AURORA
ENERGY RESEARCH

Hydrogen Market Outlook for Europe and Greece

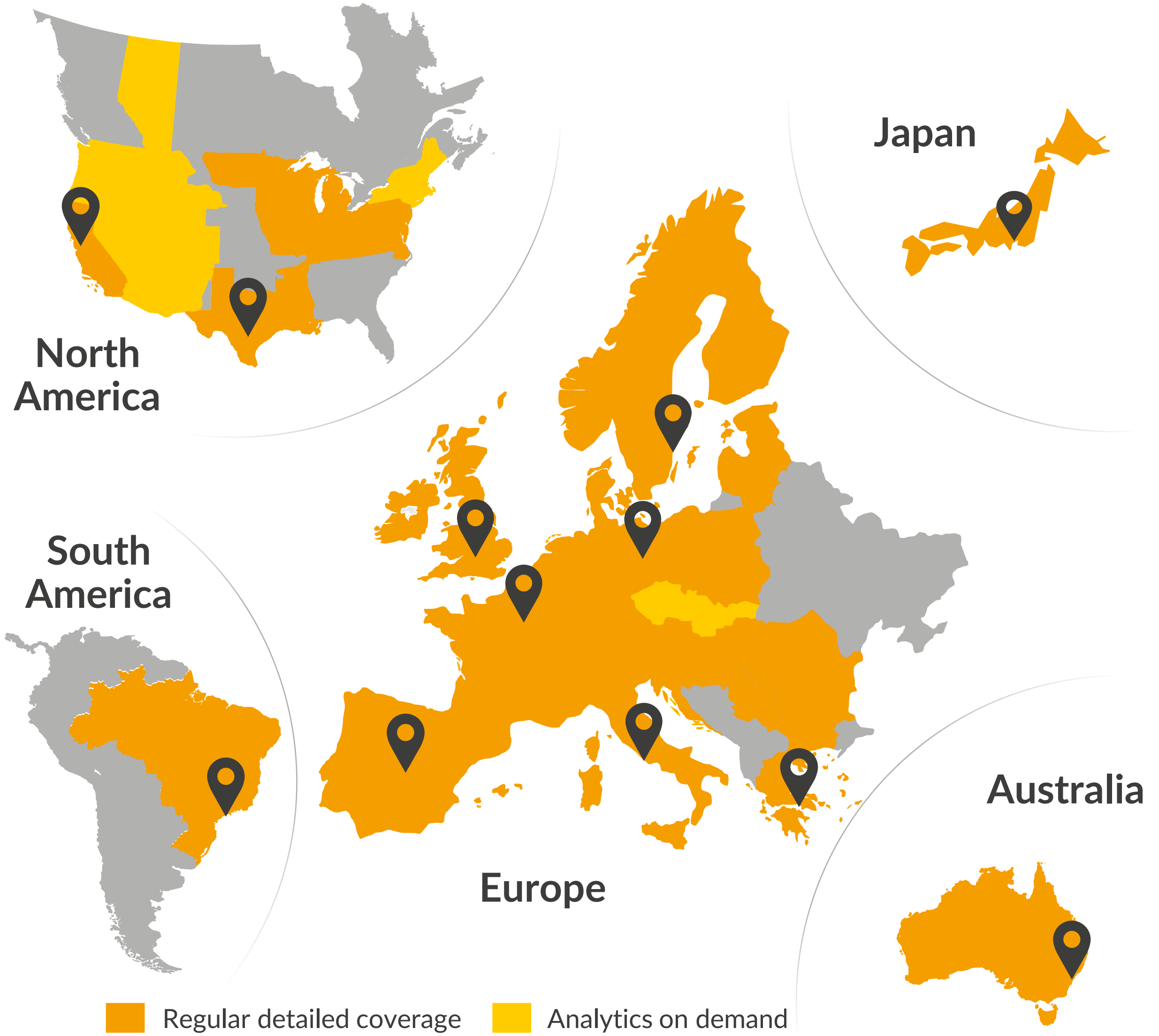
Dr Evangelos Gazis
Head of Southeastern Europe

Prepared for Hydrogen & Green Gases Forum
June 2023

Aurora provides market leading forecasts & data-driven intelligence for the global energy transition

AURORA

- Power markets
- Renewables
- Storage
- Electric vehicles
- Hydrogen H_2
- Carbon CO_2
- Natural gas



12 Offices
Oxford | Berlin | Madrid | Athens
Paris | Sydney | Austin | Oakland
Rome | Stockholm | Tokyo
São Paulo

430+
market experts

700+
subscribing companies

150+
transactions supported in 2022

Source: Aurora Energy Research

Latest EU Delegated Acts on Renewable Hydrogen proposed detailed rules to define hydrogen produced from renewable sources

AURORA

The first Delegated Act defines under which conditions hydrogen, hydrogen-based fuels or other energy carriers can be considered as an RFNBO[1]. Electricity will be considered fully renewable under the following circumstances:

1 When electricity is obtained from a direct connection with an installation generating renewable electricity, if:

- the renewable energy generator and the installation producing RFNBO are connected via a direct line, or both actions take place within the same installation
- the facilities producing electricity were operating a maximum of 36 months before the electrolyser's start of operation
- the installation producing electricity is not connected to the grid or, if connected, a smart meter shows that no electricity has been consumed from to produce RFNBO

