large amount of literature data, resulting in a very wide range of cost values, ranging from about 2 €/kg to 20 €/kg. This was attributed to the large variability of the underlying assumptions and working parameters of the different sources, the production scale being the most important one [11]. Moreover, when evaluating the potential and economic viability of such green hydrogen production by water electrolysis, it is current price of fossil SMR-based H2 often appears as a rather challenging benchmark [12]. For a fair comparison though, it was recently pointed out [13] that one should always keep in mind that the industrial SMR production price is usually considered for immediate use, while often additional storage is necessary to meet fluctuations in demand and delivery as well. On top of that, hydrogen from SMR still needs to be purified for most applications in order to reach the same grade as electrolytic one. Moreover, in such cost comparisons, the potential valorisation of ultra-pure electrolytic oxygen (8 kg for each kg of H2) is totally neglected. In any case, on a macro-economical level, according to Ref. [14], the global hydrogen feedstock market represented in 2015 a total estimated value of 115 billion €, corresponding to a hydrogen demand of about 56 Mt/yr. By dividing the total estimated market value by the total worldwide hydrogen demand at the same year, a reasonable first-order estimation of the “average” market price for fossil H2 can then be obtained as 115/56 = 2,0 €/kg. In the current paper, we aim at critically assessing the production scale that would be required to reach such fossil parity using electrolytic hydrogen. While doing so, it is important to acknowledge that significant regional differences may...
still exist on a micro-economical level. This is not only due to geographical variations in the production price of SMR H2, but also depending on the availability of sufficient and low-cost renewable electricity. It is for instance well-known that the production cost of hydrogen from SMR is significantly influenced by natural gas prices, which account for 45%-75% of the total SMR production cost. As a result, the low gas prices in the Middle East, the Russian Federation, and North America give rise to some of the lowest hydrogen SMR production costs, sometimes even down to 1.5 €/kg [15]. On the other hand, gas importers such as Japan, Korea, China and India have to contend with higher gas import prices, which inevitably results in higher hydrogen production costs. As a result, it will be much more feasible for electrolytic hydrogen produced from renewable electricity to compete effectively with SMR in countries relying on natural gas imports and characterised by good renewable resources.

Hydrogen production
Hydrogen production today
As of today, hydrogen is being used as a specialty chemical in a number of applications. These are generally classified into 4 main categories [14], as illustrated in Table 1:

1. the chemical industry, where H2 is a basic building block for the synthesis of ammonia, methanol and a number of technical polymers;
2. a number of downstream refining processes, like hydro-cracking and hydro-treating;
3. iron, steel and glass manufacturing, where H2 is the preferred reducing gas during annealing, blanketing and forming processes;
4. other specialty applications, like the semiconductor industry, the use as a propellant fuel or the cooling of generators. The first two categories represent with 65% by far the largest contribution to the total H2 demand, followed by refining, iron, steel and glass manufacturing (altogether about 25%) and the remaining 10% for the other specialty applications.

An important difference between each of these 4 categories is the scale of the so-called unit process or production size, i.e. the typical individual plant or reactor capacity required to generate the appropriate amount of H2 feedstock in each application. Table 7 gives in this respect some indicative numbers (in Nm³/h of H2 demand) for each of these 4 categories. In its last column, it also provides the equivalent electrolyser capacity that would be required to satisfy these unit size H2 feedstock demands by on-site electrolytic H2 production (assuming a state-of-the-art electrolyser efficiency of 70% [16], corresponding to a renewable electricity need of 47.1 kWh/kg H2). Large variations in production scale can be noticed across the different sectors, ranging from about 250 kW at the low-end (typical for float glass production) to a few GW at the high-end (typical for H2 demand in refineries).

As of today, the great majority of all of the above H2 is being delivered by a centralised, off-site hydrogen production, dominated by large-scale chemical processes: steam methane reforming (SMR) and coal gasification. According to Ref. [15], these processes made up about 76% and 23% respectively of the total H2 production in 2018. Unfortunately, as shown in Figure 38, both of these processes are heavily CO2 intensive, SMR emitting up to 8 tons of CO2 per ton of H2 produced. Therefore, to reach the CO2 emission targets in today’s fossil-based H2 production, the part of green electrolytic hydrogen production from renewable electricity (which represents less than 4% today) can be expected to significantly increase over the coming years. To meet the current global H2 demand of around 70 Mton/year, a total of 200 GW installed electrolyser capacity would be required. This is some 15% of the total global power capacity. The 60% of today’s electricity production is produced from renewable sources, which is a remarkable achievement. However, further efforts are needed to significantly increase this share.

Table 7
Today’s major industrial sectors using H2. For each sector, a typical unit plant size is given (in Nm³/h demand), as well as the corresponding equivalent electrolyser power.

<table>
<thead>
<tr>
<th>Industry Sector</th>
<th>Key Applications</th>
<th>Unit plant size (in Nm³/h demand)</th>
<th>Equivalent electrolyser power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td>Ammonia (NH₃)</td>
<td>80.000</td>
<td>400 MW</td>
</tr>
<tr>
<td></td>
<td>Methanol (CH₃OH)</td>
<td>10.000</td>
<td>50 MW</td>
</tr>
<tr>
<td>Refining</td>
<td>Hydrocracking</td>
<td>400.000</td>
<td>2.000 MW</td>
</tr>
<tr>
<td></td>
<td>Hydro-treating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>Annealing</td>
<td>400</td>
<td>2 MW</td>
</tr>
<tr>
<td></td>
<td>Blanketing gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forming gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>Semiconductor</td>
<td>50</td>
<td>0.25 MW</td>
</tr>
<tr>
<td></td>
<td>Float glass production</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Propellant fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cooling of generators</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 38
Summary of today’s main hydrogen production technologies.

1. Steam methane reforming (SMR)

\[
\text{CH}_4 + 2\text{H}_2\text{O} \rightarrow 4\text{H}_2 + \text{CO}_2 \text{(8 tons/ton H}_2\text{)}
\]

2. Coal (oil) gasification

\[
2\text{C} + \text{O}_2 + 2\text{H}_2 \rightarrow 2\text{H}_2 + \text{CO}_2
\]

3. Water electrolysis: 2H₂O → 2H₂ + O₂

Electrolyser efficiency 70% → 47.1 kWh/kg H₂

60 Mton/year requires ~ 300 GW installed RE ~ 20% of total RE today ~ 2% of total RE by 2050

60 Mton/year, a total of 300 GW installed electrolyser capacity would be needed. As this represents today about 20% of the total installed renewable power capacity, such massive electrolyser deployment is currently not very realistic. As a result, a selection of technologically feasible market penetrations for electrolytic H2 needs to be made. Such selection also implies that today’s local H2 consumers, besides becoming local (on-site) producers of renewable electricity, also need to become local (on-site) producers of electrolytic H2, at a production scale which still allows meeting the stringent requirement of fossil parity at about 2.0 €/kg. On the longer run, with the projected 10-fold increase in renewable power to 15.000 GW in 2050, a mere 2% use of this capacity would be required to satisfy the equivalent 300 GW water electrolysis demand. This
Green hydrogen production scale-up

Contrary to the intrinsically large-scale SMR, water electrolysis is intrinsically small-scale, as illustrated in Figure 39. Both the geometrical area of the electrodes (a few m² at most) and the number of electrodes that can be compiled in series in a single stack is relatively limited. As a result, the unit size of water electrolyzers has long been limited to the kW-range, a typical on-site containerized production unit being a few 100 kW at most. However, in order to be able to realise the mandatory coupling to renewables, mainly wind and solar, the power scale of water electrolyzers needs to become of the same order of magnitude as the renewable electricity source itself. As illustrated in Figure 40 (reproduced from Ref. [17]), this requires a major scale-up from the kW-scale, typical for state-of-the-art electrolyzers about a decade ago, towards the multi-MW scale typical for state-of-the-art on-shore wind turbines today. Figure 40 also shows that this mandatory scale-up has the potential to significantly reduce the investment cost (CAPEX) of electrolyzers, potentially reaching the same order of magnitude as small-scale SMR installations from the MW-level onwards. Figure 40. Projected cost reduction associated with a scale-up of green electrolytic hydrogen production. The blue diamonds represent real CAPEX data for PEM electrolysers, except for the ones between 100 and 1000 Nm³/hr, which are cost projections. The red squares and green triangles are real SMR CAPEX data for small-scale (on-site) and large-scale (centralised) reformers, respectively. Taken from Refs. [17]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Such an electrolyser scale-up has initially been realised by increasing the number of cells per stack, as illustrated in Figure 39. However, from the state-of-the-art data that we recently collected from several electrolyser manufacturers, such a “keep-on-stacking” approach seems to have a practical limit at around 100 cells/stack [18]. Beyond that number, other balance-of-plant issues come into play, including the risk of electrical shorts [19] and the technological complexity of a safe large-scale gas collection [20]. There are also a number of specific issues related to electrochemical reactor design, like the increased risk of a non-homogenous electrolyte distribution when pumped through a larger stack [21], and a non-homogeneous current distribution within the different cells [22]. Note that this apparent 100-cell limitation is by no means a stringent intrinsic limitation, but rather an empirical observation based on the above-cited industrial data. In other words, it appears that for a number of electrochemical and/or technical reasons, electrolyser manufacturers are currently limited to a few 100 cells/stack.

The above-suggested transformation from centralised (off-site) fossil-based H₂ production to a decentralised (on-site) green electrolytic H₂ production provides a significant paradigm shift, allowing local consumers to become local producers as well. Up to now, in an industry largely governed by CO₂-intensive chemical processes, such a local H₂ production in line with the local H₂ consumption was simply not feasible, because of the minimum production scale required for both SMR and coal or oil gasification. The latter typically starts at a few 10,000 Nm³/hr (about 8000 ton/yr) for the smallest unit size installations, equivalent to a 50 MW electrolyser. As can be seen in Table 7, this largely exceeds the industry needs in a general industry. Moreover, additional CO₂-intensive logistics (ind. Transport, compression and storage) are required in these applications as well.

Can be considered to be within the range of grid balancing services, making such green electrolytic hydrogen production on the long run an even more viable and attractive alternative hydrogen production technology.
Figure 41 Examples of multi-stack alkaline electrolyser systems: (a) A 135 MW electrolyser plant from 1953 [23]; (b) Current multi-MW plant designs from a major electrolyser manufacturer, based on a single stack electrolyser capacity of 2.2 MW [24].

Figure 42 Electrolytic H₂ production cost as a function of electrolyser’s annual operating time (1 yr = 8760 h), simulated according to Eq. (1) for two different CAPEX/electricity cost combinations. The electrolyser’s efficiency was fixed at 70%, corresponding to 47.1 kWh/kg. The additional dashed trendlines for the 2 data sets include, besides the electricity cost, also an additional fixed OPEX cost equal to 30% of CAPEX.
numbers [27]. During its initial testing phase, when operation time was limited to 8 h during working days, the electrolyser load demand curve led to an average electricity cost (as purchased from the EPEX SPOT day-ahead auction market) of about 36 €/MWh. After full automation of the plant to a 24/7 operation so that electricity could be bought in times of low spot prices, additional cost savings of more than 15 €/MWh could be realised.

Secondly, as to the electrolyser CAPEX, Figure 44 shows state-of-the-art data from NEL, one of the world’s largest alkaline electrolyser manufacturers. They clearly show a significant decrease well below the value of 1000 €/kW used for the red data set in Figure 42. In particular, a CAPEX value of 750 €/kW, considered by utility providers to be the capital cost for storing renewable electricity, is already realistic today for a single stack 2 MW system. Moreover, a significant further reduction in CAPEX as low as 500 €/kW is projected for multi-stack systems when scaling up to 50–100 MW. Also, note from Figure 44 that single stack electrolysers are much more susceptible to CAPEX reduction than multi-stack systems when upscaled.

Based on the above-updated numbers, the green data set in Figure 42 then allows to anticipate a significant reduction in the electrolytic H2 production cost. Indeed, assuming the most favourable but still realistic CAPEX value of 500 €/kW in combination with an electricity cost of 30 €/MWh and a state-of-the-art electrolyser efficiency of 70% (i.e. 47.1 kWh/kg), green electrolytic H2 can indeed start competing with SMR from 4500 operating hours onwards (i.e. a load factor of about 50%). Note that under these conditions, the total H2 cost calculated from Eq. (1) comes down to 1.41 €/kg and is mainly determined by the electricity cost, which represents 47.1* 0.03 = 1.41 €/kg. The right axis gives the resulting % contribution of the electrolyser CAPEX to the total H2 cost; (b) Renewable electricity price (in €/MWh) as a function of electrolyser efficiency to arrive at an electrolytic H2 cost of 2.0 €/kg for three different CAPEX values (500, 1000 and 2800 €/kW).

Secondly, as to the electrolyser CAPEX, Figure 44 shows state-of-the-art data from NEL, one of the world’s largest alkaline electrolyser manufacturers. They clearly show a significant decrease well below the value of 1000 €/kW used for the red data set in Figure 42. In particular, a CAPEX value of 750 €/kW, considered by utility providers to be the capital cost for storing renewable electricity, is already realistic today for a single stack 2 MW system. Moreover, a significant further reduction in CAPEX as low as 500 €/kW is projected for multi-stack systems when scaling up to 50–100 MW. Also, note from Figure 44 that single stack electrolysers are much more susceptible to CAPEX reduction than multi-stack systems when upscaled.

Based on the above-updated numbers, the green data set in Figure 42 then allows to anticipate a significant reduction in the electrolytic H2 production cost. Indeed, assuming the most favourable but still realistic CAPEX value of 500 €/kW in combination with an electricity cost of 30 €/MWh and a state-of-the-art electrolyser efficiency of 70% (i.e. 47.1 kWh/kg), green electrolytic H2 can indeed start competing with SMR from 4500 operating hours onwards (i.e. a load factor of about 50%). Note that under these conditions, the total H2 cost calculated from Eq. (1) comes down to 1.95 €/kg and is mainly determined by the electricity cost, which represents 47.1* 0.03 = 1.41 €/kg or 72%. One should therefore be aware that any efforts to further reduce the CAPEX of alkaline water electrolysers below 500 €/kW will only have a minor overall effect. For instance, for a CAPEX of 250 €/kW, Figure 45a shows that the total H2 cost goes down to 1.68 €/kg, of which only 15% would come from the very stringent techno-economical
Figure 46

Total Cost of Ownership (TCO) of electrolytic H₂ (delivered at 35 bar) as a function of power input, obtained from the Danish electrolyser manufacturer GreenHydrogen.

**Figure 46**

Total Cost of Ownership (TCO) of electrolytic H₂ (delivered at 35 bar) as a function of power input, obtained from the Danish electrolyser manufacturer GreenHydrogen. The data is presented in Figure 46b, showing that the TCO decreases as the power input increases. The minimum TCO is achieved at a power input of about 50 MW, where the cost is approximately 40 €/MWh.

The scale of fossil parity for green hydrogen

A final issue then relates to the production scale that is required for obtaining such fossil parity with electrolytic H₂. Indeed, from the data in Figure 44, one could wrongly conclude that reaching the required reduction in electrolyser CAPEX down to 500 €/kW would require very large-scale electrolytic H₂ production units, on the order of 100 MW. In that case, the minimum scale for economically viable electrolytic H₂ production would need to become similar to current SMR installations (cfr. Figure 40). As already suggested from Table 1, for some feedstock applications, like ammonia or methanol production, such a large unit size can be relevant even for an on-site, decentralised green H₂ production. However, Figure 44 indicates that there might still be a much smaller production scale for reaching such low CAPEX values. Indeed, when extrapolating the CAPEX data of single-stack alkaline electrolysers in Figure 44, the level of 500 €/kW (dashed horizontal green line) can already be reached around 3–4 MW. Such a significant reduction in the scale required for fossil parity is directly related to the much steeper reduction in CAPEX that can be realised for single-stack as compared to multi-stack systems. A straightforward consequence of the above observation is that the minimum investment cost needed to install electrolytic hydrogen production units capable of delivering green H₂ at fossil parity goes down significantly as well: from about 100·10³*500 = 50 M€ to a mere 200 k€, a very realistic number in view of local, decentralised production.

Even more direct corroborating evidence for this relatively small-scale fossil parity for green electrolytic H₂ is provided in Figure 46. The latter presents state-of-the-art industrial data for the Total Cost of Ownership (TCO) of electrolytic H₂ as a function of power input, as obtained from GreenHydrogen, a Danish electrolyser manufacturer who produces pressurized stacks. Values are based on a 10-year operation, including a 10 years’ service and maintenance agreement, for a complete turnkey, containerized alkaline electrolyzer unit (including inverter and water treatment), delivered and installed in Europe. The electrolyser power consumption is guaranteed.
at 46.7 kW/kg and delivers H₂ at 35 bars. The hydrogen production cost in Figure 46 also takes into account the OPEX part, including the use of water, nitrogen (for purge) and electricity, assuming a renewable electricity price of 40 and 45 €/MWh, respectively. A number of striking observations can be made from this figure. First of all, these TCO data confirm the trend already observed in Figure 44, namely the much steeper decrease in unit price for hydrogen delivered from a single-stack vs. a multi-stack system. Secondly, until now, it was commonly agreed that the only option to decrease the electrolytic H₂ production cost towards fossil parity was to increase the capacity of the (multi-stack) system up to 50–100 MW, as already discussed with Figure 44. Figure 46 now clearly shows that in that case, even a decrease in renewable electricity cost (from 45 to 40 €/MWh) only slightly affects the scale of fossil parity, due to the relatively small decrease in TCO with power typical for such multi-stack systems. As a result, large-scale electrolyser systems would still be necessary to reach fossil parity. However, as suggested by the dashed red line in Figure 46 through the TCO data for single stack systems, there is another technological alternative. It consists of extending the power input that can be taken up by a single stack electrolyser up to a few MW, the exact power depending on the electrolyser technical characteristics. This then also corresponds to the scale of the basic units of renewable electricity generation. Also note that when considering an even more stringent SMR price level of 1.5 €/kg (corresponding in Figure 46 to the horizontal axis rather than the dashed green line at 2.0 €/kg), our conclusions on the required scale for reaching fossil parity do not fundamentally change. Indeed, in that case, extrapolation of the single-stack TCO data would arrive at 3 MW, instead of 1.5 MW for 2.0 €/kg. Note that at this stage, there is not really a rigorous scientific reasoning behind the single-stack cost line extrapolations in Figure 44, Figure 46 it is a mere empirical observation, but still a rather reliable one since based on two independent industrial data sets over a relatively large power scale. It is also important to realise that the obtained extrapolated single-stack power for fossil parity is not a unique number, but something that is specific to each stack geometry (e.g. the number and area of electrodes used). For instance, the Norwegian HydrogenPro already has a 3.7 MW single-stack alkaline electrolyser on the market, while the Belgian-Chinese Cockerill Jingle Hydrogen even sells 7.5 MW single-stacks, to the best of our knowledge the largest single-stack on the market. The challenge on the electrolyser level is then to try to technologically implement this single-stack extrapolation in order to arrive at higher single-stack power levels. As the number of cells/stack seems to have reached its limit [18], an alternative option is to increase the specific area of each individual electrode, e.g. by replacing classical 2-D plates by 3-D foams [29-30] hence allowing for a higher current density operation [31]. Incidentally, a recent European demonstration project (Demo4Grid) showing the technical feasibility and greening potential of a single-stack 4 MW alkaline electrolyser has been launched in that sense [32]. Such small-scale fossil parity has the important advantage of allowing a decentralised local H₂ production. Renewables can then be harvested anywhere and used directly for the local production and consumption of green electrolytic hydrogen. This will not only allow to open up today’s market to electrolytic H₂ in a number of small unit scale segments (like iron & steel and glass manufacturing, cfr. Table 1) but also widen the use of green electrolytic H₂ to a number of new small-scale markets (like the food industry targeted in Ref. [32]). This is a significant paradigm shift with respect to the current large-scale fossil fuels (SMR) based centralised hydrogen production, the latter also requiring an additional cost to transport the H₂ both in terms of €/kg and CO₂ footprint.

Conclusion

In this paper, we have addressed the question of what would be an economically viable (minimum) production scale for green hydrogen, produced from water electrolysis using renewable electricity. A realistic benchmark to do so is the current price of grey hydrogen produced by fossil-based and thus CO₂ intensive processes (the so-called fossil parity), currently estimated at 2.0 €/kg. Firstly, we acknowledged the promising market opportunities for such green hydrogen in today’s H₂ markets. The latter represents about 60 Mt/yr and can be classified in 4 major applications, all of them having their own typical unit size in terms of equivalent H₂ demand, ranging from a few hundreds of kW up to several GW. Secondly, it was shown how based on current state-of-the-art CAPEX data for today’s multi-stack electrolysers and using a renewable electricity price of 30 €/MWh, such fossil parity can be reached already today at 50–100 MW. This is about the same scale as the smallest SMR installations. Finally, using the most recent TCO values for electrolytic hydrogen, it was concluded that fossil parity could potentially also be reached at a much smaller production scale, on the order of a few MW. Although this still requires a further intensification of the water electrolysis process, e.g. by extending the power range of a single-stack electrolyser, such small-scale fossil parity provides an important paradigm shift. Indeed, for the current, large-scale fossil fuels (SMR) based centralised hydrogen production, it has the important advantage of allowing a decentralised local H₂ production. Renewables can then be harvested anywhere and used directly for the local production and consumption of green electrolytic hydrogen, in line with the small-scale local H₂ demand.

Acknowledgements

We cordially thank Eric Dane from NEL and Henrik Steen Pedersen from Greenhydrogen for providing their state-of-the-art CAPEX and TCO data on electrolytic hydrogen. This paper was realised within the framework of the Hydrogen Technology Collaboration Programme (TCP) of the International Energy Agency (IEA), more specifically Task 38 on Power-to-Hydrogen. It also benefited from a number of insightful discussions with Uwe Remme and Cédric Philibert at the IEA’s Energy Technology Policy Division and the Renewable Energy Division, respectively. Finally, financial support from the Public Service of Wallonia – Dept. Of Energy and Sustainable Building is gratefully acknowledged for allowing these fruitful interactions with the IEA.
REFERENCES


CHAPTER IV
Part 4: Task Force Security Services
Power to hydrogen’s role in ancillary markets of power networks

Introduction
To set up the context for this Chapter, it is necessary to distinguish at the outset between the following two distinct electricity system operation markets:
1) Two-way electrical energy commodity trading (EECT)
2) Electricity system security markets (ESSM)

The second, ESSM, is also designated as ancillary markets. Like most terms, this can mean subtly different things to different people. Here we use it in the broadest (dictionary definition) sense: markets that provide support to the primary market (electrical energy commodity trading).

Electrical energy commodity trading (EECT)
The notion of soaking up “excess variable renewable energy (VRE)” using power to hydrogen is well known and is discussed in other parts of this Final Report. This includes “power to gas”: power to hydrogen to injection into natural-gas networks. This is part of EECT (buying or selling electricity) and does provide support to EECT. Other sometimes ill-defined concepts include “demand response”. This term was originally coined to refer to very large consumers being willing to drop out of the consumption market during rare but high-power price periods resulting from conventional demand approaching current supply availability. In contrast, power to hydrogen’s primary role in EECT will be buying low-cost power during periods otherwise low demand, far more than “not buying” during a period of high demand. Prospective power to hydrogen participation in EECT markets in terms of response times is graphically outlined in Figure 47.

Further, electricity market operation rules for supporting two-way markets are now emerging, whereby electricity producers will continue to bid to supply, but will soon do so concurrently with electricity consumers bidding for consumption. That is, the choice of whether or not to consume power to produce hydrogen, and if so, how much power, will soon be made based on price bids (willingness to pay) submitted to the operator every 5 minutes. This is expected to yield Certifiable clean hydrogen as a result of the increasingly clear, inverse relationship between (VRE - conventional demand) and price: When VRE production increases concurrently with conventional demand decreasing, the power price decreases. This is graphically outlined in Figure 48 to Figure 53.

[Adapted from Figure 30 “Benefits of participation from price elastic demand and supply” of [1]. Quoting from page 91 of [1]: “The two-sided market work specifically promotes the effective uptake and utilization of DER and demand response by: Establishing a framework for the trading of ‘services’ in the market as opposed to asset-level obligations and performance requirements — supporting higher levels of flexible capacity and facilitating innovation in services for consumers.”]

In conclusion, the techno-economics modelling of the input-electricity cost of emerging participation of power to hydrogen can be founded quite simply on bottom-up purchase-price bidding in consumption price markets every 5 minutes.

This is independent of the following electricity system security markets (markets for...
Figure 48
Profiles of the increasing frequency of below-average-demand prices in the SA Region of Australia’s NEM

Figure 49
Numerics of the three demand price relationships in Figure 48

Figure 50
Profiles of the increasing production over a decade in the SA Region of Australia’s NEM

Figure 51
Profiles of the effect of VRE on prices in the SA Region of Australia’s NEM

*(Demand - Wind - Curtailment - Solar)* duration / average price curves* for SA; with % VRE Production / Demand. All plots graphically clipped to below average scaled offset demand *dmwcs

Load duration / average price curves* for SA: 3X4 - year periods; graphically clipped to below average scaled offset demand.
ancillary services). All other concepts that are otherwise described as “generic energy balancing services to the grid” fall into the above electricity energy commodity trading framework in a very natural way.

**Electricity system security markets (ESSM / Markets for ancillary services)**

In contrast to frameworks reviewed in the previous section, system security markets are needed to provide products and services that keep the crucial parameters of electricity network within ranges required to “keep the lights on”. By “keeping the lights on” we’re not referring to the ongoing availability of generation. Rather we’re referring keeping the system as a whole up and running despite the risk of instantaneous failures of major components such as transmission lines collapsing under the weight of an ice-storm or sudden down-burst storms, or the unexpected unplanned dropout of a large-scale generator, and so on. ESSM, in general, is about much more than just frequency control in particular, but this particular power systems parameter provides a useful starting point for distinguishing between EECT and ESSM, as graphically outlined in Figure 55.

Note that Figure 47 and Figure 56 allude exclusively to prospective technical participation in respective EECT and ESSM markets: there is no reference to the prospective market value of such participation. To set the stage for the prospective revenues from participation in ESSM markets over and above participation in two-way commodity trading markets, consider the example of the “world’s largest battery” (at its time of initial deployment): the 100 MW input capacity system supplied by Tesla to the Neoen’s Horsdale Power Reserve in South Australia. Consider the 5 min resolution buy and sell profiles EECT (conventional energy commodity trading) of this facility, along with the 7-day (2016 sample) moving averages, presented...
in Figure 55 clearly this facility operated in this way is not financially substantial in and of its EECT market participation. Instead, by continuously being available for ESSM markets, specifically, frequency control ancillary services (FCAS), the capital cost of this facility has been paid off in record time relative to the original budget, as presented in Figure 56- Figure 59.

The very large marginal revenue in January 2020 was the result of a convective downburst in the adjacent Region of Victoria which downed a major transmission line, resulting in the operation of the South Australia Region of the NEM as an island for 17 days starting 31 January 2020. As a result, the lights stayed on for the entirety of this event despite SA being dominated by inverter-based resources (IBR), including periods of 100% IBR.

Nevertheless, the function of the FCAS market was stretched well beyond its normal limits, highlighting the need for not only technical design considerations being paramount to managing the evolution towards higher VRE proportions, but also, market design considerations [2]. In summary, while the security technology and market designs are expected to continue to evolve quickly in the coming years, the balance might well be in favour of accounting for the value of electrolysis participation in security markets (ESSM) over and above conventional energy trading (EECT). In turn, this suggests that those who model the viability of power to hydrogen in terms of just electricity purchases, hydrogen selling, and capital write down, are potentially missing a crucial future contributor to the viability of power to hydrogen.
Figure 58
Empirical cumulative probability distributions for HPR, excluding 17 days from 31 Jan 2020

Hornsdale Power Reserve FCAS “normal” revenue statistics: excluding period from 31 January to 16 Feb 2020

Figure 59
Empirical cumulative probability distributions for HPR, “normal”, and “islanded”.

