The Economics of Green Hydrogen in The Netherlands and France

8th December 2022

Public Report

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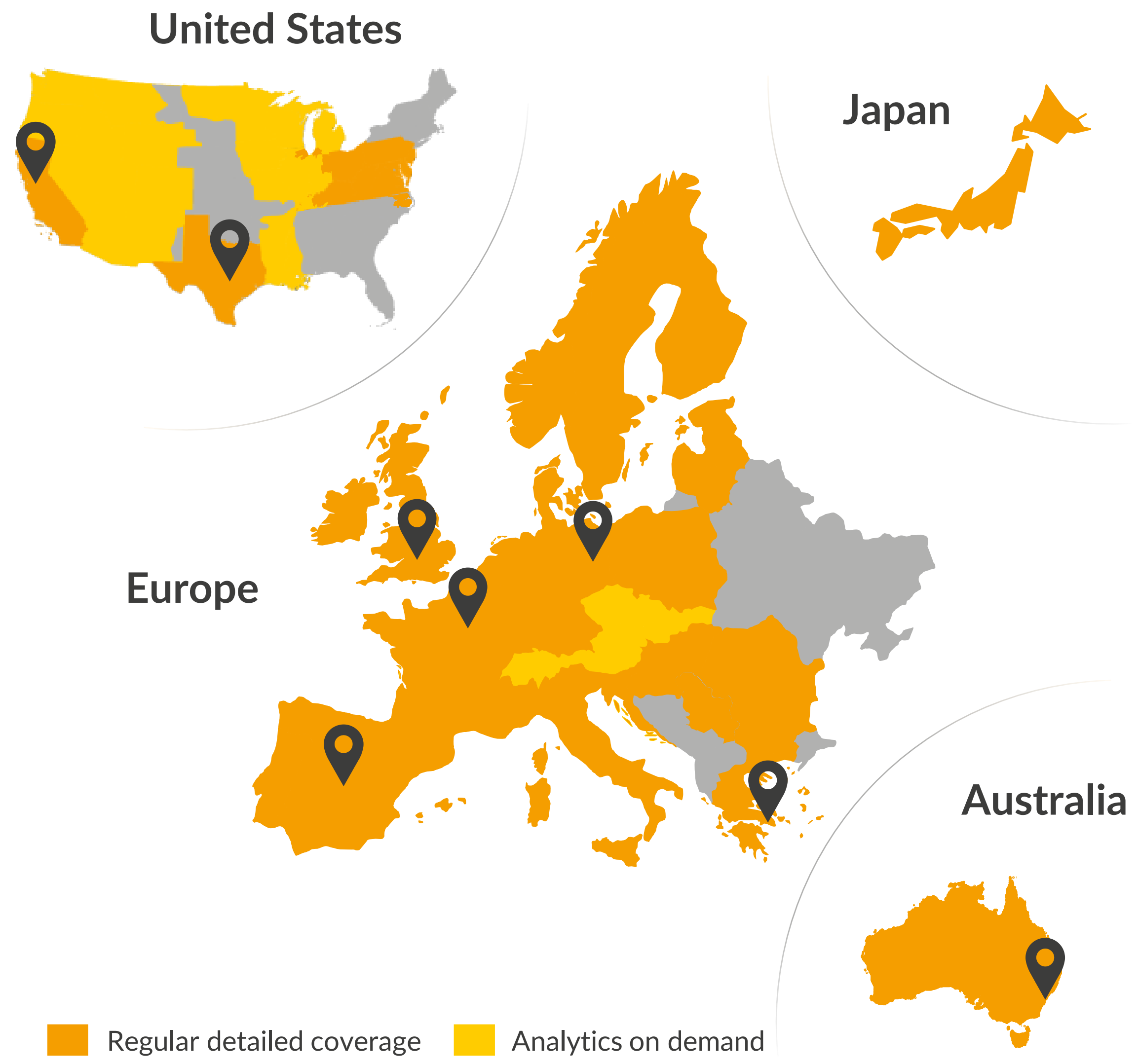

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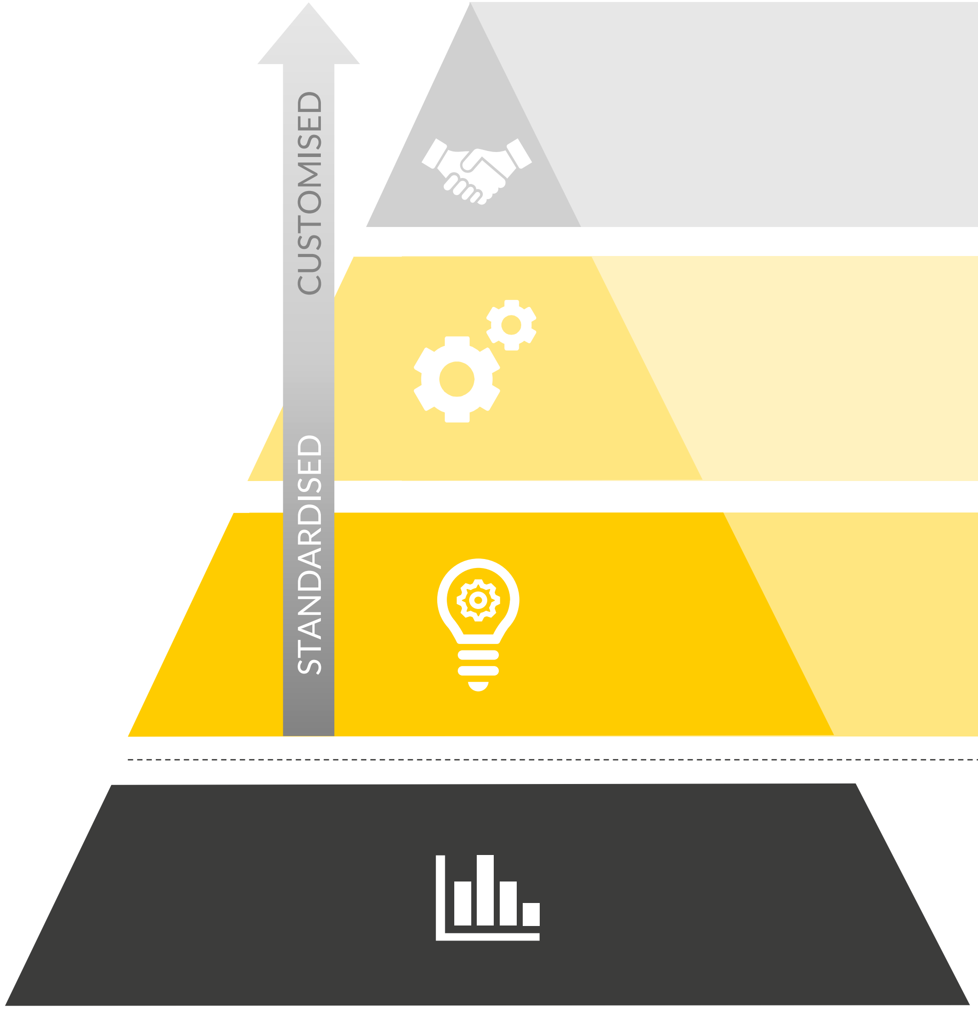

