Spatial-economic analysis of low-carbon hydrogen supply to the European market

Construction of an international merit-order of low-carbon hydrogen

Peter Perey

Centre for Energy Economics Research
Faculty of Economics and Business
University of Groningen

Joint work with **Machiel Mulder**
With support of **Katie K. Kwok**

9 June 2021, 1st IAEE Online Conference

Outline

1. Background
2. Low-carbon hydrogen production and transport
3. Construction of an international merit-order of hydrogen supply to Europe
4. Preliminary results
5. Preliminary conclusions

Background

European ambitions for deployment and supply of low-carbon hydrogen

- Low-carbon hydrogen is anticipated to replace natural gas in heating, to be used as a fuel for transportation, and to serve as input for energy-intensive industry. As a result, the share of hydrogen in Europe’s energy mix is projected to grow to 13-14% by 2050 (European Commission, 2018)
- Low-carbon hydrogen is either produced using renewable electricity, or with fossil fuels (Steam Methane Reforming) combined with Carbon Capturing and Storage (CCS) technology
- High local renewable electricity prices make electrolysis production within Europe relatively expensive (Hydrogen Council, 2020; IRENA, 2019)
- Production of low-carbon hydrogen with CCS technology seems more price-competitive (Blanco et al., 2018)

Low-carbon hydrogen supply

Hydrogen production

- SMR is globally the most used option (95%), with natural gas as the most common used energy input in the EU. Most important cost components are natural gas costs, investment costs and costs of emitting/storing carbon (Collodi et al., 2017)

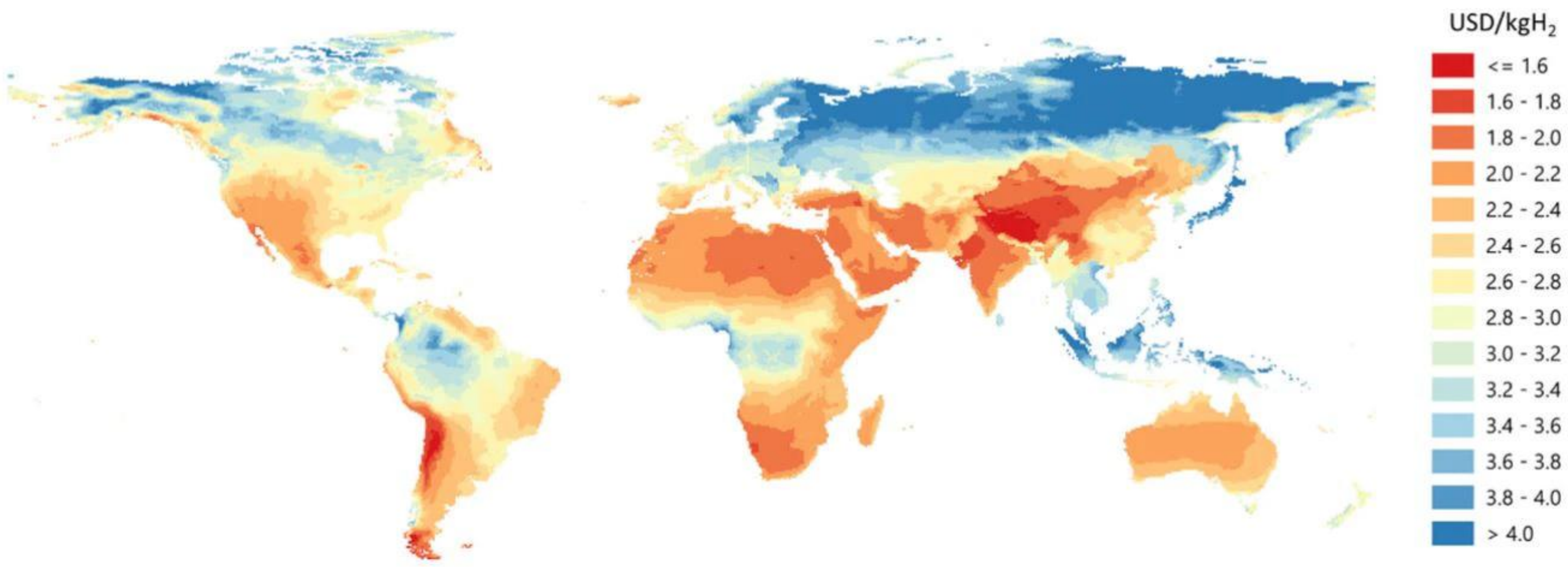
- Several electrolysis techniques exists, with proton exchange membrane (PEM) electrolysis seen as most suitable for hydrogen production with renewable electricity (FCH, 2017)

