The role of green hydrogen in the energy transition

The electrification of final consumption, using energy from renewable sources, already represents the cheapest and most efficient way to decarbonize sectors such as transport, domestic heating, various industrial uses, and manufacturing processes. However, there are sectors where direct electrification struggles to penetrate due to physical or technological reasons, the so-called “hard to abate” sectors such as steel mills, worldwide shipping and aviation. In these cases, hydrogen represents the best complement to electrification as a decarbonization solution since it does not produce carbon dioxide emissions during its use and is the basic feedstock to produce renewable synfuels.

Nonetheless, hydrogen production processes are not all the same in terms of their effects on the environment. Currently, more than 99% of the hydrogen produced is derived from fossil fuels (Grey and Brown Hydrogen), with significant carbon dioxide emissions along the entire supply chain. In the production of hydrogen from renewable sources, however, there is no generation of greenhouse gas emissions: this is why it is considered the only hydrogen that is truly sustainable.

Substituting Grey and Brown Hydrogen with Green Hydrogen will in itself be the first and best use of the Green Hydrogen technology.

We believe that the best complement to electrification to achieve full decarbonization is green hydrogen, strictly produced from 100% renewable sources. Its production requires rather simple systems, it supports a decentralized and more flexible energy model, and it has no critical impacts on health, safety, and the environment. However, we need to start working now to make green hydrogen economically competitive with respect to hydrogen produced from fossil fuels.

As one of the largest and fastest growing renewable energy producers we are committed to testing at an international level, from Chile to Italy, new models and innovative solutions capable of reducing the costs of the electrolyzers used to produce green hydrogen and promote the development of an economy of scale. We want to do this by working together with our partners, our technology suppliers, startups, and anyone who develops ideas and technologies that point in our same direction, according to an open and collaborative model.

Many countries are publishing ambitious hydrogen strategies with their visions for the future. These will establish regulatory frameworks which, we hope, will allow the development of green hydrogen in the “hard to abate” sectors through a distributed production model. This would have a double benefit: on the one hand, hydrogen is produced where its decarbonization potential can be fully exploited, on the other hand it relies on the electricity grid to directly feed electrolyzers on-site with renewable energy. This would minimize the risk of investing massively in assets, such as new gas pipelines or retrofitting existing infrastructures, even before a demand and a market are well defined.

We also think that regulatory frameworks under developments around the world should identify a rigorous taxonomy of the various production methods signaling to final users the real value of green hydrogen and guiding governments in their policy choices.

Francesco Starace
CEO & General Manager Enel Group
Green hydrogen and electrification: what is the most efficient solution to decarbonize final energy uses

<table>
<thead>
<tr>
<th>INDUSTRY</th>
<th>TRANSPORT</th>
<th>BUILDINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="checkmark" alt="Green Hydrogen" /></td>
<td><img src="checkmark" alt="Long Haul Ship Powertrain" /></td>
<td><img src="x" alt="Hard to Abate Sectors" /></td>
</tr>
<tr>
<td><img src="checkmark" alt="Green Hydrogen" /></td>
<td><img src="checkmark" alt="If Electrification is Not Possible" /></td>
<td><img src="x" alt="Buildings" /></td>
</tr>
</tbody>
</table>

**GREEN HYDROGEN**

- Hard to Abate Sectors
- Long Haul Ship Powertrain
- If Electrification is Not Possible
- Buildings

**ELECTRIFICATION**

- Electrification, if possible, represents the most efficient solution to decarbonize all three sectors of energy consumption.

**INDUSTRIAL PROCESSES:**
- Electrification is key to decarbonize the industrial sector, with green hydrogen representing a viable option for the so-called “hard to abate” sectors.

**TRANSPORT**
- **Road transport:** Electric powertrains are more efficient, have a better environmental performance and are more convenient than their hydrogen counterparts.
- **Shipping:** Cold ironing represents a ready and proven solution for electrification of energy needs of moored ships. In upcoming years, green hydrogen might become an effective solution for long haul shipping.
- **Railways:** Electrification represents the ideal solution unless it is not achievable due to the line’s physical logistics or expense factors with green hydrogen representing a viable option.
- **Aviation:** Electrification is a long-term opportunity so the decarbonization of this sector can occur through the use of green hydrogen.

