



UNIVERSITY OF
BATH

Robinius, M., Welder, L., Ryberg, S., Dickinson, R., Gammon, R., Samsatli, S., Mansilla, C., Lucchese, P., Tlili, O., Balan, M., Dolci, F., Meeks, N.D. and Valentin, S. (2017) Power-to-Hydrogen and Hydrogen-to-X: Which markets? Which economic potential? Answers from the literature. 2017 14th International Conference on the European Market (EEM).

Link to official URL (if available):

Opus: University of Bath Online Publication Store

<http://opus.bath.ac.uk/>

This version is made available in accordance with publisher policies.
Please cite only the published version using the reference above.

See <http://opus.bath.ac.uk/> for usage policies.

Please scroll down to view the document.

Power-to-Hydrogen and Hydrogen-to-X: Which markets? Which economic potential? Answers from the literature

Martin Robinius, Lara Welder, D. Severin Ryberg
Institute of electrochemical process engineering (IEK-3)
Forschungszentrum Jülich GmbH
Jülich, Germany
m.robinius@fz-juelich.de, l.welder@fz-juelich.de,
s.ryberg@fz-juelich.de

Esther Albertín, Jesus Simon
Fundación Hidrógeno Aragón
Huesca, Spain
ealbertin@hidrogenoaragon.org

Robert R. Dickinson
Hydricity Systems Australia; and
University of Adelaide, Centre for Energy Technology
Adelaide, Australia
robert.dickinson@hydricity.com.au

Rupert Gammon
Institute of Energy and Sustainable Development
De Montfort University, Leicester, United Kingdom
rgammon@dmu.ac.uk

Sheila Samsatli
Department of Chemical Engineering
University of Bath
Bath, United Kingdom
S.M.C.Samsatli@bath.ac.uk

Christine Mansilla, Paul Lucchese, Olfa Tlili, Alain Le
Duigou
CEA, Université Paris Saclay
Gif-sur-Yvette, France
christine.mansilla, paul.lucchese, olfa.tlili, alain.le-
duigou@cea.fr

Mihai Balan
National Center for Hydrogen and Fuel Cell (ROM-EST)
ICSI Rm. Valcea
Rm. Valcea, Romania
mihai.balan@icsi.ro

Francesco Dolci, Eveline Weidner
European Commission
Petten, Netherlands
francesco.dolci, eveline.weidner@ec.europa.eu

Noah Daniel Meeks
Southern Company
Birmingham, Alabama, USA
ndmeeks@southernco.com

Solène Valentin
Air Liquide
Jouy-en-Josas, France
solene.valentin@airliquide.com

Abstract— With the expansion of renewable energy's contribution to the energy mix, balancing the electricity grid is becoming increasingly challenging. Alongside other solutions, Power-to-Hydrogen concepts are gaining significant interest. In this paper, the “Task 38”, initiated by the Hydrogen Implementing Agreement of the International Energy Agency, presents the first of a two-step literature review regarding Power-to-Hydrogen and Hydrogen-to-X concepts with a focus

on prospective market and economic potential. The study reveals a large scope of literature that shows a considerable variety of suggested implementation schemes. The transportation sector is identified as the most promising consumer market. Hydrogen-to-Gas pathways will require subsidies in order to be profitable. Hydrogen-to-Power becomes an economically promising option in the context of systems with high shares of renewables and a need for longer-term storages.

Additionally, key enablers for Power-to-Hydrogen concepts are identified; namely support policies, concurrently with ongoing progress on the development and implementation of industry standard.

Index Terms-- Hydrogen in the Economy, Hydrogen-to-X, Power-to-Gas, Power-to-Hydrogen, Renewable Energy

I. INTRODUCTION

Energy systems are changing around the world due to a variety of factors, including:

- Increasing demand for energy in the world caused by globalization and the economic growth of emerging countries;
- Increasing share of renewables in the energy mix, especially in the electricity mix;
- The need for constraints on greenhouse gas (GHG) emissions, including CO₂ reduction in the energy sector;
- The need for limiting local air pollution;
- Deregulation in the energy sector, allowing new challengers to enter the market (although not encouraging the building of new infrastructure);
- The requirements of energy security and reliability;
- Increasing decentralization of power networks due to the growth of local generation.

