Assessing the role of hydrogen in Europe towards 2050 through models and scenarios

Full study available at: https://www.hydrogen4eu.com

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Reaching net-zero emissions in the EU by 2050 is a formidable challenge.

The European Union has reduced its carbon emissions during the last decade but the path towards net-zero requires a step change in efforts.

Note: The figure includes emissions from international aviation, and net removals from land use, land use change and forestry sector (LULUCF). Completed with linear trajectories to comply with enacted legislations.
Is hydrogen the missing piece in the transition puzzle?

**Opportunities**

Hydrogen allows a cost-effective transition:

- Mitigate costs and challenges linked with deep electrification
- Avoid stranding gas assets
- Allow diversification and exploiting synergies between energy sectors.

Support emission reductions in “hard-to-decarbonize” sectors such as energy intensive industries, freight transport, aviation etc.

Manage seasonality of renewables in the power grid

**Challenges, barriers and uncertainties**

**Technology uncertainties:**

- **Supply-side:** readiness and competitiveness of hydrogen production technologies
- **Demand-side:** high potential for fuel shifting end-uses (e.g., FCV, fuel-cells, etc.) but adoption remains uncertain.

**Regulatory uncertainties:** Limiting view of opposing complementary sources in current policies (blue vs. green).

**Transport infrastructure:** lack of clarity with respect to blending rates and interoperability issues in the gas network, and timeline for building-up a European hydrogen backbone.
The design of the Hydrogen for Europe study in a nutshell

The study rests on a quantitative analysis, relying on three models and their interaction: MIRET EU (IFPEN), Integrate Europe (SINTEF) and HyPE (Deloitte).

**Methodology and tools**

- **Detailed energy system model (MIRET-EU)**
  - Linear programming
- **Import model (HyPE)**
  - Linear programming
- **Learning optimization model (Integrate Europe)**
  - Dynamic programming

**Scenarios and results**

- **Technology Diversification pathway**
  - Illustrates how an inclusive approach helps minimize the cost of the transition
- **Renewable Push pathway**
  - Shows the implications of a deliberate focus on renewables in policymaking

Both pathway are aligned with key EU policy goals:

- 55% reduction in GHG by 2030,
- Net-zero by 2050

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The *Hydrogen for Europe* study relies on energy system modelling that integrates a wide range of existing and future hydrogen technologies with the most up to date knowledge and data.
A focus on the hydrogen value chain in MIRET EU

Each European country has the potential to develop hydrogen value chains.
**Global learning – time dependency**

- Certain factors are **only** affected by local learning (e.g. installation costs and balance of system costs).
- Inclusion of these factors is important for proper cost estimation (RHS figure):

\[
C_n = C_0 \left[ \alpha \left( \frac{x_{n,row} + x_{n,eur}}{x_{0,row} + x_{0,eur}} \right)^{b_{lbd,global}} + (1 - \alpha) \left( \frac{x_{n,eur}}{x_{0,eur}} \right)^{b_{lbd,eur}} \right]
\]

Global expansion data for PV based on IEA WEO 2019 SDS

**Learning model**

(Integrate Europe)

H2 4EU study (2021)
Global learning – time dependency and investment packages

The **Integrate Europe model** bring capacity expansion planning of the EU energy system with endogeneous learning:

Discretization of investments in packages

H2 4EU study (2021) and Ouassou et al. (2021)
Widening the scope by including hydrogen import potential

Hydrogen Pathways Exploration [HyPE]: value chain optimization for hydrogen trade

**H2 Import model [HyPE]**

1. **LCOH exploration**
   - Hydrogen production (onsite)
   - Conversion 1 (onsite)
   - Domestic transport
   - Conversion 2 (Exporting point)
   - International transport
   - Reconversion (Importing point)
   - Domestic inland transport and logistics
   - International transport and logistics

2. **Route optimisation**
   - L2H liquefaction / Ammonia synthesis
   - Pipelines
     - 2040, Russia-Germany
     - 2040, Ukraine-Serbia
     - 2040, Turkey-Greece
     - 2040, Tunisia-Italy
     - 2040, Algeria-Spain
     - 2040, Morocco-Spain
   - L2H regasification / Ammonia cracking
     - 2030, Spain, Barcelona
     - 2030, Spain, Cartagena
     - 2030, Spain, Huelva
     - 2030, France, Fos-Tonkin
     - 2030, France, Montoir-de-Bretagne
     - 2035, UK, Grain
     - 2035, Italy, Panigaglia
     - 2035, Spain, Bahia de Biskaia
     - 2035, France, Fos-Cavaou
     - 2040, Fos-Cavaou
   - Hydrogen point-to-point flow analysis
   - Hydrogen point-to-point cost curves