Summary of potential roles for power to hydrogen

At the time of writing, the required time and resources had yet to be allocated to assessing which physical parameters of the electricity system might be open to the prospect of power to hydrogen participation.

Frequency control (FCAS) is clearly one such prospect and is potentially the most important in terms of revenue potential. That is, some PEM electrolyser manufacturers demonstrated a while back that their hardware and software is capable of responding at speeds comparable to those in which the above large-scale batteries operate. Nevertheless, we do not present quantitative data in this report.

Beyond the scope of FCAS, going forwards to (for example, IEA Hydrogen Task 41), it will be crucial to adopt agreed to terminology – terms that can be used across the relevant disciplines, as follows:

The **security** of the power system refers to its ability to remain stable in response to disturbances.

In turn, **stability** refers to the limit of variation of system parameters within specific ranges (such as frequency, phase angle, voltage, active and reactive power). e.g. Frequency of 50Hz ± tol, where if the frequency exceeds tol above or below 50 then fast responding action is required to bring the system back to “stable”.

In turn, for frequency control, in many regions **fast responding actions** are called Frequency Control Ancillary Services (FCAS).

**Reliability** is distinct from security and stability (but is not defined in this paper).

**Synchronous** mechanical rotating turbines are directly connected and are synchronized with the grid, rotating with the same speed and delivering electricity at the same phase angle.

**Asynchronous** generators have no rotating mass and connect to the grid via power electronic inverters.

**Inverters** convert Direct Current (DC) electricity into grid-compatible Alternating Current (AC) delivering in-phase electricity at the grid’s frequency.

**An inverter-based resource** (IBR) is any DC power generation technology that uses an inverter to connect to the electricity grid.

**Variable Renewable Energy** (VRE) refers to intermittent production. VRE in MW(t) varies with respect to time t, independently of grid demand (consumption) and other system parameter variations. This includes both production-consumption balancing time scales (> 5 minutes), and system security time scales (In Aus NEM FCAS: <= 5 minutes, <= 60 second and <= 6 seconds).

**Inertia:** the spinning mass of rotating turbines have a continuous store of kinetic energy. If a turbine's energy source flow fails, this kinetics enables rotating turbines to deliver a smoothed out impact on the grid. Instead of an impulse (step-change) to grid parameters, such a failure imposes a steady but slowly decaying impact over a period of time.

**Fault current:** On the occurrence of a fault, **synchronous resources** inject high levels of current into the fault, thereby limiting the rate of voltage degradation.

Similarly, it is crucial that cross discipline agreement is achieved in accepted that the risk of failure can at best be mitigated, but not eliminated. In turn this leads to the need for several parallel processes such as [2]:

- **limit the risk and magnitude of those imbalances to within the operational tolerances of the system.**
- **ensure that there are sufficient emergency mechanisms to mitigate impacts when the tolerances are breached.**
- **recover the system effectively and expeditiously when there is an interruption to service.**

**Inverters** convert Direct Current (DC) electricity into grid-compatible Alternating Current (AC) delivering in-phase electricity at the grid’s frequency.

An **inverter-based resource** (IBR) is any DC power generation technology that uses an inverter to connect to the electricity grid.

**Variable Renewable Energy** (VRE) refers to intermittent production. VRE in MW(t) varies with respect to time t, independently of grid demand (consumption) and other system parameter variations. This includes both production-consumption balancing time scales (> 5 minutes), and system security time scales (In Aus NEM FCAS: <= 5 minutes, <= 60 second and <= 6 seconds).

**Inertia:** the spinning mass of rotating turbines have a continuous store of kinetic energy. If a turbine's energy source flow fails, this kinetics enables rotating turbines to deliver a smoothed out impact on the grid. Instead of an impulse (step-change) to grid parameters, such a failure imposes a steady but slowly decaying impact over a period of time.

**Fault current:** On the occurrence of a fault, **synchronous resources** inject high levels of current into the fault, thereby limiting the rate of voltage degradation.

Similarly, it is crucial that cross discipline agreement is achieved in accepted that the risk of failure can at best be mitigated, but not eliminated. In turn this leads to the need for several parallel processes such as [2]:

- **limit the risk and magnitude of those imbalances to within the operational tolerances of the system.**
- **ensure that there are sufficient emergency mechanisms to mitigate impacts when the tolerances are breached.**
- **recover the system effectively and expeditiously when there is an interruption to service.**
### Table 8

**Market and non-market mechanisms for supplying system security**

(Adapted from Figure 11 of [2])

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>License conditions</td>
<td>Mandatory conditions imposed on network access to provide or contract system services</td>
</tr>
<tr>
<td>Regulatory obligations</td>
<td>Regulatory obligations on transmission network owners to provide system services</td>
</tr>
<tr>
<td>Regulatory delegations</td>
<td>Regulated delegations to supply services via contracting or auctions</td>
</tr>
<tr>
<td>Spot markets</td>
<td>Market for supplying system services under an operational-ahead or real-time timeframe</td>
</tr>
<tr>
<td>Constraints and interventions</td>
<td>Operator intervention or the imposition of technical constraints on operational dispatch to maintain system security</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Examples</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual inertia (Québec and Ontario, Canada)</td>
<td>Stabilization auctions (UK’s National Grid)</td>
</tr>
<tr>
<td>Primary frequency control (Australia’s National Electricity Market (NEM), North American Electric Reliability Corporation (NERC), UK’s National Grid)</td>
<td>Enhanced frequency response (UK’s National Grid)</td>
</tr>
<tr>
<td>Mandatory reserves (Spain)</td>
<td>Enhanced reactive power services (UK’s National Grid)</td>
</tr>
<tr>
<td>Do-no-harm conditions imposed on generator (Australia NEM)</td>
<td>MVAR services tender (Belgium)</td>
</tr>
<tr>
<td>Conditions imposed to supply reactive power services (UK’s National Grid)</td>
<td>Fast regulation markets (North East US’s PJM, US and Canada’s Midcontinent Independent System Operator (MISO))</td>
</tr>
<tr>
<td>Obligation to support of a minimum system strength (Australia’s NEM)</td>
<td>Ramp products (California Independent System Operator (CAISO), mid-continent’s MISO)</td>
</tr>
<tr>
<td>Obligation to contribute to a minimum inertia (Australia’s NEM)</td>
<td>Primary frequency reserve (proposed for Australia’s Wholesale Electricity Market (WEM), Finland’s Fingrid)</td>
</tr>
<tr>
<td>Delegation schemes for supplying system integrity protection (Australia’s NEM)</td>
<td>Market for supplying system services under an operational-ahead or real-time timeframe</td>
</tr>
<tr>
<td>Delegation markets for control ancillary services (Australia’s NEM)</td>
<td>Participation requirements in electricity markets vary considerably regarding the service, availability, pricing, location, auction times, and clearing time and payment</td>
</tr>
<tr>
<td>Stability auctions (UK’s National Grid)</td>
<td>Security-based constraints on unit commitment and otherwise exclusively market-based dispatch</td>
</tr>
<tr>
<td>Enhanced frequency response (UK’s National Grid)</td>
<td>Residual unit commitment</td>
</tr>
<tr>
<td>Enhanced reactive power services (UK’s National Grid)</td>
<td>Market intervention: security-based direction</td>
</tr>
</tbody>
</table>

- ensure that the inevitable interactions between different aspects of security are manageable

For ongoing assessment of the potential for power to hydrogen to participate in security markets, it will also be crucial going forwards to understand both past and prospective future mechanisms (e.g. [2]) and how they might differ. Both market and non-market mechanisms are enumerated in Table 8, but it seems likely that the opportunities for power to hydrogen will lie primarily in market mechanisms.

In conclusion: The physical characteristics of electricity system security are complex and multifaceted, with many facets interacting with each other. Regardless of the evolving and emerging details market and non-market methods for supplying system security, there is clear potential value in having grid-connected power-to-hydrogen infrastructure participate in both.

1. Two-way electrical energy commodity trading (EECT)
2. Electricity system security markets (ESSM)

An assessment of the physics of electrolysis hardware in this context will deliver crucial foundation to future assessments of the additional value of ESSM participation to power to hydrogen, and above EECT participation.

For readers seeking more detail, the following section provides a more comprehensive review.

### A more detailed review of key global market and non-market security mechanisms

Participation requirements in electricity markets vary considerably regarding the service, availability, pricing, location, auction times, and clearing time and payment schemes, size of asset and/or system requirements; additionally, the varying logistics and participation rules in differing geography zones can often render energy storage project economics and logistics complex. Today, larger consumers economically benefit from optimizing their consumption via participation in balancing services like demand response (real-time energy balancing), avoiding demand charges at times of peak consumption and high electricity prices, and even arbitrage with markets with a large variation of daily electricity prices. Other new technologies target frequency regulation markets and capacity markets to seek appropriate remuneration for large-scale energy storage projects, which still possess costly investments. One of the most important technical parameters for frequency-related ancillary services are the reaction times and ramping rates to limit deviations in the frequency. As electrolyzer technologies advance and increase in efficiency and reaction and skew times, they could prove to be valuable assets in an electric power network due to their range of flexible operation. Despite the technical capabilities, the economics and market participation size remain obstacles for investors to justify deploying energy storage projects and other new technologies for services to the grid. Adjusting electrolyzer operation in response to grid signals suggests to strategically lower hydrogen production, suggesting that the costs must be spread over less revenue from the sale of hydrogen. Additionally, a flexible operation may affect the overall lifetime of the power to gas system; limiting project lifetimes which increases the Levelized cost of hydrogen and availability to participate in services to the grid. Despite the current economic barriers, electrolyzer technologies have the technical ability to respond to several services to the grid – whether for ancillary services for the system operator or in energy balancing to ameliorate the operation and electric landscape. Power to gas systems, when combining the hydrogen production
chain (for mobility, chemical industry, or even re-electrification via fuel cells) with services to the grid may prove to be a relevant solution in the future [3].

1. Definitions and technical requirements of ancillary services (focus on frequency regulation) in several electricity markets

Definitions relevant to services to the grid (using European Network of Transmission System Operators for Electricity terms) [4]:

- **Ancillary services**: Ancillary services refers to a range of functions which Transmission System Operators (TSOs) contract to guarantee system security. These generally include black start capability (the ability to restart a grid following a blackout); frequency response (to maintain system frequency with automatic and very fast responses); and fast reserve (which can provide additional energy when needed); the provision of reactive power and various other services. An important aspect of balancing is the approach to procuring ancillary services. These services generally adhere to the needs of the system operator in order to have an operational electric power network.

- **Frequency control (response and reserves)**: The grid requires access to sources of additional power in the form of either generation or demand reduction, to be able to deal with unforeseen fluctuations in the alternating current frequency which occurs due to imbalances in supply and demand (e.g. loss of a generator, losses in variable renewable energy sources, etc.). These additional sources of power available are referred to as “reserves” and are comprised of synchronised and non-synchronised sources. Different sources require different timescales in order to deliver frequency control. In general, there are typically three types of services to contain, restore, and ensure frequency control of an electric power network – these are generally separated into what are referred to as primary, secondary, tertiary and/or reserves, which respectively take place when imbalances or generator losses occur within the network. Figure 60 displays an event (i.e. loss of a generator) which requires frequency control services to restore the frequency to operational levels (generally within a few hertz):

As seen in Figure 60, primary frequency control limits and contains large frequency deviations, secondary control restores the frequency back to its target value, and the tertiary and/or reserves react later (and even manually) for longer durations to keep this imbalance from recurring, ensuring the restoration of a stable frequency. In Europe, these services are separated and denoted as follows:

- Frequency Containment Reserve (FCR): Primary reserve (included in the ancillary services) – European ENTSO-E nomenclature (see Error! No se encuentra el origen de la referencia. for different names of frequency regulation services for differing electric power networks)
- aFRR - automatic Frequency Restoration Reserve: Secondary reserve (included in the ancillary services)
- mFRR: manual Frequency Restoration Reserve: Manual reserve with a mobilization time shorter than 15 minutes (fast reserve, included in the ancillary services)
- RR - Replacement Reserve: Manual reserve with a mobilization time longer than 15 minutes (complementary reserve and other, included in the balancing services and reserve and response services)
- Reactive Power Services: Reactive Power describes the background energy movement in an Alternating Current (AC) system arising from the production of electric and magnetic fields. Devices which store energy by virtue of a magnetic field produced by a flow of current are said to absorb reactive power, those which store energy by virtue of electric fields are said to generate reactive power. The flows of reactive power on the system will affect voltage levels. Unlike system frequency, which is consistent across the network, several voltages may be experienced at points across the system form a ‘voltage profile’, which is uniquely related to the prevailing real and reactive power supply and demand. The Grid must manage voltage levels on a local level to meet the varying needs of the system. Without the appropriate injections of reactive power at correct locations, the voltage profile of the transmission system will exceed statutory planning and operational limits.

- Spinning and non-spinning reserves: A generating unit already connected to the network and able to supply additional power rapidly. Essentially the unused capacity which can be activated on the decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power. This can refer to the secondary reserve as well as the tertiary. The term spinning reserve is generally in contrast with non-spinning reserves, suggesting the asset is not connected or synchronized to the network but can be brought online in order to respond to the frequency to operational levels. (e.g. in California non-spinning reserves should be online within 10 minutes of notification and provide power to restore frequency for 2 hours).

- Fast response: Fast reserves provide the rapid and reliable delivery of active

![Figure 60](image_url)

**Figure 60** Frequency control diagram of reserve responding to an event

- Grid Frequency (Hz)
- Control Reserve (MW)
- Time (minutes)
- Event = imbalance between generation and consumption
- Stop the frequency drift
- Resolve the frequency drift
- Primary Reserve
- Secondary Reserve
- Tertiary Reserve
- Time (minutes)
power through increased output from generation or a reduction in consumption from demand sources, following receipt of an electronic dispatch instruction from TSO. Fast Reserve is used, in addition to other energy balancing services, to control frequency changes that might arise from sudden, and sometimes unpredictable, changes in generation or demand. The quicker the response, the smaller the deviation, suggesting that the total market size (MW) to respond to imbalances with fast response assets is less than if responding with slower responding assets – as the frequency deviation will be larger with increasing time and require more power for containment and restoration.

The main interest for new storage technologies which can respond quickly to events and instructions generally include frequency control (regulation, reserves, etc.) as well as the ability to consume in a flexible manner. The activation time as well as discharge duration are of importance in determining which grid services are suitable when determining the most appropriate technologies. Recently, energy storage technologies like batteries, flywheels, super/ultracapacitors, and power to gas technologies are able to smooth and stabilize variable renewable energies (VRES), react quickly to signals and changes in the electric power networks, as well as provide energy for longer-term capacity needs within electric power networks. The interest of newer energy storage technologies lies in their ability to function both as a generator and consumer in addition to storing electricity. In this sense, power to gas systems can operate both in the interest of producing hydrogen for the chemical, industrial, or mobility sectors, and adjust their operation to additionally function as an asset to the system operators who manage electric power networks. This concept has been in addressed in several demonstrations previously completed and suggests that utilizing the flexibility of electrolyzers (which can operate under varying loads) to provide services to the grid to account for fluctuations is a technical reality. Thus, ancillary services (i.e. frequency regulation and reserves) and energy balancing (i.e. load shifting for renewables and/or demand management) have been identified as the most appropriate services to the grid in which electrolyzers and power to gas systems may contribute. Below, Figure 61 visually portrays the concept of frequency control (using the three reserves discussed previously) as well as the relative time scale regarding reaction and duration times to respond to frequency deviations — which is generally defined by national policies. Figure 62 Note that these figures use the European Network of Transmission System Operators for Electricity (ENTSO-E) terms and abbreviations.

Though the same rules and regulations do not apply to all-electric power networks, the general concepts and services are the same. Electric grid service requirements in different zones vary in response time (including ramping and time to provide full power), duration time, as well as minimum size for participation, market size, remuneration structure, as well as average prices and potential revenues possible. Some markets are more established than others, which may facilitate participation requirements and entry points for power to gas systems as newer technologies as their beneficial characteristics are increasingly understood. Every electric power network has certain services which may contribute. Below, Figure 61 visually portrays the concept of frequency control service reserves (using ENTSO-E nomenclature) as well as the relative time scale regarding reaction and duration times to respond to frequency deviations — which is generally defined by national policies. Figure 62 Note that these figures use the European Network of Transmission System Operators for Electricity (ENTSO-E) terms and abbreviations.

Below, Table 9 displays some of the designated names for frequency control reserves in different established electric power networks across the world. This gives an idea of the various markets and frequency reserves to which power to gas systems could participate, technically. Note that the ENTSO-E network, which is synchronized...
Names for different frequency regulation services in different countries and electric power networks

<table>
<thead>
<tr>
<th>Primary frequency control reserves</th>
<th>Secondary frequency control reserves</th>
<th>Tertiary frequency control reserves</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENTSO-E (several European countries*)</td>
<td>Frequency containment reserve (FCR)</td>
<td>Frequency restoration reserve – automatic (mFRR) (followed by Replacement reserve (RR))</td>
</tr>
<tr>
<td>France*</td>
<td>Réserve primaire</td>
<td>Réserve secondaire</td>
</tr>
<tr>
<td>Belgium*</td>
<td>Réserve de puissance pour réglage primaire</td>
<td>Réserve de puissance pour réglage secondaire</td>
</tr>
<tr>
<td>Germany*</td>
<td>Primärregelreserve</td>
<td>Sekundärregel-reserve</td>
</tr>
<tr>
<td>Netherlands*</td>
<td>Primaire reserve</td>
<td>Secundaire reserve</td>
</tr>
</tbody>
</table>

Transmission grid as described the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) [5]. Following this, several tables of information (Table 10, Table 11, and Table 12) summarize the frequency regulation market services for three different European networks, including the respective frequency service names and specific rules of participation. Though there may be no specific mention of power to gas or electrolyzer technologies in these rules and regulations; overall, it seems that power to gas systems are technically capable of providing services to the grid and can provide flexible grid assets.

Outside of Europe, the United States and Australia consider frequency control in terms of typical deviations during normal operation, and then in the event of a contingency (a large loss). This makes it difficult to compare the different services on frequency regulation between different market structures, but essentially the concept remains similar. Additionally, most of the products for regulation in Europe are symmetric, suggesting that assets can consume or generate to aid in stabilizing or restoring the frequency as needed. Some markets have asymmetric products for ancillary services, allowing assets to contribute to only increase or decrease in consumption. This is important for electrolyzers, as remuneration for increase (up or raise), as well as decrease (down or lower), are not equivalent and affect the operational efficiency of hydrogen production – greatly affecting the economics of power to gas grid-connected projects.

Services to the grid all have their purposes, though the terminology can be confusing, as
**Table 10**

**ENTSO-E frequency regulation services**

<table>
<thead>
<tr>
<th>Grid</th>
<th>System Operator(s)</th>
<th>Countries</th>
<th>Frequency Regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>Approx.</td>
<td>=15</td>
</tr>
<tr>
<td></td>
<td>0.5 – 15</td>
<td></td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>3% total capacity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Figure 63

**FCH hydrogen participation in frequency control in Europe [6]**

<table>
<thead>
<tr>
<th>Frequency Containment Reserve (FCR)</th>
<th>Frequency Containment Reserve (FRR)</th>
<th>Replacement Reserve (RR)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>FCR automatically and continuously regulates the positive and negative frequency fluctuations; electrolyzers can support the system via increased/decreased demand</td>
<td>RR is used to restore the required level of operating reserves; supersedes FCR and FRR to be prepared for further disturbances in the grid</td>
</tr>
<tr>
<td><strong>Suitable electrolyser technology</strong></td>
<td>PEM / Alkaline</td>
<td>PEM / Alkaline (when operated adequately)</td>
</tr>
<tr>
<td><strong>Activation time &lt; 2 min; utilisation for &gt; 15 min max; minimum bid size +1 MW; 1 week commitment per auction</strong></td>
<td>Activation time 2-15 min depending on country-specific regulation; no standardized technical requirements</td>
<td>Activation time (&gt; 15 min) depending on country-specific regulations; no standardized technical requirements</td>
</tr>
<tr>
<td><strong>Procurement</strong></td>
<td>Frequency regulation across the European Union; procurement via auctions organised by TSOs in various European countries</td>
<td>Fragmented regulation across the European Union, procurement via auctions organised by TSOs in various European countries</td>
</tr>
</tbody>
</table>

Australia’s “reserves” designate investments in generation capacity and not frequency control reserves. In the United States, the Operating Reserves refer to real-time corrections in imbalances (like frequency regulation and demand response), whereas planning reserves refer to capacity adequacy for longer time energy procurement. It is difficult to characterize non-European frequency control services by primary, secondary, and tertiary services, as each operator chooses their method(s) in the case of events or imbalances to best manage their electric network. Below the table referring to PJM (the Pennsylvania Jersey Maryland network in the USA) suggests that the frequency control service providing market opportunities lies mainly within the secondary regulation. When comparing with the European definition of primary, secondary, and tertiary, this concept is difficult to compare due to market structure and method of containing the frequency; nevertheless, this frequency service has been categorized within the primary for simplification – as an inertial response is generally mandatory (and thus not remunerated) for large generators in many electric power networks; followed by synchronized (online spinning reserves) and quick-start reserves (which technically compare more to secondary regulation when comparing with ENSTO-E terminology). Mandatory frequency regulation requirements for large generators may be procured by agreements and outsourced – suggesting there is much flexibility in securing sufficient capacity and technically responding to imbalance solutions in different electricity markets [7].

### 2. Definition of energy balancing services (focus on demand management)

Beyond services to ensure system stability and security, energy balancing services generally refer to providing energy (as opposed to power for ancillary services). System operators have the responsibility to plan for events as well as to procure enough capacity to provide electricity to its customers despite imbalances in supply and demand. Specifically, generators can provide energy for long periods of time and power to gas technologies have previously been associated with being an alternative for long-term energy storage with its ability to convert, store, and reconver electricily. Though hydrogen can be used as a source of energy, its production via water electrolysis provides not only a fast-responding flexible asset for ancillary services but a flexible asset for energy balancing. Hydrogen can store electricity (in its hydrogen chemical form as well as syngas or mixed with natural gas) as well as optimize the way in which helps to correct the short and long occurring imbalances which arise due to unforeseen consumption events, loss of generator events, and other unexpected events. This study specifically concentrates on energy balancing using electrolyzers for demand management – either at the system operators demand (denoted “dispatchable”) or the customer’s volition to adjust consumption (“non-dispatchable”) based on price signals. Below brief definitions of these concepts are described below.

- **Energy balancing**: Balancing refers to the situation in which a system operator acts to ensure that demand is equal to supply, in and near real-time. Efficient balancing markets ensure the security of supply at the least cost and can potentially deliver environmental benefits by reducing the need for back-up generation.
Demand management: Demand management consists of adjusting consumption or generation based on economic and technical incentives. Generally, a generator or consumer can adjust generation or consumption based on system operator needs or market price signals (time-based rates) to operate in an efficient manner for economic and technical purposes. Demand response (sometimes called demand side response or demand side management, DSM), specifically refers to assets or aggregated assets which react accordingly after being given a signal by the operator to increase consumption or decrease consumption based on the generation profile at certain times. This can be at the utility, industrial, or even residential scale; though is recognized to be more effective at larger scales. This service and programs assist the operator in correcting the unbalance in generation and consumption during certain unforeseen periods (minutes to hours). Demand charge specifically refers to the consumer efforts to avoid consuming at certain peak demand periods where electricity is more expensive and additional costs may be associated with using the transmission and distribution infrastructures at this time. Thus, the consumer may respond to price signals and peak hours by decreasing consumption, or inversely, consuming during periods of low consumption to avoid decreasing consumption from generators (which may be unideal due to economics, planning logistics, or system efficiencies).

Programs dedicated to demand response are relatively new for many electricity markets around the world. Demand response schemes can be a form of capacity mechanism if they are introduced by the State to ensure the
Table 13
United States PJM frequency regulation services

<table>
<thead>
<tr>
<th>Grid</th>
<th>System Operator(s)</th>
<th>Countries</th>
<th>Frequency Regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; PJM Interconnection</td>
<td>&gt; United States (Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia (D.C.))</td>
<td>Type: Inertial Response (Frequency Response) and Primary Control (part of Operating Reserves)</td>
<td>Minimum Size (MW): 0.1, 0.1 – 0.1</td>
</tr>
</tbody>
</table>

Table 14
Australian NEM frequency regulation services

<table>
<thead>
<tr>
<th>Grid</th>
<th>System Operator(s)</th>
<th>Countries (States)</th>
<th>Frequency Regulation – Frequency Control and Ancillary Services (FCAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; AusNet Services, ElectraNet, Powerlink Queensland, TasNetworks, TransGrid</td>
<td>&gt; Australia: Queensland, New South Wales, Victoria, and South Australia</td>
<td>Type: Regulation</td>
<td>Minimum Size (MW): 0.1, 0.1 – 1</td>
</tr>
</tbody>
</table>

Electrolyser and fuel cell technical specification.

As electric power networks transition to newer technologies and methods using state of the art, more efficient, faster-responding technologies, power to gas technologies can react quickly when in standby mode and with ramping rates to respond to imbalances in the grid. Depending on the priorities of hydrogen production and participation to the grid, reaction times for alkaline and PEM technologies have been stated to range between 1 second to 1 minute. Of course, the ramping and slew rates vary depending on the technology, temperature, pressure, and other factors – which if poorly optimized or operated
Table 15
Demand response program in different electric power networks

<table>
<thead>
<tr>
<th>Country</th>
<th>Demand Response Program(s) or Pilots</th>
<th>Market size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Several pilots currently being funded by the Australian Renewable Energy Agency (ARENA) in NSW, South Australia, and Victoria</td>
<td>To procure 200 MW by 2020</td>
</tr>
<tr>
<td>France</td>
<td>Mécanisme d'effacement</td>
<td>2,500 MW procured for 2019</td>
</tr>
<tr>
<td>Germany</td>
<td>Verordnung zuabschaltbaren Lasten – &quot;AbLaV&quot; (Switchable loads and fast disconnectable loads)</td>
<td>1,500 MW each week</td>
</tr>
<tr>
<td>Finland</td>
<td>Demand-side response (as part of the Smart Kalasatama demonstration)</td>
<td>≈ 1,000 MW</td>
</tr>
<tr>
<td>United States</td>
<td>Demand Response (also known as curtailment service providers (CSPs) for PJM)</td>
<td>&gt; 2,200 MW</td>
</tr>
<tr>
<td></td>
<td>Demand Response Auction Mechanism (DRAM) - procured by several utilities in CAISO network</td>
<td>7,500 MW PJM</td>
</tr>
<tr>
<td></td>
<td>Demand Response (assets and resources) for ISO-NE</td>
<td>2,700 MW for ISO-NE</td>
</tr>
</tbody>
</table>

Market Size data sources: Aus [9], France [10], Germany [11], Finland [12], UK [13], US [14][15]

Energy and NREL in the USA. It is thought that a reduction of up to 30% in hydrogen cost is achievable (based on California rates) for the production and delivery of H2 without large impacts on hydrogen consumers [16]. Simply avoiding or reducing consumption during periods of high demand charge in California can potentially reduce the production cost of H2 by 6 – 7% [16].