2 When electricity is consumed from the grid, if any of following conditions are met:

- the installation's bidding zone[2] has an average proportion of renewable electricity over 90% in the previous calendar year, and RFNBO production does not exceed a maximum number of hours
- the bidding zone electricity emission intensity is lower than 18 gCO_2eq/MJ and there is a RES PPA fulfilling geographical and temporal correlation[3]
- the electricity used to produce RFNBO is consumed during an imbalance period when generators using RES are re-dispatched downwards
- the producers have a RES PPA that fulfils additionality[4], geographical and temporal correlation

	Until 1 July 2027	1 July 2027 – 1 January 2028	1 January 2028 – 1 January 2030	1 January 2030 – 1 January 2038	From 1 January 2038
Additionality	Not required	Not required	Required for all projects except 1. projects built before 1/1/2028 or 2. in low CO2[5] or high RES[6] grids	Required for all projects except 1. projects built before 1/1/2028 or 2. in low CO2[5] or high RES[6] grids	Required for all projects except in low CO2[5] or high RES[6] grids
Temporal correlation	Monthly. High RES grids[2] exempt	Monthly, but member states can introduce hourly correlation. High RES[6] grids exempt	Monthly, but member states can introduce hourly correlation. High RES[6] grids exempt	Hourly. High RES[2] grids exempt	Hourly. High RES[2] grids exempt
Geographical correlation	Electrolyser in the same bidding zone as the RES asset or in an interconnected bidding zone with day ahead prices higher than that of the RES asset				

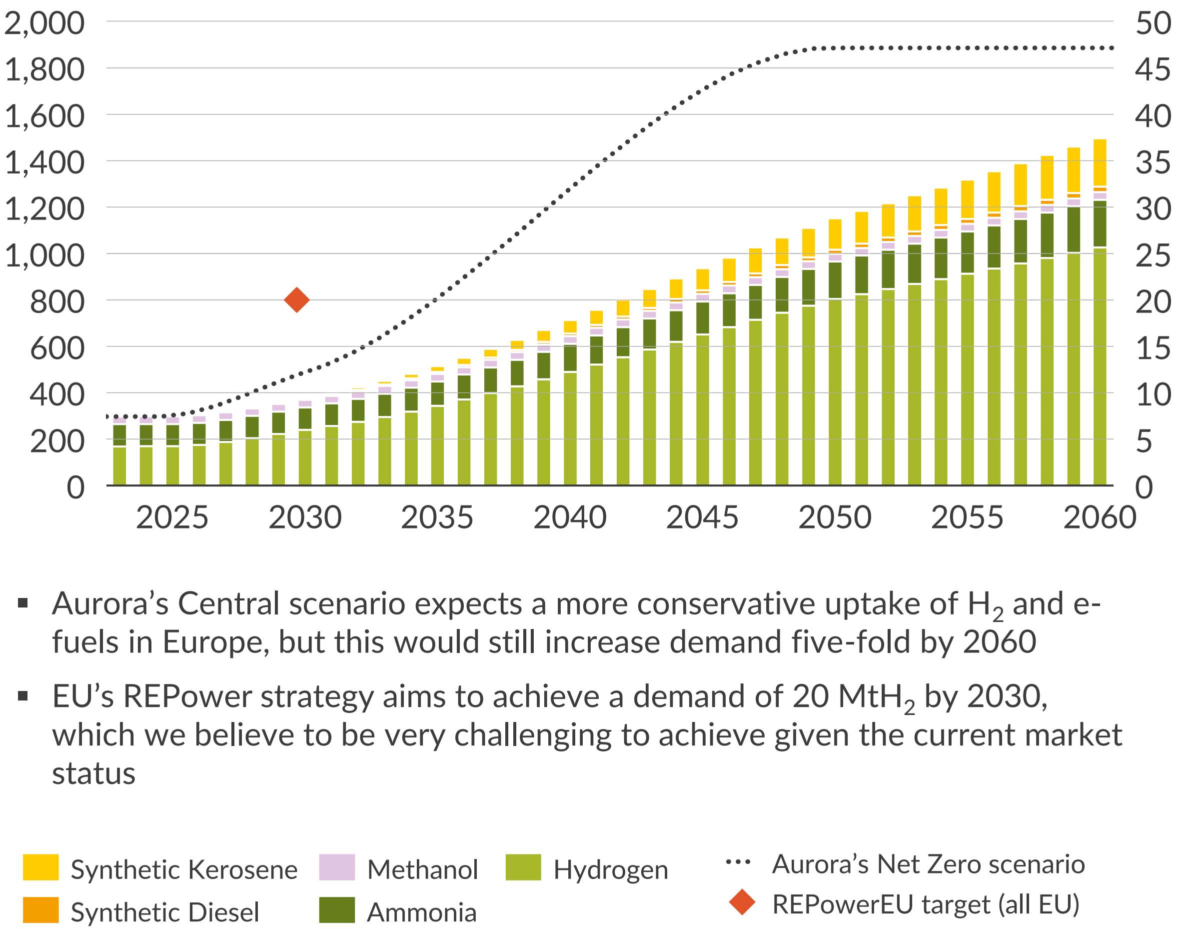
1) Renewable Fuel of Non-Biological Origin; 2) Defined in Article 2, point (65), of Regulation (EU) 2019/943 of the European Parliament, meaning the largest geographical area within which market participants are able to exchange energy without capacity allocation; 3) Defined in Article 6 and Article 7 of the proposal; 4) Defined in Article 5 of the proposal; 5) GHG footprint of the grid below 18gCO_2/MJ (65gCO_2/kWh) in at least one of the previous 5 years; 6) Share of Renewable Electricity Production in Total Electricity Production greater than 90% in at least one of the previous 5 years.