3. **Point-to-point H2 imports**
   - LCOH exploration
   - Resource potential & topology
   - Solar onsite LCOH distribution in 2050
   - Wind onsite LCOH distribution in 2050
   - Biomass gasification in Russian federal districts

Note: Existing gas terminals are also entry point for hydrogen shipping
The model linking strategy

Avoiding overlapping, fostering synergies and adding value

1. Model alignment
   - Scenario definition and translation into technical assumptions

   **MIRET-EU adopts a disaggregated representation of sectors and focuses on optimal paths for each EU country**
   - Detailed representation of technologies, sectors and countries in MIRET-EU:
     - Detailed description of technologies and energy chains (electricity, gas, hydrogen...), centralized vs. decentralized.
     - Individual representation of demand and supply in all sectors (residential, services, agriculture, transport, industry)

   **Complete and disaggregated optimization modeling at a country level:**
   - Hydrogen imports from the **HyPé model**
   - Least-cost technology pathways and disaggregated investment trajectories according to each scenario under any policy constraint.
   - Policy implementation

   **Provides a disaggregated view of the future of hydrogen on each EU country**

2. Data collection, common database on energy consumption, technology costs, regulatory measures

3. Integrate Europe captures the dynamic issues and path dependencies of the energy transition at the European level

4. Aggregated model of the European energy system. A detailed modelling of energy supply chains is possible for multiple energy carriers.

5. Optimizes and evaluates investment pathways for Europe considering:
   - Emission-free energy needs, and other policy choices
   - Technology learning (learning-by-doing)
   - Hydrogen imports from the **HyPé model**

   **Assesses the impact early investment decisions and corresponding policies have on the learning effects, cost and deployment pace of hydrogen technologies.**
The transformation of energy supply

The share of renewable energy sources in primary supply more than triples

The share of renewable energy supply more than triples to reach 49% in the Technology Neutral scenario and as high as 61% in the Renewable Push, sustained by very ambitious increases in wind and solar (tenfold increase between 2016 and 2050).

- x3.5 in 30 years
- Meets almost half of primary energy by 2050
- 32% share by 2050
- Resilient during the transition
- Dwindling role of coal and oil
- 3% share by 2050

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Electrification and energy efficiency play their expected role in the transition...
Energy transition and final uses

As the share of hydrogen in final energy use grows, the share of natural gas falls, underscoring the ability of hydrogen to replace natural gas where CO₂ capture is difficult.
Hydrogen demand

Hydrogen plays a similar role in the two scenarios as it proves a robust solution for hard-to-abate sectors, which hydrogen consumption is very similar between the two scenarios.

- Hydrogen demand already reaches 30 million tons in 2030.
- The biggest ramp-up phase happens between 2030 and 2040 as the demand is multiplied by more than x2.6.
- Transport and industry make up the vast majority of hydrogen demand in both scenarios, confirming the role of hydrogen in hard to abate sectors.
- Hydrogen also contributes to decarbonization in buildings and power generation (resp. 2-4 MtH₂ and <1 MtH₂).

Evolution of hydrogen demand by sector

- Buildings - Residential
- Industry
- Power
- Hydrogen in e-fuels
- Hydrogen in biofuels for transport
- Hydrogen in fuel cells for transport

H₂ 4EU, 2021
Hydrogen demand

Focus on Technology Neutral pathway: by 2050, hydrogen is mostly consumed in industry and transport

- Industrial hydrogen demand, primarily for energy, reaches some 44 Mt by 2050.
- Hydrogen is consumed in a diverse set of industry sectors mainly to provide process heat and steam.
- Its potential is particularly strong in the steel sector and in the chemical industry.

Note: only included energy-related hydrogen uses in the industry. Feedstock uses of hydrogen are also expected to be key for decarbonizing chemical and petrochemical products.
Hydrogen demand

Focus on **Technology Neutral** pathway: in 2050, hydrogen is mostly consumed in industry and **transport**

Hydrogen in transport is consumed as a direct end-use fuel or as an interim energy carrier for e-fuel production. Combined, it represents 43% of transport energy consumption by 2050.

Its main uses are in airplanes, vessels, trucks and buses.

