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Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization

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HIGHLIGHTS

- Power-to-Liquid (PtL) can reduce import costs and improve EU energy independence.
- Biomass-to-Liquid (BtL) combined with PtL boosts production of carbon neutral fuels.
- Electrolysis potential is the largest when there is limited carbon storage.
- Transport demand is met by electricity and hydrogen complemented by PtL/BtL.

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ABSTRACT

Hydrogen represents a versatile energy carrier with net zero end use emissions. Power-to-Liquid (PtL) includes the combination of hydrogen with CO_2 to produce liquid fuels and satisfy mostly transport demand. This study assesses the role of these pathways across scenarios that achieve 80–95% CO_2 reduction by 2050 (vs. 1990) using the JRC-EU-TIMES model. The gaps in the literature covered in this study include a broader spatial coverage (EU28+) and hydrogen use in all sectors (beyond transport). The large uncertainty in the possible evolution of the energy system has been tackled with an extensive sensitivity analysis. 15 parameters were varied to produce more than 50 scenarios. Results indicate that parameters with the largest influence are the CO_2 target, the availability of CO_2 underground storage and the biomass potential. Hydrogen demand increases from 7 mtpa today to 20–120 mtpa (2.4–14.4 EJ/yr), mainly used for PtL (up to 70 mtpa), transport (up to 40 mtpa) and industry (25 mtpa). Only when CO_2 storage was not possible due to a political ban or social acceptance issues, was electrolysis the main hydrogen production route (90% share) and CO_2 use for PtL became attractive. Otherwise, hydrogen was produced through gas reforming with CO_2 capture and the preferred CO_2 sink was underground. Hydrogen and PtL contribute to energy security and independence allowing to reduce energy related import cost from 420 bln€/yr today to 350 or 50 bln€/yr for 95% CO_2 reduction with and without CO_2 storage. Development of electrolyzers, fuel cells and fuel synthesis should continue to ensure these technologies are ready when needed. Results from this study should be complemented with studies with higher spatial and temporal resolution. Scenarios with global trading of hydrogen and potential import to the EU were not included.

1. Introduction

Global surface temperature has already increased by 0.9 °C and global mean sea level has already risen by 0.2 m compared to pre-industrial times. To limit the temperature increase to 2 °C by 2100, cumulative emissions over the 2012–2100 period have to stay within 1000 $GtCO_{2e}$. Delayed action will only lead to more drastic changes required later on to stay within the carbon budget [1]. To achieve this target, key alternatives are carbon capture and storage (CCS), sustainable biomass use, energy efficiency and renewable energy sources (RES). Hitherto, a lot of attention has been given to the power sector, which is the one with the highest RES penetration mainly through the

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contribution of hydropower, wind and solar. Nevertheless, for a fully decarbonized system, the emissions from all sectors of the energy system (power, heat, transport), but also non-energy related sectors (e.g. agriculture and land use) have to be eliminated.

A promising option to decarbonize all sectors is to use a versatile energy carrier that can be easily transported and converted in mechanical power, heat and other forms of energy. This has been the motivation to propose an electricity based economy and hydrogen economy [2–5]. In spite of fulfilling the requirement of versatility, electricity has two main disadvantages. First, there are no existing technologies to directly store large amounts of it for long (> 1 month) periods of time. The best (fully developed) technology is pumped hydro storage, which constitutes more than 99% of existing electricity storage capacity [6]. However, in its conventional configuration, it is limited by geographical constraints (e.g. existence of reservoirs, height difference and water source) and its potential might still not be enough to satisfy the needs of a fully renewable system [7]. The other disadvantage of electricity is that sectors like aviation and maritime transport present challenges for electrification due to weight, drag and space requirements.

Hydrogen can provide a solution for transport, while still being a versatile energy carrier to be used across sectors. Tail pipe emissions for hydrogen are zero since it does not contain carbon. Instead, its emissions are defined by the production technology and upstream value chain [8–12]. A proposed route for a low CO_2 footprint is to use RES electricity for hydrogen production with electrolysis. This would allow moving away from fossil fuels in transport, which can contribute to energy security (electrolyzers can be installed locally and produce hydrogen from local RES sources), lower market volatility (oil is a global market continuously affected by upheavals and political interests) leading to more stable prices and smaller effect on consumers. With hydrogen, the end use technology can change to a fuel cell rather than an internal combustion engine leading to a higher efficiency[2] and less energy required per traveled distance. It can complement the usually shorter range of electricity vehicles. Fast response electrolyzers can provide flexibility and balancing to the power system while reducing curtailment. Lastly, it can have distributed applications where hydrogen is produced and consumed locally. Among its disadvantages are the infrastructure development needed, the current high costs for electrolyzers and fuel cells where the potential development is linked to learning curves and technology deployment, their efficiency loss (typical efficiencies for electrolyzers are 65–75% (HHV) on energy basis [13]) and the volumetric energy density in spite of being higher than batteries, it is still about 4 times lower than liquid fuels.[3] Even with the importance of volume (due to drag) in aviation, hydrogen has been continuously evaluated for such application [14–18]. A key limitation for this use is cost, where the fuel can represent up to 40% of the operating cost and a small increase due to drag or weight can represent a large increase in total cost.