**BUILDINGS:**
- Electric heat pumps represent the most cost-effective path towards the decarbonization of both residential and commercial heating since they are a more mature market solution compared to hydrogen boilers.

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1) Cold ironing is the process of providing shoreside electrical power to a ship at berth while its main and auxiliary engines are turned off.
GREEN HYDROGEN: THE DECARBONIZATION SOLUTION FOR INDUSTRY, AVIATION AND SHIPPING
How can hydrogen be produced without having an impact on the environment?

**BROWN**

- 25 kg of CO$_2$ emitted obtained from the gasification of coal.

**PINK**

- Nuclear waste obtained from the electrolysis of water powered by nuclear energy. It has a strong environmental impact due to the production of nuclear waste, even if it does not emit CO$_2$.

**BLUE**

- 11–13 kg of CO$_2$ generated
- 3–6 kg of CO$_2$ emitted obtained with the same method that is used for grey hydrogen, but with the partial capture, transport, and storage of CO$_2$.

**GREY**

- 11 kg of CO$_2$ emitted produced by the steam reforming of natural gas.

**GREEN**

- Zero CO$_2$ emissions obtained from the electrolysis of water powered by renewable energy.

CO$_2$ emissions figures source: IEA and BNEF
Hydrogen today derives from fossil fuels but it is turning green to meet tomorrow’s decarbonization goals.

75 Mt

900 Mt CO\textsubscript{2}
The dominance of fossil fuels has made H\textsubscript{2} production responsible for 2.5% of global CO\textsubscript{2} emissions in energy and industry.

FEEDSTOCK FOR SOME INDUSTRIAL PROCESSES
Today it is mainly used for refining and producing ammonia and fertilisers.

0 Mt CO\textsubscript{2}
Only Green Hydrogen is fully zero-impact, without polluting emissions and without consuming fossil natural resources.

HARD-TO-ABATE SECTORS
Decarbonization goals and technological improvements will enhance the crucial role of hydrogen as a complement to electrification.

165 Mt
>2x possible growth in hydrogen production to reach net-zero emissions.
Why Green Hydrogen is better than Blue?

- **Zero Emissions**
- **Established Technology with Simple Plant Configuration**
- **Cheapest Option already in 2030**
- **Decentralized and more flexible model**
- **No critical health, safety and environment impacts**
Green Hydrogen has zero emissions

3–6 kg CO₂
PER KG OF BLUE H₂
BLUE HYDROGEN EMISSIONS RANGE

- As a matter of fact, blue hydrogen generates CO₂ and manages it downstream but is able to capture only up to 90% of the CO₂ generated.
- The remainder is emitted into the atmosphere.
- In addition, methane, a gas with a much larger greenhouse gas potential, is also leaked into the atmosphere in the upstream process of production and transport.

0 kg CO₂
PER KG OF GREEN H₂
GREEN HYDROGEN DOES NOT GENERATE ANY CO₂ NOR_EMIT IT INTO ATMOSPHERE
Green Hydrogen plants support a distributed model

**DECENTRALIZED MODEL**
Green Hydrogen production takes place where it is consumed.

**LOW COMPLEXITY**
- Lower design complexity vs Carbon Capture and Storage plants.
- Easy to use: it just requires an electrolyzer, a storage system and a water treatment system (if necessary).

**ADDITIONAL BENEFITS**
- CO$_2$-free → no CO$_2$ handling nor storage needs.
- High flexibility in the plant size and location.
- Leverage on electric grid infrastructure.
- No Health, Safety and Environment impacts.

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**CO-LOCATED GREEN HYDROGEN SYSTEM AT RENEWABLE PLANT**
Green hydrogen production takes place at the renewable power plant premises and green hydrogen is transported to the final off-taker through dedicated bottled trucks or through local 100% hydrogen-dedicated pipelines.
Transporting hydrogen vs. transporting electricity: the grid transporting renewable electricity fears no comparison with the gas network

Why hydrogen transport should be avoided

- Strong impact in geopolitical dependency
- High stranded asset risk
- Limited decarbonization potential
- Low efficiency of conversion in final use (e.g., Fuel Cell)
- Gas unilateral flow
- Leakages contribute to GHG emissions
- Large dedicated H2 network or blending in the existing gas network