Sources: Aurora Energy Research, European Commission, European Parliament, European Council

Hydrogen demand is expected to increase five-fold by 2060; we assume half of e-fuel demand will be met by domestic production in Europe

Demand assumptions for H_2 in Europe[1] (excl. demand for gas to power generation)

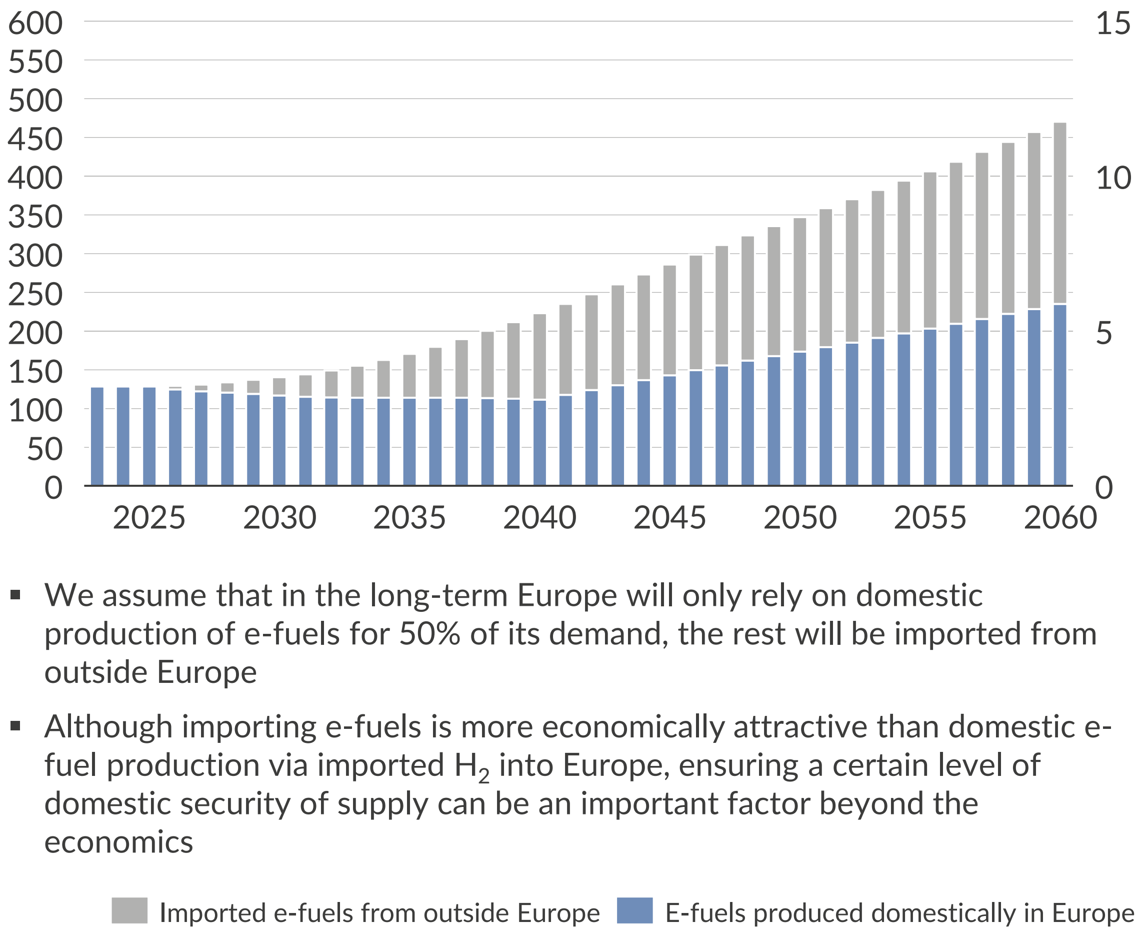
TWh, final energy consumption



- Aurora's Central scenario expects a more conservative uptake of H_2 and e-fuels in Europe, but this would still increase demand five-fold by 2060
- EU's REPower strategy aims to achieve a demand of 20 MtH_2 by 2030, which we believe to be very challenging to achieve given the current market status

E-fuel[2] demand assumptions

TWh, final energy consumption



- We assume that in the long-term Europe will only rely on domestic production of e-fuels for 50% of its demand, the rest will be imported from outside Europe
- Although importing e-fuels is more economically attractive than domestic e-fuel production via imported H_2 into Europe, ensuring a certain level of domestic security of supply can be an important factor beyond the economics

1) European countries include 15 HyMAR countries analysed by the European Hydrogen Service, the demand is estimated for BEL, DNK, DEU, ESP, FIN, FRA, GBR, IRL, ITA, NLD, NOR, POL, PRT, ROU, and SWE. 2) E-fuels considered in this analysis cover ammonia, methanol, synthetic diesel, and synthetic kerosene.