Therefore, as most quick response requires less than 1 second to roughly 10 seconds, if an electrolyser is on standby-mode or in full operation, it theoretically can technically respond to quick response frequency regulation; though is more appropriate in contributing to secondary or tertiary frequency control services in terms of response time and ramping to full power within less than 30 seconds – as this may prolong the lifetime. Nevertheless, upon technical advancements in the field of water electrolysis, this may become possible in the future – regarding response and ramping rates to respond to ultra-fast frequency regulation products like the Enhanced Frequency Regulation (EFR) in the U.K. or 6-second upper or lower in Frequency Control Ancillary Services (FCAS) in Australia. ITM power claims to have electrolyser available in 1 MW modules responds in 1-second self-pressurises to 80 bar [17]. Hydrogenics noted that in the demonstration HyBalance, they are “down to seconds” in response times – suggesting that development within water electrolysis technologies continues to respond to real-time electric power network fast-response products as well as aiding in VRES integration and storage [18]. Seeing as typical operation ranges noted for electrolyser are 0% – 100% or 15% – 100%, the flexibility and relatively quick response times strongly suggests that electrolyser in conjunction with hydrogen production can be valuable assets to electric power grid network optimization and operation.

Generally, all of the secondary and tertiary reserves, and demand (side) response programs have response, ramp, and duration times which state-of-the-art electrolyser can provide, technologically. The typical response times for secondary and tertiary reserves and dispatchable demand response providers (to ramp up to 100% power) range generally from 1 minute to 30 minutes depending on the nationally defined requirements.

Economics and efficiency of power to gas systems

The economics of any project depend on the application(s), size, operation, technologies, and location. For power to gas systems, there are several possible configurations and applications; nevertheless, overall project economics can remain a barrier to the deployment of these systems. When regarding power to gas power applications, the efficiency remains low compared to other technologies which are active in fast response and ancillary markets. However, electrolyser and power to gas systems are flexible and have the ability to store electricity in the chemical form of hydrogen for longer periods of time than other electrochemical energy storage methods, which may increase the value of electrical energy stored (ratio of electrical energy returned over lifetime energy required for the power to gas asset) [19]. Since electrolyser are created from stacks as well, larger hydrogen systems are modulable and several stacks in parallel can be arranged in order to improve the performance and/or increase the operational range [20]. Nevertheless, the efficiency of power to gas systems may be compromised to decrease overall capital expenditures and costs, as dynamic systems can require a complex balance of plant to work at partial loads — especially for the case of systems containing electrolyser coupled to fuel cells [21]. Beyond the purely technical and economical specified functionalities of power to gas technologies, the importance of coupling...
A non-exhaustive list of literature studies regarding power to gas services the grid

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Key findings</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jørgensen and Ropenus</td>
<td>2008</td>
<td>Suggested optimized operation of electrolyser for hydrogen production using grid electricity in a market with high wind penetration and minimization of the hydrogen production price and its dependence on estimated power price fluctuations in the West Danish area</td>
<td>1</td>
</tr>
<tr>
<td>Lück and Larscheid</td>
<td>2008</td>
<td>Completed several techno-economic analyses in order to understand the effect of components in energy generation and resulting electricity prices which affect flexible hydrogen production costs and selling price. Ultimately, the results from these studies suggested that the selling price of hydrogen produced by means of electrolysis is too high in order to recover the initial investment of a PV-grid system in a reasonable lapse of time (i.e. ten years)</td>
<td>2</td>
</tr>
<tr>
<td>Barton and Gammon</td>
<td>2010</td>
<td>Simulated several future energy mix scenarios to understand the role of hydrogen in the U.K. The different scenarios suggest that the use of hydrogren in the transport sector is important for reducing CO2 emissions - while simultaneously avoiding demand-side management response for the electric power network. This study stressed the importance of sector coupling of the transport and energy sectors, as scenarios which did not employ hydrogen for transport required substantially larger amounts of imported coal for primary energy sources</td>
<td>3</td>
</tr>
<tr>
<td>Bennoua, et al.</td>
<td>2015</td>
<td>Suggested that the most important aspects economically for the deployment of water electrolysis coupled with a generator (like nuclear) depend on the lifetime of the technology, as well as its ability to operate as a flexible asset to enable a longer lifetime</td>
<td>4</td>
</tr>
<tr>
<td>Mansilla et al.</td>
<td>2012</td>
<td>Explores hydrogen production as a double possibility to be a demand-side management tool, by operating according to price signals from the spot market (avoiding high prices, hence periods when the balance between supply and demand is tense) and through the balancing mechanism (thus helping the system cope with unexpected events occurring in real-time). The best operating strategy seems to offer lower regulation only (and not raise services). Such operating strategies enable lowering the hydrogen production cost by a few percent in the investigated context. Later, Mansilla et al. (2013) also showed that market-driven operation only is not highly favourable to valorize fluctuating hydrogen production, without the added value from balancing services. This may change in the context of increasing VRES shares.</td>
<td>5</td>
</tr>
<tr>
<td>Caumon et al.</td>
<td>2015</td>
<td>Showed to which extent the demand to power the electrolyser can mitigate the VRES curtailment, showing that hydrogen production can indeed help to integrate fluctuating renewable energies into the power system</td>
<td>6</td>
</tr>
<tr>
<td>Cany et al.</td>
<td>2017</td>
<td>Like Caumon, also investigated the opportunity for hydrogen to take advantage from available low-carbon energy in the French context, with increasing VRES. It appears that hydrogen production (as well as any other flexible demand) would be more beneficial for the system than power modulation</td>
<td>7</td>
</tr>
<tr>
<td>Larscheid, Lück, and Moser</td>
<td>2018</td>
<td>Examined the potential business models for grid integrated water electrolysis for hydrogen production. Their analyses suggest that for grid-connected electrolyzers, exemption from certain system charges is crucial for profitability as well as that the economic efficiency is highly dependent on the end-user sector. Despite the potential increased profitability in providing grid services towards transmission operators, this case is highly dependent on the point of grid connection. This publication suggests sector coupling between energy and transport sectors is the most promising scenario in terms of economic potential, and that future decreased investment costs will result in viable business models for power to gas systems (especially deployed in areas with high renewable penetration which are often curtailed)</td>
<td>8</td>
</tr>
</tbody>
</table>

Citations of ID: 1 [24], 2 [25], 3 [26], 4 [27], 5 [28], 6 [29], 7 [30], 8 [31]

Table 16

Table 16 displays a non-exhaustive list of demonstrations of power to gas services during 2004 – 2020 which addressed potential service to the grid and as a flexible asset. Several demonstrations around the world have previously addressed the concept of providing services to the grid using power to gas systems – whether they are just electrolyser, fuel cells, or both systems with storage included. Task 38 [32] under the IEA H2 TCP identified over 200 power to gas demonstrations during 2004 – 2020 which addressed potential service to the grid applications for power to gas systems [33]. Below, Table 17 displays a non-exhaustive list of demonstrations of power to gas systems which aim to participate in ancillary services or energy balancing using either the electrolyser and/or re-electrification with a fuel cell. Here the common applications are described as Demand Management, Load Shifting which may be in terms of just energy storage or shifting of VRES to respond to peak consumption periods, as well as Curtail avoidance (as some may call surplus energy from generators which are running but not feeding into the grid due to periodic overproduction), as well as Capacity

Demonstrations which have investigated aspects regarding services to the grid

Several demonstrations around the world have previously addressed the concept of providing services to the grid using power to gas systems – whether they are just electrolyser, fuel cells, or both systems with storage included. Task 38 [32] under the IEA H2 TCP identified over 200 power to gas demonstrations during 2004 – 2020 which addressed potential service to the grid applications for power to gas systems [33]. Below, Table 17 displays a non-exhaustive list of demonstrations of power to gas systems which aim to participate in ancillary services or energy balancing using either the electrolyser and/or re-electrification with a fuel cell. Here the common applications are described as Demand Management, Load Shifting which may be in terms of just energy storage or shifting of VRES to respond to peak consumption periods, as well as Curtail avoidance (as some may call surplus energy from generators which are running but not feeding into the grid due to periodic overproduction), as well as Capacity
Table 17
A non-exhaustive list of PtG demonstrations which address services to the grid

<table>
<thead>
<tr>
<th>Name</th>
<th>System</th>
<th>Size</th>
<th>Application(s)</th>
<th>Actors</th>
<th>Location</th>
<th>Start Date</th>
<th>End Date</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYUNDER</td>
<td>PEM electrolyser and tanks</td>
<td>66 Nm³/h</td>
<td>&gt; Load shifting</td>
<td>Aragon Hydrogen Foundation</td>
<td>Huéscar (Spain)</td>
<td>2008</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Myrte</td>
<td>PEM electrolyser, fuel cell, and storage</td>
<td>50kW (120 Nm³/h): Fuel cell: 200 kW</td>
<td>&gt; Grid balancing</td>
<td>CEA, Areva</td>
<td>Corsica (France)</td>
<td>2012</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>INGRID</td>
<td>Electrolyser with fuel cell and solid-state tanks</td>
<td>1.2 MWe</td>
<td>&gt; Grid balancing</td>
<td>Enetrag AG</td>
<td>(Italy)</td>
<td>2012 2015</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Don Quichote</td>
<td>PEM and alkaline electrolysers</td>
<td>30 Nm³/h</td>
<td>&gt; Load shifting</td>
<td>Hydrogénics</td>
<td>(Belgium)</td>
<td>2012 2018</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Energie park Mainz</td>
<td>PEM electrolyser</td>
<td>6 MWe</td>
<td>&gt; Load shifting</td>
<td>Siemens</td>
<td>Mainz (Germany)</td>
<td>2012</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Creative Energy Homes</td>
<td>Li-ion battery with electrolyser</td>
<td>Battery: 24 kWh Hydrogen: 155 kWh</td>
<td>&gt; Demand management, &gt; Frequency regulation</td>
<td>University of Nottingham</td>
<td>(UK)</td>
<td>2013 2015</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Levensmouth Projects*</td>
<td>PEM electrolyser and fuel cell</td>
<td>250 kW electrolyser: 100 kW fuel cell</td>
<td>Load shifting (microgrid)</td>
<td>Logan Energy, Hydrogénics</td>
<td>(Scotland)</td>
<td>2014</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>ELIntegretion</td>
<td>Alkaline electrolyser</td>
<td>Multi-MW goal</td>
<td>Grid balancing</td>
<td>Aragon Hydrogen Foundation</td>
<td>Huéscar (Spain)</td>
<td>2015</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>HyBalance</td>
<td>PEM electrolyser</td>
<td>1.2 MW</td>
<td>Grid balancing</td>
<td>Hydrogénics, Air Liquide</td>
<td>(Denmark)</td>
<td>2015</td>
<td>-</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>System</th>
<th>Size</th>
<th>Application(s)</th>
<th>Actors</th>
<th>Location</th>
<th>Start Date</th>
<th>End Date</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2PEMGAS</td>
<td>PEM electrolyser</td>
<td>300 kW</td>
<td>Grid balancing</td>
<td>Consiglio, Nazionale dell' Ricerca, ITM</td>
<td>(Italy)</td>
<td>2016</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Demo4Grid</td>
<td>Pressurized alkaline electrolyser</td>
<td>4 MW</td>
<td>Grid balancing</td>
<td>Aragon Hydrogen Foundation</td>
<td>(Austria)</td>
<td>2017</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td>QualiGridS</td>
<td>PEM and alkaline electrolysers</td>
<td>50 – 300 kW</td>
<td>Grid balancing</td>
<td>ITM, Aragon Hydrogen Foundation</td>
<td>(Germany)</td>
<td>2017</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>H_Future</td>
<td>PEM electrolyzer</td>
<td>6 MW</td>
<td>Grid balancing</td>
<td>Verbund, Siemens</td>
<td>(Austria)</td>
<td>2017</td>
<td>-</td>
<td>13</td>
</tr>
<tr>
<td>Lam Takhong wind hydrogen hybrid project*</td>
<td>PEM electrolyser and fuel cell</td>
<td>Electrolyser: 1 MWe Fuel cell: 200 kW</td>
<td>Load Shifting (microgrid)</td>
<td>Hydrogénics</td>
<td>Lam Takhong (Thailand)</td>
<td>2018</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>Fukushima Hydrogen Energy Research Field (PH2R)</td>
<td>Alkaline electrolyser</td>
<td>10 MW</td>
<td>Load shifting Capacity Mechanism</td>
<td>Toshiba, Asahi</td>
<td>(Japan)</td>
<td>2019</td>
<td>-</td>
<td>15</td>
</tr>
</tbody>
</table>

Citations of ID: 1 [34], 2 [35], 3 [36], 4 [37], 5 [38], 6 [39], 7 [40], 8 [41], 9 [42], 10 [43], 11 [44], 12 [45], 13 [46], 14 [47], 15 [48]

*Note that these demonstrations work with microgrids and are not connected to larger electric power networks. These electrolysers may work to stabilize the microgrid or store energy in order to provide energy at later times (when renewables are not producing) or to economically manage peak consumption depending on the load.

Mechanism which procures capacity for longer, or even seasonal energy balancing and security. Grid balancing is also noted as an application to which power to gas seems to respond well – this is a generic term for reducing fluctuations in the network, suggesting that the system most likely performs frequency regulation or reserves, VRES smoothing or shifting, or demand management.

In general, these demonstration projects are suggested to possess technology readiness levels (TRL) of ranging around 7 – 8, suggesting that the technology used are overall ready for grid services. The latest demonstrations generally include larger MW-scale electrolysers with shorter response times. For example, Demo4Grid (2017 – 2022) uses a 4 MW pressurized alkaline electrolyser technology (IHT) in Austria with a 2-second response time and ability to operate under partial loads to participate in primary and secondary – ideally, the electrolyser will use electricity from a regional hydroelectric plant and commercialize the hydrogen produced for mobility and in the chemical industry [44]
Conclusions and remarks

a. A high share of renewable electricity is crucial for environmental benefits of using hydrogen as an energy carrier – certificates of origin, regulatory incentives and legal frameworks require hydrogen systems definitions as well as acknowledgement in participation and standards for operation.

b. Size, operating conditions, and production logistics all will determine optimal sizing for project economics and certain aspects may need to be compromised to prolong the lifetime, produce less hydrogen, or make fewer revenues. For example, by shifting (in advance or delay) from a planned hydrogen production schedule, electrolysers can adapt electricity consumption to variable RES production – and thus provide grid balancing services to better integrate intermittent production

c. Electrolysers, as well as power to gas systems, can technically respond to the majority of ancillary and energy balancing services in energy markets; nevertheless, the price of hydrogen, system economics, and overall profitability remain barriers to the massive deployment of power to gas systems to participate as a flexible asset in an electric power network.

d. Electric power networks enabling smaller assets, aggregated assets, and taking into account new technology capabilities is crucial for future optimization and transformation of the energy sector. Allowing quick-response and flexible assets to participate in several services (ancillary and/or energy balancing) based on the technical specifications and capabilities is also very important – as “stacking” services is possible with newer technologies and may enable more expensive and clean alternatives to participate economically in the electricity sector.

References


Three kinds of stakeholders can influence hydrogen deployment in a specific region:
1) industries setting the hydrogen system price (that depends on its costs),
2) policymakers that show ambition or not in hydrogen deployment and that act accordingly to make sure the regulatory framework is suitable for it,
3) and last but not least, academics and organizations running models and publishing energy system scenarios, so often used to enlighten industries and policymakers.

After discussing point 1) and 2) in the last chapters, Chapter 5 addresses point 3). A review on the role of hydrogen in the renowned global energy scenarios is suggested analyzing whether hydrogen is suitably presented or not, based on the available techno-economic data, but also conducting a deeper analysis to inspect whether hydrogen pathways are well presented in the models used to generate the scenarios. Some conclusions and best practices for scenarios development and hydrogen modelling are provided (ST4). For accurate modelling, accurate data is needed, a discussion on data is hence proposed based on the learning from Task Force Data in part 2 of the Chapter.

Abstract
As energy systems transition from fossil-based to low-carbon, they face many challenges, particularly concerning energy security and flexibility. Hydrogen may help to overcome these challenges, with potential as a transport fuel, for heating, energy storage, conversion to electricity, and in industry. Despite these opportunities, hydrogen has historically had a limited role in influential global energy scenarios.Whilst more recent studies are beginning to include hydrogen, the role it plays in different scenarios is extremely inconsistent. In this chapter, the reasons for this inconsistency are explored.

Authors
Christopher J. Quarton1, Gifa Tili2, Lara Welder1, Christine Mansilla1, Herib Blanco1, Heidi Heinrichs2, Jonathan Leaver2, Nouri J. Samsatli1, Paul Lucchese2, Martin Robinius2, and Sheila Samsatli*1.

Affiliations
1. Department of Chemical Engineering, University of Bath, Claverton Down, Bath BA2 7AY, UK. E-mail: s.m.c.samsatli@bath.ac.uk
2. CEA, I-tésé, Université Paris-Saclay, Gif-sur-Yvette, France
3. Forschungszentrum Jülich, Institute of Energy and Climate Research, Electrochemical - Process Engineering (IEK 3), Wilhelm-Johnen-Straße, 52428 Jülich, Germany
4. Chair for Fuel Cells, RWTH Aachen University, c/o Institute of Electrochemical Process Engineering (IEK 3), Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany
5. Center for Energy and Environmental Sciences, IVEM, University of Groningen, Nijenborgh 6, 9747 AG Groningen, The Netherlands
6. School of Engineering, Unitec Institute of Technology, Auckland, New Zealand
7. Process Systems Enterprise Ltd., London SW7 2AZ, UK
8. CEA, Université Paris-Saclay, Gif-sur-Yvette, France
In different scenarios is extremely inconsistent. In this perspective paper, the reasons for this inconsistency are explored, considering the modelling approach behind the scenario, scenario design, and data assumptions. We argue that energy systems are becoming increasingly complex, and it is within these complexities that new technologies such as hydrogen emerge. Developing a global energy scenario that represents these complexities is challenging, and in this paper, we provide recommendations to help ensure that emerging technologies such as hydrogen are appropriately represented. These recommendations include using the right modelling tools, whilst knowing the limits of the model; including the right sectors and technologies; having an appropriate level of ambition and making realistic data assumptions. Above all, transparency is essential, and global scenarios must do more to make available the modelling methods and data assumptions used.

Introduction

To combat climate change there is increasing interest in achieving net-zero greenhouse gas (GHG) emissions before the end of the century. Energy systems decarbonisation is an essential part of this, as energy sectors contribute around three-quarters of global GHG emissions. Renewable energy technologies have progressed tremendously in recent decades, now offering economically credible alternatives to fossil fuels in many sectors. However, these technologies are fundamentally different from fossil fuels, so a like-for-like replacement is not possible. Renewable resources such as wind and solar are diffuse and intermittent, creating new challenges for matching energy supplies to demands, in both time and space. Furthermore, fossil fuels have unrivalled storage capabilities. It is essential to find low-carbon energy storage options, for temporal balancing of supply and demand, and use in transport. We need to develop technologies that will enable increased energy systems flexibility and interconnectivity while maintaining reliability and stability.

In this context, hydrogen has potential. Apart from small reserves of “natural” hydrogen, hydrogen is not a resource that can be extracted at scale in the same way as fossil fuels. However, it can be produced with minimal GHG emissions, for example through electrolysis powered by renewable electricity, or from bioenergy or fossil fuels with carbon capture and storage (CCS). Hydrogen has many possible energy applications, including for heating, transport, industry, and electricity generation. Energy scenarios can provide valuable insights into possible future trajectories of energy systems. Many different national, regional and global energy scenarios exist. Some scenarios, such as those produced by global institutions, can be very influential to political discourse.

However, energy scenarios are generated using various methods and, given the complexity of the systems being represented, it is unsurprising that the scenarios produce differing results. In particular, the prominence of hydrogen in different scenarios varies noticeably. Hanley et al. reviewed the role of hydrogen across different energy scenarios, finding a range of results regarding the uptake of hydrogen. Whilst many scenarios included some hydrogen in the transport sector, uptake of hydrogen in other sectors varied significantly depending on the emphasis in the scenario design. Furthermore, the review found a correlation between the level of ambition (e.g. decarbonisation or renewables integration targets) and the contribution of hydrogen in the scenario results.

Given hydrogen’s potential to transform energy systems, the variation in its contribution to global energy scenarios is surprising. Whilst Hanley et al. identified some of the trends in hydrogen prevalence, they did not explore the reasons for differing results in detail.

In this perspective, we assess hydrogen’s potential as a contributor to energy systems and examine the methods used in global energy scenarios in order to understand the reasons for differing results regarding hydrogen. We focus on global energy scenarios produced by prominent institutions, as these are typically the most influential. The entire scenario development process is considered, including conceptualisation, model construction, and input data. Based on this analysis, we suggest some best practices for energy scenarios so that they can provide the best insight, and correctly quantify the potential of energy technologies such as hydrogen.

Section 2 provides an overview of hydrogen as an energy carrier. Section 3 provides details of hydrogen prevalence in scenarios from 12 global studies. In Section 4, the reasons for varying results between scenarios are discussed. Finally, some conclusions and suggestions for best practice in scenario development are provided in Section 5.

Global energy scenarios and the representation of hydrogen

Energy scenarios

Energy scenarios can address the uncertainties surrounding the socio-technical evolution of energy sectors. Scenarios can be qualitative, relying on inputs from experts and stakeholders, or quantitative, usually based on energy systems models. Scenario development aims to construct possible futures and the paths leading to them and can guide strategic decision-making processes, for example for maintaining long-term energy supply-demand balances and optimising investment decisions. Consequently, these scenarios can be highly influential to the future of the technological “ecosystem” in different sectors. Due to the size and complexity of the energy systems being represented by energy scenarios, simplifying assumptions must be made, and these can have significant implications for the scenario results.

Several reviews of model-based scenarios and the modelling tools they use have been carried out, highlighting a variety of methods and results. Penningten et al. reviewed energy systems models in the context of present-day energy systems and identified several challenges that these models face, stemming from the increased complexity of modern energy systems. The review also provided recommendations for modelling practice, encouraging innovation with modelling methods, appropriate handling of uncertainty and modelling transparency. Meanwhile, Gambhir et al. reviewed energy scenario results, finding that the level of climate change ambition has a significant effect on the scenario results. Lopian et al. investigated trends in energy system models developed for national greenhouse gas reduction strategies, in the context of underlying research questions and their shift over time, and found that there is an increasing need for high temporal and spatial resolutions.

As Hanley et al. found, the prominence of hydrogen varies significantly between energy scenarios. Whilst many of the scenarios Hanley et al. studied included some hydrogen in the transport sector, hydrogen prevalence in other sectors was low, except where hydrogen was a specific focus of the study. The scenarios that focus on hydrogen, such as the IEA Energy Technology Perspectives (ETP) 2 °C “high hydrogen” scenario, have begun a trend of greater hydrogen representation, and hydrogen prominence is growing in the most recent scenarios.

In this perspective, we discuss why there has been a historical absence of hydrogen.
Table 18
Details of the studies and scenarios that were reviewed. Global studies from influential institutions were chosen, focussing on quantitative (model-based) scenarios. Two qualitative scenarios were also included.

<table>
<thead>
<tr>
<th>Study</th>
<th>Abbreviation</th>
<th>Model used</th>
<th>Scenario end year</th>
<th>Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>REMap (IRENA) [51]</td>
<td>REMap</td>
<td>E3ME</td>
<td>2050</td>
<td>Reference REMap</td>
</tr>
<tr>
<td>Energy Technology Perspectives (IEA) 2016 [52]</td>
<td>ETP 2016</td>
<td>ETP TIMES + MoMo</td>
<td>2050</td>
<td>6DS, 4DS, 2DS</td>
</tr>
<tr>
<td>Energy Technology Perspectives (IEA) 2017 [53]</td>
<td>ETP 2017</td>
<td>ETP TIMES + MoMo</td>
<td>2060</td>
<td>RTS, 2DS, B2DS</td>
</tr>
<tr>
<td>Energy Revolution (Greenpeace) [54]</td>
<td>ER</td>
<td>REMix</td>
<td>2050</td>
<td>Reference E[R], ADV E[R]</td>
</tr>
<tr>
<td>Shell scenarios [16] [55]</td>
<td>Shell</td>
<td>Shell World Energy Model</td>
<td>2100</td>
<td>Mountains, Oceans, Sky</td>
</tr>
<tr>
<td>Global Energy Assessment (IIASA) [56]</td>
<td>GEA</td>
<td>MESSAGE + IMAGE</td>
<td>2050</td>
<td>Supply (Conv. Trans), Mix (Conv. Trans), Efficiency (Conv. Trans), Supply (Adv. Trans), Mix (Adv. Trans), Efficiency (Adv. Trans)</td>
</tr>
<tr>
<td>Hydrogen Council (2017) [57]</td>
<td>H₂ Council</td>
<td>Qualitative</td>
<td>2050</td>
<td>Hydrogen – scaling up</td>
</tr>
<tr>
<td>Technology Roadmap: Hydrogen and Fuel Cells (IEA) [30]</td>
<td>H₂FC Roadmap</td>
<td>Qualitative</td>
<td>2050</td>
<td>2DS high H₂</td>
</tr>
</tbody>
</table>

In global energy scenarios, and why that is beginning to change. Many energy scenarios exist at regional and national levels, such as the EU Reference scenario, [62] ASEAN Energy Outlook (SE Asia), [63] IDB Lights On scenario (Latin America), [64] EIA Annual Energy Outlook (USA), [65] China Renewable Energy Outlook, [66] the Japan Strategic Energy Plan, [67] and the Deep Decarbonization Pathways Project (various countries). [68] However, in this perspective we focus on global scenarios with the greatest international impact.

The 12 studies that were considered are shown in Table 18. We focus on the scenarios from 10 model-based studies and also consider two hydrogen-focussed qualitative scenarios: the IEA Hydrogen and Fuel Cells Technology Roadmap [30] and the Hydrogen Council “Scaling Up” scenario, [57] as they provide a counterpoint for the potential for hydrogen, as perceived by experts and stakeholders.

Table 18. Details of the studies and scenarios that were reviewed. Global studies from influential institutions were chosen, focussing on quantitative (model-based) scenarios. Two qualitative scenarios were also included.

Hydrogen representation in global energy scenarios

Between the 35 scenarios considered there is significant variation regarding which hydrogen technologies and end-use applications are considered, and the level of detail with which they are included. In Figure 64, the level of representation of these hydrogen technologies is presented, including whether the technology is modelled, whether data assumptions are provided, and whether hydrogen contributes to the final results. Whilst there are conflicts in the prominence of hydrogen between scenarios, what is common is that limited specific techno-economic information is provided. Often, concepts are discussed but with little detail, so it is difficult to understand how these concepts are represented and what assumptions have been made.

Regarding technologies, hydrogen production is covered in the most detail, and in this case, techno-economic assumptions are often provided. Electrolysis is commonly considered, although the technology type is rarely specified (WEO 2018, [14] Shell, [16] Shell [55] GEA, [56] ER, [54] REMap[69], ETP 2017 specifically...
**Figure 64**
Differing representation of hydrogen in scenarios from 12 global studies. Hydrogen representation is separated into seven sectors, covering the supply-side (production, storage, transportation), and applications of hydrogen (conversion to electricity, mobility, industry, gas grid). Colours refer to the level of representation in the scenario design; “R” denotes technologies that are included in the results of the scenario. See the legend for more details.