The balancing of the electricity grid is increasingly challenging as the installed renewable energy capacity is increasing. Solutions like creating a transmission super-grid, smart grids and demand management, or back-up capacity implementation could assist in overcoming this issue; but new measures that go beyond increasing transmission and distribution capacity and flexible generation or consumption will need to be introduced to manage the grid as the level of renewable energy sources is increased. In this context, hydrogen systems are part of the global discussion on energy system modernization [1].

The characteristics of hydrogen production through electrolysis make it possible to quickly adjust the power consumption: electrolyzers can reach full load operation in a few minutes, even a few seconds [2]. Accordingly, hydrogen production appears a promising new means to contribute to electricity system management. Also, hydrogen can be injected into the natural gas grid, directly or as a constituent of synthetic methane [3]. Such pathways lead to consideration of an integrated energy systems with interconnections between the energy carriers [4].

In this context, an annex of the Hydrogen Implementing Agreement of the International Energy Agency was approved by the Executive Committee as “Task 38”, to examine hydrogen as a key energy carrier for a sustainable and smart energy system. It is entitled “Power-to-Hydrogen and Hydrogen-to-X: System Analysis of the techno-economic, legal and regulatory conditions”. Currently, the task brings together over 50 experts from 34 organizations in 15 countries [5].

The general objective of the task is to provide a comprehensive understanding of the various economic

pathways for Power-to-Hydrogen applications in accordance with local conditions, and a comprehensive assessment of existing legal frameworks. Identifying the key local parameters, combined with a varied portfolio of different business cases, will be a key aspect of Task 38. The task will include both business model evaluation as well as analysis of benefits in terms of macro-economic impacts through a systemic approach. A specific objective will be to deliver general guidelines and recommendations to both business developers and policy makers interested in promoting hydrogen system deployment in energy markets.

The “Power-to-hydrogen” (PtH) concept implies that, once hydrogen is produced from electricity from the grid, a large variety of uses are possible. It opens the door to new and diversified applications in diverse sectors, such as:

- Transport (hydrogen for fuel cells, biofuels, synthetic methane for transport ...),
- The natural gas grid (by mixing hydrogen directly with natural gas or through synthesis of methane for injection into the natural gas network),
- Re-electrification, through hydrogen turbines or fuel cells,
- The general business of merchant hydrogen for energy or industry (especially for refineries, the steel industry, ammonia production, etc.).

Additionally, ancillary services or other grid management services can be provided for electricity networks, at the transmission or the distribution level.

Many Power-to-Hydrogen demonstration projects are already underway or under construction. They cover diverse applications and have been deployed across a wide range of local and regional situations. A lot of studies have been published, including also some economic aspects [3]-[4]; [6]-[27]. However, business models are not always clearly defined and reliable, and are very dependent on the local geographic, economic and energy landscape. There is a lack of global outlook on business models in this domain and there is no global overview on the macro-economic and systemic impacts of the role of hydrogen in the energy system. There is a rich contemporary literature, including articles in academic journals and industry-orientated reports, exploring the future potential of Power-to-Hydrogen and Hydrogen-to-X (PtH – HtX). However, despite the vast literature, there is a lack of a systematic overview and a comprehensive understanding of the various technical and economic pathways for Power-to-Hydrogen and Hydrogen-to-X applications in diverse situations.

This paper presents an extensive literature review of the current Power-to-Hydrogen and Hydrogen-to-X literature, and maps the state of the art of existing techno-economic modelling, scenarios, and roadmaps. The review undertaken for this work is not an exhaustive list of all hydrogen studies ever published. Rather, the aim has been to capture the diversity of the current literature by identifying groups of studies. Over 200 documents were reviewed with a methodology developed to analyze the variety of studies considered. The methodology will be detailed in next section, and the results in Section III.

II. METHODOLOGY

To carry out the literature review on PtH – HtX, we proceeded in several steps.

First, we relied on the expertise of the members within Task 38 to co-construct a database of existing studies on PtH – HtX. Having experts from all over the world was a major asset and made it possible to include regional studies published in languages other than English. Documents were uploaded by the experts onto a private website, thus being available to all the Task members.