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Aurora's offerings

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Agenda

Aurora expects hydrogen demand to grow strongly across Europe to reach Net Zero emissions

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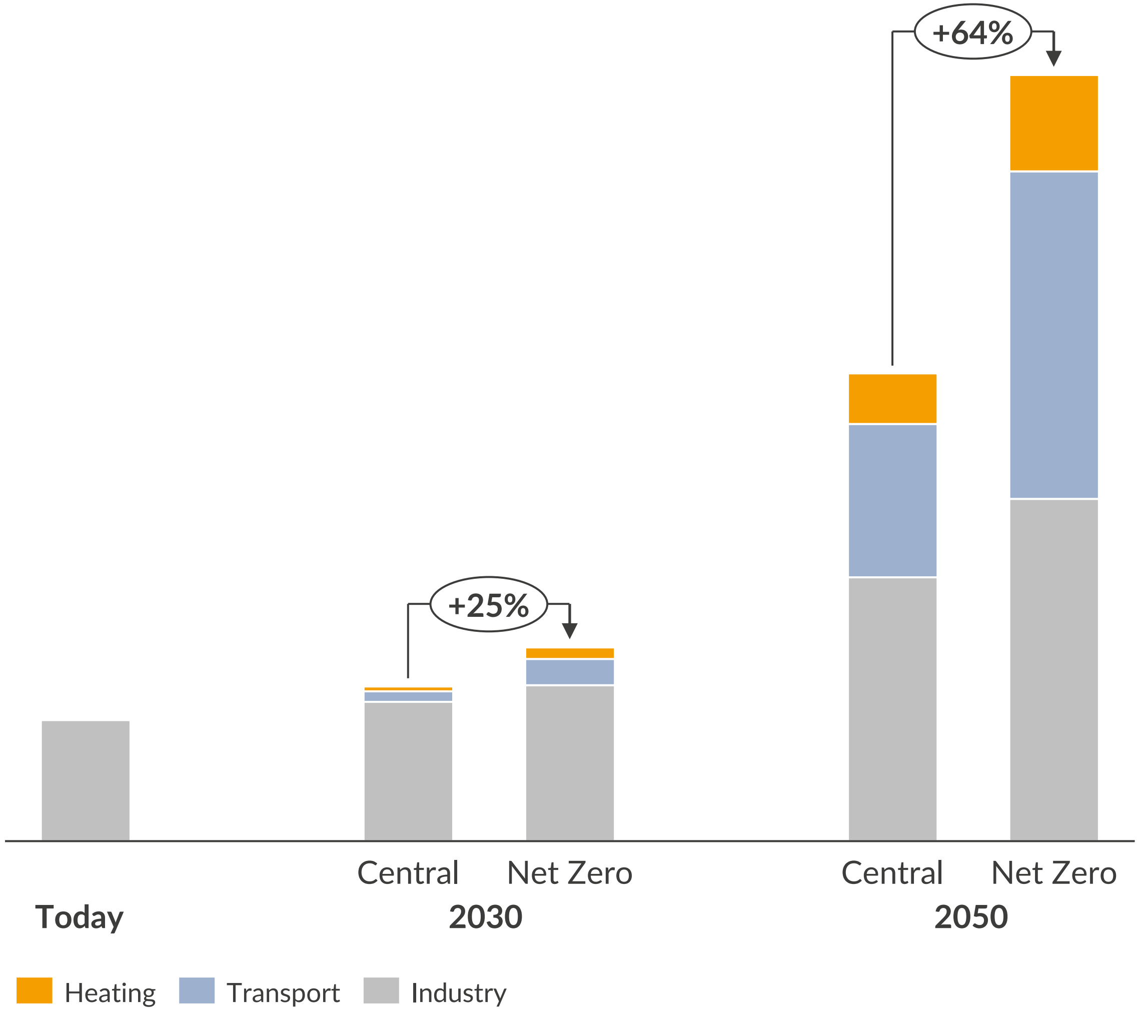
European[1] H_2 demand by sector, including H_2 derivatives and imports[2]
TWh, final energy consumption



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 a few countries are pursuing hydrogen for heating
- We do not expect heating with H_2 to be of major importance in France and the Netherlands, due to the high degree of electrification in this sector

1) European countries analysed include BEL, DNK, DEU, ESP, FIN, FRA, GBR, IRL, ITA, NLD, NOR, POL, PRT, ROU, and SWE; 2) Numbers are available to subscribers of our service. . 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

France pursues the development of low-carbon hydrogen, while the Netherlands’ focus is on renewable hydrogen

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While the Netherlands currently focuses on renewable hydrogen, the French government puts more emphasis on low-carbon hydrogen

Hydrogen terminology[1]	Colour	Technology	Primary energy	Direct CO_2 emissions
Renewable hydrogen		Electrolysis	Solar, wind, hydro	Minimal[2]
		Steam reforming	Biogas	Low[3]
		Thermolysis	Biomass	Low
Low-carbon hydrogen		Electrolysis	Nuclear	Minimal
		Electrolysis	Power grid	Low in FR (High in NL)
		Steam reforming, gasification	Gas, coal + CCUS	Low
Carbon-intensive hydrogen		Steam reforming	Natural gas	High[4]
		Gasification	Lignite	Very high[5]
		Gasification	Coal	Very high

Two systems were introduced to track and certify renewable and low-carbon H_2 and to trace its origin in France[6]

Guarantees of Traceability

- The renewable or low-carbon hydrogen produced is not mixed with another type of hydrogen or another gas between the stage of its production and that of its consumption
- The guarantee issued is transferred at the same time as the hydrogen produced, this guarantee certifies its physical traceability