<table>
<thead>
<tr>
<th>STUDY</th>
<th>SCENARIO</th>
<th>TECHNOLOGY</th>
<th>SECTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2016 New Policies</td>
<td></td>
<td>Supply (Conv Trans)</td>
</tr>
<tr>
<td></td>
<td>2017 New Policies</td>
<td></td>
<td>Supply (Conv Trans)</td>
</tr>
<tr>
<td></td>
<td>2018 New Policies</td>
<td></td>
<td>Supply (Conv Trans)</td>
</tr>
<tr>
<td>The Grand Transition</td>
<td>2016 Hard Rock</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td></td>
<td>2016 Unfinished Symphony</td>
<td>Electrolysis, Production</td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td></td>
<td>2016 The Future is Electric</td>
<td>Electrolysis</td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>REMap (RENA) 2018</td>
<td>Reference</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>Energy Technology</td>
<td>2016 BTS</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>Perspectives (IEA)</td>
<td>2016 ZO5</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>Energy Technology</td>
<td>2017 Reference</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>Perspectives (IEA)</td>
<td>2017 ECO5</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>Energy Revolution</td>
<td>2016 Reference</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>(Greenpeace) 2015</td>
<td>2017 ECO5</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>Shell scenarios 2018</td>
<td>Reference</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td></td>
<td>2012 H2 Council</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
<tr>
<td>H2FC Roadmap 2015</td>
<td>2015 ZO5 High H2</td>
<td></td>
<td>Supply (Adv Trans)</td>
</tr>
</tbody>
</table>

Consideration of the more commercially developed alkaline electrolysis, whereas the H2 Council focus on PEM electrolysis, which many expect to overtake alkaline as the favoured technology. [40] The qualitative H2FC road map [30] is the only study to consider solid-oxide electrolysis.

Several studies discuss other production options, such as SMR, coal gasification and biomass-based production. These production options are typically mentioned when comparing hydrogen production costs (WEO 2018, [14] H2FC Roadmap [30]) or as a transitional step to fully decarbonised hydrogen (Shell [16][55]). The technoeconomic assumptions related to these technologies (mainly SMR, with or without CCS) are often presented, and it is observed that the costs of electrolysis and SMR + CCS are converging. [30]

Other hydrogen infrastructures, such as transportation and storage, receive little coverage in most studies. A few studies discuss storage, but provide no data, suggesting it is not modelled (GEA, [56] ER, [54] H2 Council [57]). Hydrogen transportation receives slightly more coverage, most commonly shipping for global transportation (WEO 2018, [14] H2 Council, [57] GEA [56]). In general, limited data is provided for transportation, so it is unclear what assumptions are made (e.g. how transportation is costed), or whether it is considered at all.

End-use applications are described in more detail in the scenarios. The most prominent end-use is mobility, which is considered in some form in all but WEO 2016 (49) and WEO 2017. [50] Fuel Cell Electric Vehicles (FCEVs) for light-duty passenger vehicles (LDVs) are predominant but heavier duty vehicles (HDVs), e.g. trucks and buses are also discussed in more-recent studies (though rarely quantified). Instead, the discussion is more focussed on societal issues, such as government policies. The qualitative studies [30][57] provide more techno-economic data for HDVs. Finally, there is some interest in hydrogen for alternative fuels but limited details on techno-economic assumptions are provided (ER, [54] ETP 2017, [53] H2 Council [57]).

Beyond mobility, other hydrogen applications are discussed in less detail. Several studies consider industrial applications, with refining applications such as steel and iron, and chemical applications such as ammonia production being the most popular. Electrification of processes via electrolysis is mentioned (WEO 2018 [14]), but again with little detail. Interactions with the gas grid (either direct hydrogen injection or methanation) are often mentioned in the discussion but rarely quantified in the results (GEA; [56] WEO 2017, [14] H2FC Roadmap, [30] H2 Council [57]). Finally, conversion of hydrogen to electricity and heat is rarely mentioned. Where it is considered, the most common technologies are fuel cells, gas turbines and combined heat and power applications. The E[R] scenarios [54] are the only ones to include these applications in the scenario results.

**Conflicting roles of hydrogen in global scenario results**

The variability in representation of hydrogen in scenarios leads to conflicts in the level of contribution of hydrogen in the scenario results. Figure 65 shows the contribution of hydrogen to final energy demand in 2050 in different sectors, for each of the scenarios that include hydrogen in its results.

Overall, the scenarios indicate that hydrogen has the most potential in the mobility sector. Most scenarios have some level of hydrogen in this sector but they offer conflicting levels of contribution: in many cases, this is less than 2% of transport energy demand in 2050 (e.g. WEC [15] and ETP 2017 [53] (scenarios), whereas the Greenpeace E[R] and Adv E[R] scenarios give contributions as high as 19% and 25%, respectively. [54].

Similarly, the contribution of hydrogen in the
**Figure 65**

Contribution of hydrogen to final energy demand in 2050 in power, mobility, industrial and heat sectors for a range of scenarios. Where studies state the inclusion of hydrogen in the results without precisely quantifying it, values have either been estimated by the author (IEA ETP 2016, Shell Sky and H₂ Council scenarios), or the result has been denoted by a hashed box.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>The Grand Transition (WEC 2016)</td>
<td>Hard Rock</td>
<td>Unfinished</td>
<td>Modern Jazz</td>
</tr>
<tr>
<td>REMAP (IRENA) 2018</td>
<td>Reference</td>
<td>REmap</td>
<td></td>
</tr>
<tr>
<td>Energy Technology Perspectives (IEA) 2016</td>
<td>605</td>
<td>405</td>
<td>205</td>
</tr>
<tr>
<td>Energy Technology Perspectives (IEA) 2017</td>
<td>205</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>Energy Revolution (Greenpeace 2015)</td>
<td>Reference</td>
<td>EER</td>
<td>ADV EER</td>
</tr>
<tr>
<td>Shell scenarios 2018</td>
<td>Mountains</td>
<td>Oceans</td>
<td>Sky</td>
</tr>
<tr>
<td>Global Energy assessment 2012</td>
<td>Supply (Conv Trans)</td>
<td>Mix (Conv Trans)</td>
<td>Efficiency (Adv Trans)</td>
</tr>
<tr>
<td>H₂ Council 2017</td>
<td>Hydrogen - scaling up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen FC Roadmap 2015</td>
<td>2DS High H₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Contribution of hydrogen to final energy demand in different sectors

- **POWER**
- **MOBILITY**
- **INDUSTRY**
- **HEAT**

Industrial sector ranges between 0.7% of 2050 industrial demands (Shell Sky [16]) and 12% (H₂ Council [57]), but many scenarios do not include it at all.

The focus between these two sectors can also shift between scenarios: the Grand Transition scenarios suggest hydrogen should contribute to the mobility sector and not to industry whereas several of the Global Energy Assessment scenarios advocate the opposite.

### Discussion: what must scenarios do to represent hydrogen fairly?

From the results in Section 3, and previous reviews, there is clearly significant variation between scenarios concerning the prominence of hydrogen in energy systems. Although most of these scenarios rely on energy system models, the representation in these models is not sufficient to capture all of the advantages of hydrogen. In this section, we examine the key steps in quantitative scenario development, to understand why differing results may arise, and consider what scenario developers should be doing to make sure hydrogen, and other flexibility options, are appropriately represented.

### Scenarios must use appropriate modelling tools

Energy systems models form the basis of most quantitative energy scenarios. A vast number of energy system modelling tools exist and can be categorised in different ways, including simulation vs. optimisation, top-down vs. bottom-up, etc. In a review of computing tools for energy systems, Connolly et al. [71] identified 68 different energy system modelling tools. Lopion et al. [65] reviewed 24 energy system models in detail, also categorising them as above, and found a clear trend towards technoeconomic bottom-up optimisation models in order to answer current research questions.

Each energy systems model is designed for its unique purpose and has its own strengths and weaknesses. Some of the oldest models were developed in the second half of the 20th century to help understand energy systems in the context of the oil crisis and concerns over the security of energy supply. These models are the predecessors of many models in use today, where due to climate change, we face significantly different energy challenges. It is important that energy systems models in use today are appropriately designed to represent the challenges we face in the twenty-first century.

The most difficult task for modern-day energy systems models is to capture the full degree of variability and complexity that exists in energy systems. Traditionally, energy systems were centralised and underpinned by fossil fuels. In the electricity sector, for example, supply would be made up of either baseload or dispatchable generation. However, as more and more renewable sources such as solar and wind are introduced to aid decarbonisation, systems are becoming more spatially distributed, technologically diverse and temporally variable. Meanwhile, new technologies and increased interconnectivity are enabling more interaction between different energy sectors, known as “sector-coupling”. [72] To ensure that energy system models not only provide an accurate representation of energy systems but also do not miss the potential of new technologies such as hydrogen-based technologies, they must capture the required level of temporal, spatial, technological, and inter-sectoral detail.

### Models must capture sufficient temporal detail

Many large-scale energy models are unable to represent the time scales at which flexibility technologies such as electrolyser, hydrogen storage and fuel cells are most useful. For example, traditional energy system models typically use representative time slices, such as representative time slices.
as day, night, and peak for a series of day types throughout the year. In some cases, a within-day chronology is retained, meaning that it is possible to model some level of intraday storage. However longer-term chronology is rarely retained, thus losing the ability to represent long-term storage.\(^{[73][74]}\) which is an area where hydrogen is seen to have strong potential.\(^{[6]}\)\(^{[75]}\) Novel methods for modelling seasonal storage are beginning to emerge\(^{[76][77]}\) but they have not been applied to any of the global energy scenarios. Meanwhile, short-term dynamics, such as electricity dispatch on a sub-hour basis, are also not modelled by large-scale energy models. This means that another opportunity for hydrogen, as a short-term load balancer through electrolysis, is also not modelled by large-scale energy models. This means that another opportunity for hydrogen, as a short-term load balancer through electrolysis,\(^{[73]}\)\(^{[78]}\) is also missed. The effects of under-representing temporal detail in energy scenarios have been explored and it has been found that investment optimisations will underestimate the contribution of dispatchable power generation and instead favour baseload and intermittent renewables.\(^{[80]}\) It is therefore likely that flexibility options such as those based on hydrogen are also being under-valued.

The challenge for large-scale energy systems models is to capture the full range of time scales necessary. The models are designed for long-term investment planning and therefore require multi-decadal time horizons. However, the dynamics of the energy system at all time scales (including seasonal, weekly, daily, and sub-hour) are important to how the system should be designed and operated.\(^{[81]}\) Approaches to improve the accuracy of the time-slicing method include using a higher resolution of time intervals; probabilistic representation of the loads and renewable energy supplies; and using real historical data for the time intervals.\(^{[73]}\)\(^{[79]}\) However, each of these approaches suffers the same issue of failing to maintain chronology across the whole time horizon, hence some representation of flexibility is lost. Alternatively, energy systems models can be soft-coupled to power sector models, taking advantage of the latter’s improved temporal representation.\(^{[73]}\) However, this approach can increase overall complexity, as there are two separate models to maintain and run. Furthermore, due to the required iteration between the two models, there is no guarantee that an optimal solution will be obtained.

Models must capture sufficient spatial detail

As well as temporal flexibility, hydrogen can provide spatial flexibility to energy systems. Hydrogen transportation by road, pipeline and shipping provide opportunities for the transportation of energy that cannot be provided by other energy carriers (e.g., electricity). Large-scale (e.g., global) energy models usually have limited spatial detail, using average resource demands and supplies over large spatial regions.\(^{[58]}\) Consequently, they do not capture the value of energy transportation at a smaller scale, such as across country. Furthermore, spatial variabilities in solar and wind generation will affect supply profiles across a region: this “spatial smoothing” cannot be fully represented with too coarse a spatial resolution.\(^{[73]}\)

One option for improving this modelling would be to include a higher spatial resolution but this would significantly increase the complexity of the model. Alternatively, models should seek to use representative data and relationships to value within-region energy transportation and distribution.

Models must appropriately represent technologies and inter-sectoral connectivity

Technological representation in large-scale energy models is often restricted to blanket details for each technology type, rather than representing individual technologies or plants.\(^{[80]}\) Consequently, realistic operation of plants, taking their flexibility constraints into account, is not modelled. This is not helped by the lack of temporal resolution and chronology.

To improve technological representation, approaches include further modelling of ancillary markets (e.g., flexibility markets), and broader constraints that attempt to represent the overall behaviour of many individual technologies of a given type.\(^{[73]}\)

Finally, hydrogen is central to several sector-coupling options, including power-to-gas (for the gas grid),\(^{[37]}\) power-to-heat,\(^{[82]}\) power-to-liquids,\(^{[83]}\) and power-to-ammonia.\(^{[84]}\) Energy systems models need to include the opportunity for transfers of energy between sectors, as this can unlock potential for cost and resource efficiency savings.

Models must represent the complexity of consumer behaviour

Uptake of new technologies is not only driven by cost or efficiency-based metrics for the entire energy system, but also by consumer choice, dependent on social factors and personal preference. For example, market adoption of FCEVs is sensitive to consumer perception of factors such as driving range, battery life, depreciation and capital cost. Furthermore, vehicle uptake is affected by consumer perception in the used vehicle market. There are significant variations between models regarding how consumer choices are represented, for example, the inclusion and relative importance of different utility factors representing consumer choice. Improvements in modelling can be achieved with more readily available data on elasticities and utility factors. Furthermore, a more detailed representation of different technology types (e.g., different weight and range categories for vehicles) will allow for a more accurate representation of consumer choice.

Models must remain manageable and user-friendly

Increasing computational power means that larger, more complex and more realistic models can be developed. However, this greater detail can introduce difficulties for the model users, in terms of managing the much larger datasets that are required as inputs and generated as outputs, analysing the results and communicating them to a general audience, such as policymakers and the general public. The challenge for energy systems models is to use appropriate techniques such as those described above whilst preventing the model from becoming too difficult to use and to communicate. Although the detailed outputs of a complex model can be summarised using averages and high-level metrics, some of the important insights can only be understood from the details and presenting these in a manner that is easy to understand remains a key goal and challenge.

Model methodologies must be transparent

Due to the complexities in representing the details of energy systems, it is important that when scenarios are presented, the methodologies behind them are shared. The fact that these models are being used to predict what future energy systems may be, often many decades into the future, means that there is no real-life system against which the models can be validated. As most energy system models use optimisation and today’s energy systems are far from optimal, it is difficult even to validate these models against current data. For this reason, it is important that the mathematical formulations behind the models be published so that they can be appropriately peer-reviewed. However, this practice is very rare among the global energy scenarios: none of the scenarios reviewed in Section 3 has published the mathematical formulations of their models. Indeed, most give no or very little information regarding the modelling approaches used and only the IEA ETP studies\(^{[52][53]}\) describe qualitatively the
Challenges and pitfalls

We have argued that models must be much more detailed, and therefore complex than are currently being used in global energy scenarios. Including features such as high spatial and temporal resolutions, uncertainty analysis, consumer behaviour and including a large range of technologies and energy carriers in a model is extremely challenging. Of course, the models should be made only as complex as is necessary to represent all of the features and details of hydrogen (and other) technologies that may play a role in the future energy system (such as rapid-response load balancing technologies). Modellers and scenario planners should follow a structured approach to developing new models similar to the one below:

1. **Describe the purpose of the study carefully.**
2. **Define the scope so that the purpose can be achieved satisfactorily and with sufficient accuracy.**
3. **Build the simplest model that can accurately represent all of the features and interactions of the system defined in the scope.**
4. **Provide assumptions and limitations.**
5. **Discuss results in light of assumptions and limitations, acknowledging that the model is imperfect.**

Deciding the necessary level of detail and accuracy is itself a difficult decision but this can be helped by performing smaller studies involving particular technologies to determine what level of spatial and temporal detail are required. The greatest difficulty for a modeller is when the required level of detail is so high that the model becomes computationally very demanding but further simplifications make the model no longer fit for purpose.

It is understandable that time pressure or intractability may tempt researchers into oversimplifying models to obtain results. This is a pitfall that needs to be avoided or at least taken with extreme caution. The results and conclusions obtained from an oversimplified model can be misleading and possibly erroneous. In the context of hydrogen, if a technology does not appear in the results then it is not possible to determine whether this is because of an inherent disadvantage of the technology or whether it is due to the inadequacy of the model to represent the technology’s benefits.

Despite the challenges of including an unprecedented level of detail in energy system models, these are not insurmountable goals. As has been mentioned, techniques have already been developed that allow national energy systems to be optimised with high levels of spatial and temporal disaggregation. With increasing computing power and further research into advanced techniques and algorithms, more complex and detailed models will be possible in the near future. Scenario developers should be aiming to take advantage of these developments to obtain more reliable, and perhaps surprising, results.

**Scenarios must be designed appropriately**

Scenario design, including which sectors and technologies are included, what the level of ambition is, and what performance metrics are used, has a significant influence on scenario results. Scenario design will partly be determined by the capabilities of the model used. However, many decisions will also be made by the developer.

**Scenarios must include all relevant sectors**

As the results in Section 3 show, there is significant variation in the sectors that are included in different scenarios. Some sectors, such as mobility, are represented in almost all scenarios, but others have significant variability. For example, hydrogen is widely discussed as a key decarbonisation option for industry, as shown by its strong representation in the qualitative scenarios. Furthermore, in almost all quantitative scenarios where hydrogen in industry is included as an option, it contributes to the final results (e.g. ReMap, Shell and the Global Energy Assessment).

However, several studies omit hydrogen in industry altogether, such as the early WEO and ETP scenarios, the WEC Grand Transition, and even the ambitious Energy Revolution scenarios. Given that hydrogen does appear in the results of many of the scenarios that included it, it is reasonable to wonder if it would have also played a role in the other scenarios had they included it.

The other applications of hydrogen (re-conversion, gas grid) show similar variability between different scenarios and there is no consistent trend regarding which scenarios include which sectors. For studies that have re-produced scenarios in consecutive years (WEO, ETP), it is noticeable that the newer scenarios have a more comprehensive inclusion of sectors than the older scenarios. For example, WEO 2018 had at least some discussion of re-conversion, mobility, industry, and the gas grid, whereas the previous iterations of the study (2016 and 2017) did not consider any of these sectors. Assuming that the modelling methods for these scenarios are not changed significantly from one year to the next, this again suggests that had these sectors been included earlier, they would have been seen in the scenario results. This shows the importance of including the sectors that have the most potential and suggests that awareness of the potential solutions of applications such as hydrogen is important for their prevalence in scenario results.

**Scenarios must be technology-rich: a technology not included will not appear in the results**

As well as the importance of which sectors are included in a given scenario, it is important
to consider which specific technologies are included. Again, Figure 64 shows the variability in the hydrogen technologies that are included in each scenario. Figure 64 would suggest that electrolysis is a key technology for hydrogen, as it is included in almost all scenarios. However, some scenarios even omit this technology. Despite referring to hydrogen as a transport fuel and the use of fuel cells, the WEC Grand Transition [15] makes no reference to electrolysis or any other hydrogen production technology. The scenarios with a richer representation of hydrogen production technologies (e.g., fossil or biomass-based options as well as electrolysis) typically also include a greater representation of hydrogen in the scenario results.

A challenge for energy scenarios is to keep pace with and to estimate future technology developments so that they can be appropriately represented in scenarios for energy systems several decades in the future. For example, solid oxide electrolysis is a technology with significant interest due to its potential for higher efficiencies, reversible operation and co-electrolysis with carbon dioxide. [39] This is reflected in the technology’s inclusion in the H2FC Roadmap. [30]

However, the technology currently has a low level of commercial development, so it is not included in any other scenarios.

Some of the most widely discussed advantages of hydrogen are its useful as an alternative energy vector, particularly for large-scale storage and transportation. However, these technologies are omitted from many scenarios. Hydrogen has high volumetric energy compared to alternative energy storage options, so it is seen to have the potential for large-scale energy storage applications, for example for balancing electricity supplies and demands in systems with large penetrations of intermittent renewable energy. This potential is reflected in the qualitative scenarios, as well as in the Shell and GEA scenarios, however, no other scenarios include hydrogen storage.

Similarly, another advantage of hydrogen is that it can be transported easily at a range of scales. Unlike electricity, hydrogen can be shipped across long distances internationally, creating the potential for global supply chains. [37] Pipelines also provide the opportunity for hydrogen transportation, and there is interest in both purpose-built hydrogen pipelines and re-purposing existing natural gas grids.

At a smaller scale, hydrogen can also be transported on road by a truck. Like storage, hydrogen transportation is hardly included in any of the scenarios.

The omission of these key hydrogen infrastructures is significant, as they are central to what makes hydrogen a potentially valuable energy carrier in future systems. Whilst the technologies for hydrogen production and consumption may not be the most efficient or the lowest cost, benefits arise from the efficiency with which hydrogen can be stored and transported, and hence these infrastructures should be included in energy scenarios.

Scenarios must have an appropriate level of ambition

In addition to the technologies and sectors included in the scenario, the level of scenario ambition also influences the prevalence of hydrogen in the results. Most scenarios investigate how an energy system may evolve over time, under existing or expected policies, and can be described as “explorative”, whereas other scenarios impose strict targets on the final energy system and can be referred to as “normative”. Reduction of greenhouse gas emissions is a typical target in normative scenarios. While some explorative global energy scenarios can even show an increase in global greenhouse gas (GHG) emissions, normative scenarios often target drastic cuts in GHG emissions, including nearly net-zero emissions scenarios.

GHG reductions and hydrogen prevalence is challenging, due to the tendency for scenarios to discuss hydrogen usage without providing specific data. However, Figure 66 shows estimated hydrogen usage as a percentage of total final energy demand in several scenarios, compared with the GHG emissions reduction in the scenario. A negative GHG emissions reduction represents an increase in emissions over the scenario time horizon.

Ambitious GHG reduction targets are achieved to some extent with increased uptake of intermittent renewables such as wind and solar. Consequently, energy system flexibility is required to balance electricity supplies and demands. With intermediate decarbonisation objectives, such as an 80% reduction in emissions this “backup” can be provided by fossil fuels. However, in close to “net-zero” scenarios, nearly any usage of fossil fuels must be balanced by carbon sequestration. Where carbon sequestration is unattainable (due to technical, economic or social factors), alternatives such as hydrogen for energy storage become much more attractive.

Furthermore, with more variable renewable electricity generators on the grid in ambitious GHG scenarios, there is increased complexity in energy markets, for example with increased occurrence of near-zero power prices arising from excess electricity generation. In these situations, there is greater potential for alternative technologies such as power-to-gas to find viable business cases. [92][93]

Finally, scenarios with less ambitious decarbonisation objectives do not always consider the decarbonisation of the more challenging sectors, such as industry or long-haul transport. Certain hydrogen pathways, such as power-to-fuels, are particularly
Scenarios must consider other objectives

Besides the level of decarbonisation and renewables integration ambition, many other objectives and constraints, such as political interest, social acceptance and national strategies, may be included in a scenario that will affect its outcomes. For example, nuclear power is a politically controversial technology that many countries are choosing to phase out. Other potentially controversial technologies include CCS and even onshore wind power. Meanwhile, there are also resource-based constraints: e.g. some regions have limited biomass potential, limiting this option for future energy systems aiming for energy independence. These choices shape the scenario design and the evolution of the energy system. As these become more constrained, it is possible that hydrogen pathways will emerge as one of the remaining degrees of freedom to achieve ambitious climate targets.

Scenarios must use consistent and substantiated data assumptions

As well as broad scenario design, the thousands of data parameters that are input into each scenario will influence the scenario results. Typical input data for technologies in energy systems models will include cost data (e.g. capital and operating costs) and performance data (e.g. operating rates, efficiencies, environmental impacts, etc.). For any technology there will be an uncertainty range in these data, depending on how, when and where the technology is installed and operated. As an example, some cost estimates for key hydrogen technologies are shown in Table 19, showing the wide uncertainty range in the literature. Energy scenarios are not able to capture this range in every detail, due to the large number of variables already being considered, and consequently must carry out some “averaging”.

Energy scenarios also need to capture the changes in cost and performance data that will occur over time. Rapid progress in energy technologies has been seen before, for example in solar PV[3] and lithium-ion batteries. [96] This sort of progress is dependent on the scale of production. Learning curves can be used to estimate improvements in cost and technical performance with increased production rates but estimating the rates of uptake of technologies is challenging, particularly as these can be influenced by government policy.

Large-scale energy scenarios are typically based on policies that are already in place and free-market decisions. For the future, usually broad policies (e.g. system-wide GHG targets) are used rather than sector-specific. Technology agnostic measures are usually preferred, to promote the development of the most competitive options, and ensure that governments do not choose technologies with higher costs for society. However, due to the learning curve effect, some technologies that are not economically attractive in the early stages of deployment may deliver a lower long-term cost. This requires additional incentives to go beyond this “valley of death” region to be able to reach that long term target. [103]

For example, although electrolysis is a relatively well-established technology, studies that find hydrogen from electrolysis to be competitive with conventional hydrogen production or even fossil fuel alternatives usually rely on reductions in cost resulting from significant scale-up of production [97], which most likely would only occur with strong government support. Similarly, for technologies at the R&D level, incentives need to be technology-specific since this will determine the research strategy and priorities. In turn, this R&D can lead to cost and efficiency improvements, which will influence the prominence of technology in energy scenarios. Experience from the power sector has shown that a mix of technology-specific and technology-neutral policies achieve the best results in promoting low carbon options. [104]

Model-based scenario studies should model a full range of technology and policy assumptions. Ideally, sensitivity analysis would be used to understand the significance of different data uncertainties on scenario results. This analysis may also provide insights into the relative value of R&D for different technologies and sectors. Of course, sensitivity analyses can be expensive when applied to large, complex models, hence there is an argument for simpler models, with a more thorough treatment of data uncertainty. [105] Despite this, the models should not be simplified to the point where they no longer represent the energy system with sufficient accuracy, as this will result in unrealistic sensitivities, especially when non-linear effects are involved. The simplified model should only be used for sensitivity analysis and the more-detailed model used to explore interesting “corner” points identified in the analysis – to check that the analysis is correct.

As a minimum, studies should share the data assumptions that were made in their analysis but unfortunately even this is rare. The IEA H2P2 Roadmap [39] and IASA Global Energy Assessment [56][106] contain detailed descriptions of the technical and economic performance of most hydrogen technologies throughout the supply chain. However, as Figure 64 shows, several studies include hydrogen in their scenario results but little or no information at all is given on the data assumptions made (e.g. WEC [15] Shell [16]).

Conclusions

Energy systems are becoming more technologically diverse, spatially distributed and temporally variable. Consequently, there is an opportunity for new “flexibility” options, such as hydrogen, to play a role. In the authors’ view, the greatest opportunities for hydrogen lie in the industrial and heavy-duty transport sectors, where hydrogen’s high energy density and low greenhouse gas emissions could make it the preferred energy carrier. With the establishment of large-scale hydrogen production, transportation and storage infrastructure for these sectors, there will be many opportunities to use hydrogen for additional flexibility in other sectors, such as the power sector.

---

### Table 19

<table>
<thead>
<tr>
<th>Technology</th>
<th>Units</th>
<th>Capex Today</th>
<th>Capex 2050</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyser (alkaline)</td>
<td>€ per kW</td>
<td>800–1700</td>
<td>400–700</td>
<td>[39][97][98]</td>
</tr>
<tr>
<td>Electrolyser (PEM)</td>
<td>€ per kW</td>
<td>1300–3200</td>
<td>300–700</td>
<td>[39][97][98]</td>
</tr>
<tr>
<td>SMR (with CC)</td>
<td>€ per kW</td>
<td>600–1300</td>
<td>400–600</td>
<td>[11][30][98][99]</td>
</tr>
<tr>
<td>H₂ storage (vehicle on-board)</td>
<td>€ per kW</td>
<td>13-20</td>
<td>8 (target)</td>
<td>[100]</td>
</tr>
<tr>
<td>Fuel cell (vehicle on-board)</td>
<td>€ per kW</td>
<td>38-152</td>
<td>34 (target)</td>
<td>[100]</td>
</tr>
<tr>
<td>H₂ storage (NG compressed)</td>
<td>€ per kW</td>
<td>0.1-2.0</td>
<td>0.1-2.0</td>
<td>[98][99][101]</td>
</tr>
<tr>
<td>Fuel cell (stationary)</td>
<td>€ per kW</td>
<td>640–2900</td>
<td>330–1500</td>
<td>[30][102]</td>
</tr>
</tbody>
</table>
However, the exact role that new technologies such as hydrogen will have is unclear, and it is the purpose of energy scenarios to help to indicate what the role might be. In the authors’ view, global energy scenarios, especially those based on energy system models, have been pessimistic concerning hydrogen. This is beginning to change but coverage of hydrogen is still often restricted to a few main applications, such as mobility.