The review process itself is implemented in two main steps. The intention was to analyze the studies through a common reading guide (the “screening sheet”). Given the number of collected documents, it was proposed to have two screening levels. A first level analysis made it possible to sort out the most interesting studies and collect the main facts and figures of the studies, including:

- The context of the study and general issues: date, type of document, geographical scope and time horizon;
- Which PtH – HtX pathways are dealt with and is the issue of grid services addressed?;
- Generic results: key issues/bottlenecks identified in the study, general perspective for the pathway (positive, negative, neutral).

In the second (upcoming) step, the objective is to focus on the documents that were selected after the first step and build a database to compare:

- The underlying assumptions: e.g. fossil fuel prices, power prices, carbon price, CAPEX and OPEX;
- The results: e.g. hydrogen production cost, compared to target/market.

Over 200 documents have been collected up to now. A dozen of the experts volunteered to review the studies according to this process. The results of the first level screening are detailed hereafter, as well as the key findings of the most important studies.

III. RESULTS

A. Analysis of the literature database

First, we classified the studies according to the type of documents. As displayed in Fig. 1, more than half of the documents are reports, which shows that the PtH – HtX issue is not only addressed through academic works published in scientific peer-reviewed journal articles (approximately 20% of the collected documents), but also via in-depth studies for a given local context. These studies may be requested by institutions such as ministries or regional bodies, as well as by firms that investigate the business opportunities related to these contexts.

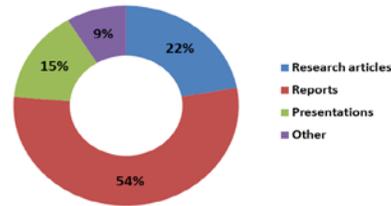


Figure 1. Typology of documents.

Although publications are most often published in English (80% of the collected documents), the regional coverage is broad. As depicted in Fig. 2, 16 regions were identified among the case studies. More than half of the studies deal with a specific local context.

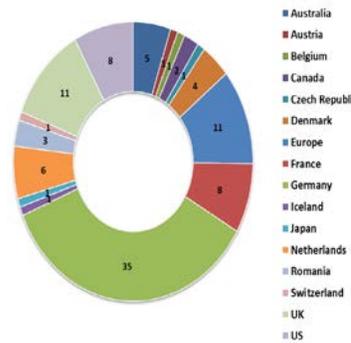


Figure 2. Geographical scope of the studies.

Another interesting fact to indicate is the publication dates of the studies. The number of documents issued each year in the two past decades is shown in Fig. 3.

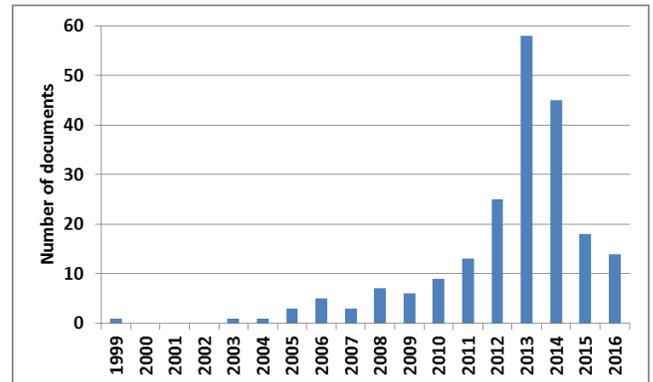


Figure 3. Issue dates of documents.

We observe that studies of PtH – HtX pathways have become more numerous in the last five years. Over 75% of the studies were published during this period.

The timeframes range from today to the mid- to long-term (2050). PtH – HtX pathways are not only considered in future scenarios but today’s opportunities are assessed as well. This is also revealed by the fact that half the documents deal with business cases or market studies. Nonetheless, most of the studies are theoretical in nature; only very few are carried out with relation to a pilot plant. This is probably due to the

current need for projects to concentrate on demonstrating technical feasibility ahead of economic competitiveness.

B. Major results from the literature

Hydrogen has the potential to be present in multiple applications (multi-use and multi-sector systems): hydrogen has a role to play in the electric, gas, transportation, and industrial sectors [8]. An attempt at categorizing precisely the different PtH – HtX pathways was presented in [28].