Why electricity transport is the best choice

- Boost to the development of renewables
- Extended Electricity network
- Strong infrastructure reliability
- Flexibility in adapting to different scenarios
- Bi-directional flow
- High capillarity of existing grid
- Electricity network is already available
- Strong stranded asset risk

Transport Green Electricity extensively. Produce Green Hydrogen locally.
Green Hydrogen is the only sustainable hydrogen and is expected to be competitive already by 2030

MARKET – Green Hydrogen is expected to be competitive already by 2030 thanks to:

- Sharp capex reduction >80%
- Efficiency improvements of electrolyser
- No CO₂ emission cost vs. grey hydrogen
- No exposure to gas price fluctuations

Focus on cost reduction of green hydrogen technology through:

- Industry scale-up
- Innovation (capex reduction and efficiency increase)

What are the applications of green hydrogen?

Green Hydrogen is an efficient decarbonization choice in the industrial sector and in airborne and waterborne transport.
HOW ELECTRIFICATION COMPARES TO HYDROGEN IN ROAD TRANSPORT AND BUILDINGS
## Electric powertrains are more efficient

### OVERALL EFFICIENCY BY PROPULSION TYPE

<table>
<thead>
<tr>
<th>Direct electrification 2020</th>
<th>Hydrogen 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>2050</td>
<td>2050</td>
</tr>
<tr>
<td>100% RENEWABLE ELECTRICITY</td>
<td>100% RENEWABLE ELECTRICITY</td>
</tr>
</tbody>
</table>

#### WELL TO TANK

<table>
<thead>
<tr>
<th>Component</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolysis</td>
<td>94%</td>
<td>68%</td>
</tr>
<tr>
<td>CO₂ air-capture and FT-synthesis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation, storage and distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel production efficiency</td>
<td>94%</td>
<td>68%</td>
</tr>
</tbody>
</table>

#### TANK TO WHEEL

<table>
<thead>
<tr>
<th>Component</th>
<th>2020</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging equipment</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>Battery charge efficiency</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>H₂ to electricity conversion</td>
<td></td>
<td>54%</td>
</tr>
<tr>
<td>Inversion DC/AC</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td>Engine/motor efficiency</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td>Tank to wheel efficiency</td>
<td>81%</td>
<td>49%</td>
</tr>
<tr>
<td>OVERALL EFFICIENCY</td>
<td>77%</td>
<td>33%</td>
</tr>
</tbody>
</table>

### EFFICIENCY BY POWERTRAIN

In 2020 BEV² powertrains were more efficient than FCEVs³ >2x on a Well to Wheel basis

- Well-to-Wheel = BEV efficiency is 2.3x FCEV efficiency (77% vs. 33%)⁴
- Well-to-Tank = electricity production efficiency is 1.4x hydrogen (94% vs. 68%)⁵
- Tank-to-Wheel = BEV efficiency is 1.7x FCEV efficiency (81% vs. 49%)⁶

---

Note:
1) Direct current/alternate current.
2) Battery Electric Vehicles.
4) Well-to-wheel emissions include all emissions related to fuel production, processing, distribution, and use.
5) Well-to-tank describes the transition of the supply of fuel, from the production of the energy source (gasoline, diesel, electricity, natural gas) to the supply of fuel in the tank.
6) Tank-to-wheel refers to the transition in the energy chain of a vehicle that extends from the point in which the energy is absorbed (charging point) to the discharge.

Source: T&E 2020 “Electrofuels: yes we can...if we are efficient”, 2020.
Battery Electric Vehicles run much longer than Fuel Cell Electric Vehicles per kWh

**VEHICLE AUTONOMY (KM) PER kWh OF RENEWABLE ELECTRICITY - WELL TO WHEELS**

<table>
<thead>
<tr>
<th>VEHICLE</th>
<th>BEV</th>
<th>BEV</th>
<th>FCEV</th>
<th>FCEV</th>
<th>FCEV</th>
<th>FCEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td>2.5</td>
<td>7.0</td>
<td>2.8x</td>
<td>0.54</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>Buses</td>
<td>0.30</td>
<td>0.26</td>
<td>2.4x</td>
<td>0.54</td>
<td>0.71</td>
<td>1.27</td>
</tr>
<tr>
<td>Regional Delivery Trucks</td>
<td>0.26</td>
<td>0.30</td>
<td>1.8x</td>
<td>0.71</td>
<td>1.27</td>
<td>2.5</td>
</tr>
<tr>
<td>Long Haul Trucks</td>
<td>0.26</td>
<td>0.30</td>
<td>1.2x</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
</tbody>
</table>

For every kWh of electricity produced, BEVs\(^1\) may run more km than their FCEVs\(^2\) counterparts in every vehicle category.