The main challenge for energy systems models is that many of the opportunities for new technologies such as hydrogen are in spaces that previously have not existed in energy systems, for example in energy storage (both at short and long-time scales) and for sector-coupling. Energy systems models have traditionally not been good at representing the fine details, such as temporal variability. Capturing these details, whilst also encompassing the big picture of a long-term global energy transition is computationally and practically complex, and therefore a big challenge for the modelling community. Nonetheless, techniques are emerging to handle these complexities, and computational power is improving all the time, enabling more ambitious projects. We believe that overcoming these challenges will be necessary to determine with confidence the role that hydrogen should play in the future energy mix.

Meanwhile, if global energy scenarios are currently unable to represent all of the fine details and nuances of future energy systems, it is essential that they acknowledge this and do not present their scenario results with overconfidence. Much greater sharing of the methodologies and input assumptions behind energy scenarios is needed so that the implications of the results can be correctly interpreted. Scenario developers should also constantly improve their practice, informed by findings from elsewhere. Numerous alternative approaches have been developed for exploring the role of new technologies in future energy systems, including qualitative scenarios and more detailed energy systems modelling at smaller scales. All of this research is valuable and should be taken into account with as much esteem as global energy scenarios.

Authors’ contribution

All authors conceptualised the study at an initial workshop. CJQ & SS coordinated and drafted the paper. OT & LW reviewed global energy scenarios. HH provided an analysis of scenario ambition and hydrogen prevalence. CM, NJS & HB helped structure the paper, contributed to the draft and provided feedback. JL and MR provided feedback and additional arguments.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

The present work was carried out within the framework of Task 38 of the Hydrogen Technology Collaboration Programme of the International Energy Agency. The task is coordinated by the Institute for techno-economic of energy systems (I–TIES) of the CEA, supported by the ADEME. CJQ and SS would like to acknowledge the Department of Business, Energy and Industrial Strategy (BEIS) and the Engineering and Physical Sciences Research Council (EPSRC) for funding his studentship. Thanks also to Dr Ian Llewelyn and Dr Jose M. Bermudez from BEIS for their very valuable inputs and feedback on this work. OT acknowledges the funding provided by Air Liquide to support her PhD thesis (framework of her contribution to this article). MR acknowledges the Helmholtz Association under the Joint Initiative “Energy System 2050 – A Contribution of the Research Field Energy” and Detlef Stolten for very important contributions and insights. SS would like to thank the

REFERENCES

[18] B. Pivorov, N. Rustagi and S. Satyapal, Hydrogen at Scale (H2@Scale) key to a clean, economic and sustainable energy system,


CHAPTER V

Part 2: Task Force – Data – The challenge of a collaborative database to support evolving modeling needs

Database – General considerations

The term database within IEA HIA tasks often references any collection of related data (such as a spreadsheet or a card index).

Formally, a “database” refers to a set of related data and the way it is organized. A “database management system” (DBMS) is a software package designed to define, manipulate, retrieve, and manage data in a database and provides ways to manage how that information is organized.

Existing DBMSs provide various functions that allow management of a database and its data which can be classified into four main functional groups:

- Data definition – Creation, modification and removal of definitions that define the organization of the data.
- Update – Insertion, modification, and deletion of the actual data.
- Retrieval – Providing information in a form directly usable or for further processing by other applications. The retrieved data may be made available in a form directly usable or for further processing by other applications. The retrieved data may be made available in a new form obtained by combining existing data from the database or in a new form obtained by altering or combining existing data from the database.
- Administration – Registering and monitoring users, enforcing data security, monitoring performance, maintaining data integrity, dealing with concurrency control, and recovering information that has been corrupted by some event such as an unexpected system failure.

Both a database and its DBMS conform to the principles of a particular database model.

“Database system” refers collectively to the database model, database management system, and database.

---


---
Task 38, when started, took into account the lessons learnt from previous tasks, which included:

- The importance of initiating data acquisition as early as possible in the process
- The need for visualisation to help data contributors check their inputs in terms of viability and consistency
- The limitations related to sticking to Excel as a unique tool when the amount of collected data starts to grow significantly

Database in the IEA Hydrogen TCP Tasks

Data gathered and used in the different tasks cover essentially:

- Geographical energy system representation (including demand), characterized by significant spatial diversity
- HFC Technologies representation, characterized by highly varying maturity (all TRLs involved) and a great diversity
- Lists of reference, studies and reports, increasing in number

Such diversity and complexity constitute, as such, a great challenge.

Besides, the acquisition process inherent to the TCPs is highly collaborative, relying on voluntary contributions from various entities, practices, geographies (e.g. time zones) adding to the challenge.

Finally, the cyclical aspect of a task-based organisation does not facilitate the maintenance and long-term management of data across them.

Then, it is yet to be acknowledged that some of the produced data have been lost or left unutilized, some data sets are incomplete, making it difficult to reuse, some data are still consistently missing.

Task 38 has proved no stranger to these challenges. Specifically, in Task 38, the effort to carry out as needed around 4 themes:

- Culture: to create alignment amongst the different contributors
- Process: to standardise data management methods across the participants and the different subtasks
- Structure: to provide a common database architecture with clear data definition
- Support (tools): to deliver data related advice and possibly build digital tools to facilitate the work of participants

Further to this, task 38 addressed the need for fundamentally richer models, with greater spatial and temporal resolution, allowing greater representativeness of the temporal and geographic flexibility provided by hydrogen systems. More details on this are addressed in Part I of this Chapter. Building databases to feed such models require larger and evolving datasets, which can be complex and time-consuming.

The need for an ad hoc effort around data management

It was then clear that a different approach to data/data management was necessary. More specifically, it was also obvious that Excel was no longer the most appropriate tool to support this effort. Excel makes it easy to store data, perform numerical calculations, format cells, and adjust layouts to generate the output and reports to share with others. Unfortunately, there’s a price for the flexibility of Excel. While spreadsheets are ideal for creating one-time analysis, they become problematic as the data grows and evolves over time. Maintainability becomes an issue, especially in a collaborative set up. For spreadsheet experts, it’s often difficult to understand what databases offer that spreadsheets don’t already have. However, one could highlight the advantages below:

- Data structure and normalization through multiple tables
- Scalability: adding more records is free
- Data and Referential Integrity
- Queries and Reports
- Automation through programming

Two concrete examples:

The first attempt focused on supporting the literature review in ST3A. Based on the desired functionalities, structure and supporting tools where proposed and discussed with the IEA.

However, the constraints in terms of programming language and SW infrastructure constituted a bottleneck for Persee to conduct the development of the desired tool and the initiative was stopped as no other resources could be mobilised to address the above-mentioned constraints.

The second attempt focused on supporting the modelling effort of ST4. However, the decision about the model to be used remained unsure for the first few years of the task as model decision remain a key topic at IEA H2 TCP. The idea then was to develop a data structure ‘fit for purpose’ and as the purpose was not defined whilst data collection was going on the data structuring effort, squizzed between the two was not feasible within this approach.

Finally, task force data concluded that the effort around data management is significant and requires proper resources. This is why a new task within the Hydrogen TCP is defined, called Task 41. This task aims to address the hydrogen data issue in a closer manner with regards to the needs of different energy system models.
After presenting the techno-economic and regulatory aspects of Power to X system deployment, this chapter addresses specific case studies in order to analyse the profitability conditions of hydrogen systems, with different steps of the supply chain and in different countries. The aim is to challenge these systems in different geographic contexts.

Introduction

In this chapter specific business cases related to power to X applications (power to ammonia, power to methanol and power to hydrogen mainly) are described. After a short introduction, the location is specified, followed by background information regarding the concrete application. Concrete application and specifications will define the facility requirements. In addition, the local configurations and peculiarities of the case study are described. The aim is to give an idea of the challenges faced by the different cases.

Authors

Carlos Funez1, Martin Robinius2, Darja Markova3, Ezequel Serwatka4.

Affiliations

1. Centro Nacional del Hidrógeno, Spain
2. Forschungszentrum Jülich GmbH, Institute of Electrochemical Process Engineering (IEK-3), Germany
3. Energie Institut an der Johannes Kepler Universität Linz, Austria
4. Hychico, Argentina
specifications are used to adapt the power to X applications (electricity price, transport price, renewables energies availability, etc.). For this purpose, the case studies in which the power to X facility and the product consumer are distant from each other, include a transport cost. Based on the derived applications, economic and environmental analyses are performed. In the end, characteristic barriers for the case study are identified.

The business cases considered in the ST5 are:

- Power to green ammonia for blasting industry in Chile.
- Power to green ammonia produced in Australia and transport to Japan (to use as hydrogen).
- Power to green hydrogen in Austria for the usage in a variety of applications in different sectors.
- Power to green hydrogen produced in Patagonia, Argentina and transport to Japan.
- Power to green hydrogen with waste CO₂ from green methanol production in China.

These five case studies allow addressing a variety of geographic contexts with different strategies regarding Power to X deployment. The selected applications have important potential by region respectively, following the governmental and industrial orientations.

- Chile, for instance, has an important renewable potential that not only can be exploited “onsite” to decarbonize the energy sector but also can be exported so that other regions with limited renewable resources and voluntarist hydrogen targets can benefit from this green hydrogen potential [1]. As an “onsite” application, Power to green Ammonia has been selected as Chile has leading industries consuming ammonia for blasting applications (mining activities, etc.).
- Australia has giant export potential [2]. As part of its national strategy [3], these exports will be mainly oriented, in the short term, to the Japanese market [4], [5]. In this case study, hydrogen is transported from Australia to Japan, in the form of ammonia in ships.
- In the south of South America, we can find the Patagonia, both Argentina and Chile. There we have one of the highest wind potentials worldwide. In this case study, hydrogen is transported from Patagonia, Argentina to Japan, in the form of liquid. This will allow contrasting international hydrogen transport as hydrogen in liquid form (previous case study from Australia to Japan) with transport costs when considering ammonia or liquid carriers.
- China is a giant stakeholder that could, seeing its size, with small shares of hydrogen in its market, bring down the costs. The selected application is Power to green Methanol. The latter being the second hydrogen consumer nowadays in China (after ammonia) [6].
- Austria is a case study from Europe, the latter being among the front-runners to integrate hydrogen. After mainly addressing industrial hydrogen applications, in this case, study, Power to green Hydrogen is tackled for a variety of applications in different sectors (mobility, heat, injection in gas networks, etc.). Valourising the excess heat vector is addressed in this case study.

It is clear that a new trend towards international trade of hydrogen is gaining importance in the last few years [7], [8]. Hence, two case studies address this topic. International hydrogen transport is tackled considering two forms: ammonia transport and liquid hydrogen transport. More insights regarding the adopted methodology are detailed hereafter.

### Methodology

The case studies were prepared using expert interviews with stakeholders that currently are working within the task 38 “POWER-TO-HYDROGEN AND HYDROGEN-TO-X”. The economic analysis is based on the Task38 Subtask5 “Specific case studies” excel tool, which for a concrete power to X application, and for a concrete Internal Return Rate, allows defining the hydrogen, methanol, or ammonia price to the market. An explanation of the whole cost components can be found in the Annex.

New technologies typically come to market at a cost premium. Therefore, the Internal Return Rate (IRR), Net Present Value (NPV) and Pay-Back period (PB) of the power to X applications in question were analysed. The analysis is based on data provided by international reports, by the industry and has been challenged and validated by Task 38 experts as well as hydrogen and fuel cells external experts. It is expected that in each business case, the hydrogen, methanol, or ammonia price will change trying to adjust the IRR at 10%. The upside to the business case comes from the utilization of the by-products (oxygen and heat mainly) and the monetisation of externalities (i.e. greenhouse gases emissions).

A brief perspective on this will be provided below. Please note that detailed and location-specific business cases (incl. environmental...
If no additional parameters were known, the calculation was customised for subsequent additional case-specific data was available, the calculation will also rely on the standard cost energy prices, salaries etc.). The basic cost scheme, feedstock prices, financing costs, taken into the model (e.g. deployment application, country and transportation if parameters for each specific power to X costs are computed based on basic input For the specific cases studied in this chapter, local requirements. Therefore, assumptions considered power to X applications considered with all the associated infrastructure. A first input data set contains all cost assumptions for the hydrogen, ammonia or methanol production, storage facilities, transportation and end-uses. All the considered power to X applications are in an early stage of development, therefore, current and future costs are difficult to forecast. Also, for hydrogen, ammonia or methanol production and storage facilities, cost figures can vary significantly depending on specific local requirements. Therefore, assumptions included in the tool or the cases need to be treated with caution and should be validated individually for each deployment project. For the specific cases studied in this chapter, costs are computed based on basic input parameters for each specific power to X application, country and transportation if is needed. Country-specific data sets were taken into the model (e.g. deployment scheme, feedstock prices, financing costs, energy prices, salaries etc.). The basic cost calculation will also rely on the standard cost data that was already obtained from technical papers and professional experiences. The tool itself does not automatically reflect specific circumstances of individual countries or the parameters of individual local operation set-ups. Therefore, the results generated by this tool are indicative and are no substitute for the development of detailed business cases for individual locations (based on real power to X facilities from potential suppliers) and taking into consideration all individual associated risks and costs (e.g. for prolonged permitting processes, infrastructure configurations differing from the standard assumptions included in the tool, project and stakeholder management etc.). Besides, the tool also takes into account the country-specific feeds price (electricity, water, land rental, transportation, etc.), for the calculation of the technical and environmental impact assessment. After all parameters for the countries, power to X applications and transportation (if needed) were defined; the infrastructure and basic concept design was done and discussed with the STS stakeholders. These additional configurations of the standard NPV, PB and product price (hydrogen, ammonia or methanol) model will allow the calculation of the NPV, PB and product price items of each power to X application.

Specific Business Case 1: Power to Green Ammonia for Blasting Industry in Chile

Mining industry has been the main consumer of industrial explosives in Latin America, accounting for around 80% of the overall demand in the region. Open-pit mining and underground mining are prominently driving the demand for industrial explosives, whereas the latter accounts for a significant share in the region's industrial explosives landscape. Increasing investments in metal mining in Latin America is a major factor expected to drive the consumption of industrial explosives in the region. Metal extraction, especially from underground mines, involves intensive use of industrial explosives. Countries in Latin America such as Chile, Peru, Colombia, Brazil, and Bolivia are rich in metallic minerals and thus, metal mining is anticipated to be a major sub-segment in mining, which is anticipated to drive the demand for industrial explosives. The industrial explosives market landscape in the Latin America region is fairly consolidated with a few players making up the majority of the market share. Manufacturers like AEL Mining Services, Enaex S.A., ORICA Ltd., MaxamCorp Holding S.L., Exsa S.A. and Austin Powder Company make up more than 50% of the market share, accounting to more than US$ 600 Mn in terms of combined revenue of industrial explosives in the Latin America region.

Ammonium nitrate consumption is one of the main industrial explosives because of its safety advantage over other products such as dynamite. Ammonium nitrate can be shipped and stored and mixed with fuel oil when needed. Ammonium nitrate fuel oil (ANFO) is made of about 94% ammonium nitrate and 6% fuel oil. ANFO is widely used as an explosive in mining, quarrying, and tunnelling construction or wherever dry conditions exist. The industrial production of ammonium nitrate entails the acid-base reaction of ammonia with nitric acid: HNO3 + NH3 → NH4NO3. Ammonia is used in its anhydrous form (a gas) and the nitric acid is concentrated. The ammonia required for this process is obtained usually by the Haber process from nitrogen and hydrogen. Existing ammonia production plants are a major emitter of CO2, accounting for around 1.6 per cent of current global emissions. While being cost-effective for today's industrial uses of ammonia, the use of fossil feedstock and energy sources means ammonia has yet to play a role as an energy vector but that is now changing. Today, hydrogen is produced via steam methane reforming, by moving over to green hydrogen, that is hydrogen produced with renewable energy via water electrolysis, the carbon emissions from producing ammonia can be negated. The main goal of this business case study is the production of 300 tonnes per day of green ammonia in order to be used in the ammonia nitrate production for blasting industry in Chile (Figure 68).

In order to produce 300 tonnes per day of green ammonia, a facility with the following main equipment is necessary:

- 120 MW of alkaline electrolyser (127.2 MW total power supply to the complete electrolysis system and 120 MW total power supply to the electrolyser stack system). This green hydrogen production facility needs up to 127.2 MWh of green electricity and 33,424 liters/h of water in order to produce up to 2,335 kg/h of hydrogen (99.95% of purity and 30 bar of pressure), up to 18,591 kg/h of oxygen (98.5% of purity and ambient pressure) and up to 28.8 MWh of thermal energy (temperatures between 60ºC and 50ºC).
- Low-pressure hydrogen storage with 56.5 tonnes of capacity at 30 bar of pressure.
- Hydrogen compression system in order to compress the hydrogen from the low-pressure hydrogen storage up to the Haber-Bosch system. The hydrogen compression system will compress up to 2,335 kg/h of hydrogen from 10 up to 30 bar of pressure.
- Small size Haber-Bosch process in order to produce up to 12.5 tonnes/day of green ammonia. The nitrogen will be taken from the air using an Air Separation Unit (ASU). This facility can reach up to 300 tonnes/day of green ammonia. The green ammonia production will be sent directly to ammonia storage existing in the ammonium nitrate facility.

The main goal of the facility is to produce green ammonia. However, it is possible to use the oxygen as well as the heat as by-products...
Due to the facility location (industrial area with a lot of industries around), each tonne of hydrogen produced via electrolyser with green electricity instead of steam methane reforming reduce around 12.1 tonnes of CO₂. In this regard, this facility can reach a reduction of the CO₂ emission rights that usually the ammonia facilities need to buy in the market. This means that the facility receives revenues from CO₂ emissions reduction.

As previously indicated, to be economically viable, the produced green ammonia price must allow reaching an Internal Rate of Return (IRR) of 10%. The main technical and economic considerations taken into account are the following:

- **Study period**: 20 years.
- **Price of green electricity supplied with a Purchase Procurement Agreement (PPA)**: 32 €/MWh.
- **Tap water cost**: 2 € per cubic meter.
- **Operation hours per year**: 8,000.
- **Alkaline electrolyser CAPEX**: 600 €/kW.
- **Alkaline electrolyser system OPEX (% investment cost per year)**: 1.5.
- **Operation hours up to 10% of stack degradation**: 80,000.
- **Stack replacement cost (% of the total cost)**: 20%.
- **Low-pressure hydrogen storage at 30 bar CAPEX (€/kg)**: 24.5.
- **Low-pressure hydrogen storage system OPEX (% investment cost per year)**: 0.5.
- **Hydrogen compression system from 10 to 30 bar CAPEX (€/kg/h)**: 2,112.8.
- **Hydrogen compression system from 10 to 30 bar OPEX (% investment cost per year)**: 6.
- **Haber-Bosch system CAPEX (€/kW of electrolyser system)**: 450.
- **Haber-Bosch system OPEX (% investment cost per year)**: 5%.
- **Personal cost (€/year)**: 1,000,000.
- **Land rental cost (€/year)**: 200,000.
- **French loan duration**: 10 years.
- **Finance (% of the total investment)**: 70.
- **Own resources (% of the total investment)**: 30.
- **Financial interest (%)**: 5.
- **Taxes (%)**: 25.
- **Integration cost (piping, electricity, control, safety, etc.) (% of the main equipment)**: 12.
- **Depreciation (%)**: 95.
- **Depreciation (years)**: 20.
- **Discount rate (%)**: 7.5.
- **Inflation (% per year)**: 1.5.
- **Weighted Average Cost of Capital (WACC) (%)**: 9.11.
- **Oxygen sales price (€/tonne)**: 30.
- **Heat sales price (€/MWh)**: 15.
- **CO₂ avoided emission rights (€/tonne)**: 28.5.

The main results of this specific business case, taking into account that the goal is fixed (10% IRR), are the following (Figure 69):

- **Total investment needed (€)**: 163,141,763.
- **Ammonia sales price (€/tonne)**: 459.67.
- **Total cost per year (€)**: The total cost can be different in the years because the degradation of the electrolyser stack and the degradation of the Haber-Bosch reactor make that the hydrogen and ammonia production change in the years. However, the total cost per year is between 47 and 41 million euros.
- **Total revenues per year (€)**: In the same way that the total cost per year, the total revenues per year is between 63 and 57 million euros.
- **CO₂ emission reduction per year (tonnes of CO₂)**: In the same way that the total cost per year, the CO₂ emission reduction per year is between 63 and 57 million euros.
- **Net Present Value (NPV) (€)**: 4,885,196.
- **Pay-Back (PB) (years)**: 18.15.

In order to know how the business case can change when some parameters are changed, some sensitivity analysis is performed. Two of the main parameters are the ammonia sales price (€/tonne) and the CO₂ emission right (€/tonne). The sensitivity analysis will consider for one hand ammonia sales price (€/tonne)

---

**Figure 68**

Power to Green Ammonia in order to produce up to 300 tonnes per day.

- 18.591 kg/h O₂
- 127.2 MWh green electricity
- 33,424 l/h tap water
- 120 MW alkaline electrolyser facility
- 56.5 tn hydrogen storage at 30 bar, 1 day at full load
- 12.5 tn/h NH₃, 22.5 bar
- 8,58 MWh green electricity
- 28.8 MWh heat 60°C - 50°C
- 2.335 kg/h H₂, 10-30 bar
- 2.335 kg/h H₂, 30 bar
- 2.6 MWh green electricity

**Figure 69**

Cumulated Net Present Value VS years.
from 350 up to 550, and for the other hand CO2 emission right (€/tonne) from 10 up to 100. The parameter that will be observed in the sensitivity analysis is the Internal Rate of Return (IRR). IRR lower than 10% will be put in white colour and IRR higher than 10% will be put in green colour. All the combinations between ammonia sales price and CO2 emissions that obtain an IRR higher than 10% (green colour) will be desirable scenarios for the investors (Figure 70). Ammonia production in northern Chile seems a particularly low hanging fruit, due to the existence in the area of a mature solar market, with an excellent resource, interesting wind options, available water desalination technology, better present financial conditions, and large local consumption due to mining, in particular for the direct use in explosives (as well as local consumption of oxygen and heat). Armijo and Philibert [9] in their study-related with green hydrogen and ammonia production in Chile and Argentina estimated near-term production costs for green hydrogen, around 2 USD/kg, and green ammonia, below 500 USD/t, are encouragingly close to competitiveness against fossil-fuel alternatives. In this study, the authors consider the best locations in Chile like Taltal and Atacama. In Figure 71 the ammonia cost in Chile is represented in a period between 2004 and 2018. Following the blue line, it is possible to see the ammonia price when the hydrogen is produced using steam methane reforming (SMR) [10]. The red line is the ammonia price that Armijo and Philibert estimate in their study. Our results show a value of 459.67 €/tonne for the ammonia price which corresponds to more or less 542 USD/t, depending on the currency change value between American Dollar and Euro. This value is a little bit higher than the value obtained for Armijo and Philibert. However, even in Japan, the hydrogen market is not yet economically viable. At present, almost all hydrogen and fuel cell technologies are highly dependent on public funding. The retail price for hydrogen is currently around 100 yen per cubic metre (yen/Nm3). The goal is to reduce it to 30 yen/Nm3 by 2030 and to 20 yen/Nm3 in the long term. Japan's strategy could have a positive global impact and in particular, contribute to the creation of new synergies regarding international energy trading and business cooperation. These will be crucial to drive development and make technologies more affordable. Japanese companies are already involved in international hydrogen projects such as in Specific Business Case 2. Power to Green Ammonia Produced in Australia and Transport to Japan (to use as hydrogen)

With the Basic Hydrogen Strategy released on December 26, 2017, Japan reiterated its commitment to pioneer the world's first “Hydrogen Society”. The Strategy primarily aims to achieve the cost parity of hydrogen with competing fuels, such as gasoline in transport and Liquified Natural Gas (LNG) in power generation.

To this end, the government already six years ago began investing in R&D and providing, including support for low-cost, zero-emission hydrogen production, an expansion of the hydrogen infrastructure for import and transport abroad within Japan, and an increase of hydrogen use in various areas such as mobility, cogeneration of power and heat, as well as power generation. However, even in Japan, the hydrogen market is not yet economically viable. At present, almost all hydrogen and fuel cell technologies are highly dependent on public funding. The retail price for hydrogen is currently around 100 yen per cubic metre (yen/Nm3). The goal is to reduce it to 30 yen/Nm3 by 2030 and to 20 yen/Nm3 in the long term. Japan's strategy could have a positive global impact and in particular, contribute to the creation of new synergies regarding international energy trading and business cooperation. These will be crucial to drive development and make technologies more affordable. Japanese companies are already involved in international hydrogen projects such as in

![Figure 70](image-url) Sensitivity analysis between green ammonia sales price and CO2 emission right price.

![Figure 71](image-url) Market costs of ammonia in Chile, compared with Taltal estimate with advanced flexibility at 483 USD/t.
Brunei, Norway, and Saudi Arabia. Just recently Kawasaki Heavy Industries also announced the construction of a liquefaction plant, storage facility and loading terminal for hydrogen export to Japan in the Australian state of Victoria as a pilot project for 2020/2021. The fact that hydrogen is obtained from lignite, as in the case of Australia, does not seem to be of concern. For the Japanese government, the top priority is for hydrogen to become a cheaper energy carrier and thus more attractive for the industry. According to the roadmap of the Japanese Ministry of Economy, Trade and Industry, Japan expects hydrogen technologies to become profitable by 2030. Only afterwards the Japanese government plans to focus more on emission-free hydrogen production. Australia and Japan share a strong commitment to cooperating on the deployment of hydrogen as a clean, secure, affordable, and sustainable source of energy. Minister Caravan said Australia and Japan are well placed to maximise the opportunities presented by hydrogen, based on a long history of successful energy and resource trade. Australia and Japan recognise that hydrogen is a key contributor to reducing emissions, especially when produced from renewable energy or fossil fuels combined with Carbon Capture, Utilisation and Storage (CCUS).

Australia has long been a reliable supplier of energy needs and as global demand for hydrogen continues to grow so does the potential to turn Australia into a major global exporter of hydrogen, particularly to countries such as Japan (Figure 72). Australia can lead the global shift to green hydrogen or green ammonia:
- Abundant renewable energy potential at low cost. Integral for the development of industrial-scale green hydrogen or green ammonia.
- Strong existing trade links. Well-positioned geographically for the high hydrogen demand economies of Japan, South Korea, China and Singapore;
- Proven track record in industrialising commodity production. At the forefront of natural gas production and trade, with well-developed regulatory, safety and market infrastructure.

The main goal of this business case study is the production of 300 tonnes per day of green ammonia in order to be stored in an ambient temperature ammonia storage and after transport up to Japan (Figure 73). In Japan, the ammonia will be used directly or as hydrogen using an ammonia reformer. However, the business case considers up to the ammonia will be put in a Japanese harbour.