Source: Aurora Energy Research

Aurora expects hydrogen demand to exceed 1800 TWh across Europe to reach Net Zero emissions

AURORA

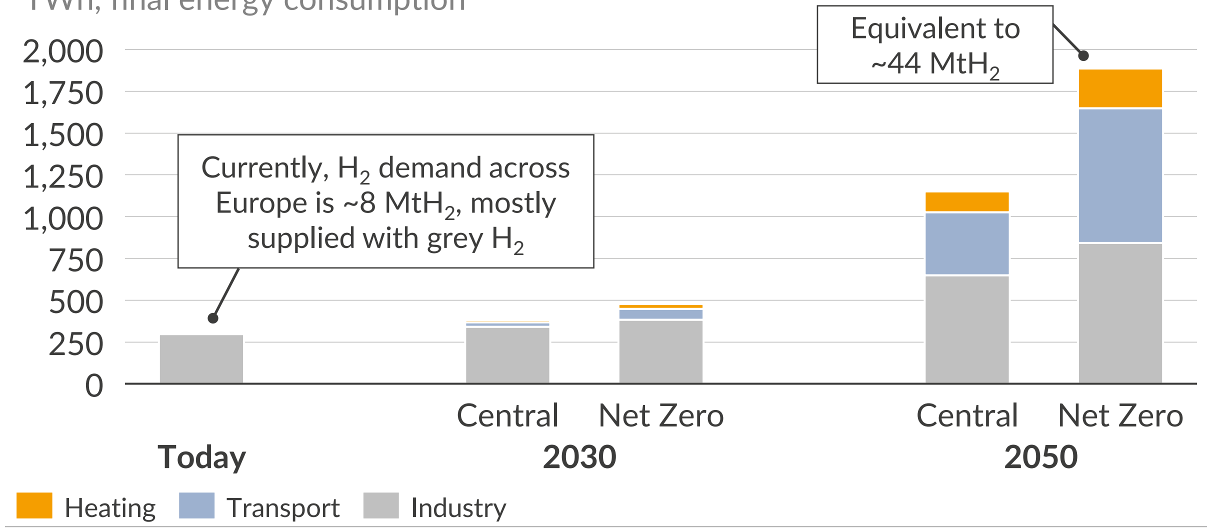
Hydrogen demand in Europe

We consider two scenarios given the high degree of uncertainty around technological and financial feasibility of hydrogen applications:

Aurora's Net Zero scenario is aligned with Europe's plan to reach net zero emissions economy-wide by 2050

Aurora's Central scenario represents a more conservative view on the evolution of the energy transition, where hydrogen penetration is more limited to the most economically viable applications and does not meet government targets. This scenario is aligned with meeting Net Zero across Europe only after 2050

European[1] H_2 demand by sector, including H_2 derivatives and imports[2]
TWh, final energy consumption



Industry

- Until 2030, we expect uptake of green H_2 mostly from ammonia and refinery industries, without much increase in total H_2 demand
- Beyond that, we expect increasing uptake in high-grade process heat, especially at temperatures that are difficult to electrify
- We also expect increasing demand for hydrogen in the steel industry from the mid-2030s

Transport

- Hydrogen road transport will have a more important role for coaches and heavy duty vehicles, particularly for vehicles of intensive use (e.g. long-distance travel)
- Additionally, maritime and aviation sectors will significantly increase the use of hydrogen and its derivatives, mostly after the mid-2030s

Heating

- The role of hydrogen for space heating is limited as only few countries are pursuing hydrogen for heating
- We expect uptake driven by the injection of hydrogen in gas networks, which can be used without major equipment changes

1) European countries include HyMAR countries analysed in this report. These countries include BEL, DNK, DEU, ESP, FIN, FRA, GBR, IRL, ITA, NLD, NOR, POL, PRT, ROU, and SWE. 2) Includes hydrogen required to produce derivatives such as ammonia or synthetic fuels. The hydrogen demand shown accounts for the total domestic consumption, including any potential imported hydrogen or hydrogen derivatives.

Source: Aurora Energy Research

The targeted 1.2 GW electrolyser capacity and the preparation of a national H_2 plan reflect Greece's ambitions for green hydrogen production

AURORA

Technology	NECP targets
Solar	▪ The amended NECP prescribes **14.1 GW of solar,** by 2030, which is 6.4 GW higher compared to the current target
Wind	▪ The NECP target for **onshore wind assets remains at 7.0 GW** ▪ For the first time, Greece is committed to a **2.7 GW target of offshore wind** capacity by 2030. The respective target for 2050 is set to 17.3 G
Batteries	▪ Updated NECP includes for the first time a target for substantial battery energy storage of **5.6 GW** by 2030 ▪ **1000 MW to be granted via auctions**
Electrolysers	▪ **Electrolysers capacity of 1.2 GW is foreseen until 2030**

Hydrogen outlook
▪ Development of a **national hydrogen plan** is currently underway
▪ The generated hydrogen is expected to replace progressively carbon-containing fuels (including natural gas and oil), mainly in the sectors of **refining, transportation and manufacturing**
▪ Regarding the **road transportation sector**, a **Joint Ministerial Decision** was published in April 2023, (118664/2023 - FEK 2570/B/20-4-2023), which summarises the legal framework regarding the licensing and the required technical specifications for deploying **H_2 refueling stations** in Greece
▪ **First green hydrogen projects,** owned by major players in the Greek energy market are currently underway (e.g. Linde[1], ADVENT[2], Motoroil[3] etc.) ▪ The region of **Western Macedonia** has recently become the **first Greek region-member of Hydrogen Europe** promoting green hydrogen technologies penetration

1) Green hydrogen generation via electrolysers, energized by wind and solar assets. 2) Manufacturing of innovative fuel cell and electrolyser systems, in the frame of the IPCEI Green HiPo project. 3) HELLENIC HYDROGEN S.A. a joint venture between Motoroil and PPC with an aim to produce green hydrogen.