- The costs of electricity input makes up a large amount of the total long-term hydrogen costs (Michalski et al., 2017), hence electrolysis production is most competitive where the production costs of renewable electricity are lowest (van Renssen, 2020; Timmerberg & Kaltschmitt, 2019)

Potential production areas

Costs of renewable electricity are largely determined by favourable conditions as solar irradiation and wind speed

Hydrogen costs from hybrid solar PV and onshore wind systems in the long term



Source: IEA; Future of hydrogen (2019)

Low-carbon hydrogen supply

Hydrogen transport

- Options for hydrogen transport include gaseous hydrogen through pipelines, liquefied hydrogen per ship and liquid ammonia as a hydrogen carrier per ship. The most suitable option depends on distance and ratio onshore/offshore

What is the most competitve supply route of low-carbon hydrogen to North-west Europe?

Construction of an international merit-order of hydrogen supply to Europe

- We construct a merit-order for low-carbon hydrogen supply to the port of Rotterdam, which is taken as the entry to the North-West European market, based on the levelised costs of hydrogen supply (LCOHS)
- We determine the long-term unit production costs for low-carbon hydrogen production, given spatial economic conditions in different regions
- Based on national hydrogen strategies we analyse hydrogen produced through SMR with CCS in Norway and hydrogen produced through PEM-electrolysis in Australia, Chile, Morocco, Norway and Saudi Arabia
- Subsequently, we calculate which transportation method is most suitable for each of the identified regions, enabling us to construct a long-term unit cost of supplying low-carbon hydrogen from each selected region
- As benchmark, we include the hydrogen production in Rotterdam for both techniques

Levelised costs of hydrogen supply (LCOHS)

Unit costs of production of hydrogen — Levelised costs of hydrogen production (LCOHP)

+

Unit costs of conversion for hydrogen tranport

+

Unit costs of transport method

+

Unit costs of conversion to hydrogen at landing site

} Levelised costs of hydrogen transport (LCOHT)

=

Total unit costs of supply (LCOHS)

$$LCOHS_i = \frac{LCOHP_i}{l_i^x} + LCOHT_i$$

Loss of hydrogen during transport

Levelised costs of hydrogen production (LCOHP)

Hydrogen production costs

$$LCOHP_i^x = \frac{PV\left(HPC_i^x\right)}{PV\left(Q_i^x\right)} = \frac{\sum_{t=1}^{T} \frac{HPC_{i,t}^x}{(1+r)^t}}{\sum_{t=1}^{T} \frac{Q_{i,t}^x}{(1+r)^t}}$$

Quantity produced depends on:
Capacity, operating hours and efficiency

$$Q_{i,t}^x = \frac{Cap_i^x * h_{i,t}^x * \eta_i^x}{LHV}$$

$$HPC_{i,t}^{pem} = \underbrace{\left(CAPEX_{i,t}^{pem} + OPEX_{i,t}^{pem}\right) * Cap_i^{pem}}_{Fixed\ costs\ plant} + \underbrace{\left(Cap_i^{pem} * h_{i,t}^{pem}\right) * \left(p_{i,t}^{el} + p_{i,t}^{c}\right)}_{costs\ of\ energy\ input} + \underbrace{\left(w^{pem} * p_{i,t}^{w}\right) * Q_{i,t}^{pem}}_{water\ costs}$$

$$HPC_{i,t}^{SMR} = \underbrace{\left(CAPEX_{i,t}^{SMR} + OPEX_{i,t}^{SMR}\right) * Cap_i^{SMR}}_{Fixed\ costs\ plant} + \underbrace{\left(Cap_i^{SMR} * h_{i,t}^{SMR}\right) * p_{i,t}^{NG}}_{costs\ of\ energy\ input} + \underbrace{\left[\left(w^{SMR} * p_{i,t}^{w}\right) + \left(\frac{CC_{i,t}*p_i^{CCS} + CE_{i,t}*p_{i,t}^{CE}}{1000}\right)\right] * Q_{i,t}^{SMR}}_{water\ and\ carbon\ costs}$$