Source: Internal elaboration on Terna “L'Italia, con l'Europa, alla sfida della decarbonizzazione”, Webinar 2020 and T&E 2020 “Electrofuels: yes we can...if we are efficient”, 2020 (well to tank).

*BNEF Hydrogen: the economics of production from renewables* 2019.

*Hydrogen: fuel cell vehicle outlook*, 2020 (tank to wheel).

Notes: Regional Delivery Trucks refer to medium duty commercial trucks, Long Haul trucks refer to Heavy duty transport trucks.

1) Battery Electric Vehicles 2) Fuel Cell Electric Vehicles
Battery Electric Vehicles have a better environmental performance than other powertrains including Fuel Cell Electric Vehicle, especially considering their impact towards Global Warming Potential.

Source: European Commission. DG Climate Action, "Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA", 2020.

Note: Buses refer to urban buses, Regional Delivery Trucks refer to rigid lorries, Long Haul trucks refer to articulated lorries.
1) g CO₂ e/vkm stands for g CO₂ equivalent per vehicle km.
2) g CO₂ e/ton km stands for g CO₂ equivalent per ton-km.
Battery Electric Vehicles are more convenient in terms of Total Cost of Ownership.\textsuperscript{1}

**TOTAL COST OF OWNERSHIP BREAKDOWN BY VEHICLE PROPULSION – €/KM**

<table>
<thead>
<tr>
<th></th>
<th>Cars\textsuperscript{2}</th>
<th>Buses\textsuperscript{3}</th>
<th>Regional Delivery Trucks\textsuperscript{4}</th>
<th>Long Haul Trucks\textsuperscript{5}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CAPEX</td>
<td>FUEL O&amp;M\textsuperscript{6}</td>
<td>CAPEX</td>
<td>FUEL O&amp;M\textsuperscript{6}</td>
</tr>
<tr>
<td>FCEV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BEV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>0.55</td>
<td>0.21</td>
<td>0.85</td>
<td>0.45</td>
</tr>
<tr>
<td>2050</td>
<td>0.34</td>
<td>0.16</td>
<td>0.33</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>0.99</td>
<td>0.48</td>
<td>0.53</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>0.82</td>
<td>0.41</td>
<td>0.31</td>
<td>0.22</td>
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<tr>
<td></td>
<td>0.84</td>
<td>0.31</td>
<td>0.30</td>
<td>0.19</td>
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<tr>
<td></td>
<td>0.63</td>
<td>0.17</td>
<td>n.a.</td>
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</tbody>
</table>

Source: Deloitte elaboration - TCO estimates.
Notes: Regional Delivery Trucks refer to medium duty commercial trucks, Long Haul trucks refer to Heavy duty transport trucks.
\textsuperscript{1} Total Cost of Ownership refers to the purchase price of an asset plus the costs of operation over the asset’s lifespan; \textsuperscript{2} Assuming 650 Kms range passenger car, 11.5 years life-time, 12,000 km by year (BEV and FCEV); \textsuperscript{3} Assuming 200 Kms range passenger bus, 12 years life-time, 65,000 km per year (BEV and FCEV); \textsuperscript{4} Assuming 400 Kms range heavy-duty truck, 13 years life-time, 80,000 km by year 400 Kms range car (BEV and FCEV); \textsuperscript{5} Assuming 1,000 Kms range long-haul truck, 13 years life-time, 120,000 km by year; \textsuperscript{6} Operation & Maintenance.
EV charging infrastructures are more developed than Hydrogen refueling stations.