Current global hydrogen production is in the order of 50 mtpa,[4] out of which the EU28 share is close to 7 mtpa (equivalent to 0.84 EJ). Industry sector dominates with more than 90% of the use. 63% of this is used by the chemicals sector (ammonia and methanol), 30% by refineries and 6% by metal processing [19]. Only 9% of the hydrogen market is merchant (meaning traded between parties as most of it is actually produced on-site and resulting from process integration). The size of the transport sector is 12.3 EJ for road transport (cars, trucks, buses) and close to 2 EJ for both aviation and navigation sectors (where the largest contribution is from international transport by a ratio of 9:1 vs. domestic).[5] Even if hydrogen covers only a small part of the sector, it would imply a significant increase in H_2 production capacity compared to current values.

This study uses a bottom-up cost optimization modeling approach that includes capacity expansion, covers the entire energy system for EU28+ (EU28 plus Switzerland, Norway and Iceland). The reason for this choice is to be able to evaluate the Power-to-X (PtX) options and integration between sectors and at the same time, consider the optimal capacities needed to achieve a low carbon system. Scenarios evaluated cover 80–95% CO_2 reduction by 2050 (vs. 1990) in agreement with the EU strategy [20]. The main targeted questions for hydrogen are to identify the production technologies as well as its main process chains, end use allocation to the different sectors and infrastructure cost. On PtL, the main questions are sources for CO_2, competition with biofuels, electricity and hydrogen itself and range of conditions (system constraints) that make the technology attractive. Given the long term nature and high uncertainty associated to the evolution of the system, an objective is to do a systematic analysis of system drivers that favor or constrain these technologies and determine their robustness (e.g. if deployment is present across multiple scenarios). This complements a previous exploration of Power-to-Methane [21], which is another technology satisfying similar boundary conditions in addition to the competition for the CO_2 molecule with PtL.

2. Literature review and gaps

The literature review is divided mainly into two sections: one tackling the activities at EU level from research to policy with the objective to put in perspective the levels of deployment foreseen in this study in comparison with current policies and initiatives. The second section summarizes trends and gaps observed in previous energy system models that have focused on hydrogen and based on this, identifies the additions of this work to that literature.

2.1. Hydrogen landscape in the EU

Activity at the EU level on hydrogen can be analyzed from three different perspectives: research activities, roadmaps and potential role in future low-carbon systems and consideration in current policy frameworks.

In terms of research, 90% of all the EU funds for hydrogen are covered by the FCH JU (Fuel Cell and Hydrogen Joint Undertaking), which is a public private partnership. The first phase ran from 2008 to 2013 with a budget of 940 M€ and a second phase from 2014 to 2020 with an increased budget of 1330 M€. In terms of roadmaps, one of the best known is HyWays [22]. It was published in 2008 and considered start of commercialization by 2015, 2.5 million FCEV (Fuel Cell Electric Vehicles) by 2020 (EU) and a penetration rate of up to 70% for FCEV by 2050 (~190 million FCEV). A more recent roadmap has been done by the IEA in 2015 [23], which proposes 30,000 FCEV worldwide by 2020, 8 million by 2030 and 30% penetration by 2050. In terms of future scenarios for EU as a whole, the EU Reference Scenario [24] only considers hydrogen for transport, where it barely plays a role with 0.1% by 2030 and 0.7% by 2050. This only considered a (greenhouse gas) GHG emission reduction target of 48%. On the other hand, the Energy Roadmap 2050 [25] does have a more ambitious target (80% reduction), but make no mention of hydrogen and transport relies on higher efficiency standards, modal choices, biofuels and electricity. The 2 °C scenario with high hydrogen from IEA [23] uses hydrogen for transport and foresees a demand of 2 mtpa for 35 million FCEV in EU4[6] by 2050.

In terms of policy, hydrogen and synthetic fuels are not explicitly mentioned in most of the directives. The Renewable Energy Directive

[2] 42–53% for fuel cells, while an ICE is around 20%.

[3] The mass energy density is around 2.5 times higher for hydrogen, which would lead to less weight. The trade-off for fuel consumption is drag (volume) vs. weight.

[4] mtpa = million tons per annum.

[5] Eurostat. [nrg_100a] – Simplified energy balances – annual data.

[6] Germany, France, Italy and United Kingdom.