Guarantees of Origin

- If the renewable or low-carbon hydrogen produced is likely to be mixed with another type of hydrogen or another gas between the same stages or if the guarantee issued during its production is likely to be transferred independently of the hydrogen produced
- A guarantee of origin for renewable gas injected into the natural gas network is valid for 12 months following the injection of the corresponding unit of renewable gas into the natural gas network

1) Based on the French Ordonnances n°2021-167; 2) < 2 kgCO2eq/kgH2 ; 3) < 3 kgCO2eq/kgH2; 4) Around 11 kgCO2eq/kgH2; 5) > 20 kgCO2eq/kgH2. 5) The two systems were introduced on the 17th of February 2021 in the French Ordonnance Hydrogène 6) for the Netherlands the rules are not completely clear yet and seem to differ per subsidy mechanism

Source: Aurora Energy Research

The Netherlands and France have high ambitions for green hydrogen production, with a target of respectively 3-4 GW and 6.5 GW in 2030

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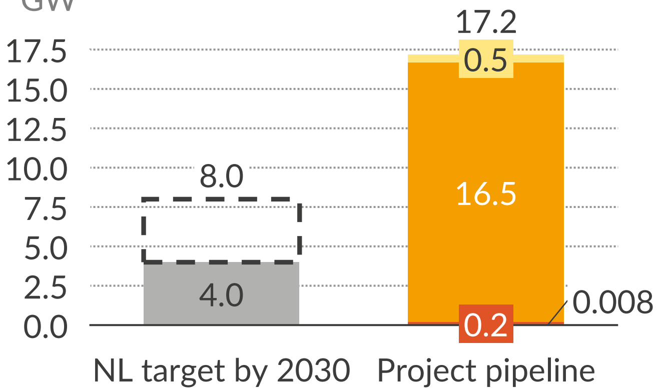
Breakdown of electrolyser projects in NL

GW

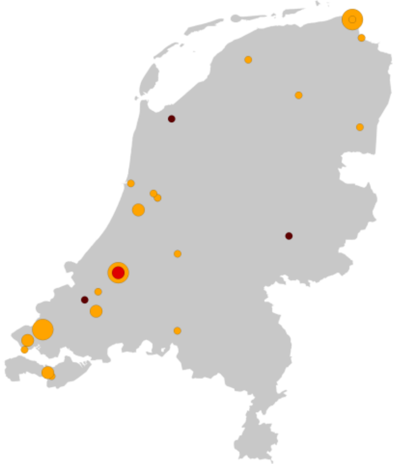


- The current electrolyser target for 2030 is 3-4 GW, but since recently the government seems to aim for 6-8 GW
- 500 MW of the pipeline is still in early planning stages with 16.5 GW in development and just 8 MW already operational

Locations of electrolyser projects in NL

MW

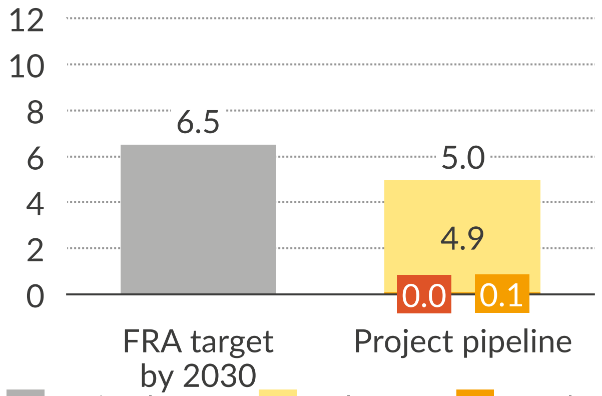
- The Netherlands boasts a total pipeline of 39 announced projects widely distributed across the region
- A number of projects are strategically located close to industrial clusters



Capacities (MW) >501 101-500 < 101

Breakdown of electrolyser projects in FRA

GW



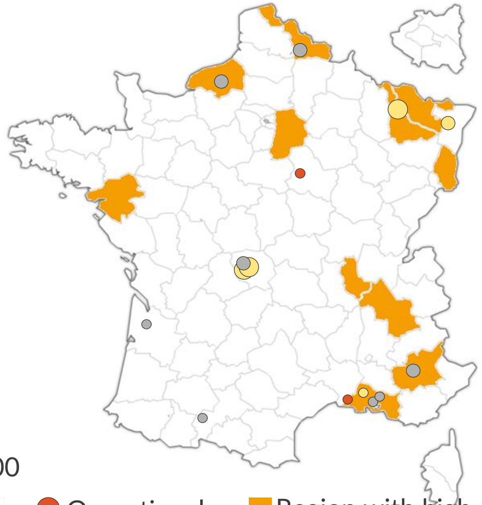
- The current French electrolyser pipeline falls short of the 2030 government targets by 23%
- The majority of projects is at an early stage, with about 3.5 GW being currently part of feasibility studies

National Target | Early stage | Development | Construction | Operational

Locations of electrolyser projects in FR

MW

- France boasts a total pipeline of 52 announced projects
- The estimated hydrogen demand hub in France in 2030 will be mainly located close to the most emitting industries



Capacities (MW) 1-49 50-500 ≥500

Project status Early stage Development Operational Region with high demand

Source: Aurora Energy Research

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We have identified four key business models to produce hydrogen via electrolysers which we will investigate in this report

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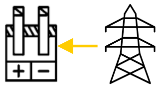

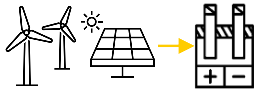

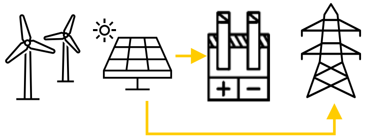

	I Inflexible	II Flexible	III Co-located (island)	IV Co-located (grid)
Description	▪ Runs close to baseload on grid electricity only	▪ Runs on grid electricity only, optimizing operating hours to minimize LCOH	▪ Electrolyser connected to renewable asset only (no grid connection)	▪ Electrolyser and co-located on-site renewable assets plus direct connection to grid
Key drivers	▪ High load factor achievable ▪ Produces regular output of hydrogen	▪ 'Smart' operation avoids periods of high power prices and high grid charges, accessing lower LCOH but at an unstable output level	▪ Availability of zero carbon, low marginal cost renewable energy ▪ Benefits from decreasing renewable LCOEs ▪ Can optimize capacity ratio of electrolyser - RES in order to minimize LCOH but at an unstable output level	▪ Combines the benefits of grid connected and co-located business models ▪ Availability of zero-carbon, low marginal cost renewable energy ▪ Option to sell renewable energy to the grid to increase revenues – grid imports are deactivated
	▪ Can decouple electrolyser from RES location to be closer to demand ▪ Asset can produce renewable hydrogen when closing a corresponding PPA[1]; this is outside of the scope of this report			

Today's focus

1) Assuming required geographical proximity and temporal alignment of the production pattern.