Sources: Aurora Energy Research, EnergyPress

The refining, transportation and heating sectors are considered as main components of the national H_2 demand outlook

AURORA

Sector	Keynotes
Industry	▪ Within this sector, **refineries'** share in hydrogen demand is is in the order of **90%**[1] ▪ Other major H_2 industrial uses may include **NH_3 and fertilisers** production ▪ **Primary steal production**[2], currently performed via electrical furnaces (total production capacity of 3.45 million tones per annum) may be another potential use of H_2
Road transportation	▪ The majority of the demand in transport is expected to come from **heavy-duty vehicles** (trucks and buses) ▪ H_2 can be used either as a fuel for internal combustion engines, and/or as a fuel for FCs. In this case pressurised H_2 is employed[3]
Maritime	▪ **Hydrogen internal combustion engines** for the shipping industry are also under development[4]. In 2021, the first dual fuel engine, allowing for combustion of 20% containing H_2 fuel, was released. For H_2 engines, overseas transportation of H_2 will allow for 100% H_2 combustion. Green ammonia will be used in dual fuel ship engines. The respective deployment is expected by 2024
Heating	▪ Hydrogen is expected to be fed in the **gas network** (already suggested in the NECP targets published in 2019) and therefore could partially replace electrical heating (both space and water heating) and power generation

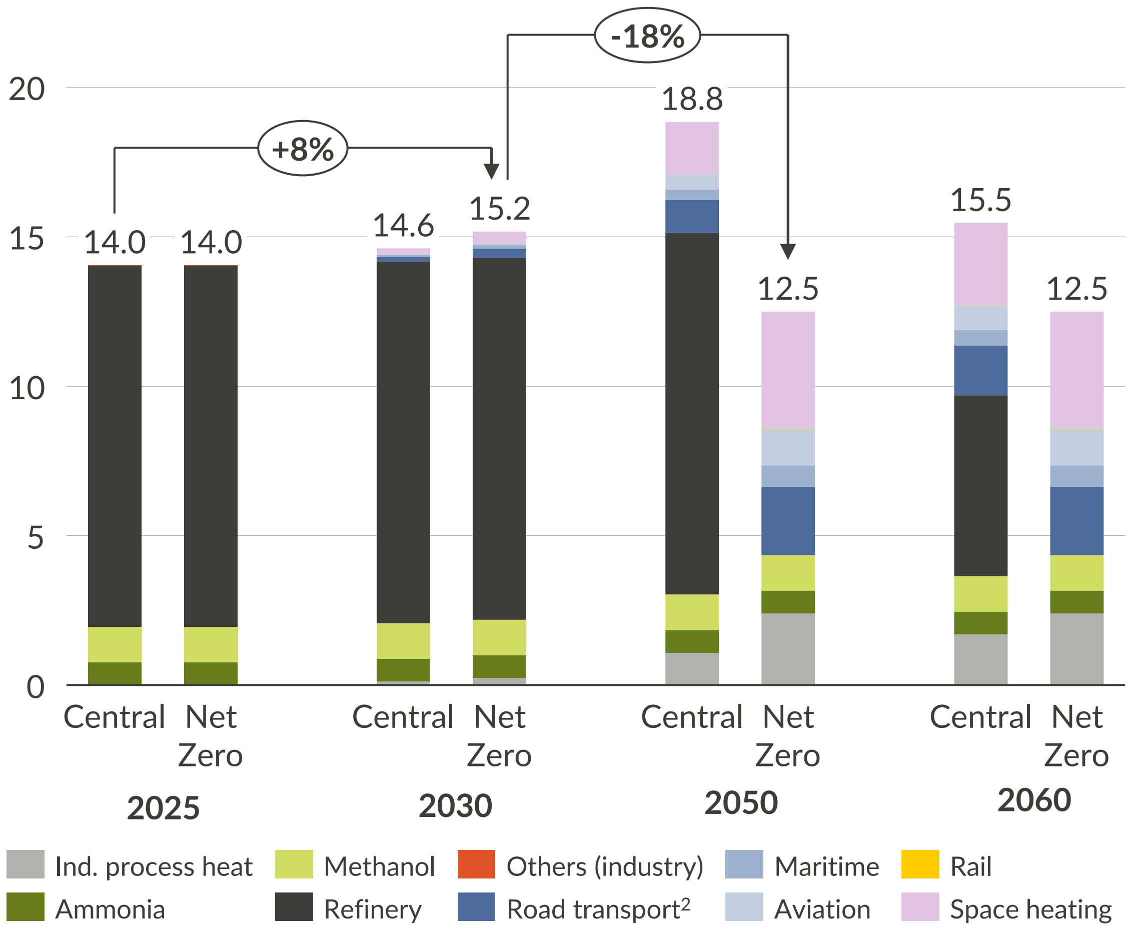
1) Fuel Cells and Hydrogen Observatory. 2) EUROFER. 3) oyota Motor Corporation. 4) MAN Energy Solutions

Source: Aurora Energy Research

Greece's hydrogen demand can reach 18.8 TWh by 2050, mainly driven by the refining sector

AURORA

Hydrogen demand (including H_2 derivatives) in Greece by sector[1]
TWh, final energy consumption



Industrial hydrogen demand mostly covers refining

- Almost 86% of total hydrogen demand will be potentially absorbed in the refining sector until 2030, with the remaining demand being covered for ammonia and methanol production
- In the long run, hydrogen is expected to be used in industrial process heating and industrial spaces heating, whereas the respective demand from refineries will diminish

Hydrogen demand in transport includes its direct use in FCEVs, as well as the consumption of e-fuels

- The majority of the demand in transport comes from commercial vehicles, aviation and maritime
- A total of ca 2 TWh is expected to be consumed in the maritime and aviation sectors, according to our Net Zero scenario

H_2 demand in space heating covers all use in the heating of buildings (inclusive of residential, commercial and industrial space heating)

- Aurora assumes the majority of space heating will be decarbonised by heat pumps or renewables, yet hydrogen is still expected to play some role
- Despite the modest role of hydrogen here, the required amount of hydrogen in the space heating is estimated to be around 1.8 TWh in 2050 according to our central scenario

1) Includes demand for hydrogen and derivatives, as well as any imported fuels. 2) Fuel cell electric vehicles, including passenger cars, buses and coaches, as. Well as light and heavy-duty commercial vehicles.