### H2 Refueling Stations

- **Total 100%**
  - Japan: 23%
  - S. Korea: 16%
  - Germany: 13%
  - US: 9%
  - China: 20%
  - Other: 19%

### EV Charging Points

**Private Charging Points**

- Total: 100%
  - Residential: 88.3%
  - Workplace: 7.3%
  - Depot (Bus & Truck): 4.5%

**Publicly Accessible Charging Points**

- Total: 100%
  - China: 67.1%
  - US: 6.5%
  - Germany: 3.6%
  - France: 2.5%
  - UK: 2.3%
  - Japan: 1.8%
  - Italy: 1.3%
  - Other: 15%

**Publicly Accessible, Fast Charging Points**

- Total: 100%
  - China: 84.5%
  - US: 4.0%
  - Germany: 1.5%
  - France: 0.7%
  - UK: 1.0%
  - Japan: 0.7%
  - Italy: 0.3%
  - Other: 7.3%

**Total 2021:**

- Residential: 7.4 Mln
- Workplace: 1.7 Mln
- Depot (Bus & Truck): 574k
- Publicly Accessible: 9.7 Mln

---

Battery Electric Vehicles are expected to lead the decarbonization of the transport sector.

**FUEL CELL ELECTRIC VEHICLES VS. GLOBAL BATTERY ELECTRIC VEHICLES**

<table>
<thead>
<tr>
<th>Cars¹</th>
<th>Buses²</th>
<th>Regional Delivery Trucks³</th>
<th>Long Haul Trucks³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>Min. vehicles</td>
<td>Min. vehicles</td>
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<td>Min. vehicles</td>
<td>Min. vehicles</td>
<td>Min. vehicles</td>
<td>Min. vehicles</td>
</tr>
<tr>
<td>0.0</td>
<td>0.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7.1</td>
<td>9.5</td>
<td>0.7</td>
<td>0.0</td>
</tr>
<tr>
<td>0.4</td>
<td>1.7</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>0.0</td>
<td>2.7</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
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</tr>
</tbody>
</table>

In the next 20 years, BEV technology is expected to become the leading alternative powertrain.


Notes: 1) Includes Light Commercial Vehicles 2) BNEF’s Bus estimates also include PHEVs Regional Delivery 3) Trucks refer to medium duty commercial trucks, Long Haul trucks refer to Heavy duty transport trucks.
Heat pumps are more efficient than Hydrogen boilers in the decarbonization of buildings and rely on the electricity grid which is extremely widespread.

For every kWh of electricity, Heat pumps produce x5.4 more heat than a hydrogen boiler.

This also means that decarbonizing heating with hydrogen requires x5.4 more generation in renewables than with heat pumps (and therefore more investment for the same degree of decarbonization).

Source: EU – Hydrogen for Heating February 2021

Notes: Internal analysis based assuming: Heat pump COP 3.5 (air – air), hydrogen boiler performance of 90%, electricity network efficiency of 94%, hydrogen production efficiency of 68% with 53 kWh of RES needed to produce 1 kg of H2 (36kWh/kg). Does not include losses in hydrogen network.
Heat pumps are more cost efficient than other alternatives

ANNUAL HOUSEHOLD HEATING COSTS (€/YEAR)

- Heat Pump: 100
- Hybrid Heat Pump: Electrolysis Hydrogen (Low Cost): 100
- Boiler with Electrolysis Hydrogen (Low Cost): 100
- Boiler with SMR + CCS Hydrogen: 81
- Fuel Cell with Electrolysis Hydrogen (Low Cost): 100
- Fuel Cell with Steam Methane Reforming + Carbon Capture and Storage (SMR + CCS) Hydrogen: 81
- Fuel Cell with Electrolysis Hydrogen (EU Average): 100
- Boiler with Electrolysis Hydrogen (EU Average): 100
- Fuel Cell with Electrolysis Hydrogen (EU Average): 100

Heat pumps represent the most cost-effective path towards the decarbonization of residential heating technology. In 2050 they are expected to imply at least 50% lower costs than hydrogen-only based technologies.

Even if natural gas costs were 50% lower or renewable electricity prices were 50% higher in 2050, heat pumps would still be more cost-effective than hydrogen boilers or fuel cells.

It could be argued that Heat Pumps are already a more cost efficient solution than H₂, since there is no value chain as of today to deliver H₂ to residential customers out of pilot projects, whereas heat pumps are already a mature market solution.

ES1. Cost comparison and greenhouse gas intensity reduction potential of different technology options for heating a household for one year in the EU in 2050.


Note: These costs include annuitized capital expenses, operating expenses and fuel costs.