Source: Aurora Energy Research

For grid connected electrolysers, costs are lower when run flexibly; for co-located units optimal sizing is crucial for cost-effectiveness

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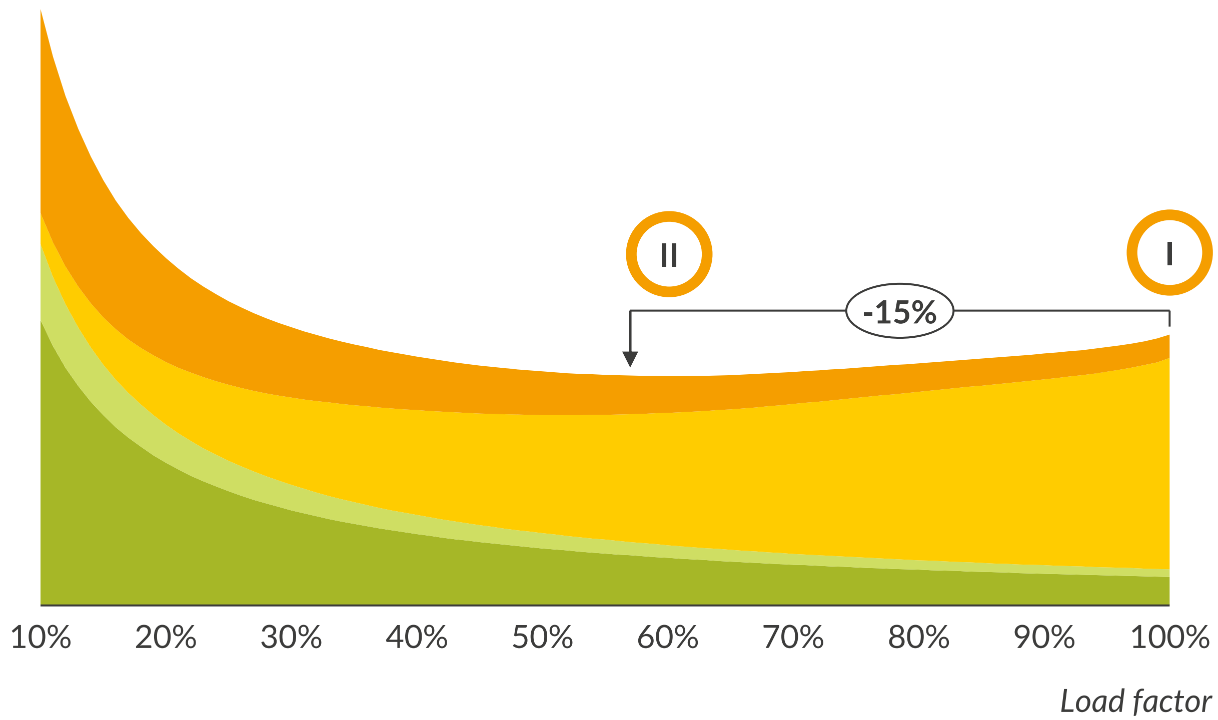
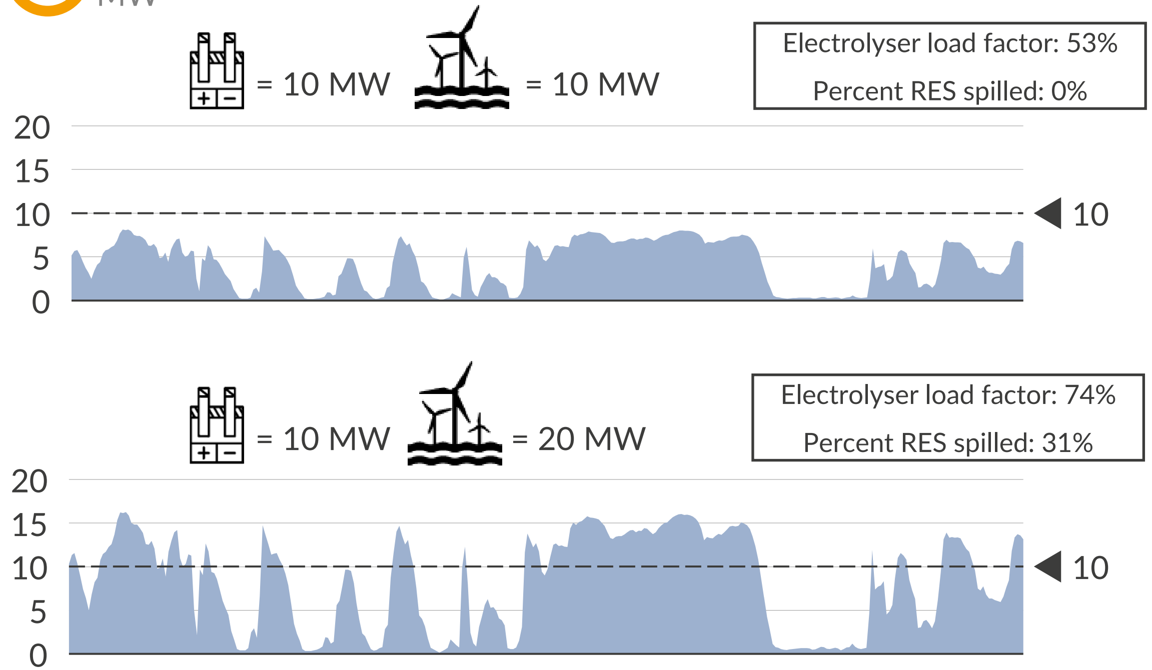
LCOH[1] for different load factors – 2030
EUR/MWh H_2 (real 2021)



- Flexible electrolysers (point 2), benefit from a 15% cost reduction compared to inflexible (point 1), as the decrease in the wholesale power price is stronger than the effect of lower utilisation of the electrolyser

Electrolyser CAPEX[2] | Wholesale power price | Electrolyser FOM[3] | Additional charges

III Example electricity generation profiles for co-located electrolyser
MW



- For electrolysers co-located with renewables, sizing is important to avoid high hydrogen production costs due to under-utilisation of the electrolyser or curtailment of a high share of the wind energy
- We explored different capacity combinations of renewables and electrolyser to find the lowest LCOH[1] and consequently the optimal sizing combination