Technical assumptions production plants

Input	SMR with CCS	PEM-electrolysis
Lifetime plant (years)	25	20
Energy efficiency	69%	Based on operating hours
CAPEX (€/kw input capacity)	919	650 + 30% for stack replacement after 10 years
OPEX (annual as % of CAPEX)	3%	1.5%
Water input (l/kg h2)	4.7	15
Water price (€/L)	0.0007	0.0007
Co_2 emitted (kg/kg h2)	0.99	0
Co_2 captured (kg/kg h2)	8.90	0

Sources: Chardonnet et al. (2017); Collodi et al. (2017); Guerra et al. (2020) & IRENA (2018)

Number of operating hours per year	Assumed efficiency electrolyser
<3000	65%
≥3000 and <7000	70%
≥7000	75%

Country specific inputs

Operating hours, energy price and carbon price

SMR with CCS	Netherlands	Norway	Sources
Operating hours	8322	8322	Collodi et al. (2017)
Natural gas price (€/MWH)	21	21	Eurostat
CO_2 allowance price (€/ton)	45	45	EU-ETS price
CO_2 storage costs (€/ton)	50	35	PBL (2020)

For PEM- electrolysis, both the price of the electricity and number of operating hours are based on the renewable power production facility

	PEM-electrolysis in selected regions
Operating hours	Capacity factor of renewable energy
Electricity price (€/MWh)	LCOE of renewable electricity

Capacity factors

Capacity factors per renewable power technique, per country realized in 2018

$$Capacity\ factor = \frac{Produced\ electricity}{Installed\ capacity * 8760}$$

	Onshore wind	Offshore wind	Solar PV	Solar thermal (CSP)
Australia	27%		13%	17%
Chile	28%		23%	
Morocco	36%		15%	20%
Netherlands	26%	43%	9%	
Norway	23%	29%	10%	
Saudi Arabia	19%		22%	34%

Sources: IRENA (2020); IEA (2019)

Levelised costs of energy (LCOE)

To calculate the price for electricity from renewable power generation:

$$LCOE = \frac{\sum(Capital_t + O\&M_t + Decomissioning_t) * (1+r)^{-t}}{\sum(MWh) * (1+r)^{-t}}$$

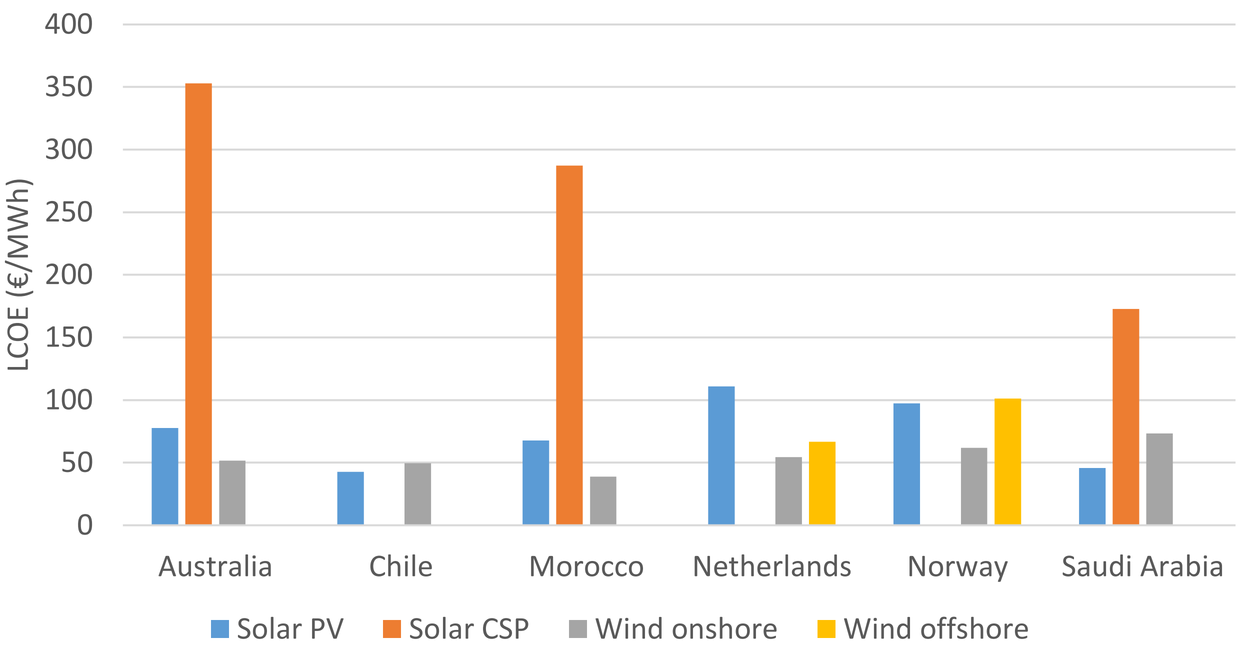
Production is based on the capacity factors calculated before.
Costs per kW are determined by the following parameters:

	Solar PV	Solar CSP	Wind onshore	Wind offshore
Lifetime	25	25	25	25
Overnight costs ($/kW)	995	5857	1391	2876
Annual fixed O&M (% of overnight)	4%	4%	4%	4%
Decommissioning costs (% of overnight costs)	5%	5%	5%	5%
Discount rate	0.05			
Exchange rate (€/$)	0.84			

Sources: IEA, Projected Costs of Generating Electricity - 2020

LCOE per technique, per country

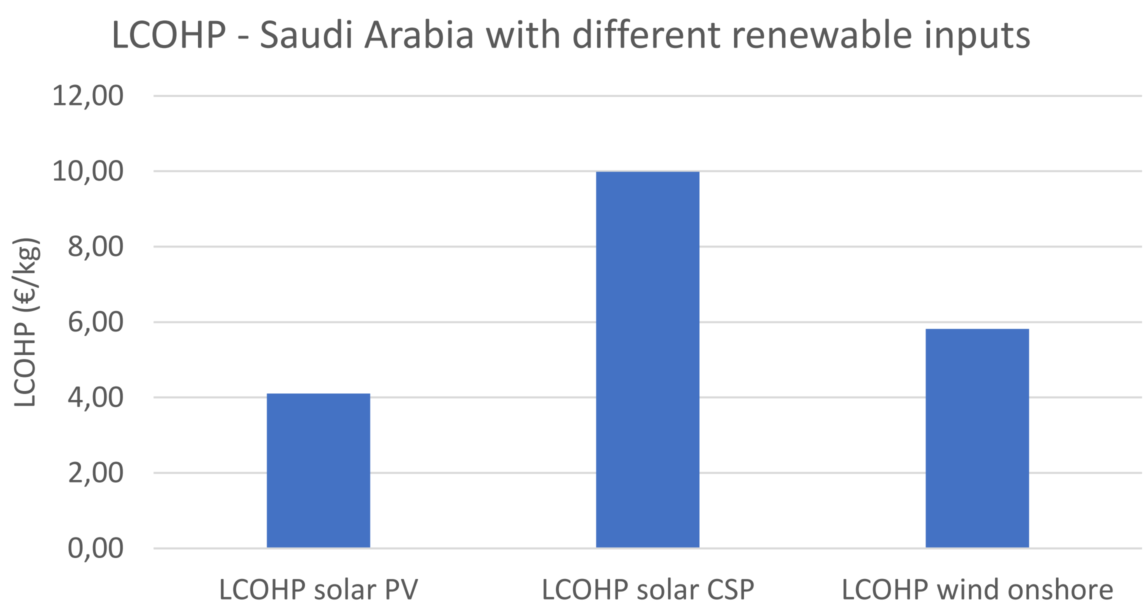
Combining this gives the following results for the LCOE per technique, per country



The LCOE for solar CSP plants is high, due to high investment costs
Other techniques have LCOE’s in the range of 39 – 111 €/MWh