It is difficult to draw generic results from the studies, since the business cases are tightly linked with specific local contexts, as highlighted in [4]. However, three major potential markets emerge from the literature:

- The transportation sector (Hydrogen-to-Fuel, HtF);
- The injection of hydrogen into natural gas networks, either directly or as synthetic methane synthesized via a methanation step (Hydrogen-to-Gas, HtG);
- The power generation sector (Hydrogen-to-Power, HtP).

A similar number of studies address each of these three markets whereas only a few studies to date deal with industrial markets (Hydrogen-to-Industry, HtI) or heat generation (Hydrogen-to-Heat, HtQ).

The need for decarbonization of the transport sector provides a very strong incentive for producing low carbon fuel. Switching to hydrogen and electricity for transportation can improve air quality and reduce GHG emissions over the long term [27]. According to [6], the CO₂ emissions of hydrogen-fuelled vehicles could be 75% lower than for equivalent diesel vehicles, and enable 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 a promising option for reducing the GHG intensity of established transport fuels in the short term [22]. Business cases for the application of hydrogen in the transport sector are presented in several studies. According to [12], hydrogen production can be competitive with taxed gasoline in 2030 if produced with tax-free electricity and competitiveness could be achieved with taxed electricity in 2050. For the business case of a fuel station with on-site hydrogen production, financial projections are made [24] for both cars and buses. The study suggests that both business cases are expected to be profitable for 2030 and 2050. In [7], a break-even point for hydrogen fuel stations is projected for the late 2020s. Additionally, [7] also states that, with a mix of hydrogen produced from electrolysis and steam reforming, prices can be competitive with the that of diesel, while having 65 % lower CO₂ emissions. According to [12], HtF pathways already compete with low carbon fuels. Overall, as stated in [3], the utilization of renewable hydrogen in the transport sector has the potential to become an economically-sound business case.

Besides hydrogen applications in the transport sector, hydrogen from PtH can (in its pure form or as synthetic natural gas via methanation), be directly injected into natural gas pipelines. Work has been done in this area, but the overall potential, economic feasibility, and limitations still need to be assessed diligently [27]. While the production and injection of

synthetic natural gas is more expensive than employing pure hydrogen [12], [24], [25], the former path can utilize existing infrastructure with almost no modification whereas, in the latter case, hydrogen injections are currently limited to values (depending on various factors) between 2-10%, [25], [27]. However, the available estimates that were reviewed conclude that commercial competition is out of reach for synthetic methane blending, in particular in comparison with potentially low carbon options such as biomethane [12]. To become competitive, direct injection of hydrogen from electrolysis would need low power prices along with tax exemption in order to foresee this pathway becoming competitive by 2050 [12]. Thus, in the mid-term, profitability is only possible with the support of subsidies and/or premiums. Additionally, [12], [24] conclude that the electricity price and natural gas price have the most significant impact on the possible competitiveness of these pathways. To improve profitability, multimodal operation is frequently suggested. For example, participation in the heat market would improve the business case [25], selling oxygen and providing ancillary grid service would improve economics [24], or elsewhere an integral “smart gas” system is proposed [13]. The smart gas systems, which are designed in a style similar to electrical smart grids, thereby 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 highlighted [24], [27].

Moreover, hydrogen can enhance renewable energy integration [27]. Re-conversion of hydrogen to grid electricity is generally seen as a potentially viable option in the context of premium backup or seasonal storage [1]. 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 become the best storage solution [4]. For remote locations, which are reliant on renewable energy production and therefore require longer-term energy storage, re-conversion of hydrogen is also likely to prove viable [27]. In the broader scope, integration of long-term storage solutions into the energy system can reduce the need for conventional backup energy and capacity, but only along with the trade-off of lower utilization of the backup capacity [10]. However, in the near-term, re-electrification schemes are expected to be economically challenging, primarily due to low round-trip efficiencies [27]. As such, re-conversion is projected to be last in the merit order of hydrogen end-uses [4]. 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. In this case, the low cost of energy storage partially compensates for the round-trip losses [10]. As a controllable load, it is seen that flexible operation of electrolyzers is not a game-changer in regards to the economic competitiveness if flexibility services to the grid are not valorized [26]. In general, regional energy systems with large seasonal demand variations could prove attractive on a marginal cost basis when existing infrastructure (gas networks, energy stores, power plants) can be rededicated for hydrogen-centric purposes [27]. In addition, the use of heat recovery can significantly improve overall system efficiencies in all cases [4].