In order to produce 300 tonnes per day of green ammonia, storage the ammonia at ambient temperature ammonia storage and after transport the ammonia from Australia to Japan is necessary a facility with the following main equipment:
- 120 MW of alkaline electrolyser (127.2 MW total power supply to the complete electrolysis system and 120 MW total power supply to the electrolyser stack system). This green hydrogen production facility needs up to 127.2 MWh of green electricity and 33,424 litres/h of water in order to produce up to 2,335 kg/h of hydrogen (99.95% of purity and 30 bar of pressure), up to 18,591 kg/h of oxygen (98.5% of purity and ambient pressure) and up to 28.8 MWh of thermal energy (temperatures between 60ºC and 50ºC).
- Low-pressure hydrogen storage with 56.5 tonnes of capacity at 30 bar of pressure.
- Hydrogen compression system in order to compress the hydrogen from the low-pressure hydrogen storage up to the Haber-Bosch system. The hydrogen compression system will compress up to 2,355 kg/h of hydrogen from 10 up to 30 bar of pressure.
- Small size Haber-Bosch process in order to produce up to 12.5 tonnes/h of green ammonia. The air will be taken from the air using an Air Separation Unit (ASU). This facility can reach up to 300 tonnes/day of green ammonia. The green ammonia production will be sent directly to ammonia storage existing in the green ammonia production facility.
- Ambient temperature ammonia storage with the capacity to store up to 18,000 tonnes of green ammonia. When the storage temperature is ambient, it is needed have pressure around 18 bar (another option is storage at ambient pressure but in this case will be necessary reduce the ammonia temperature up to -33°C). In order to transport the ammonia from Australia to Japan, an ammonia ship will be used and will be fuelled from ambient temperature ammonia storage.

The main goal of the facility is to produce green ammonia and transport from Australia to ammonia production facility. In order to transport the ammonia to Japan, the ammonia will be used directly or as hydrogen using an ammonia reformer. However, the business case considers up to the ammonia will be put in a Japanese harbour.

In order to produce 300 tonnes per day of hydrogen, storage the hydrogen at ambient temperature ammonia storage and after transport the ammonia from Australia to Japan is necessary a facility with the following main equipment:
- 120 MW of alkaline electrolyser (127.2 MW total power supply to the complete electrolysis system and 120 MW total power supply to the electrolyser stack system). This green hydrogen production facility needs up to 127.2 MWh of green electricity and 33,424 litres/h of water in order to produce up to 2,335 kg/h of hydrogen (99.95% of purity and 30 bar of pressure), up to 18,591 kg/h of oxygen (98.5% of purity and ambient pressure) and up to 28.8 MWh of thermal energy (temperatures between 60ºC and 50ºC).
- Low-pressure hydrogen storage with 56.5 tonnes of capacity at 30 bar of pressure.
- Hydrogen compression system in order to compress the hydrogen from the low-pressure hydrogen storage up to the Haber-Bosch system. The hydrogen compression system will compress up to 2,355 kg/h of hydrogen from 10 up to 30 bar of pressure.
- Small size Haber-Bosch process in order to produce up to 12.5 tonnes/h of green ammonia. The air will be taken from the air using an Air Separation Unit (ASU). This facility can reach up to 300 tonnes/day of green ammonia. The green ammonia production will be sent directly to ammonia storage existing in the green ammonia production facility.
- Ambient temperature ammonia storage with the capacity to store up to 18,000 tonnes of green ammonia. When the storage temperature is ambient, it is needed have pressure around 18 bar (another option is storage at ambient pressure but in this case will be necessary reduce the ammonia temperature up to -33°C). In order to transport the ammonia from Australia to Japan, an ammonia ship will be used and will be fuelled from ambient temperature ammonia storage.

The main goal of the facility is to produce green ammonia and transport from Australia to ammonia production facility.
Low pressure ammonia storage at 18 bar
CAPEX (€/tonne): 800.

Low pressure ammonia storage system
OPEX (% investment cost per year): 0.5.

Ammonia transport from Australia to Japan (€/tonne): 50.

Personal cost (€/year): 1,000,000.

Land rental cost (€/year): 200,000.

French loan duration: 10 years.

Finance (% of the total investment): 70.

Own resources (% of the total investment): 30.

Financial interest (%): 5.

Integration cost (piping, electricity, control, safety, etc.) (% of the main equipment): 12.

Depreciation (%): 95.

Depreciation (years): 20.

Discount rate (%): 7.5.

Inflation (% per year): 1.5.

Weighted Average Cost of Capital (WACC) (%): 9.11.

Oxygen sales price (€/tonne): 30.

Heat sales price (€/MWh): 15.

CO₂ avoided emission rights (€/tonne): 28.5.

The main data from this specific business case, taking into account that the goal is to fix the ammonia price put in a Japanese harbour, in a value that allows us to have an Internal Rate of Return of 10% are the following (Figure 74):

- Total investment needed (€): 179,269,763.
- Ammonia sales price (€/tonne): 583.45.
- Total cost per year (€). The total cost can be different in the years because the degradation of the electrolyser stack and the degradation of the Haber-Bosch reactor make that the hydrogen and ammonia production change in the years. However, the total cost per year is between 58.5 and 51 million euros.
- Total revenues per year (€). In the same way that the total cost per year, the total revenues per year is between 76 and 69 million euros.
- CO₂ emission reduction per year (tonnes of CO₂): In the same way that the total cost per year, the total revenues per year is between 76 and 69 million euros.
- Net Present Value (NPV) (€): 5,419,864.
- Pay-Back (PB) (years): 18.12.

In order to know how the business case can change when some parameters are changed, to Japan. However, it is possible to use the oxygen as a by-product and also the heat as a by-product due to the facility location (industrial area with a lot of industries around).

Each tonne of hydrogen produced via electrolyser with green electricity instead of steam methane reforming reduce around 12.1 tonnes of CO₂. In this regard, this facility can reach a reduction of the CO₂ emission rights that usually the ammonia facilities need to buy in the market. This means that the facility receives revenues from CO₂ emissions reduction.

The main technic and economic considerations in order to analyse the price that is necessary put to the green ammonia tonne to reach 10% of the Internal Rate of Return (IRR) are the following:

- Study period: 20 years.
- Price of green electricity supplied with a Purchase Procurement Agreement (PPA): 36.9 €/MWh [12].
- Tap water cost: 2 € per cubic meter.
- Operation hours per year: 8,000.
- Alkaline electrolyser CAPEX: 600 €/kW.
- Alkaline electrolyser system OPEX (% investment cost per year): 1.5.
- Operation hours up to 10% of stack degradation: 80,000.
- Stack replacement cost (% of the total cost): 20%.
- Low-pressure hydrogen storage at 30 bar CAPEX (€/kg): 245.
- Low-pressure hydrogen storage system OPEX (% investment cost per year): 0.5.
- Hydrogen compression system from 10 to 30 bar CAPEX (€/kg/h): 2,112.8.
- Hydrogen compression system from 10 to 30 bar OPEX (% investment cost per year): 6.
- Haber-Bosch system CAPEX (€/kW of electrolyser system): 450.
- Haber-Bosch system OPEX (% investment cost per year): 5%.

**Figure 73**

Power to Green Ammonia in order to produce up to 300 tonnes per day and transport from Australia to Japan.

- 18.591 kg/h O₂
- 127.2 MWh green electricity
- 33.424 l/h tap water
- 120 MW alkaline electrolyser facility
- 56.5 tn hydrogen storage at 30 bar. 1 day at full load
- 2.335 kg/h H₂ 10-30 bar
- 2.6 MWh green electricity
- 12.5 tn/h NH₃, 22.5 bar
- 2.335 kg/h H₂ 30 bar
- 8.58 MWh green electricity
- Ammonia transport 18 bar from Australia to Japan

**Figure 74**

Cumulated Net Present Value VS years.
some sensitivity analysis will be performed. Two of the main parameters are the ammonia sales price (£/tonne) and the CO2 emission right (£/tonne). The sensitivity analysis will consider for one hand ammonia sales price (£/tonne) from 400 up to 620 and for the other hand CO2 emission right (£/tonne) from 10 up to 100. The parameter that will be observed in the sensitivity analysis is the Internal Rate of Return (IRR). IRR lower than 10% will be put in green colour and IRR higher than 10% will be put in white colour. All the combinations of ammonia sales price and CO2 emissions right that obtain an IRR higher than 10% will be desirable scenarios to consider for one hand ammonia sales price (£/tonne) and the CO2 emission right (£/tonne) from 10 up to 100.

Figure 75
Sensitivity analysis between green ammonia sales price and CO2 emission right price.

Specific Business Case 3. Power to Green Hydrogen in Austria

Hydrogen technologies will play an important role in achieving climate neutrality in Austria by 2040. The release of a national hydrogen strategy is expected by the end of 2020 and it will be part of the governments’ policy programme. In particular, hydrogen R&D should take place for applications in industry and mobility sectors, thus strengthening Austria’s role in the global hydrogen economy. Since 2017, the Hydroflagship model region Power & Gas – (WIVA P&G) has been established and is one of three flagship regions funded by the Austrian Climate and Energy Fund. WIVA P&G aims to show that Austria is a perfectly suitable region for the switch to a system with green hydrogen. The flagship region combines the experience of more than 30 completed and ongoing projects and continuously integrate new projects in the field of hydrogen ensuring the know-how exchange within the WIVA-community and enhance acceptance of hydrogen by the general public [13].

For the specific business case area of Linz was chosen. Linz is the capital of Upper Austria and with about 200,000 inhabitants is the third-largest city in Austria and the second-largest metropolitan area in the country with about 200,000 people. In addition, the greater area of Linz is one of the three strongest business locations in Austria due to its location an important hub and well-developed electricity network, the Linz metropolitan area is already and especially in the future an ideal hydrogen hub - H2HubLinz. However, there were also other areas in Austria with high future hydrogen demand, which would be perfectly suited for such a hub.

In this case study, H2HubLinz, a rough concept for the transition towards a renewable energy supply of the industries, transport and heat sector with hydrogen is developed. In the concept of the case study H2HubLinz it is planned to build in Linz in the near future (by 2025) a relatively large electrolyser by today’s standards, with a nominal electrical power of 100 MW, which would enable economies of scale to be exploited, thereby reducing hydrogen production costs. In Figure 76 there is an overview of H2HubLinz with the system boundary and possible consumers of green hydrogen shown. Now there are already customers for the renewable hydrogen in Linz, although not all of the production of a 100 MW electrolyser can currently be sold in that area. The surplus hydrogen can be transported to other areas due to the good infrastructure (transport hub, truck, ship) and gas grid. The availability of green hydrogen could solve the chicken and egg problem and thus motivate industry and companies to switch to a hydrogen-based system. Subsequently, as the demand for renewable hydrogen increases, more electrolysis plants will be built in Linz. However, the enormous demand for the steel and chemical industry cannot be covered by the production in Linz, which means that, in distant future (2040), the existing infrastructure (gas network, transport hub) will have to be used again, but the other way round, to transport hydrogen to Linz.

The main goal of this business case study is the production of green hydrogen (up to 45 tonnes of green hydrogen per day) to be used in steel and chemical industry and mobility in Linz (Figure 77).
Figure 76
Overview of the case study H2HubLinz. System boundary of H2HubLinz plant and possible consumer of the produced green hydrogen.

In order to produce up to 45 tonnes per day of green hydrogen to be used in the steel, chemical and mobility sector, it is necessary to have a facility with the following main equipment:

- 100 MW of PEM electrolyser (106 MW total power supply to the complete electrolysis system and 100 MW total power supply to the electrolyser stack system). This green hydrogen production facility needs a power of up to 106 MW of green electricity and 32.8 litre per hour of water to produce up to 1,900 kg/h of hydrogen (99.95% of purity and 30 bar of pressure), up to 15,000 kg/h of oxygen (98.5% of purity and ambient pressure) and up to 24 MW of thermal energy (temperatures about 60°C).
- Hydrogen compression system to compress the hydrogen for storage. This hydrogen compression system will compress up to 1,900 kg/h of hydrogen from 10 up to 30 bar.
- Low-pressure hydrogen storage with 45 tonnes of capacity at 30 bar.

The main goal of the facility is to produce green hydrogen and use it in the steel, chemical and mobility sector. However, it is also possible to use the oxygen (a by-product from the electrolyser) and the excess heat (a by-product from the electrolyser and compressor) due to the facility located in an industrial area, with a high demand for these by-products.

Each tonne of hydrogen produced via electrolysis with green electricity instead of steam methane reforming reduces around 12,1 tonnes of CO2. In this regard, this facility can reach a reduction of CO2 emissions of up to 10% of the total cost.

The main technical and economic considerations in order to analyse the price that is necessary to put to the green hydrogen tonne are the following:

- Study period: 20 years.
- Price of green electricity supplied with a Purchase Procurement Agreement (PPA): 30 €/MWh.
- Operation hours per year: 6,000.
- PEM electrolyser CAPEX: 800 €/kW.
- PEM electrolyser system OPEX (% investment cost per year): 1.5.
- Operation hours up to 10% of stack degradation: 80,000.
- Stack replacement cost (% of the total cost): 70%.
- Low-pressure hydrogen storage system CAPEX (€/kg): 245.
- Low-pressure hydrogen storage system OPEX (% investment cost per year): 6.
- Foreign loan duration: 10 years.
- Finance (¥% of the total investment): 70.
- Own resources (% of the total investment): 30.
- Financial interest (%): 4.
- Taxes (%): 25.
- Integration cost (piping, electricity, control, safety, pipes and facilities up to consumers, etc..) (% of the main equipment): 50.
- Depreciation (%): 95.
- Depreciation (years): 20.
- Discount rate (%): 7.5.
- Inflation (% per year): 1.5.
- Weighted Average Cost of Capital (WACC) (%): 9.11.
- Oxygen sales price (€/tonne): 50.
- CO2 avoided emission rights (€/tonne): 28.5.

The main data from this specific business case, taking into account that the goal is to fix the green hydrogen price in a value that allows to have an Internal Rate of Return of 10% are the following (Figure 78):

- Total investment needed (€): 142,461,781.
- Total cost per year (€): 2,13.
- Total cost per year (% of the total cost): 20.

The main data from this specific business case, taking into account that the goal is to fix the green hydrogen price in a value that allows to have an Internal Rate of Return of 10% are the following (Figure 78):

- Total investment needed (€): 142,461,781.
- Total cost per year (€): 2,13.
- Total cost per year (% of the total cost): 20.

Steel, chemical and mobility industry in Linz.
Total revenues per year (€). In the same way that the total cost per year, the total revenues per year is between 40.1 and 41.4 million euros.

CO₂ emission reduction per year (tonnes of CO₂): In the same way that the total cost per year, the CO₂ emission reduction per year is between 132,000 and 149,000.


Pay-Back (PB) (years): 18.61.

In order to know how the business case can change when some parameters are changed, a sensitivity analysis will be performed. Two of the main parameters are the green hydrogen sales price (€/tonne) and the CO₂ emission right (€/tonne). The sensitivity analysis will consider for one hand green hydrogen sales price (€/tonne) from 1.5 up to 2.6 and for the other hand CO₂ emission right (€/tonne) from 10 up to 100. The parameter that will be observed in the sensitivity analysis is the Internal Rate of Return (IRR). IRR lower than 10% will be put in white colour and IRR higher than 10% will be put in green colour. All the combinations between the hydrogen sales price and CO₂ emissions right that obtain an IRR higher than 10% (green colour) will be desirable scenarios for the investors (Figure 79).

Specific Business Case 4. Power to Green Hydrogen from Patagonia to Japan

From a global point of view, the spatial offer of renewable energy sources like wind and solar power differs significantly. Due to regions of renewable energy surplus on the one hand and regions with high energy demands on the other, a worldwide assessment is required that examines the economical performance of hydrogen provision schemes based on renewable energy sources and evaluates potential trading connections.

Having the third biggest economy worldwide Japan’s demand for energy was the fifth biggest worldwide in the year 2016. In 2015 Japan’s total primary energy supply consisted of fossil fuels to more than 93%. Since Japan has very limited mineral resources available it was and is highly dependent on the import of fossil fuels, especially crude oil and natural gas. Only by about 10% of the total primary energy consumption was produced domestically in 2015. Prior to 2011, Japan was generating around 30% of its electricity by using nuclear power. The government planned on extending this to 60% for purposes of emission reduction. However, due to the 2011’s Great East Japan Earthquake, nuclear power plants have been shut down and Japan decided to reduce the role of nuclear power in its energy portfolio. With regard to fossil fuels, Japan depends on overseas imports for about 94% of its primary energy supply. 98% of oil-based fuels are used in the mobility sector, thereof 87% are imported from the Middle East. As a result, Japan had the second-lowest
self-sufficiency among the OECD countries in 2013 with 6-7%.
Compared to 2013 Japan strives to cut 26% of its CO₂ emissions by 2030 and, in accordance with the COP 21 Agreement, the emissions are to be reduced by 80% by 2050. In 2015 the share of renewable energy sources amounted to less than 6% of the total primary energy sources in Japan. Hence, despite the Japanese trend of promoting the expansion of renewable energy sources the corresponding domestic production leaves the potential to cover the country’s prospective demand for emission-free energy. Taking into consideration its goals of emission reduction and the catastrophic nuclear accident at the Fukushima Daiichi Nuclear Power Plant in March 2011 the Japanese government strives for the sustainable implementation of an emission-free “hydrogen society” by 2020 in which hydrogen will be the primary energy medium.

Despite the recent trend of expanding renewable energy sources utilization, the Japanese transport sector still depends heavily on fossil fuel, mostly imported oil derivatives. For purposes of replacement of oil derivatives in the transportation sector to meet the emission reduction goals the import of emission-free hydrogen from overseas is considered to be an attractive energy supply option. In its “Basic Hydrogen Strategy 2017,” the Ministry of Economy, Trade and Industry stated that realizing a hydrogen-based society requires international hydrogen supply chains to ensure a reasonable and secure provision with CO₂ free hydrogen.

Unlike Japan, numerous countries or regions, respectively, are characterized by a high renewable energy sources potential while having a relatively low domestic energy demand at the same time. Among various other regions all over the world, Argentina’s Patagonia shows considerable wind potential. Characterized by average full-load hours between 4100 and 5200, Patagonia’s estimated wind energy potential of ~ 9600 TWh is about ten times higher than the total Japanese demand for electricity of 995.26 TWh. At the same time, Argentina shows an electricity demand of only 131.20 TWh. Hence, exporting a significant part of the potentially producible renewable electricity could be exported without jeopardizing a hypothetical Argentinian domestic electricity supply based only on renewable energy sources. Therefore, an attractive opportunity exists in which Patagonian wind power generation acts as a hydrogen source for Japan’s energy economy. The conversion of renewable energy sources based electricity to hydrogen and the subsequent domestic and oversea transport requires a detailed analysis of the entire supply chain. This supply chain comprises wind energy conversion, water electrolysis, a domestic pipeline transmission system, installations to liquefy and store the hydrogen, and finally special carriers for the oversea transport of liquefied hydrogen. Besides the technical feasibility, the total costs of the system are of great interest to determine the specific costs for providing hydrogen to Japan. The main goal of this business case study is the production up to 48 tonnes per day of green hydrogen and transport from Argentina to Japan (Figure 80). In order to produce up to 48 tonnes per day of green hydrogen is necessary a facility with the following main equipment:

- 100 MW of alkaline electrolyser (106 MW total power supply to the complete electrolysis system and 100 MW total power supply to the electrolyser stack system). This green hydrogen production facility needs up to 106 MWh of green electricity and 26,666 litres/h of water to produce up to 2,000 kg/h of hydrogen (99.95% of purity and 30 bar of pressure), up to 16,000 kg/h of oxygen (98.5% of purity and ambient pressure) and up to 24 MWh of thermal energy (temperatures between 60°C and 50°C).
- Low-pressure hydrogen storage with 48 tonnes of capacity at 30 bar of pressure.

Each tonne of hydrogen produced via electrolyser with green electricity instead of steam methane reforming reduce around 12,1 tonnes of CO₂. In this regard, this facility can reach a reduction of the CO₂ emission rights that usually the hydrogen facilities need to buy in the market. This means that the facility receives revenues from CO₂ emissions reduction.

In this business case, we will consider two options in order to adapt the hydrogen to be transported from Argentina to Japan. These two options are a) liquid hydrogen and b) liquid organic hydrogen carriers. In both cases, the liquefaction facility or the hydrogenation facility will not be considered as an investment. The business case considers that we will pay for the conversion system (compress hydrogen to liquid hydrogen or compress hydrogen to liquid organic hydrogen carrier), storage (liquid or liquid organic hydrogen carrier) and transport (in both cases in liquid but in cryogenic transport when we are talking about liquid hydrogen and in a conventional transport when we are talking about liquid organic hydrogen carrier). The main goal of the facility is to produce green hydrogen. However, it is possible to use the oxygen as a by-product due to the facility location (industrial area with a lot of industries around). In this business case, the heat will be not used.

---

**Figure 80**

Power to Green hydrogen to produce up to 48 tonnes per day.

- 16,000 kg/h O₂
- 106 MWh green electricity
- 26,666 l/h tap water
- 100 MW alkaline electrolyser facility
- 48 tn hydrogen storage at 30 bar, 1 day at full load
- 2.6 MWh green electricity
- 2,000 kg/h H₂
- 30 bar

Hydrogen liquefaction process or Liquid Organic Hydrogen Carrier process. after the process, the hydrogen will be transported up to Japan.
makes that the green hydrogen production change in the years. However, the total
cost per year is between 78 and 69.6 million euros.

- Total revenues per year (€). In the same way that the total cost per year, the total
  revenues per year is between 87.6 and 77 million euros.
- CO₂ emission reduction per year (tonnes of CO₂): In the same way that the total cost
  per year, the CO₂ emission reduction per years is between 147,300 and 129,500.
- Net Present Value (NPV) (€): 2,619,758.
- Pay-Back (PB) (years): 18.60.

In order to know how the business case can change when some parameters are changed, some
sensitivity analysis will be performed. Two of the main parameters are the green liquid
hydrogen sales price (€/tonne) and the CO₂ emission right (€/tonne). The sensitivity
analysis will consider for one hand green liquid hydrogen sales price (€/tonne) from 4.3 up to
5.4 and for the other hand CO₂ emission right (€/tonne) from 10 up to 100. The parameter
that will be observed in the sensitivity analysis is the Internal Rate of Return (IRR). IRR lower
than 10% will be put in white colour and IRR

Higher than 10% will be put in green colour.

The main data from this specific business case, taking into account that the goal is to fix the
green liquid hydrogen price in a value that allows to have an Internal Rate of Return of
10% are the following (Figure 81):

- Total investment needed (€): 93,329,369.
- Green hydrogen sales price in liquid form (€/kg): 4.98.
- Total cost per year (€). The total cost can be different in the years because the degradation of the electrolyser stack

Figure 81
Cumulated Net Present Value VS years.

- Alkaline electrolyser CAPEX: 600 €/kW.
- Alkaline electrolyser system OPEX (% investment cost per year): 1.5.
- Operation hours up to 10% of stack degradation: 80,000.
- Stack replacement cost (% of the total cost): 20.
- Low-pressure hydrogen storage at 30 bar CAPEX (€/kg): 175.
- Low-pressure hydrogen storage system OPEX (% investment cost per year): 0.5.
- Hydrogen compression system from 10 to 30 bar CAPEX (€/kg/h): 2,112.8.
- Hydrogen compression system from 10 to 30 bar OPEX (% investment cost per year): 6.
- Cost of hydrogen conversion from compress form to liquid form (€/kg): 1.60.
- Cost of liquid hydrogen storage (€/kg): 0.18.
- Cost of liquid hydrogen transport (€/kg): 1.10.
- Personal cost (€/year): 1,000,000.
- Land rental cost (€/year): 250,000.
- French loan duration: 10 years.
- Finance (% of the total investment): 70.
- Own resources (% of the total investment): 30.
- Financial interest (%): 5.
- Taxes (%): 25.
- Integration cost (piping, electricity, control, safety, etc.) (% of the main equipment): 12.
- Depreciation (%): 90.
- Depreciation (years): 20.
- Discount rate (%): 7.5.
- Inflation (% per year): 1.5.
- Weighted Average Cost of Capital (WACC) (%): 9.11.
- Oxygen sales price (€/tonne): 30.
- CO₂ avoided emission rights (€/tonne): 28.5.

The main data from this specific business case, taking into account that the goal is to fix the
green liquid hydrogen price in a value that allows to have an Internal Rate of Return of 10% are the following (Figure 81):

- Total investment needed (€): 93,329,369.
- Green hydrogen sales price in liquid form (€/kg): 4.98.
- Total cost per year (€). The total cost can be different in the years because the degradation of the electrolyser stack
supply risks. Secondly, by using hydrogen no CO₂ is emitted during the energy conversion reaction. And lastly, the government sees economic competitiveness potential in being the first nation to implement a hydrogen society.

In general, literature sources assume an increasing demand for hydrogen over the coming decades. According to the Japanese government’s Basic Hydrogen Strategy, the demand for hydrogen is supposed to be 4,000 tH₂/a in 2020; 300,000 tH₂/a in 2030, and around 5 to 10 million tH₂/a in 2050. The New Energy and Industrial Technology Development Organization (NEDO) estimated the prospective Japanese hydrogen demand to be 314,300 tH₂/a in 2020 and 10.6 million tH₂/a in 2050.

According to the Basic Hydrogen Strategy, the retail market of hydrogen in Japan is currently around 100 yen per normal cubic meter (yen/Nm³), (90 $ cents/Nm³) and the target is to reduce it to 30 yen/Nm³ by 2030 (27 $ cents/Nm³) and to 20 yen/Nm³ (17 $ cents/Nm³) in the long term.

The cost obtained in the specific business case considered in this study for green liquid hydrogen (4.98 €/kg or 44.7 € cents/Nm³) and for green liquid organic hydrogen carrier (3.89 €/kg or 34.9 € cents/Nm³ or 29.7 $ cents/Nm³) are already competitive. It is true that is necessary to include more steps like gasification process or dehydrogenation process, land transport, etc. However, the difference between 38.08 $ cents/Nm³ or 29.7 $ cents/Nm³ and 90 $ cents/Nm³ allow include the missing steps and the price will continue being competitive.

Philipp-Matthias et al [15] in the paper Flexible production of green hydrogen and ammonia from variable solar and wind energy. Case study of Chile and Argentina, the development of Levelized cost of hydrogen across the supply chain will be obtained, with a provision costs of 4.44 €/kg at a liquid state in the harbour of Yokohama. The biggest shares are contributed by the electricity (1.22 €/kgH₂), the electrolysis (0.94 €/kgH₂), and the ship transport (1.13 €/kgH₂). Figure 85 shows how the final green liquid hydrogen in the harbour of Yokohama result on the left side. The right side gives the cost distribution for each supply chain element. The figures obtained in this study is so close to the results obtained in this business case.

In order to know how the business case can change when some parameters are changed, some sensitivity analysis will be performed.

### Figure 82

Sensitivity analysis between green liquid hydrogen sales price and CO₂ emission right price.

### Figure 83

Cumulated Net Present Value VS years.