Source: Aurora Energy Research

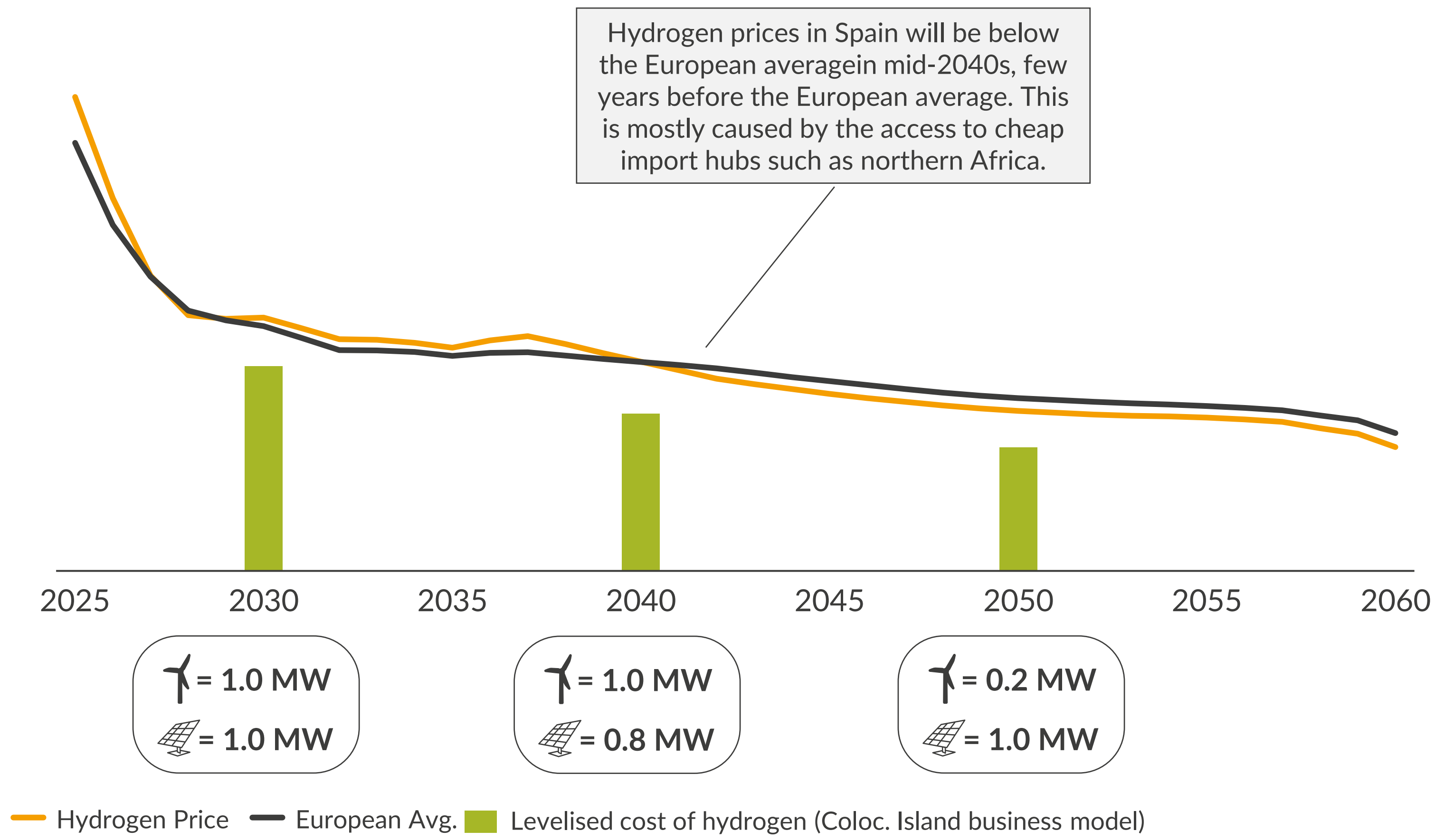
Hydrogen prices in Spain are very similar to the European average hydrogen price; but slightly above until the scale-up of imports

AURORA

Country deep-dive: Spain

Hydrogen Price and LCOH[1]

€/kg H_2



Low-carbon hydrogen price

- Low carbon hydrogen price is the short-run marginal cost of the most expensive technology[2] that fulfills the demand at each time step.

Levelised cost of hydrogen production[3]

- National LCOH forecast reported for each country is calculated for a representative location. Electrolyser size is optimised with an objective of cost minimisation.
- LCOH values do not include transport or storage costs of hydrogen.

1) Levelised cost of hydrogen. 2) Hydrogen supply technologies consists of domestic electrolysis, blue hydrogen as well as renewable hydrogen imports. 3) Levelised cost of production is calculated with Aurora's colocated (island) business model for a selected location.