Other factors include the development of policies that encourage the deployment of Power-to-Hydrogen components and the ongoing development of industry standards [14]. Regulations in support of such policies could be developed to limit the carbon intensity of energy services and products, thereby favoring low-carbon pathways with the electricity, transport, and heat sectors [27]. More specifically, hydrogen could be defined as an eligible fuel within the renewable fuel standard [27]. Renewables-derived hydrogen could be an alternative compliance option for the refining industry within the context of fuel scenarios for bio-diesel and ethanol [27]. In Europe, certification procedures and accountability of green/low-carbon hydrogen could be developed to reach EU targets, especially with regard to the EU Renewable Energies Directive and the EU Fuel Quality Directive [22].

In the mid-term, it will also encourage and facilitate diverse ownership models (e.g. private, utility, retail) and ensure, in an organic and market-driven manner, the ongoing successful deployment of Power-to-Hydrogen systems [27].

IV. CONCLUSION

'Low-carbon' hydrogen (i.e. that 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. This paper presents an extensive literature review of the current Power-to-Hydrogen and Hydrogen-to-X literature, and maps the state-of-the-art of existing techno-economic modelling, scenarios, and roadmaps. The aim is to capture diversity within the current literature and draw some major conclusions from it. Over 200 documents were reviewed with a methodology developed to analyze the variety of studies considered. This reviewing effort relied on the participation of the members of Task 38, both to co-construct a database of existing studies on PtH – HtX and to review the works.

The literature analysis revealed that the PtH – HtX topic is not only addressed through academic works, but also by regional studies requested by institutions or firms that investigate the related business opportunities. The regional coverage is broad: 16 regions were identified among the case studies; and the time frames varied, from today to the medium to long term. Half the documents deal with business or market studies.

Although business cases are tightly linked with local circumstances, three major markets emerge from the literature: transportation, injection of hydrogen into the natural gas grid, and power generation. Mobility is expected to be the first market to be penetrated. Profitability for HtG pathways is likely only possible when considering subsidies/premiums. Competitiveness is a challenge for synthetic methane blending. Remote areas can offer promising deployment opportunities for HtP, and the ability to provide grid services could even be a game-changer for some business cases. Other key enablers for hydrogen system deployment include support policies and the establishment of standardization.

Future work will focus on enhancing the analysis according to newly available publications, and moving to a

more in-depth analysis of a selection of studies to quantitatively compare assumptions and results.

ACKNOWLEDGMENT

The present work was carried out within the framework of Task 38 of the Hydrogen Implementing Agreement 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.

REFERENCES

Given the number of collected studies and the article preparation requirements, only a selection of references is presented here.