1) Numbers are available to subscribers of our service. We assume the electrolyser uses all the power generated by the renewable asset up to its capacity, any excess generation is curtailed, increasing the LCOH

Source: Aurora Energy Research

The cost drivers of green hydrogen for grid connected and co-located electrolysers are all indicating lower prices towards 2050

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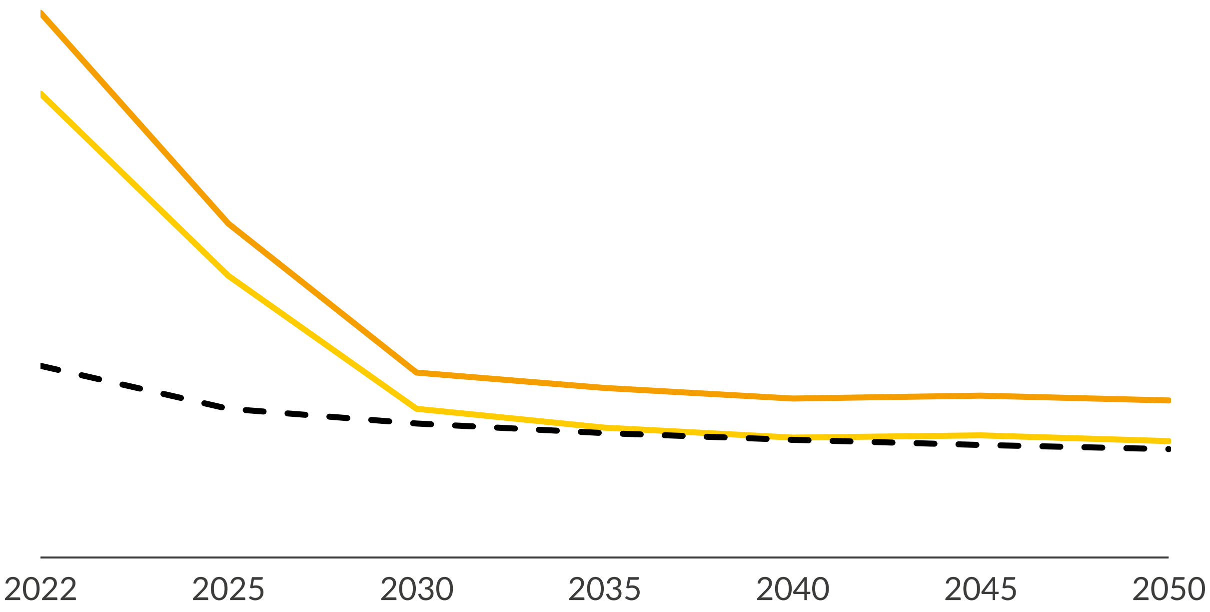
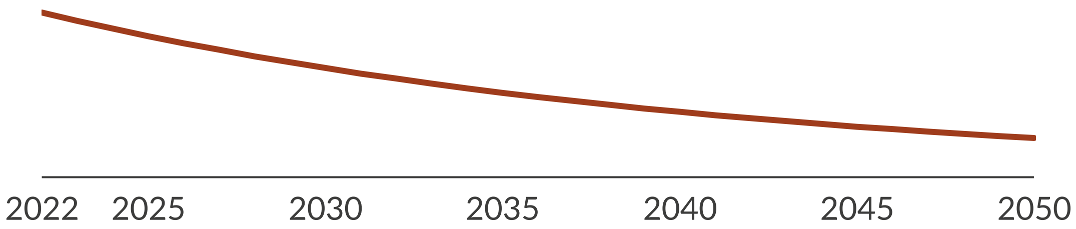
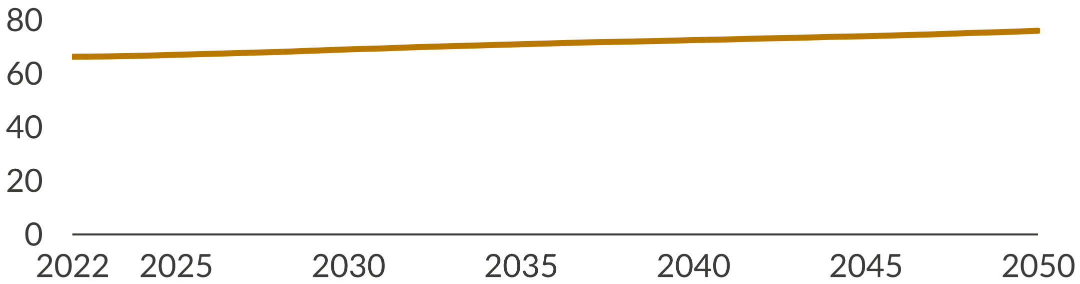
Electricity prices and LCOE – five year steps[1]
EUR/MWh (real 2021)



CAPEX – PEM electrolyser[2]
EUR/kW (real 2021)



Efficiency – PEM electrolyser
%



- Prices to expected to be paid for (renewable) power are expected to decline sharply up until 2027, after which the decline continues more gradually. Over the entire period, the discount to baseload prices increases.
- Reductions in CAPEX and installation besides improvements in capture rates and efficiency are at the basis for a steady decline in LCOE.

- CAPEX per kW is expected to decrease substantially and steadily over time, reaching levels in 2050 which are less than 25% of the 2022 ones.
- Simultaneously, efficiency is expected to gain 10 percentage points from 66% to 76% over the whole period.

Baseload   Flexible load[2]   Offshore wind LCOE

1) Numbers are available to subscribers of our service. NLD specific projections, but direction of change will be similar for France 2) Cheapest 55% of hours in the year. 2) Numbers are available to subscribers of our service.