#### Table 1

<table>
<thead>
<tr>
<th>CO₂ Emission Reduction (€/tonne)</th>
<th>4.3</th>
<th>4.4</th>
<th>4.5</th>
<th>4.6</th>
<th>4.7</th>
<th>4.8</th>
<th>4.9</th>
<th>5.0</th>
<th>5.1</th>
<th>5.2</th>
<th>5.3</th>
<th>5.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-11.04%</td>
<td>-6.51%</td>
<td>-2.54%</td>
<td>1.15%</td>
<td>4.71%</td>
<td>8.20%</td>
<td>11.67%</td>
<td>15.58%</td>
<td>19.42%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>-13.90%</td>
<td>-8.86%</td>
<td>-4.63%</td>
<td>-0.82%</td>
<td>2.80%</td>
<td>6.34%</td>
<td>9.91%</td>
<td>13.56%</td>
<td>17.33%</td>
<td>21.23%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>-11.44%</td>
<td>-8.84%</td>
<td>2.84%</td>
<td>0.86%</td>
<td>4.43%</td>
<td>7.98%</td>
<td>11.58%</td>
<td>15.28%</td>
<td>19.11%</td>
<td>23.08%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>-14.35%</td>
<td>-9.22%</td>
<td>-4.84%</td>
<td>-1.12%</td>
<td>2.52%</td>
<td>6.07%</td>
<td>9.63%</td>
<td>13.27%</td>
<td>16.93%</td>
<td>20.62%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>-12.56%</td>
<td>-7.77%</td>
<td>-3.67%</td>
<td>0.08%</td>
<td>3.60%</td>
<td>7.21%</td>
<td>10.80%</td>
<td>14.47%</td>
<td>18.17%</td>
<td>21.87%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>-14.80%</td>
<td>-9.58%</td>
<td>-5.26%</td>
<td>-1.40%</td>
<td>2.24%</td>
<td>5.79%</td>
<td>9.35%</td>
<td>12.98%</td>
<td>16.73%</td>
<td>20.61%</td>
<td>24.63%</td>
<td>28.77%</td>
</tr>
<tr>
<td>40</td>
<td>-12.74%</td>
<td>-7.51%</td>
<td>-3.38%</td>
<td>0.39%</td>
<td>7.42%</td>
<td>11.01%</td>
<td>14.69%</td>
<td>18.59%</td>
<td>22.44%</td>
<td>26.52%</td>
<td>30.72%</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>-9.69%</td>
<td>-5.58%</td>
<td>-1.69%</td>
<td>1.95%</td>
<td>5.51%</td>
<td>9.07%</td>
<td>12.69%</td>
<td>16.43%</td>
<td>20.30%</td>
<td>24.13%</td>
<td>28.04%</td>
<td>32.06%</td>
</tr>
<tr>
<td>50</td>
<td>-7.85%</td>
<td>-3.75%</td>
<td>0.01%</td>
<td>3.60%</td>
<td>7.14%</td>
<td>10.73%</td>
<td>14.40%</td>
<td>18.07%</td>
<td>21.73%</td>
<td>26.30%</td>
<td>30.97%</td>
<td>34.66%</td>
</tr>
<tr>
<td>55</td>
<td>-5.90%</td>
<td>-1.99%</td>
<td>-1.67%</td>
<td>4.23%</td>
<td>7.79%</td>
<td>11.41%</td>
<td>15.09%</td>
<td>18.76%</td>
<td>22.43%</td>
<td>26.72%</td>
<td>31.14%</td>
<td>35.65%</td>
</tr>
<tr>
<td>60</td>
<td>-4.05%</td>
<td>-0.28%</td>
<td>3.32%</td>
<td>6.86%</td>
<td>10.48%</td>
<td>14.11%</td>
<td>17.84%</td>
<td>21.58%</td>
<td>25.32%</td>
<td>29.05%</td>
<td>34.30%</td>
<td>38.71%</td>
</tr>
<tr>
<td>65</td>
<td>-2.28%</td>
<td>1.39%</td>
<td>4.05%</td>
<td>8.51%</td>
<td>12.12%</td>
<td>15.46%</td>
<td>18.98%</td>
<td>22.47%</td>
<td>25.67%</td>
<td>28.27%</td>
<td>31.34%</td>
<td>34.30%</td>
</tr>
<tr>
<td>70</td>
<td>-0.57%</td>
<td>3.04%</td>
<td>6.59%</td>
<td>10.16%</td>
<td>13.82%</td>
<td>17.59%</td>
<td>21.50%</td>
<td>25.55%</td>
<td>29.72%</td>
<td>34.00%</td>
<td>38.37%</td>
<td>42.61%</td>
</tr>
<tr>
<td>75</td>
<td>1.11%</td>
<td>4.67%</td>
<td>8.23%</td>
<td>15.83%</td>
<td>19.54%</td>
<td>23.88%</td>
<td>27.46%</td>
<td>31.69%</td>
<td>36.00%</td>
<td>40.41%</td>
<td>44.88%</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>2.90%</td>
<td>6.31%</td>
<td>9.80%</td>
<td>13.35%</td>
<td>17.29%</td>
<td>21.39%</td>
<td>25.23%</td>
<td>29.19%</td>
<td>33.66%</td>
<td>38.02%</td>
<td>42.96%</td>
<td>46.96%</td>
</tr>
<tr>
<td>85</td>
<td>4.40%</td>
<td>7.95%</td>
<td>11.59%</td>
<td>15.24%</td>
<td>19.07%</td>
<td>23.05%</td>
<td>27.17%</td>
<td>31.34%</td>
<td>35.60%</td>
<td>40.06%</td>
<td>44.57%</td>
<td>49.09%</td>
</tr>
<tr>
<td>90</td>
<td>6.00%</td>
<td>9.99%</td>
<td>13.34%</td>
<td>16.99%</td>
<td>20.88%</td>
<td>25.91%</td>
<td>29.86%</td>
<td>33.72%</td>
<td>37.68%</td>
<td>42.11%</td>
<td>46.61%</td>
<td>51.34%</td>
</tr>
<tr>
<td>95</td>
<td>7.60%</td>
<td>13.26%</td>
<td>14.95%</td>
<td>18.77%</td>
<td>22.72%</td>
<td>26.80%</td>
<td>30.03%</td>
<td>33.52%</td>
<td>37.91%</td>
<td>42.14%</td>
<td>46.70%</td>
<td>51.58%</td>
</tr>
<tr>
<td>100</td>
<td>9.31%</td>
<td>12.95%</td>
<td>16.69%</td>
<td>20.57%</td>
<td>24.58%</td>
<td>28.73%</td>
<td>32.98%</td>
<td>37.33%</td>
<td>41.76%</td>
<td>46.25%</td>
<td>50.80%</td>
<td>55.40%</td>
</tr>
</tbody>
</table>

In order to know how the business case can change when some parameters are changed, some sensitivity analysis will be performed. Two of the main parameters are the green liquid organic hydrogen carrier sales price (€/tonne) and the CO₂ emission right (€/tonne). The sensitivity analysis will consider for one hand green liquid organic hydrogen carrier sales price (€/tonne) from 3.3 up to 4.4 and for the other hand CO₂ emission right (€/tonne) from 10 up to 100. The parameter that will be observed in the sensitivity analysis is the Internal Rate of Return (IRR). IRR lower than 10% will be put in white colour and IRR higher than 10% will be put in green colour. All the combinations between green liquid organic hydrogen carrier sales price and CO₂ emissions right that obtain an IRR higher than 10% (green colour) will be desirable scenarios for the investors (Figure 84). By implementing a hydrogen society, Japan aims for several objectives. Firstly, hydrogen from different sources, but especially from different renewable energy sources, reduces the risk of supply chain.
Figure 84
Sensitivity analysis between green liquid hydrogen sales price and CO₂ emission right price.

Figure 85
Overview over the green liquid hydrogen cost contributions by each hydrogen supply chain element.

Specific Business Case 5. Power to Hydrogen with Waste CO₂ from Green Methanol in China

Road transport consumes around 33% of total energy consumption by transport [16]. Petroleum fuels are the primary fuels for road transportation. Their burning results in harmful emissions including carbon dioxide emissions. According to the International Energy Agency (IEA), carbon dioxide emissions are increasing. In 2018, their value exceeded 33 Gt [17]. To mitigate climate change, the United Nations Intergovernmental Panel on Climate Change recommended reduction of greenhouse gas emissions by 50–85% by 2050. The decrease of harmful emissions can be reached by using alternative vehicle fuels, including methanol.

Methanol could bring economic and ecological benefits to China. This fuel is environmentally friendly. Moreover, its application results in reduced fuel costs. China imports around 65% oil and 31% natural gas. The use of methanol-based fuel can decrease the import of the above Energy resources. Since 2000, the Chinese government has improved national energy independence and cut harmful emissions. Therefore, the increase of the methanol vehicle fleet ensures the sustainable economic growth of the country.

Methanol is mainly converted into the following fuels: neat methanol M100; methanol and petrol blend (M5, M10, M15, M30, M50 and M85); methanol-based petrol; methyl tertiary butyl ether (MTBE); dimethyl ether (DME); and biodiesel. Methanol can be converted to different hydrocarbons, including olefins. Olefins are valuable raw materials for the production of liquid vehicle fuels such as gasoline, distillate and dimethyl ether.

In 2018, road transport in China consumed 126 million tons of petrol and 156 million tons of diesel fuel. Meanwhile, methanol consumption was around 17.4 million tons. The production and use of methanol is growing mainly due to the use of methanol by transport in China (Figure 86 and Figure 87) [18,19].

The production of methanol in China has had a positive trend despite global methanol production growth having slowed. Green methanol is very attractive for the energy sector. It makes possible the development of the methanol economy. The transition to the methanol economy may allow China to reach the following results: strengthening of energy security; reduction of air pollution and carbon dioxide emissions; and increases in the added value of the domestic economy. Therefore, the methanol economy gives tangible benefits.

The main goal of this business case study is the production of 344 tonnes per day of green methanol in order to be used as a fuel in the transport sector, as an energy carrier and as a feedstock for chemical processes in China (Figure 88). In order to produce 344 tonnes per day of green methanol is necessary a facility with the following main equipment:

- 150 MW of alkaline electrolyser (159 MW total power supply to the complete electrolysis system and 150 MW total power supply to the electrolysis system).

There has been an increase in methanol-based fuel consumption (Figure 87). Green methanol is very attractive for the energy sector. It makes possible the development of the methanol economy. The transition to the methanol economy may allow China to reach the following results: strengthening of energy security; reduction of air pollution and carbon dioxide emissions; and increases in the added value of the domestic economy. Therefore, the methanol economy gives tangible benefits.

The main goal of this business case study is the production of 344 tonnes per day of green methanol in order to be used as a fuel in the transport sector, as an energy carrier and as a feedstock for chemical processes in China (Figure 88). In order to produce 344 tonnes per day of green methanol is necessary a facility with the following main equipment:

- 150 MW of alkaline electrolyser (159 MW total power supply to the complete electrolysis system and 150 MW total power supply to the electrolysis system).
power supply to the electrolyser stack system). This green hydrogen production facility needs up to 159 MWh of green electricity and 24,900 litters/h of water in order to produce up to 2,800 kg/h of hydrogen (99.95% of purity and 30 bar of pressure), up to 22,400 kg/h of oxygen (98.5% of purity and ambient pressure) and up to 52.5 MWh of thermal energy (temperatures between 60°C and 50°C).

• Low-pressure hydrogen storage with 76.2 tonnes of capacity at 30 bar of pressure.
• Hydrogen compression system in order to compress the hydrogen from the low-pressure hydrogen storage up to the Fischer-Tropsch system. The hydrogen compression system will compress up to 2,800 kg/h of hydrogen from 10 up to 30 bar of pressure.
• Small size Fischer-Tropsch process consumes up to 2.8 tonnes/hour of hydrogen and up to 19.62 tonnes/hours of carbon dioxide, in order to produce up to 14.43 tonnes/h of green methanol. The carbon dioxide will be supplied for a steel factory directly to the Fischer-Tropsch process (the green methanol facility will be bought the carbon dioxide from the steel factory and the steel factory will be paid money to green methanol facility in order to reduce their carbon dioxide emissions).

The green methanol production will be sent directly to methanol storage and after to their main consumers like transport, energy carrier or chemical process.

• Green methanol storage with the capacity to store up to 550 tonnes. This storage system will be used in order to supply green methanol to the mobility sector, energy carrier sector and the chemical industry sector.

The main goal of the facility is to produce green methanol. However, it is possible to use the oxygen as a by-product and also the heat as a by-product due to the facility location (industrial area with a lot of industries around).

Each tonne of hydrogen produced via electrolyser with green electricity instead of steam methane reforming reduce around 12.1 tonnes of CO₂. In this regard, this facility can reach a reduction of the CO₂ emission rights that usually the methanol facilities need to buy in the market. This means that the facility receives revenues from CO₂ emissions.
The main technic and economic considerations in order to analyse the price that is necessary put to the green methanol tonne to reach 10% of the Internal Rate of Return (IRR) are the following:

- Study period: 20 years.
- Price of green electricity supplied with a Purchase Procurement Agreement (PPA): 37.5 €/MWh.
- Tap water cost: 2 € per cubic meter.
- Operation hours per year: 8,000.
- Alkaline electrolyser CAPEX: 600 €/kW.
- Alkaline electrolyser system OPEX (% investment cost per year): 1.5.
- Operation hours up to 10% of stack degradation: 80,000.
- Stack replacement cost (% of the total cost): 20%.
- Low-pressure hydrogen storage at 30 bar CAPEX (€/kg): 245.
- Low-pressure hydrogen storage system OPEX (% investment cost per year): 0.5.
- Hydrogen compression system from 10 to 30 bar CAPEX (€/kg/h): 2,112.8.
- Hydrogen compression system from 10 to 30 bar OPEX (% investment cost per year): 6.
- Carbon dioxide purchase price (€/tonne): 50.
- Carbon dioxide revenues from reducing the steel factory carbon dioxide (€/tonne): 30.
- Fischer-Tropsch system CAPEX (€/kW of electrolyser system): 800.
- Fischer-Tropsch system OPEX (% investment cost per year): 5%.
- Green methanol storage system CAPEX (€/t): 550.
- Green methanol storage system OPEX (% investment cost per year): 0.5.
- Personal cost (€/year): 1,000,000.
- Land rental cost (€/year): 200,000.
- French loan duration: 10 years.
- Finance (% of the total investment): 70.
- Own resources (% of the total investment): 30.
- Financial interest (%): 5.
- Taxes (%): 25.
- Integration cost (piping, electricity, control, safety, etc.) (% of the main equipment): 12.
- Depreciation (%): 95.
- Depreciation (years): 20.
- Discount rate (%): 7.5.
- Inflation (% per year): 1.5.
- Weighted Average Cost of Capital (WACC) (%): 9.11.
- Oxygen sales price (€/tonne): 30.
- CO₂ avoided emission rights (€/tonne): 28.5.

The main data from this specific business case, taking into account that the goal is to fix the methanol price in a value that allows to have an Internal Rate of Return of 10% are the following (Figure 89):

- Total cost per year (€): The total cost can be different in the years because the degradation of the electrolyser stack and the degradation of the Fischer-Tropsch reactor make that the hydrogen and methanol production change in the years. However, the total cost per year is between 77 and 67 million euros.
- Total revenues per year (€): In the same way that the total cost per year, the total revenues per year is between 103 and 93 million euros.
- CO₂ emission reduction per year (tonnes of CO₂): In the same way that the total cost per year, the CO₂ emission reduction per year is between 298,000 and 264,000.
- Net Present Value (NPV) (€): 8,031,868

In order to know how the business case can change when some parameters are changed, some sensitivity analysis will be performed. Two of the main parameters are the methanol sales price (€/tonne) and the CO₂ emission right (€/tonne). The sensitivity analysis will consider for one hand ammonia sales price (€/tonne) from 450 up to 700, and for the other hand CO₂ emission right (€/tonne) from 10 up to 100. The parameter that will be observed in the sensitivity analysis is the Internal Rate of Return (IRR). IRR lower than 10% will be put in white colour and IRR higher than 10% will be put in green colour. All the combinations between ammonia sales price and CO₂ emissions right that obtain an IRR higher than 10% (green colour) will be desirable scenarios for the investors (Figure 90).

Methanol is currently produced from fossil fuels, mainly natural gas. China is the biggest methanol producer. This country uses primarily coal (around 64%). Methanol production costs mainly depend on feedstock and an electricity price. Biomass-based methanol cannot compete with fossil fuel-based methanol. Its production cost ranges from EUR500/t to EUR600/t.

The production costs of renewable methanol based on wind power and carbon dioxide depend on electricity cost and vary from 610 €/t to 1520 €/t, but are falling [23,24]. The green methanol cost obtained in the business case is 612.4 €/tonne. The obtained value is in between and in the low part for the value obtained in the references defined previously.

### Conclusions

In this chapter five business cases related with green hydrogen, green ammonia and green methanol in different locations like Chile, China, Australia, Argentina and Austria were studied deeply.

The main conclusions for the five-business...
The main conclusions for the five business cases developed in the chapter are the following:

- All the products (hydrogen, ammonia and methanol) obtained in the facilities defined in the business cases are more expensive than the products with fossil fuels origin. However, the extra cost will be covered mainly with the expected higher price related directly to the carbon dioxide emissions.

- All the business case studied in the chapter, the pay-back value when we consider 10% of Internal Rate Return are always around 18 years. This means that the business will work properly but with not so much improvised problems.

- The parameter that has more impact on the business cases defined in this chapter is the electricity price. Lower electricity prices imply a net present value increase and a pay-back reduction.

- One of the main parameters that can help the business case viability is the carbon dioxide emission price. Higher values of carbon dioxide imply directly better results from an economical point of view.

- All the values obtained regarding the sales price in the different business cases (hydrogen, ammonia and methanol) are aligned with information obtained in different forecast reports. This means that the methodology used in all business cases is validated and can be a good tool for the next business cases studies.
REFERENCES


Based on the results of the different Sub-Tasks and Task Forces presented in this report as well as the expertise of the Task38 members, a set of recommendations for easing the deployment of P2X systems is suggested hereafter. Techno-economic, regulatory and modelling related recommendations are addressed allowing to target a wide range of stakeholders: policymakers, industries and analysts (academic, research organisations, etc.). First, general recommendations (non-specific to one pathway) are suggested then, the different Power to X pathways are tackled.

### Techno-economic recommendations

The value chain for low-carbon hydrogen is not completely developed at commercial scale today. Depending on the P2X pathway and on the step of the supply chain, different stages of maturity are faced with specific technical challenges. As stated in the IEA Innovation report [1], unlocking the steps of the supply chain with the lowest maturity levels is essential to allow the deployment of the full pathway.

To do so, further research, development and innovation (R&D&I) is required as well as further demonstration projects. This is not only the responsibility of research organizations or industries working on the specifically related technologies, but also of governments and local authorities via adequate R&D&I financing tools.

Overall, improvements are still needed in order to ensure high global efficiency of the pathway [2]. The use of critical materials is also problematic and further research should be dedicated to this issue [3]. Enhancing the lifetime of certain technologies such as SOEC by improving the material stability is also a major research field to be supported.

The Innovation IEA report details specific recommendations to foster innovation in PtX field (among other new technologies) [1].

For more developed pathways, the challenges are different, as addressing the economic viability of the PtX systems, and the related technologies. Several technologies have reached the required maturity and the next step is to be deployed in the market. However, only relying on the market system will not allow these technologies to enter the market, since these technologies are today not competitive compared with historic solutions (generally fossil-based) providing the same services.

The highlighted next step is upscaling these technologies. This will allow reducing the costs as a consequence of the economies of scale and the learning experience behind.

When the demand is existent, one way to
do it is by building on existing industries, and infrastructure [4]. For instance, the IEA Hydrogen report highlights the importance of making industrial clusters the nerve centres for scaling up the use of clean hydrogen. This offers “the opportunity to create hubs that bring down the cost of low-carbon hydrogen pathways and kick-start new sources of demand”. In particular, the coastal industrial hubs, located near ports, can be attractive [4]. Beyond relying on the existing demand in industry to bring down the costs, benefitting from the existing infrastructure, when possible, can help prevent big expensive delivery infrastructure investments.

By relying on the existing industrial demand to scale up clean hydrogen technologies, and reduce the costs, the new demands can be fostered. However, this does not mean to focus on the industrial pathway only. The other pathways (Hf, Hg, Hq) also need to be advanced in order to reach an appropriate scale for competitive technologies.

One business case helping to improve the overall system cost is targeting different markets for the produced hydrogen as part of the sector coupling potential. This will help enhance the profitability of the electrolysers by increasing its utilisation rate while helping to unlock new markets with lower hydrogen production costs.

Next to the economics of hydrogen systems, there is also the environmental impact. The interest in hydrogen is led by the environmental concern and the target to lower the global GHG emissions. For a specific service, the interest in substituting fossil-based technologies by hydrogen-based ones is conditioned by the carbon footprint of the hydrogen production. Low carbon hydrogen production may not match big hydrogen demand hubs, geographically speaking. Hence, a need for international trading of hydrogen is foreseen. It will allow linking the regions with low carbon hydrogen production potential with regions where the demand is voluntarist but under low carbon production resource constraints. Hence kick-starting international hydrogen trade for the ultimate global low-carbon market (Asia Pacific, Middle East, North Africa, Europe) will be one of the next major steps to be taken [4].

Pathway specific

**Pth**

The electrolysers that are the foundation of PtX pathways are already available in the market, however, still need further cost reductions in order to be “market-ready”. Lowering the costs to trigger the demand will depend on two major components. First, the capital cost of the technology and second the operation costs are driven by the electricity prices and the utilization rates.

On the first point, lowering the technology cost depends on the scaling up of manufacturing capacities and on its ability to bring down the costs [5]. PEMEC still has to be improved in its cost and efficiency compared to AEC. The latter being the most mature technology in markets today. Regarding SOEC electrolysers, they are still in the development phase, but there are a number of pilot projects underway [6].

Regarding the second point, there would be obvious benefits from making productive use of curtailed renewable allowing to benefit from cheap electricity [4]. However, it is not possible to base the business case only on surplus electricity, since this will lead to low utilization rates of the electrolysers.

Ensuring an acceptable utilization rate is crucial in order to reach competitive costs. This can present an issue in regions relying on renewable hydrogen and where renewable resources are scarce. Hence, international hydrogen trade is expected to grow in size and importance.

Furthermore, benefitting from the electrolysers flexibility can present an economic interest, since it allows an extra-profit coming from the services provided to the electricity system (reserve market participation, frequency control remuneration, etc.). However, this participation can be considered as a double-edged sword, since the more numerous the participants to the flexibility market, the lower the remuneration for the service provision, which is somehow a “cannibalisation” effect [7].

**HtP**

Further work on the system overall efficiency is needed to ensure the techno-economic viability of this pathway. There is a potential for competitiveness of producing electricity from hydrogen but only when considering peak hours, where electricity prices are already high. H.P can however be a serious alternative in a future where fossil-based electricity generation means (for peak hours) are “forbidden” [8].

**HtG-H2**

The injection of hydrogen in the gas infrastructure can help boost low carbon hydrogen supply while making one of the most reliable sources of demand. According to the IEA, even 5% blending (volume-based) would create large new global hydrogen demand. A total shift to 100% hydrogen can also be foreseen (projects are already in place, like Leeds in the UK [9]). This will enable deep emissions reduction for the long term [4].

Various studies [10]–[12] suggest that a transition of the gas pipeline system to hydrogen is viable, but that only practice will show the technical and economic viability. Hence, further demonstration and pilot projects are still needed in order to assess materials as well as end-use adequacy to the transition towards hydrogen in the gas grid. It is critical that learnings from the existing and planned demo projects in the years to come addressing these issues are shared to help unlock the challenges of this pathway [2].

Industrial transparency will be key in the years to come to help accelerate learnings for a shared benefit.

Centralizing this kind of information can be the objective of a dedicated international initiative.

**HtG-M**

The Htg-Methanation pathway has the advantage of requiring much less conditions with regards to the adequacy of the infrastructure. However, the final cost of the process leads to higher costs than the direct injection of H2. Hence specific support mechanisms are needed to trigger this market. These will be discussed in the Policy recommendations part.

The availability of source and storage of carbon is also a major point to address when considering this pathway. This can even condition the viability of this pathway.

**Htf-H2**

Hydrogen use for mobility via fuel cells might be the most “popular” energy-related application. However, specific attention should be given to supporting the transport options where hydrogen has most to offer [4]. Long-distance transport means are an attractive market for hydrogen that can be fairly competitive once the required scales are reached [13].

The availability of the refuelling infrastructure is also key. In order to avoid the chicken-egg dilemma, some suggest vertical integration of the whole pathway, meaning that, one stakeholder, can master both vehicle and refuelling facility manufacturing. In this way, the deployment of both can be synchronized.

Another option is to adopt a strategy where refuelling infrastructure is dedicated to a specific fleet of vehicles, like captive fleets. This will help start with “affordable” investments. Then, these vehicle fleets have the advantage of predictable driving and refuelling patterns.
The availability and cost of the CO2 feedstock high today.

aviation, shipping, etc.). However, the costs are

decrease considerably. Accordingly, it is critical
can play a major role in removing regulatory and legal barriers that hampering investments in hydrogen today – for instance, by facilitating the process to obtain permits to install a specific facility (electrolysers, fuelling stations, etc.).

Regulation

Governments have a major role to play in defining the competitiveness of hydrogen to heat when considering a residential level [8].

Political recommendations

While for most of the applications of hydrogen, market penetration is conditioned by the ability to scale up production to bring down the costs, this scale-up is conditioned by the existence of the adequate political framework. To do so, different actions can be taken by the policymakers in order to ease the deployment of PtX pathways [15]. The policy measures can be divided as follows:

National strategies

Governments play an important role in setting national targets. Establishing these targets and/or long-term policy signals is crucial to foster investor confidence, confidence that is hampered by uncertainty and risk. This can be done via dedicated roadmaps to hydrogen deployment, as multiple examples across the globe: Japan, France, Australia, Korea, etc. These roadmaps provide strong objectives for critical stakeholders to converge around.

This can also be addressed through more global measures; like setting ambitious GHG reduction or renewable deployment targets, which will help foster low carbon technologies. The public measures are also reinforced by ambitious private pledges. The latter initiatives can be supported by public authorities via Innovation funds or by solving specific regulatory barriers.

Standardisation

Mass manufacturing of hydrogen-related equipment like electrolysers, fuel cells and components of refuelling stations will drastically contribute to reducing the costs. This is only feasible on a global scale if international standards are agreed [4]. Hence, a standardization effort is crucial in order to ease the cost drops allowed by the scale effect. Governments can play a role in supporting industries to coordinate national and international initiatives around standards (for example, regarding pressure levels, hydrogen injection rates in NG grids, safety, etc.). National standardization institutions and international bodies such as the International Organization for Standardization (ISO) have a key role to play in such a process. On the governmental side, regulatory bodies need to be on board to actually implement standards.

Incentives

Governments can also foster the development of hydrogen technologies through adequate incentives such as tax breaks, subsidies or penalties on fossil-based alternatives to encourage (or even mandate) the initial market steps of hydrogen [13]. For instance, implementing a carbon price is required to both increase the profitability of low-carbon hydrogen production (compared to benchmark processes such as steam methane reforming), and the profitability of hydrogen use as a substitute to fossil-fuel options (for transport, gas use, etc.)

For the technologies that are still in need of further research and studies, governments can also play a role by promoting R&D and knowledge sharing.

Coordination

As neutral stakeholders, governments are well-positioned to coordinate private efforts around potential local investment opportunities. Having the global view on a national basis, governments can not only coordinate but also set priorities and directions to organize the strategic investment efforts (demonstration projects and knowledge sharing) in the most optimized way, easing the first steps of deployment.

Pathway specific policy recommendations

PtH

Upstream, low-carbon hydrogen production requires low-carbon electricity. Energy policies should promote renewable energy penetration or more generally low-carbon electricity. This is a win-win strategy since hydrogen production can serve as a measure to avoid curtailment of excess electricity, to adjust the power demand by providing grid balancing services, or even to allow more renewable electricity to enter new applications in the form of green gas, green chemical and green fuel. Hydrogen business cases can become more profitable when hydrogen systems are allowed to participate in grid balancing or ancillary services and capacity mechanisms. Hence, acknowledging
the PX flexibility potential and regulating it is required.

Further incentives can consider exempting electrolysers from paying electricity taxes for example, or subsidizing part of the electrolysers cost.