- [1] C. J. Kikkert, "The effect of power renewables on the grid in 20 years' time", presented to the Electrical Engineering Society of Australia, October 5, 2016.
- [2] A. Godula-Jopek, *Hydrogen production by electrolysis*, Wiley, 2015.
- [3] S. Schiebahn, T. Grube, M. Robinius, V. Tietze, B. Kumar, and D. Stolten, "Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany", *International Journal of Hydrogen Energy*, vol. 40, pp. 4285–4294, Apr. 2015.
- [4] B. Decourt, B. Lajoie, R. Debarre, and O. Soupa, *Leading the energy transition. Factbook. Hydrogen-based energy conversion. More than storage: system flexibility*, SBC Energy Institute, 2014.
- [5] P. Lucchese, A. Le Duigou, C. Mansilla, "Power-to-Hydrogen and Hydrogen-to-X: System Analysis of the techno-economic, legal and regulatory conditions: A new task of the IEA Hydrogen Implementing Agreement", presented at the 21st World Hydrogen Energy Conference (WHEC 2016), Zaragoza, Spain, June 13-16, 2016.
- [6] UK H2 mobility, *Phase 1 Results*, 2013.
- [7] J. Newton, "Power-to-Gas & Methanation – Pathways to a 'Hydrogen Economy'", presented at the 14th Annual APGTF workshop, London, UK, March 12-13, 2014.
- [8] M. W. Melaina, O. Antonia, and M. Penev, *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*, Technical Report NREL/TP-5600-51995, March 2013.
- [9] S. Samsatli, I. Staffell, N.J. Samsatli, "Optimal design and operation of integrated wind hydrogen-electricity networks for decarbonising the domestic transport sector in Great Britain", *International Journal of Hydrogen Energy*, vol. 41, pp. 447–475, Jan. 2016.
- [10] FCH JU, *Commercialisation of energy storage in Europe*, 2015.
- [11] World energy council, *E-storage: Shifting from cost to value*, 2016.
- [12] ENEA, *The potential of Power-to-Gas*, 2016.
- [13] O. Schmidt, "Power-to-Gas Business Models in the United Kingdom", MSc dissertation, Imperial College, 2013.
- [14] P.E. Franc, "Financing Hydrogen Projects - Business cases and political support", presented at the IPHE Conference, Sevilla, Spain, November 16, 2012.
- [15] M. Beccali, S. Brunone, P. Finocchiaro, and J.M. Galetto, "Method for size optimisation of large wind-hydrogen systems with high penetration on power grids", *Applied energy*, vol. 102, pp. 534-544, Feb. 2013.
- [16] P. Bolat and C. Thiel, "Hydrogen supply chain architecture for bottom-up energy systems models. Part 1: Developing pathways", *International Journal of Hydrogen Energy*, vol. 39, pp. 8881–8897, Jun. 2014.
- [17] P. Bolat and C. Thiel, "Hydrogen supply chain architecture for bottom-up energy systems models. Part 2: Techno-economic inputs for hydrogen production pathways", *International Journal of Hydrogen Energy*, vol. 39, pp. 8898–8925, Jun. 2014.
- [18] ITM Power, "Hydrogen energy storage", presented at Nextgen, October 11, 2012.
- [19] New Energy World IG, *Fuel Cell and Hydrogen technologies in Europe - Financial and technology outlook on the European sector ambition 2014- 2020*, 2011.
- [20] T. Ramsden, D. Steward, and J. Zuboy, *Analyzing the Levelized Cost of Centralized and Distributed Hydrogen Production Using the H2A Production Model - Version 2*, Technical Report NREL/TP-560-46267, Sept 2009.

- [21] Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW GmbH), *Integration von Wind-Wasserstoff-Systemen in das Energiesystem*, 2014.
- [22] W. Vanhoudt, F. Barth (Hinicio), P. Schmidt, W. Weindorf, (LBST), et al., *Power-to-gas – Short term and long term opportunities to leverage synergies between the electricity and transport sectors through power-to-hydrogen*, Brussels/Munich, 19 February 2016.
- [23] S. M. Schoenung, and J. O. Keller, "Commercial Potential for Renewable Hydrogen In California", presented at the 21st World Hydrogen Energy Conference (WHEC 2016), Zaragoza, Spain, June 13-16, 2016.
- [24] D. Thomas, D. Mertens, M. Meeus, W. van der Laak, and I. Francois, *Power-to-Gas roadmap for Flanders*, Oct. 2016, Available: <http://www.power-to-gas.be/final-report>
- [25] D. Parra, and M. K. Patel, "Techno-economic implications of the electrolyser technology and size for power-to-gas systems", *International Journal of Hydrogen Energy*, vol. 41, pp. 3748–3761, Feb. 2016.
- [26] C. Mansilla, J. Louyrette, S. Albou, C. Bourasseau, and S. Dautremont, "Economic comparison of off-peak hydrogen production today – A European comparison", *Energy*, vol. 55, pp. 996-1001, Jun. 2013.
- [27] M. Melaina, and J. Eichman, *Hydrogen energy storage: grid and transportation services*, Technical Report NREL/TP-5400-62518, Feb 2015.
- [28] R. Dickinson, F. Dolci, A. Le Duigou, P. Lucchese, Nikolaos Lympelopoulos, C. Mansilla, et al., "Power-to-Hydrogen and Hydrogen-to-X pathways: opportunities for next generation energy systems", to be presented at the 14th International Conference on the European Energy Market (EEM 2017), Dresden, Germany, June 6-9, 2017.