Source: Aurora Energy Research

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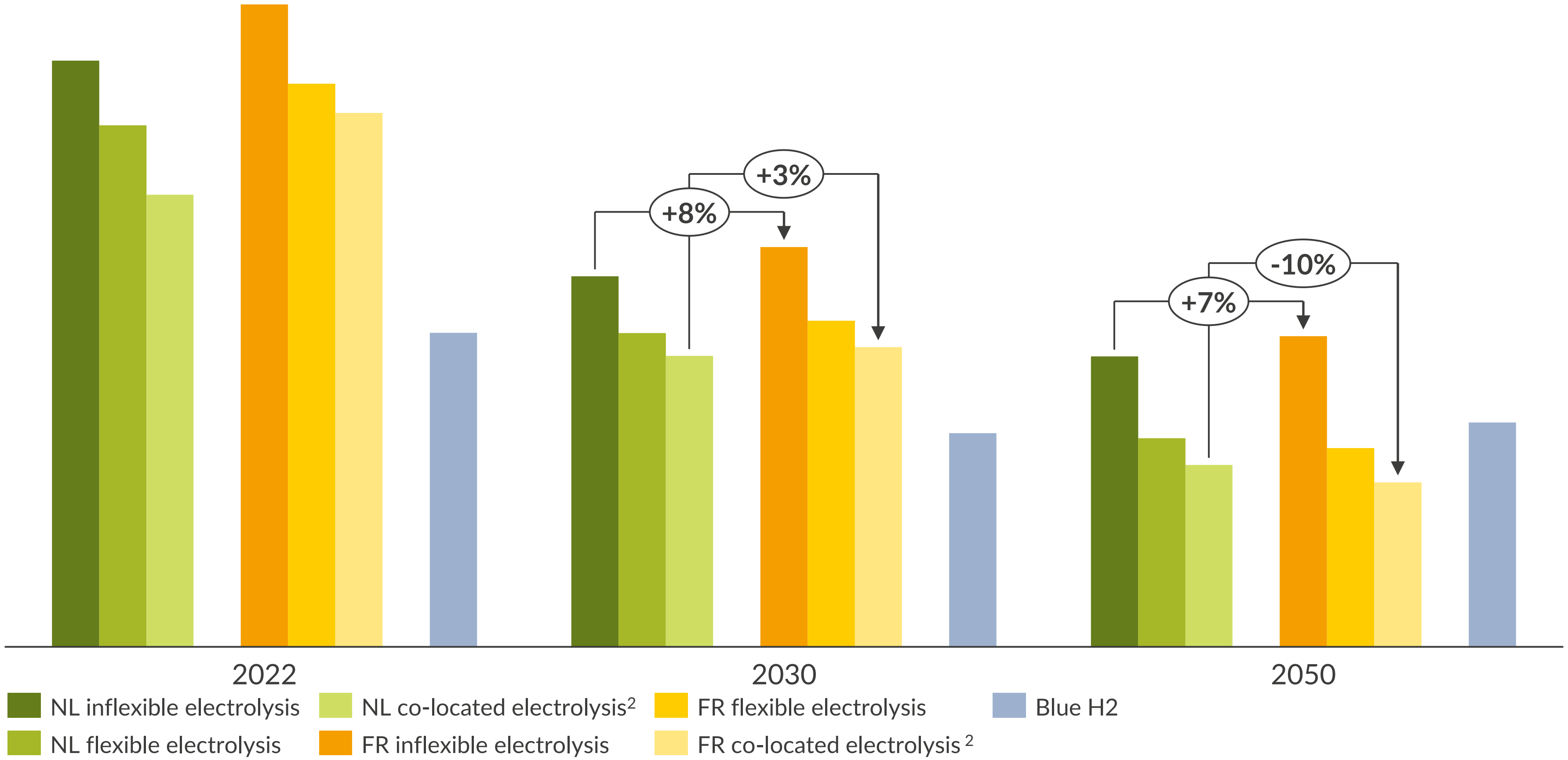
Lowest cost green hydrogen drops by 36% from 2022 to 2030 in the Netherlands and by 44% in France

Levelised cost of hydrogen (vs gas)[1]
EUR/MWh (real 2021)



1) Numbers are available to subscribers of our service. All LCOHs are shown for the entry year of a project over a lifetime of 25 years 2) Co-located with an offshore wind asset in NL and with a wind and a solar asset in FR
Source: Aurora Energy Research

- The levelised cost of green hydrogen in 2022 decreases by 23% in NL and by 17% with co-located electrolysis[2] in comparison to inflexible electrolysis
- In 2030, blue hydrogen drops below the grey hydrogen costs as CO_2 prices go up, but all the green hydrogen technologies remain above it
- On the long run, the drop in electrolyser CAPEX and input electricity costs allows co-located and flexible electrolysis, to drop below grey hydrogen prices and to overtake blue hydrogen as the cheapest sources of hydrogen

Agenda

I. Hydrogen targets in the Netherlands and France

II. The economics of green hydrogen in the Netherlands and France

III. The economics of hydrogen import in the Netherlands

IV. Key takeaways

Other countries have lower production costs for green hydrogen than the Netherlands, which drives the case for imports

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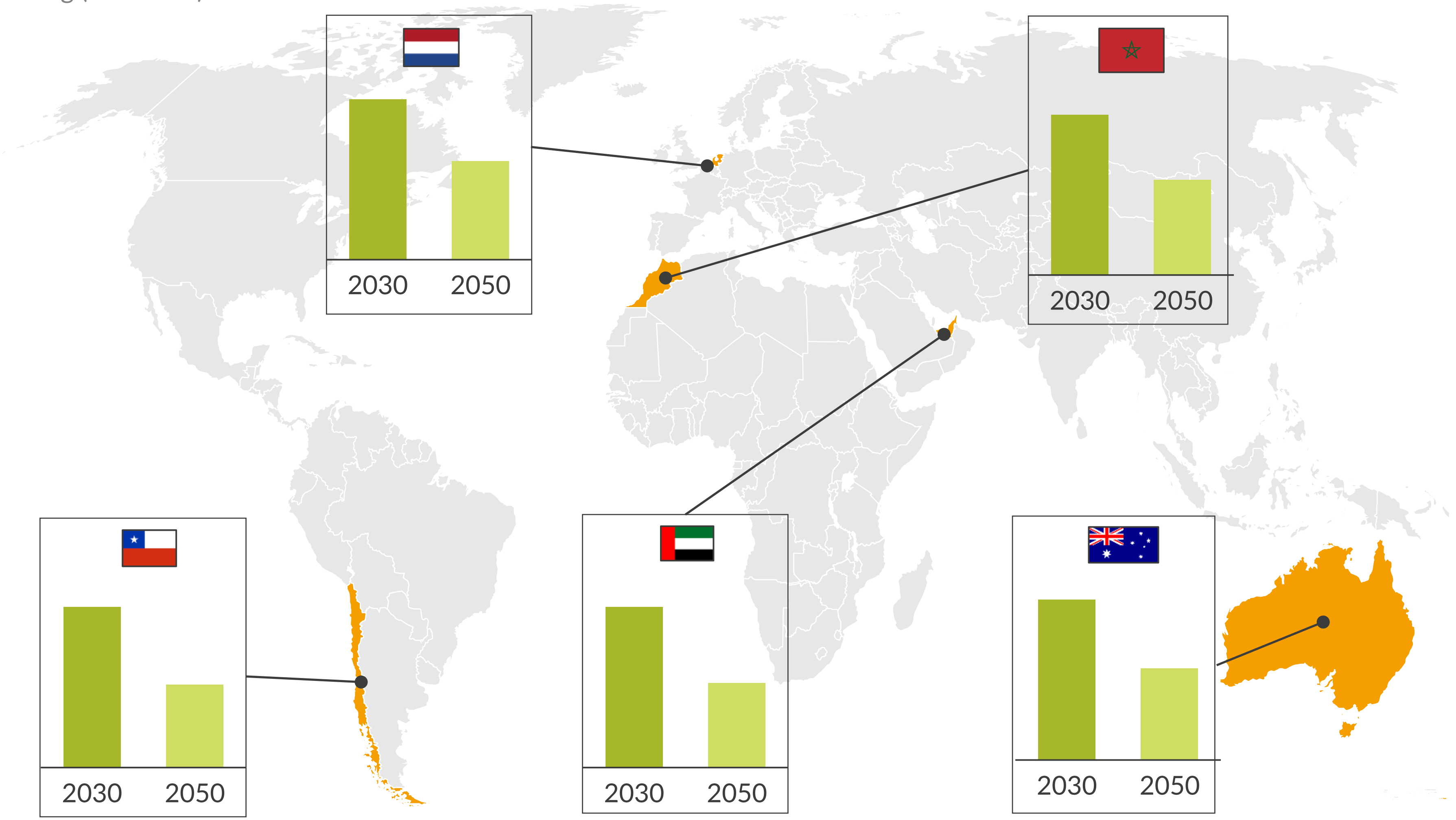
Indicative costs[1] of producing H_2 across the globe