Source: Aurora Energy Research

Ammonia, liquid hydrogen, and LOHC have unique advantages and disadvantages

AURORA

Energy Vector	Conditioning Process	Reconditioning Process	Advantages	Disadvantages
Compressed H_2	Compression Pipelines: 30-80 bar Tanks: 250-700 bar	Expansion	▪ Low conditioning cost ▪ Commercially available	▪ Low energy density
Liquid H_2	Liquefaction (-253 °C)	Hydrogen regasification	▪ Cheap and easy reconditioning	▪ Conditioning is costly ▪ Infrastructure not ready at commercial scale
Ammonia	Haber-Bosch process	Ammonia cracking	▪ Direct utilization	▪ High capital investment for conditioning ▪ High energy demand for reconditioning
LOHC[1]	Hydrogenation	Dehydrogenation	▪ Well developed oil infrastructure	▪ High cost of carriers

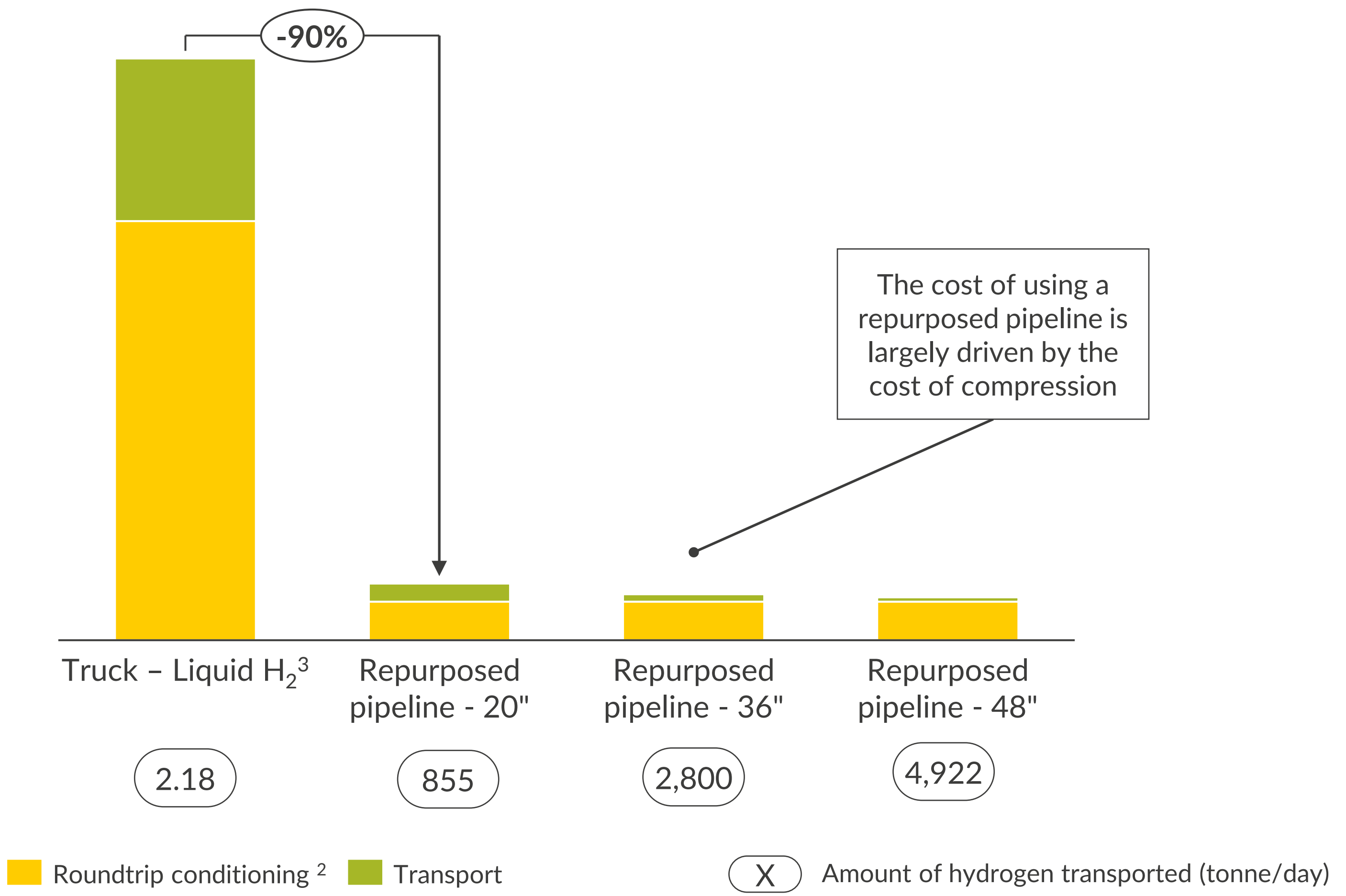
1) LOHC: Liquid organic hydrogen carrier

Source: Aurora Energy Research

Transporting hydrogen via repurposed pipelines is about ten times cheaper than truck transport, but requires high volumes

AURORA

Levelised cost of conditioning and transporting hydrogen for 500 km via repurposed pipelines in 2030[1]
EUR/kg H_2



Pipeline assumptions

Full load hours: 5000 h (57% load factor)

Lifetime: 30 years

Fixed O&M costs: 2% of CAPEX

WACC: 8%

- According to European Hydrogen Backbone, 69% of hydrogen pipelines in Europe in 2040 are expected to be repurposed from existing natural gas pipelines
- When compared to the cheapest truck transport, repurposed pipelines remain more economical at all distances. However, the volume of hydrogen transported must be high enough, i.e., the capacity of the pipeline should be utilised as much as possible. If a 20” diameter pipeline operated at just 10% load factor (150 t/day), the levelised cost of hydrogen transport would increase four-fold
- Repurposing pipelines reduces pipeline infrastructure cost by ~80% compared to newly built ones. However, recompression is needed along the route for both options, which contributes 55 – 90% of the levelised cost of repurposed pipelines depending on size and length