Penalizing the fossil-based competitor is also crucial to trigger the market. At present, there is a lack of regulations or penalties being applied to conventional polluting methods of hydrogen production to make them more expensive and ease the transition to low-carbon hydrogen. Carbon pricing can be one of the important mechanisms to consider.

HtX

Downstream, hydrogen system deployment can be fostered by sector-specific measures, via implementing standards and/or incentives during the transition.

HtP

The hydrogen to power pathway is still expensive today. It may have sense when considering peak hours as previously explained (techno-economic recommendations). However, in order to reach competitiveness, penalizing fossil peak electricity generation means is essential [8]. In a world where fossil fuel means are forbidden, hydrogen may be the only way to produce electricity during peak hours and hence contribute to the stability of the electricity system during “stress” hours.

HtG

The injection into natural gas networks will need government support in order to promote its market penetration. Acknowledging the actual greenhouse gas mitigation for gas applications by also accounting the contribution of methane leakages during processing and transport of natural gas (and implement the relevant incentives/penalties accordingly), a clear target for the hydrogen blending concentration into the gas grid could be set. This concentration currently varies a lot from one region to another. It can reach 10% (of the volume) like in Germany for example, while it does not exceed 6% in France and 0.1% in the UK A harmonization of the standards at the European level (but not only) is crucial to prepare a more suitable market penetration environment. Standards for natural gas pipelines cannot, and help hydrosystems, underground storage and use of gas mixtures in burners have generally been designed from the viewpoint of a few percentages of hydrogen in natural gas. In the years to come, if hydrogen gas becomes the norm, these standards need to be revised.

A system of Guarantees of Origin can be set for biogas and hydrogen as an appropriate measure to stimulate the use of renewable gases. Additionally, to foster the development of “green” gas, feed-in tariffs may be implemented in the transition. Such schemes exist for bio-methane injection [15]. Hydrogen or synthetic methane could be made eligible for similar support. A quota system can also be discussed, to foster the H₂ to gas applications.

HtF-H₂

Regarding the mobility market segment, moving to hydrogen as the fuel source for the transport sector may go through the coexistence of the different technologies in order to be able to meet the GHG emissions reduction targets. Setting a pledge for the carbon emission reductions related to the transport sector is important but not sufficient since it does not clarify the prospects for each low-carbon mobility option. It is leading to the misconception of considering that these options will only compete against each other, while they can complement each other in order to achieve the targets. A clear strategic roadmap leading to the realization of the pledged targets is required. Incentives could also include, in the transition, grants to reduce the vehicle price paid by the consumer. It is then important to think beyond the sole light passenger duty vehicles (i.e. by including trucks, trains, maritime use), and incentivize the infrastructure development jointly with the vehicle purchase. Other financial support mechanisms include carbon pricing and carbon-related taxation for vehicles, which allows penalizing the fossil-based alternatives and help hydrogen vehicles reach competitiveness. A system of tax and/or fees exemptions (example: registration fees and highway tolls) can also be taken into account to promote clean technologies, including hydrogen.

HtF-S and HtF-G

The economy of E-fuels being partly based on the carbon price, setting a clear framework of carbon pricing can be one of the major political responsibilities to foster this market. Besides, setting quotas for fuel shares (for example in aviation, shipping, other) can help boost the use of these synthesized fuels and initiate economies of scale.

Htl

The existing industrial markets: refineries or the E-fuels industry, or hydrogen for the power sector can be fostered by sector-specific measures, via implementing adequate certificates, subsidies and/or premiums (which is already the case for the injection of biogas into the grid, and in some countries for EV). Or it can be setting standards or targets such as the concentration of hydrogen into the NG grid, or the modalities of potential hydrogen participation to the electricity reserve market. Thus, relevant policies require a holistic approach, by proposing adequate measures for the industry and energy sectors (gas and power) adapted to the regional contexts.

Modelling related recommendations

Methods for producing energy scenario results are diverse, and not always clearly presented. Most major energy scenarios are based on an energy system model. In this section, based on ST4 work [17], best practice recommendations are suggested to ensure an adequate modelling of PX systems and a fair representation of the different pathways in the renowned scenarios.

Scenarios must use appropriate modelling tools

• Models must capture sufficient temporal detail: amongst the different hydrogen potential contributions to the energy system, its ability to provide flexibility to the electric development of electrolysis. Low carbon hydrogen could help to repurpose or update potential “stranded” assets, like gas turbine, by replacing fossil fuels (natural gas) by hydrogen for example.

HtQ

Overall, to unleash the hydrogen potential, governmental support is needed. Private industrial initiatives cannot, alone, foster its development. Governmental and regional support can take different forms. It can be financial like granting subsidies, feed-in tariffs or premiums (which is already the case for the injection of biogas into the grid, and in some countries for EV). Or it can be setting standards or targets such as the concentration of hydrogen into the NG grid, or the modalities of potential hydrogen participation to the electricity reserve market. Thus, relevant policies require a holistic approach, by proposing adequate measures for the industry and energy sectors (gas and power) adapted to the regional contexts.
system can be a game-changer in improving the electrolysis process profitability [18]. However, in order to capture this potential, an important factor that should be taken into account is the temporal resolution of the considered models. Furthermore, the high temporal resolution allows to accurately assess the hydrogen cost through the adequate estimation of the load factor that can be improved via the flexibility provision (participation to the reserve markets for instance). Multi-year models are attractive when addressing investment decision dynamics over a relatively long period of time. It is generally difficult to do both (refined temporal resolution and multi-year decision making, due to high computing requirements).

- Models must capture sufficient spatial detail: Likewise, the geographical scope can vary from analysing single projects or systems to modelling the energy system of the whole world. For instance, the geographic information system (GIS)-based models allow reaching very high spatial resolution through the possibility of mapping large sets of data. More details are available in [19]. The spatial resolution can be of major importance when considering the infrastructure deployment issue. In turn, the infrastructure representation impacts the cost, the energy consumption and the emissions of a given energy vector. Beyond the transmission and distribution selected pathway (pipeline or trucks), the delivery cost highly depends on the travelled distance and the geography of the travelled pathway. Furthermore, a refined geographic resolution can provide useful insights regarding the relevance of the system design and the location strategies of the different facilities, for instance, highlighting the trade-off between a centralized and a decentralized design [20].

- Models must appropriately represent technologies and inter-sectoral connectivity: A bottom-up process is a technology-rich approach based on thorough descriptions of technologic aspects of the energy system and how it can develop in the future. Hydrogen emergence in such models is hence dependent on the refined description of the current and prospective hydrogen technologies and the associated techno-economic assumptions. Representing the competitors on the different markets, it allows determining the required technology improvements (technical improvements and cost targets) in order to reach market penetration. Implementing proper learning curves in the models is also required to capture accurately the deployment potential. Beyond the technological representation, the sectoral representation is crucial in order to highlight the multi-sectorial decarbonization potential as well as the sector coupling potential of Power to X systems.

- Models must represent the complexity of consumer behaviour: Another perspective for further research is modelling and capturing consumer behaviour. This is important for modelling the new mobility services and behaviours, including the aspects that drive the user preferences, since capturing these aspects like the preference of drivers towards the vehicle recharging time and autonomy could lead to different results regarding hydrogen penetration in the mobility sector. In order to capture the consumer behavioural aspects that drive the energy demand, agent-based modelling (ABM) can be considered [21].

- Scenarios and models must also consider other objectives than minimizing the cost. Considering external costs: impact on the environment, health expenses, etc. can be a game-changer when setting an interest hierarchy in different technologies.

Scenarios must use consistent and substantiated data assumptions

Data is a very important part of the modelling experience. Adequate and consistent data is crucial in order to ensure a level playing field and do not penalize technologies over others, especially in a bottom-up modelling framework, where competitiveness between technologies in the different sectors is dependent on input data regarding current but also prospective costs and efficiencies of the different technologies. All these requirements while remaining manageable and user-friendly and preserving the transparency of the methodologies can be difficult to ensure. To sum up, all modelling approaches present assets and limitations. No model is perfectly complete. No model suits all research questions. In order to overcome the limits, one option can be to complement the models with one another: linking between different kinds of modelling tools improves the representation of the energy system. Several examples can be found in the literature [22]–[25].
REFERENCES


During these incredible four years of work, different accomplishments of the Task38 can be highlighted. Below is a list:


As part of the 22nd edition of the World Hydrogen Energy Conference (WHEC 2018), a round table co-organized by the IEA’s Hydrogen TCP Task 38 and the Hydrogen Council and moderated by Paul Lucchese (Capenergies, France) brought together researchers and industry stakeholders to talk about the role of hydrogen in energy scenarios with an orientation towards modeling and data aspects.

This roundtable was preceded by an assessment of the role of hydrogen in reference energy scenarios and a presentation of IEA Hydrogen TCP by Paul Lucchese. It was followed by a presentation of the Hydrogen Council and the H2 Scaling-Up roadmap made by Guillaume de Smet (Air Liquide, France) who highlighted the potential of hydrogen in its various applications on the horizon of 2050 with the assessment of the resulting investment needs.

The role of hydrogen in the scenarios of the International Energy Agency was also discussed. These scenarios are particularly important because they are consulted by “decision/policy makers” and can influence investment decisions.

According to Martin Robinius (Jülich Forschungszentrum, Germany), the presence of a hydrogen “module” in energy models is not sufficient to prove the full potential of this vector. The spatial and temporal granularity of the models is very important and can decide the presence or absence of hydrogen in the results. This point was supported by Sheila Samsatli (University of Bath, UK), who highlighted the fact that taking into account inter-seasonal storage and the need for flexibility of the system, in general, makes hydrogen appear more noticeable in the results, and without the required fineness of the temporal and geographical resolution, hydrogen risks being completely absent in the results and the scenarios.
Workshop on demonstrations (ST2) in Aix-en-Provence

An international workshop on the analysis of Power-to-X demonstration projects was organized on November 20, 2018, in Aix-en-Provence, hosted at the National School of Arts and Crafts (Arts et Métiers) by Capenergies and sponsored by GRTgaz. This international workshop brought together nearly 90 participants from 18 countries, with the remarkable interventions of Hychico (an Argentinian demonstration project carried out by industry without public subsidies), the AIE, and the Fuel Cell and Hydrogen Joint Undertaking (FCH-U). French demonstrators were also represented by the presentations of GRTgaz (Jupiter1000 project), Engie (GRHYD project) and Storengy (Méthycentre project).

Discussions took place during the round tables as part of the workshop as well as in the in-depth analysis sessions. In the framework of ST2, a database of more than 190 projects was established, it will feed the design of a roadmap for Power-to-X demonstration projects. This roadmap is now under development and is expected to be available online by end of 2020.

Workshop on hydrogen in energy models in Bath (ST4)

In the framework of ST4 of Task 38, a workshop on the theme “Energy system models and the role of hydrogen” was organized at the University of Bath on May 17th, 2017. Bringing together 40 participants, this workshop aimed to provide a forum for discussions on energy system models (objectives, specificities) and the potential role played (or not) by hydrogen in these models. The presentations reported on various models, macroscopic or very detailed on the Spatio-temporal level, developed by the University of Bath (United Kingdom), the Forschungszentrum Jülich (Germany), Unitec Institute of Technology (New Zealand), and the Institute of Applied Energy (Japan).

The conclusion shared during this workshop is the need for fine models to deal with hydrogen in a relevant way in all its dimensions as an energy carrier. The question of data was also raised as a key point, especially for exchanges with reputable models.

Workshop on Hydrogen in the Mediterranean region (STS) in Puertollano

In the framework of ST5 of the Task38, a workshop dedicated to the potential of a Mediterranean hydrogen hub was held on September 26, 2019, in Puertollano (Spain), hosted by the National Hydrogen Center (CNH2), and co-organized by CNH2, Task 38 and Capenergies. In front of around forty participants, the speakers shared insights addressing the many hydrogen projects, particularly in connection with maritime applications (from Spain, Italy, South of France, etc.). The workshop concluded with a round table setting out the first steps towards more collaborations on the subject.

Communication:

Papers

Five papers have been published in international journals, mainly in the International Journal of Hydrogen Energy, and one paper is still under review. A wide range of topics has been addressed: regulatory framework, demonstration projects, power to X systems modelling, electrolyser costs, etc. A list is available below:

- Z. Chehade, C. Mansilla, P. Lucchese, S. Hilliard, J. Proost. 2019, IJHE, Review and analysis of demonstration projects on power-to-X pathways in the world: Access online version here
- J. Proost, 2019, IJHE, State-of-the-art CAPEX data for water electrolyzers, and their impact on renewable hydrogen price settings: Access online version here
- J. Proost, 2020, IJHE, Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen: Access online version here

Participation in conferences (WHEC, P2G, EEM, IAAE)

Task 38 members have also participated in different conferences, not only hydrogen specific.


- Z. Chehade, C. Mansilla, P. Lucchese, S. Hilliard, J. Proost. 2019, IJHE, Review and analysis of demonstration projects on power-to-X pathways in the world: Access online version here
- J. Proost, 2019, IJHE, State-of-the-art CAPEX data for water electrolyzers, and their impact on renewable hydrogen price settings: Access online version here
- J. Proost, 2020, IJHE, Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen: Access online version here

Participation in conferences (WHEC, P2G, EEM, IAAE)

Task 38 members have also participated in different conferences, not only hydrogen specific.


Technology briefs

Three technology briefs have been published on the IEA Hydrogen TCP website. A list is suggested below. A fourth brief will soon be available to address the participation of hydrogen to the electricity security market.


Award for the Operating Agent: Christine Mansilla

Figure 96: Christine Mansilla receiving the “Outstanding Operating Agent” Award from the IEA

Following the 6th plenary meeting of the Task38 on September 25th, 2019, Christine Mansilla, received a trophy from the IEA for her outstanding work as an operating agent from 2016 till 2019. Her serious work, perseverance and exceptional human qualities made her a remarkable and unique Task operating agent.
After closing the Task 38, further collaborations and events are also foreseen in order to ensure a continuity of the work, so that it wouldn’t be a “one-shot” work effort. A list of the envisaged perspectives is presented below. The list is not comprehensive, and many future tasks will use the results of Task 38.

Furthermore, joined webinar and event will be organized in 2021 to discuss the key results of Task 38, with some collaboration with Power to X organization.

An IEA Hydrogen TCP Power to X road map will be published in 2021 as a final output of Task 38.

Establishment of a joined IEA Secretariat/Hydrogen TCP Database on projects deployment

Base on the feedback of the database created in Task 38/ST2 on PtX demo projects, a reference database will be established in 2021 through a collaboration between IEA Secretariat Paris and Hydrogen TCP. This database will include information on all hydrogen production deployment projects. This database will be very useful for data modelling, statistic, tracking progress on hydrogen deployment and many IEA tools.

Collaboration with Task 41

A new Task within the Hydrogen TCP is defined, called Task 41. This new Task will address the hydrogen data and modelling issues in details, addressing the representation of hydrogen in different sets and types of energy system models, including TIMES based models. Different members of Task 38 are participating in Task 41, some of them are even leading sub-tasks within the new Task. This will allow ensuring the continuity of some of the work done in the framework of Task 38 as well as sharing lessons and documents from our work.
A Plenary session on “Power to Hydrogen and Hydrogen-to-X” presenting the main results of Task 38 will take place in the first Online Conference of the International Association of Energy Economics on 8th of June.

The session, moderated by Hydrogen TCP Chair Mr Paul Lucchese will count with the following invited speakers:

> Ms. Olfa Tlili, as former Task Manager of Task 38
> Mr. Francesco Dolci, Joint Research Centre (JRC) - European Commission
> Mr. Benoit Decourt, SBC Energy Institute
> Mr. Joris Proost, UCLouvain
> Mr. Martin Robinus, Umlaut

Final plenary meeting

Due to covid-19 restrictions the final plenary meeting will take place online on the 7th of May.
Table of figures

**Figure 1.** Overview of key hydrogen production and usage pathways. With multiple production options and applications, hydrogen could be valuable in providing flexibility and sector-coupling to energy systems.

**Figure 2.** PtX-HX: Enumeration of the main pathways from low carbon, intermittently low valued power to high value products and services.

**Figure 3.** PtX-HX: Icons legend of products, services, and energy transformation technologies.

**Figure 4.** Power-to-X pathways.

**Figure 5.** Geographical spread (left) and temporal evolution (right) of the number of demonstration projects.

**Figure 6.** Share of each HX application of the demonstration projects (multiple nomination allowed).

**Figure 7.** Evolution of HX applications as a function of time (multiple nominations allowed).

**Figure 8.** Time evolution of subcategories in Hydrogen-to-Fuel and Hydrogen-to-Gas applications around the world.

**Figure 9.** Geographical spread of HX applications around the world.

**Figure 10.** Time evolution of the versatility (number of HX applications) of demonstrations.

**Figure 11.** Number of demos (left) and total installed capacity (right) for the 3 types of electrolyser technologies.

**Figure 12.** Evolution of the power supply schemes as a function of time.

**Figure 13.** Number of demos (left) and total installed capacity (right) for the 3 types of electrolyser technologies.

**Figure 14.** Total aggregated installed electrolyser capacity per year.

**Figure 15.** Comparison between the cumulative capacity of the Alkaline, PEM and SOE technologies.

**Figure 16.** Total installed electrolyser capacity per demonstration project per year.

**Figure 17.** Installed electrolyser capacity (in MW) vs. H₂ output (in Nm³/hr) for each demo project.

**Figure 18.** Evolution of Alkaline and PEM efficiencies in function of time, as calculated from Figure 16.

**Figure 19.** Demonstration storage technology.

**Figure 20.** Hydrogen blending rates range.

**Figure 21.** Schematics of pathways of PtX (2).

**Figure 22.** Results of review step 1: types of document collected (sum of eligible publications: 220).

**Figure 23.** Results of review step 1: Publication years of collected documents (sum of eligible publications:220).

**Figure 24.** Results of review step 1: Geographical scope of the studies (sum of eligible publications: 220).

**Figure 25.** Left: Assumed electricity supply system for electrolysis (79 eligible scenarios).

**Figure 26.** Type of electrolysis technology assumed in analyzed scenarios (109 eligible scenarios).

**Figure 27.** Average input specific electrolysis investment (eligible scenarios AEL: 26, PEM: 12, not specified: 28).

**Figure 28.** Average electricity demand for hydrogen production.

**Figure 29.** Average load factor of electrolysis (eligible scenarios: 14) and hydrogen production costs (eligible scenarios: 99).

**Figure 30.** Addressed H₂-X pathways in the reviewed scenarios (multiple nomination possible).

**Figure 31.** Experts evaluation of publication data quality expressed in level of trust (D no; 100 full confidence).

**Figure 32.** Compilation of past and expected alkaline (top) and PEM (bottom) electrolysis plant cost in Euro/kW, based on available literature studies (reproduced from Ref. [10]).

**Figure 33.** CAPEX data for PEM electrolyisers, collected from Task 33 [12], [13], as a function of H₂ production capacity (a) and replotted as a function of equivalent power input (b). The conversion factor corresponds to a specific electrical energy consumption of 5.2 kWh/Nm³ (c). The latter figure also represents the number of cells/stack needed to comply with a given input power in the range 7–700 kW.

**Figure 34.** CAPEX data for both PEM and alkaline electrolyisers, plotted as a function of power input. Data for alkaline systems are based on a single stack of 2.13 MW consisting of 230 cells, 2.6 m² in size. The change in slope for alkaline electrolyses corresponds to the use of multi-stack systems.

**Figure 35.** Reduction in CAPEX upon use of multi-stack systems, both for PEM (a) and alkaline (b) electrolyzers.

**Figure 36.** Electrolytic H₂ production cost (in Euro/kW) as a function of electrolyser operational time for different electrolyser CAPEX values; figures (a) and (b) are reproduced from Ref. [17] and ref. [18], respectively.

**Figure 37.** Electrolytic H₂ production cost (in USD/kg) as a function of electrolyser operational time (FLH = full load hours) for different renewable electricity costs (in USD/MWh), reproduced from Ref. [19]. Further assumptions are an electrolyser CAPEX of 450 USD/AW, a lifetime 30 years, and a system efficiency of 70%. The cost of hydrogen from SMR (purple area) was estimated at 1–3 USD/kg, depending on regional variations in natural gas prices. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

**Figure 38.** Summary of today’s main hydrogen production technologies.

**Figure 39.** A typical unit size configuration for an industrial alkaline water electrolyser.

**Figure 40.** Projected cost reduction associated with a scale-up of green electrolytic hydrogen production. The blue diamonds represent real CAPEX data for PEM electrolyzers, except for the ones between 1000 and 10000 Nm³/hr, which are cost projections. The red squares and green triangles are real SMR CAPEX data for small-scale (on-site) and large-scale (centralised) reformers, respectively. Taken from Refs. [17]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

**Figure 41.** Examples of multi-stack alkaline electrolyser systems: (a) A 135 MW electrolyser plant from 1953 [23]; (b) Current multi-MW plant designs from a major electrolyser manufacturer, based on a single stack electrolyser capacity of 2.2 MW [24].

**Figure 42.** Electrolytic H₂ production cost as a function of electrolyser’s annual operating time (1 yr = 8760 h), simulated according to Eq. (1) for two different CAPEX/electricity cost combinations. The electrolyser’s efficiency was fixed at 70%, corresponding to 47.1 kWh/kg. The additional dashed trendlines for the 2 data sets include, besides the electricity cost, also an additional fixed OPEX cost equal to 30% of CAPEX.

**Figure 43.** Documented and extrapolated decrease in average auction prices for renewable electricity from solar PV and onshore wind (from Refs. [26]).

**Figure 44.** State-of-the-art CAPEX data for alkaline electrolyser as a function of power input. The change in slope for alkaline electrolyser corresponds to the use of multi-stack systems.

**Figure 45.** (a) Simulated electrolytic H₂ production cost as a function of electrolyser CAPEX, assuming a 70% efficiency (i.e. 47.1 kWh/kg) and a 50% load factor (i.e. 4380 h/year).
Renewable electricity price was fixed at 30 €/MWh, corresponding to 47.1 * 0.03 = 1.41 €/MWh. The right axis gives the resulting % contribution of the electrolyzer CAPEX to the total H2 cost; (b) Renewable electricity price (in €/MWh) as a function of electrolyser efficiency to arrive at an electrolytic H2 cost of 2.0 €/kg for three different CAPEX values (500, 1000 and 2800 €/kW).

Figure 46. Total Cost of Ownership (TCO) of electrolytic H2 (delivered at 35 bar) as a function of power input, obtained from the Danish electrolyzer manufacturer GreenHydrogen. Prices are based on a 10 years operation (including a 10 year’s service and maintenance agreement) for a complete turnkey, containerized alkaline electrolyzer unit (including inverter and water treatment), delivered and installed in Europe. OPEX includes the use of electricity, water and nitrogen (for purge), assuming a renewable electricity price of 40 and 45 €/MWh, respectively.

Figure 47. Prospective participation of power to hydrogen in electricity commodity trading (EECT) 136

Figure 48. Profiles of the increasing frequency of below-average-demand prices in the SA Region of Australia’s NEM 144

Figure 49. Numerics of the three demand price relationships in Figure 47 144

Figure 50. Profiles of the increasing production over a decade in the SA Region of Australia’s NEM 145

Figure 51. Profiles of the effect of VRE on prices in the SA Region of Australia’s NEM 145

Figure 52. Numerics of the three demand - VRE price relationships in Figure 49 146

Figure 53. Broad predictions of increasing electrification upsides resulting in ongoing increases in VRE production 146

Figure 54. Electricity, Demand, and Supply: Current, (left), and proposed two-way market design (right) 147

Figure 55. Prospective participation of power to hydrogen in frequency control system security markets 148

Figure 56. Energy commodity buy and sell market value sample time-series for Hornsdale Power Reserve 149

Figure 57. Summed 9O-day averages of 8 x 2 FLAS market value sample time-series for Hornsdale Power Reserve 149

Figure 58. Empirical cumulative probability distributions for HPR, excluding 17 days from 31 Jan 2020 150

Figure 59. Empirical cumulative probability distributions for HPR, “normal”, and “islanded” 150

Figure 60. Frequency control diagram of reserve responding to an event 155

Figure 61. Frequency control service reserves (using ENTSO-E nomenclature) 157

Figure 62. Example of time scale for ancillary services and energy balancing in electricity markets 157

Figure 63. FCH hydrogen participation in frequency control in Europe (6) 160

Figure 64. Differing representation of hydrogen in scenarios from 12 global studies. Hydrogen representation is separated into seven sectors, covering the supply-side (production, storage, transportation), and applications of hydrogen (conversion to electricity, mobility, industry, gas grid). Colours refer to the level of representation in the scenario design; “R” denotes technologies that are included in the results of the scenario. See the legend for more details 182

Figure 65. Contribution of hydrogen to final energy demand in 2050 in power, mobility, industrial and heat sectors for a range of scenarios. Where studies state the inclusion of hydrogen in the results without precisely quantifying it, values have either been estimated by the author (IEA ETP 2016, Shell Sky and H2 Council scenarios), or the result has been denoted by a hashed box 184

Figure 66. Effect of greenhouse gas (GHG) emissions reduction on hydrogen prevalence in energy scenarios. A negative GHG emissions reduction represents an increase in emissions over the scenario time horizon. Exploratory scenarios are displayed in purple, while normative are displayed in green 191

Figure 67. Specific business cases considered in STS 207

Figure 68. Power to Green Ammonia in order to produce up to 300 tonnes per day 210

Figure 69. Cumulated Net Present Value VS years 211

Figure 70. Sensitivity analysis between green ammonia sales price and CO2 emission right price 213

Figure 71. Market costs of ammonia in Chile, compared with Talal estimate with advanced flexibility at 483 USD/t 213

Figure 72. Power to Green Ammonia in order to produce up to 300 tonnes per day 215

Figure 73. Cumulated Net Present Value VS years 216

Figure 74. Sensitivity analysis between green ammonia sales price and CO2 emission right price 217

Figure 75. Market costs of ammonia in Chile, compared with Talal estimate with advanced flexibility at 483 USD/t 218

Figure 76. Opportunities to put Australia on the clean hydrogen map exist across the supply chain [11]. 220

Figure 77. Power to Green Ammonia in order to produce up to 300 tonnes per day and transport from Australia to Japan. 221

Figure 78. Cumulated Net Present Value VS years 222

Figure 79. Sensitivity analysis between green ammonia sales price and CO2 emission right price 223

Figure 80. Power to Green hydrogen to produce up to 48 tonnes per day 225

Figure 81. Cumulated Net Present Value VS years 227

Figure 82. Sensitivity analysis between green liquid hydrogen sales price and CO2 emission right price 228

Figure 83. Cumulated Net Present Value VS years 229

Figure 84. Sensitivity analysis between green liquid hydrogen sales price and CO2 emission right price 230

Figure 85. Overview over the green liquid hydrogen cost contributions by each hydrogen supply chain element 231

Figure 86. Global and China methanol production 232

Figure 87. Global methanol consumption as fuel 233

Figure 88. Power to Green methanol in order to produce up to 344 tonnes per day 233

Figure 89. Cumulated Net Present Value VS years 235

Figure 90. Sensitivity analysis between green methanol sales price and CO2 emission right price 236

Figure 91. Methanol Methanex monthly average regional posted contract price history 2020 236

Figure 92. WHEC2018 Roundtable – Rio de Janeiro, Brazil 253

Figure 93. Power-to-X demonstration projects workshop – Aix en Provence, France 254

Figure 94. Workshop on “Energy system models and the role of hydrogen”, Bath University, UK 254

Figure 95. Workshop on the potential of a Mediterranean hydrogen hub, PuertoLlano, CNH 255

Figure 96. Christine Mansilla receiving the “Outstanding Operating Agent” Award from the IEA 256

Figure 97. Task41 definition meeting, Brussels, September 2019 259