EUR/kg (real 2021)



- Both in 2030 and 2050 production costs abroad are expected to be lower for expected key producers
- Better conditions for RES power production, due to better solar and/or wind resources, form the key driver for these lower prices
- In our calculation of hydrogen costs, different country risk levels are accounted for in the financing costs of projects
- Production prices only reflect a part of the import costs as pre-conditioning, transport costs based on distance, and post-conditioning will still have to be accounted for

1) Numbers are available to subscribers of our service. All costs computations correspond to business models based on co-location with either solar PV or wind assets or both

Source: Aurora Energy Research

For hydrogen supply, import through pipeline is cheaper than the ammonia route, but more expensive than domestic production

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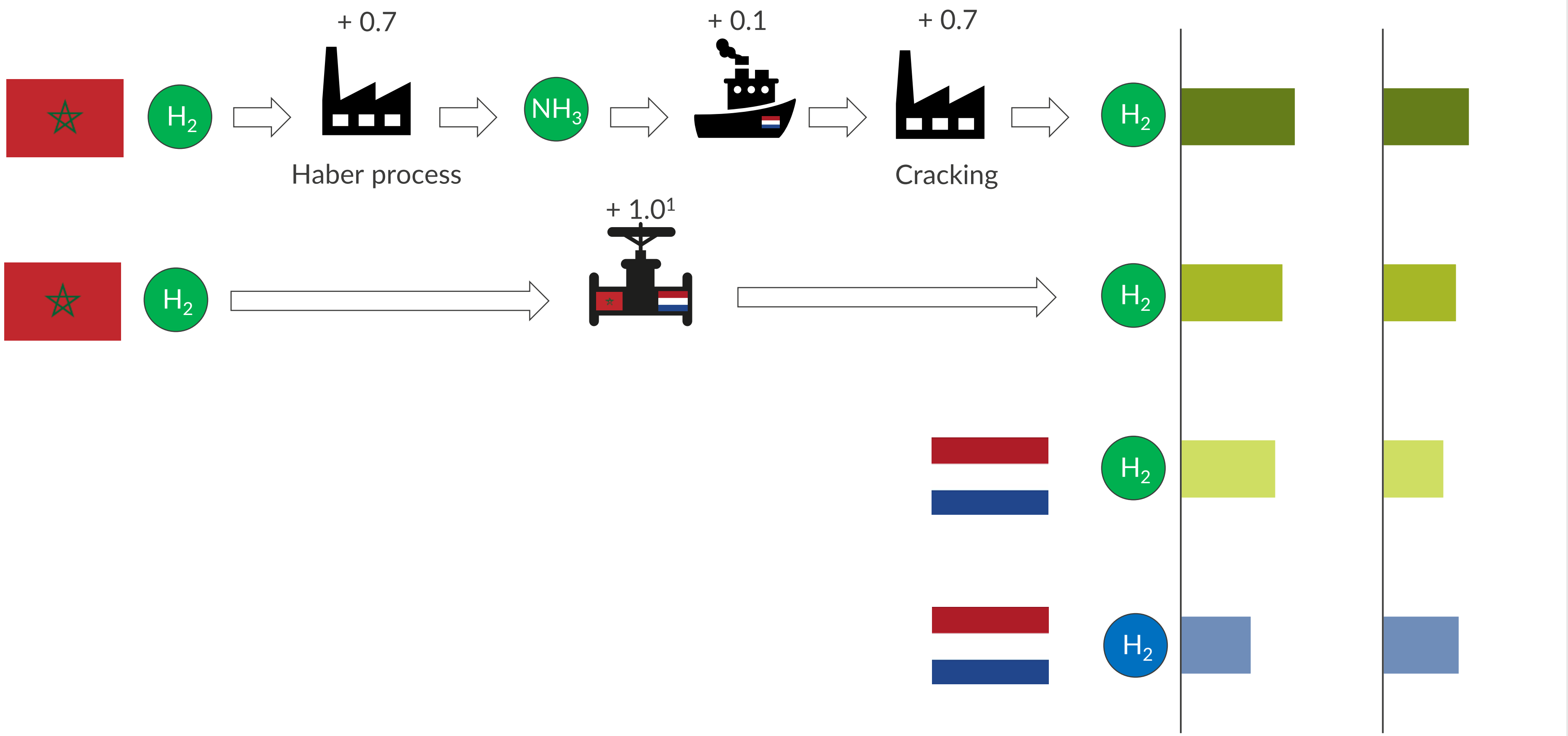
H_2 import routes and costs in 2030
EUR/kg (real 2021)

LCOH in 2030[2]
EUR/kg (real 2021)

LCOH in 2050[2]
EUR/kg (real 2021)



- Hydrogen produced in Morocco in 2030 can be transported via two routes:

1) By converting H_2 to ammonia (NH_3), which is easier to transport, shipping it to the Netherlands and converting it back to hydrogen. This proves to be the most expensive transport route in 2030, due to the high costs incurred by the different conversion processes.