*Aviation and maritime included

**Composition of road transport fleet in 2050**

- **Passenger cars:** 325 million
- **Light medium duty:** 40 million
- **Buses & heavy duty:** 15 million

Note: hydrogen also includes related hydrogen used for ammonia production for energy-use in the maritime sector
Hydrogen key for decarbonizing hard-to-abate sectors

~ 100 million tonnes of H₂ consumed by 2050
Diversity and complementarity between hydrogen supply options

Technology Diversification pathway
Supply in MTH₂

<table>
<thead>
<tr>
<th>Year</th>
<th>Electrolyzer</th>
<th>Biomass / biomass with CCS</th>
<th>Reformer with CCS</th>
<th>Imports from non-European countries</th>
<th>Total</th>
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<tr>
<td>2050</td>
<td>37</td>
<td>5</td>
<td>43</td>
<td>2</td>
<td>101 MTH₂</td>
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<tr>
<td>2030</td>
<td>2</td>
<td>28</td>
<td>3</td>
<td></td>
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Renewable Push pathway
Supply in MTH₂

<table>
<thead>
<tr>
<th>Year</th>
<th>Electrolyzer</th>
<th>Biomass / biomass with CCS</th>
<th>Reformer with CCS</th>
<th>Imports from non-European countries</th>
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<td>2050</td>
<td>77</td>
<td></td>
<td>20</td>
<td>10</td>
<td>108 MTH₂</td>
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<td>21</td>
<td>0</td>
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Low-carbon hydrogen plays an essential role in the transition

Early investments are required in low-carbon hydrogen as it allows to establish the hydrogen economy during the 2020s and 2030s.

Low-carbon hydrogen installed capacity

*Not including hydrogen from ongrid electrolysis, that is considered "renewable" (up to 5 MtH₂ – 5% of total in 2050)
Renewable hydrogen uptake relies on electrolysis powered by wind and solar.

Production of hydrogen by electrolysis reaches 1.6 Mt in 2030 in the Technology Neutral pathway and 10 Mt in the Renewable Push pathway.

*Including hydrogen from ongrid electrolysis, that is considered “renewable” (up to 5 MtH₂ – 5% of total in 2050)

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A pathway to carbon neutrality

$\text{CO}_2$ removal solutions are key to achieve net-zero in both scenarios

**Evolution of $\text{CO}_2$ flows by sector**

- Energy-related $\text{CO}_2$ emissions reach the target constraint (-55% in 2030, -100% in 2050 with interpolation between those dates).
- Between 395 and 428 MtCO$_2$ of negative emissions in 2050 to ensure net zero
A pathway to carbon neutrality

CO₂ storage and re-use as an enabler of low-carbon technologies’ full potential

![Graph showing evolution of CO₂ flows in the CCUS value chain and CO₂ storage injection rate](image)

- **Power sector**
- **Industry sector**
- **Biorefineries**
- **Hydrogen production**
- **Direct Air Capture (DAC)**
- **Underground Storage**
- **CCU**

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Learning in the Technology Neutral pathway

Learning by doing drives down the cost of key technologies

The virtuous cycle of learning by doing: fast expansion of electrolysers brings down cost and lower cost spurs greater deployment. By 2050, cost of electrolysers have fallen by some 70%.

Decrease in solar investment costs, especially in Renewable Push pathway, underpins the competitiveness of solar PV and renewable hydrogen.

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Trillions of euros are needed in both scenarios to finance the hydrogen value chain. Temporality and level of necessary investment differ between the scenarios: more money needs to be mobilized earlier in the Renewable Push pathway.
Key insights from the modelling for energy policy-making

The Technology Diversification pathway offers to European society several advantages that policy-makers should trade-off against other criteria:

- De-risking achievement of the energy transition
- Relieving the financing bottleneck
- A more competitive and efficient energy system
- Achieving the net-zero emissions goal at a lower cost
- Internalising CO₂ emissions and changing the economics in favour of clean technologies
- Accounting for CO₂ content of energy use
- Fostering innovation and R&D and bringing new technologies to commercial viability
- Enabling low-cost financing and bankability of investments in low-carbon and renewable solutions
- Ensure system integration and coordinate supply and demand uptake
Key findings and conclusions

1. Hydrogen is the missing link in the energy transition
   • Hydrogen is resilient to any pathway.
   • Hydrogen’s versatility, and its ability for storage and transport makes the molecule ideally suited to decarbonize hard to abate sectors.
   • Hydrogen is used to integrate renewable energy in the system.

2. Hydrogen demand could top 100 million tons in 2050
   • Hydrogen plays a key role for cleaning up hard to abate sectors such as transport and industry, where it is also used as an energy carrier for more suited molecules (e-fuels, ammonia).
   • It also contributes to decarbonizing buildings and power.
   • Hydrogen as a feedstock has promising potential but it will be the subject of future research.

3. Hydrogen’s optimal role in the transition is enabled by a diverse set of technologies and supply options
   • Low-carbon hydrogen (including reformers with CCS and pyrolysis) plays a critical role in establishing a hydrogen economy in the first half of the outlook period
   • Renewable hydrogen from electrolysis with renewable electricity, and biomass catches up in the second half of the outlook period and meets the bulk of the additional demand growth. In the Renewable Push pathway, it becomes the biggest hydrogen production source by 2040.
   • There is a substantial role for hydrogen imports from 2040 onwards. Imports reach 10-15 Mt in 2050 mainly from countries with interconnectors (i.e. Russia and Algeria) but not only.