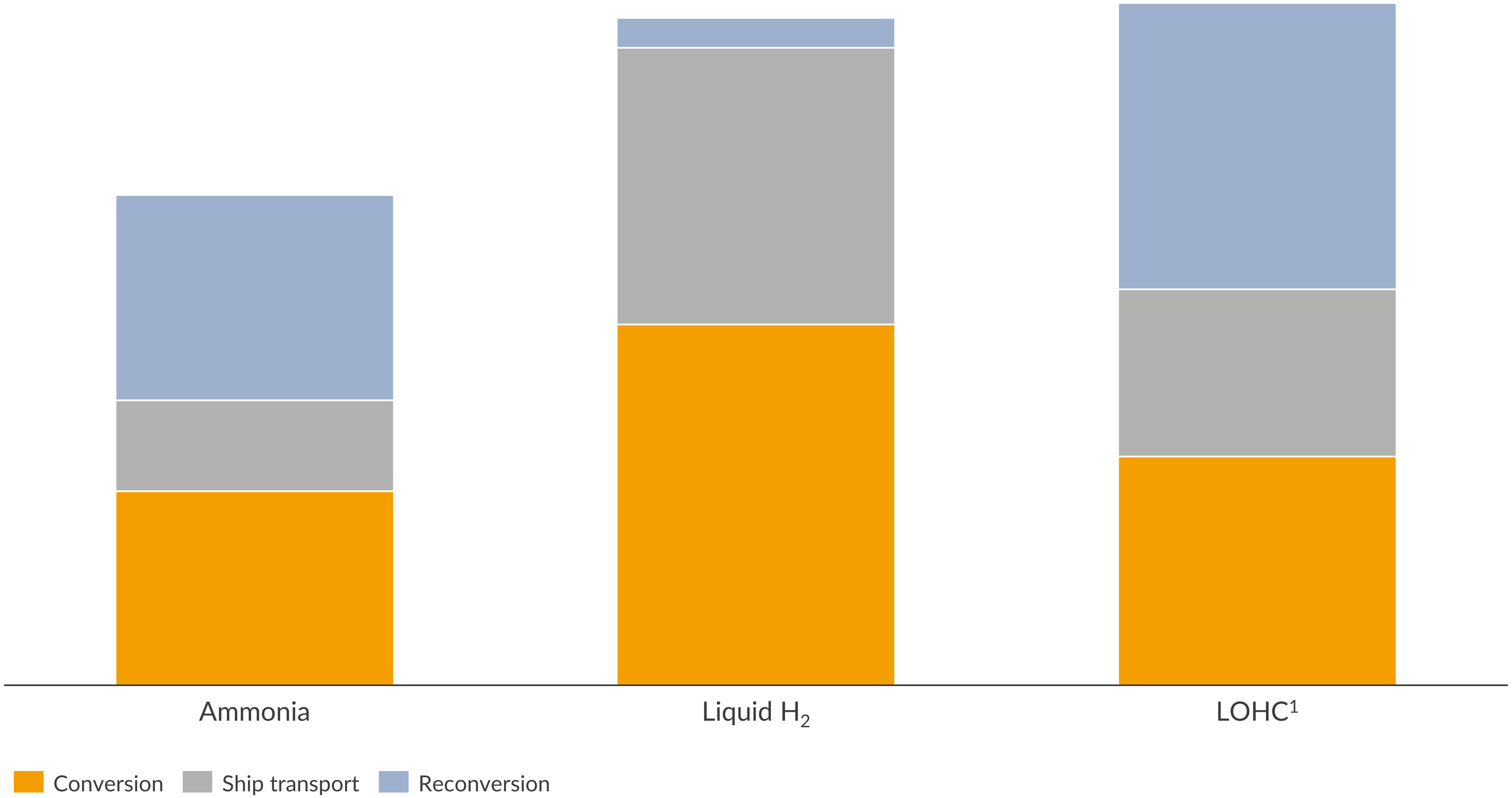
1) Assumes electricity price of 60 EUR/MWh, which is the baseload average across Europe 2) Conditioning includes compressing hydrogen for pipeline transport, liquefaction of hydrogen for truck transport and regasification of hydrogen after truck transport. 3) Conditioning costs shown here consider a large scale liquefaction unit
Source: Aurora Energy Research

AURORA

Ship transportation of H_2 from Chile to Europe can add around 2 EUR/kg to the hydrogen production costs

Levelised costs of importing hydrogen via shipping from Chile to Europe (~14,000 km) in 2030

EUR/kg H_2



1) LOHC – Liquid organic hydrogen carrier. The carrier used is Dibenzyletoluene

Source: Aurora Energy Research

- Ammonia presents some characteristics that improve its transport costs:
  - Compared to liquid H_2 and LOHC, ammonia has a higher energy density
  - The technology involved in the ship transport is more mature and requires less extreme conditions for its transport (-34 °C)
- Liquid H2 presents the highest conversion and ship transport costs, as it involves high CAPEX infrastructure, there are boil-off losses, and requires extreme temperature conditions (-253 °C)
- Both ammonia cracking and LOHC dehydrogenation are energy intensive processes adding ~0.7-1.0 EUR/kg to the costs. However, LOHC has the lowest energy density, increasing the costs per unit of H_2 delivered

AURORA

ENERGY RESEARCH