2) Using pipeline transport to the Netherlands, which is more competitive and cheaper than the first route. The downside is the larger investments in and complexity of the required infrastructure.

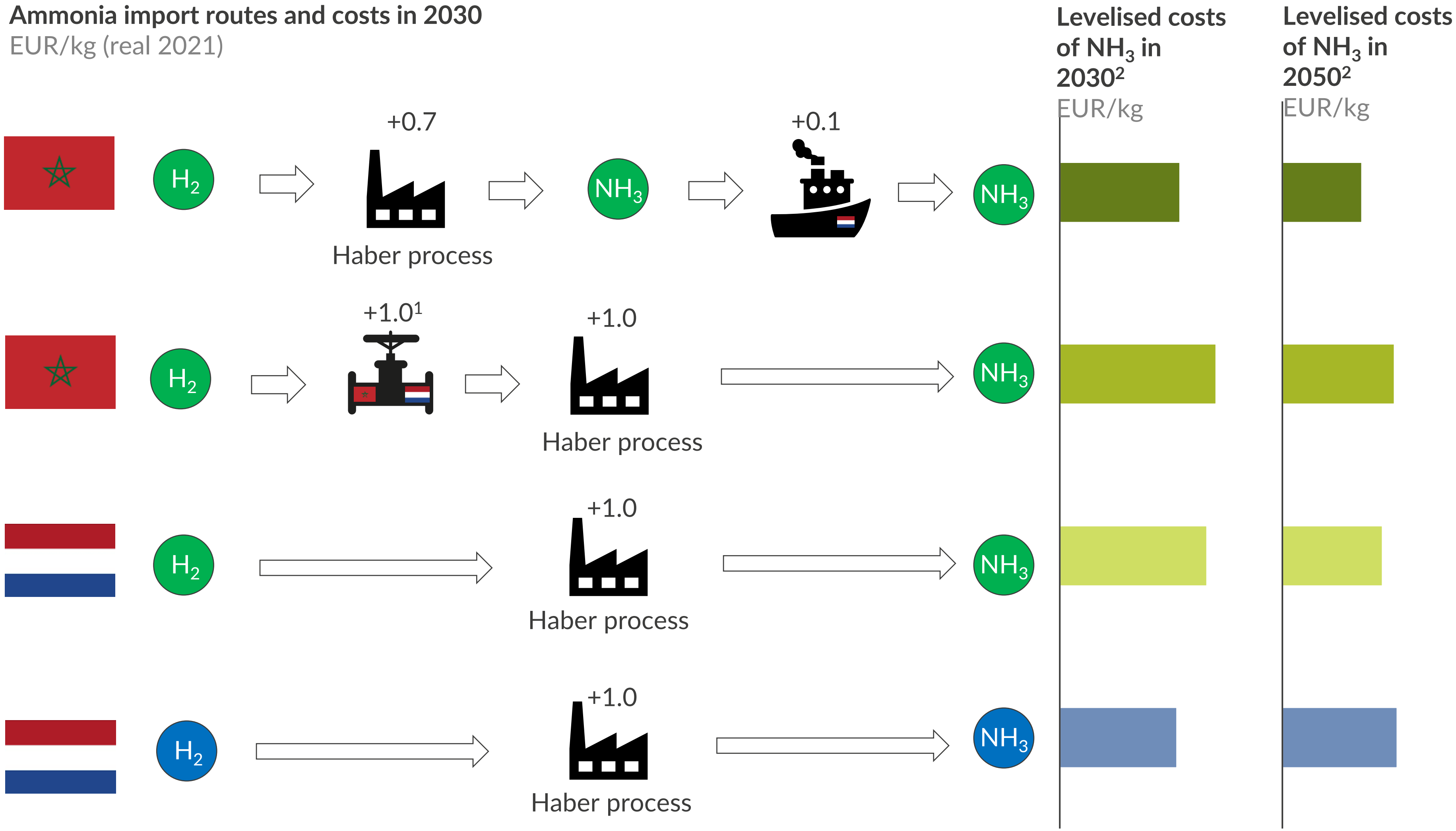
- Blue hydrogen produced in the Netherlands is the cheapest clean hydrogen product in 2030, whereas green is cheaper by 2050.

1) Assumed newly built 36" pipeline , length of 2500 km. 2) Numbers are available to subscribers of our service.

Source: Aurora Energy Research

For ammonia supply, green imports from Morocco and other countries can be close to competitive by 2030, and cheaper after

Ammonia import routes and costs in 2030
EUR/kg (real 2021)



- For ammonia demand, the dynamic of imports versus domestic production changes, since for all routes the Haber-Bosch process is required to convert hydrogen to ammonia.
- Since ammonia is easier and cheaper to import by ship than hydrogen, the most important cost driver is the input price of hydrogen.
- Already by 2030, converting H_2 to NH_3 in Morocco and shipping it to the Netherlands proves to be competitive with domestic blue hydrogen production.
- After 2030, green NH_3 from Morocco becomes cheaper whereas blue hydrogen rises in costs.

1) Assumed newly built 36" pipeline, of 2500 km length. 2) Numbers are available to subscribers of our service.

Source: Aurora Energy Research

Agenda

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IV. Key takeaways

Key takeaways

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1. The Netherlands and France differ in terms of their ambitions

- The Netherlands and France respectively target at least 3-4 GW and 6.5 GW of electrolysers by 2030, whilst the pipeline of projects is significantly higher in the Netherlands
- The port of Rotterdam and Amsterdam aim to import 5 Mt/year by 2030 from a variety of countries

2. Green hydrogen costs are forecast to drop quickly in both countries by 2030 (-36% in the Netherlands and -44% in France)

- When comparing which source of power gives you the lowest LCOH, in both countries electrolysers co-located with renewables are the cheapest source of green hydrogen, whereas grid-based options are more expensive
- By 2050, both renewables and grid-connected electrolysers see their LCOH drop below that of grey and blue, due to falling electrolyser capex costs and lower-cost power

3. By 2030, domestic production is cheaper than imports but when ammonia is the end product, imports from Morocco are more attractive

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