4. Timeliness of investments is critical
   • Timely investments are required to ensure demand and supply grow are balanced, avoid technology lock-ins, and mitigate risk of stranded assets.
   • The synchronicity of infrastructure development is another key driver.

5. The least cost pathway underscores the value of adopting an agnostic approach to hydrogen
   Technology diversification leads to lower total cost of the energy transition (first-best). The Renewable Push pathway requires on average some € 70 billion extra cost, every year.
Thanks for your attention
Appendix
A focus on CCUS technologies considered

In each country there are CO₂ flows represented by sources and uses.
Primary energy includes Gross inland consumption excluding final non-energy consumption.

Final Energy consumption includes the final energy consumed by end-use sectors (industry, transport, and other) and ambient heat from heat pumps. Excludes international aviation and maritime bunkers.

Gross inland consumption = consumption by the energy sector itself + distribution and transformation losses + final energy consumption by end users (includes now ambient heat for heat pumps but excludes international maritime bunkers).

Gross Final Energy consumption = Final energy consumption + international aviation + Losses in electricity and heat distribution and transmission.

Share of Renewables: Percentage of Renewables in Gross final energy consumption.
Energy transition and final uses

... but hydrogen and other synthetic/biofuels hold the keys to net zero

Evolution of gross final energy consumption by energy carrier

- Hydrogen plays a dual role: as a gas for final energy consumption, and as an energy carrier for the production of e-fuels and other molecules.
- Combined with e-fuels, hydrogen reaches a share of around 25% in 2050 in both scenarios.

Note: hydrogen also includes related hydrogen used for ammonia production for energy-use in the maritime sector

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H24EU, 2021
Hydrogen demand

Hydrogen also makes inroads to the buildings/residential sector

Ample availability of renewable electricity, proven technologies for electric heating and the ‘sunk’ nature of distribution infrastructure challenge the penetration of hydrogen in buildings. However, constraints in the supply of electricity, protection of the value of existing distribution grids and wider economic considerations could well lead to a more important role of hydrogen in buildings.

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Hydrogen and electricity

Expansion of renewables increases the need for flexibility

Power generation and withdrawal for electrolysis, 2016 compared to 2050

Solar and wind power generation are multiplied by 11 in Technology Diversification pathway and by 16 in the Renewable Push pathway.

Power-to-hydrogen and other flexibility means, especially gas-fired power plant with CCS can accommodate the increasing share of variable renewables in the system.

A smaller amount of hydrogen is also consumed for power generation (12-17 TWh by 2050). Innovation in hydrogen turbine technology and backlash on the roll-out of CCS and nuclear could create a role for hydrogen in power generation that goes far beyond balancing.

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H2 4EU, 2021
Three to five trillion euros of dedicated investments in the hydrogen value chain

Cumulative investment in the hydrogen value chain to 2050

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Investment (€ billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Diversification</td>
<td>562</td>
</tr>
<tr>
<td>Renewable Push</td>
<td>2,863</td>
</tr>
</tbody>
</table>

The difference of more than two trillion in capital spending between the two scenarios demonstrates the higher capital intensity of a pathway focusing primarily on renewable assets and electrolyzers. As such, one of the main challenges of the Renewable Push pathway is the ability to mobilize almost twice as much capital over the next thirty years to accomplish the hydrogen uptake.

*Fixed investment costs for the hydrogen value chain (CAPEX + O&M fixed costs)
Post treatment of results was carried out to retrieve CAPEX from offgrid renewables
Investment pathways

Timeliness of investments in low-carbon hydrogen production is critical

New installed capacities in low-carbon hydrogen technologies

Investors targeting low-carbon hydrogen projects, need to sanction such projects from the mid-2020s onwards to take advantage of a temporary but wide-open window of opportunity.

In the Renewable Push pathway, new low-carbon hydrogen projects would no longer be financially viable in the second half of the outlook period; as such, no more installations are added from the mid-2030s.

*Not including hydrogen from ongrid electrolysis, that is considered "renewable" (up to 5 MTH₂ – 5% of total in 2050)
Renewable hydrogen can take the pole position if the industry manages to expand electrolysis, wind and PV at a high and steady rate

**New installed capacities in renewable hydrogen technologies**

In the Technology Diversification pathway, investments in electrolyzers (and connected renewables) ramp up progressively during the transition. Around 515 GW of electrolyzers are installed during the last decade.

In the Renewable Push Pathway, the ramp-up in investments starts earlier because renewable hydrogen already plays a role in 2030. The deployment pace then accelerates significantly, with more than 1000 GW of new electrolyzers installed during the last decade.

Including hydrogen from ongrid electrolysis, that is considered “renewable” (up to 5 MtH₂ – 5% of total in 2050)