LCOHP per technique, per country

For each country, the information on the LCOE and capacity factor are used to calculate the LCOHP. From these, the technique with the lowest LCOHP is selected for that country



Here, we select solar PV as renewable electricity input for Saudi Arabia

Levelised costs of hydrogen transport (LCOHT)

$$LCOHT_i = \min \{LCOHT_i^{pipe}, LCOHT_i^{liq}\ LCOHT_i^{amm}\}$$

We select the transportation method with minimal levelised costs

Hydrogen transportation costs

$$LCOHT_i^x = \frac{PV(HTC_i^x)}{PV\left(volume_i^x\right)} = \frac{\sum_{t=1}^{T} \frac{HTC_{i,t}^x}{(1+r)^t}}{\sum_{t=1}^{T} \frac{volume_{i,t}^x}{(1+r)^t}}$$

$$volume_{t,i}^x = Q_{t,i} * (1 - l^x)$$

Volume delivered to Rotterdam is quantity produced minus the loss of hydrogen during transport

Levelised costs of hydrogen transport (LCOHT)

$$HTC_{i,t}^{pipe} = \underbrace{\left(CAPEX_t^{on} + OPEX_t^{on}\right) * d_i^{on}}_{installation\ costs\ onshore} + \underbrace{\left(CAPEX_t^{off} + OPEX_t^{off}\right) * d_i^{off}}_{installation\ costs\ onshore} + \underbrace{el_{i,t}^{pipe} * p_{i,t}^{el}}_{electricity\ costs}$$

$$HTC_{i,t}^{liq} = LC_{i,t} + SC_{i,t}^{liq}$$

$$HTC_{i,t}^{amm} = CC_{i,t} + SC_{i,t}^{amm}$$

Preparation for seaborne transport

$$LC_{i,t} = \underbrace{CAPEX_t^{liq} + OPEX_t^{liq}}_{Fixed\ costs} + \underbrace{q_t^{el,liq} * p_{i,t}^{el}}_{electricity\ costs}$$

$$CC_{i,t} = \underbrace{CAPEX_t^{amm} + OPEX_t^{amm}}_{Fixed\ costs} + \underbrace{q_t^{el,amm} * p_{i,t}^{el}}_{electricity\ costs}$$

$$SC_{i,t}^{x} = \underbrace{CAPEX_{i,t}^{ship,x} + OPEX_{i,t}^{ship,x}}_{Fixed\ costs\ fleet} + \underbrace{\left(f_t^{ship,x} * p_{i,t}^{f} * d_i^{ship} * 2\right) * N_i^{trips,fleet}}_{fuel\ costs\ fleet}$$

$$N_i^{trips,fleet} = N_i^{ships} * \frac{h_i^{ship}}{\frac{d_i^{ship} * 2}{v^{ship}} + L^{ship}}$$

Technical assumptions pipeline transport

Compressor	
Capital costs (€/kW)	3000
Capacity needed per input (kW/km)	250
Compressor replacement costs after 20 years (% of initial costs)	40%
Compressor power consumption (MWh/kg h2)	0.000015
Yearly fixed costs (% of CAPEX)	4%
Compressor distance (km)	250

Pipelines	
Lifetime	40
Transported volume (kg/s)	85
Utility pipeline	90%
Construction costs pipeline onshore (€/km)	2000000
Construction costs pipeline offshore (€/km)	3000000
Yearly fixed costs (% of CAPEX)	5%
Loss of hydrogen by pipeline	8%

Sources: European hydrogen backbone (2020); Kriel (2012); Yang & Ogden (2007)

Technical assumptions conversion

	Liquefaction	Conversion to NH_3	Reconversion
Lifetime	20	20	20
Loss of hydrogen (%)	1.66	0	16
Operating hours	7000	7200	7200
Input capacity (ton/year)	71	840	1016
Capital costs (€/MW)	1393724	697737	380360
Yearly opex (%/CAPEX)	6	4	4
Electricity requirement (MWh/kg)	0.007	0.004	0.002
Energy for heating (MWh/kg)	-	-	0.01

Sources: Al-breiki & Bicer (2020); Bartels (2008); IEA, the future of hydrogen (2019); Tijdgat (2020); Weiss et al. (2018)

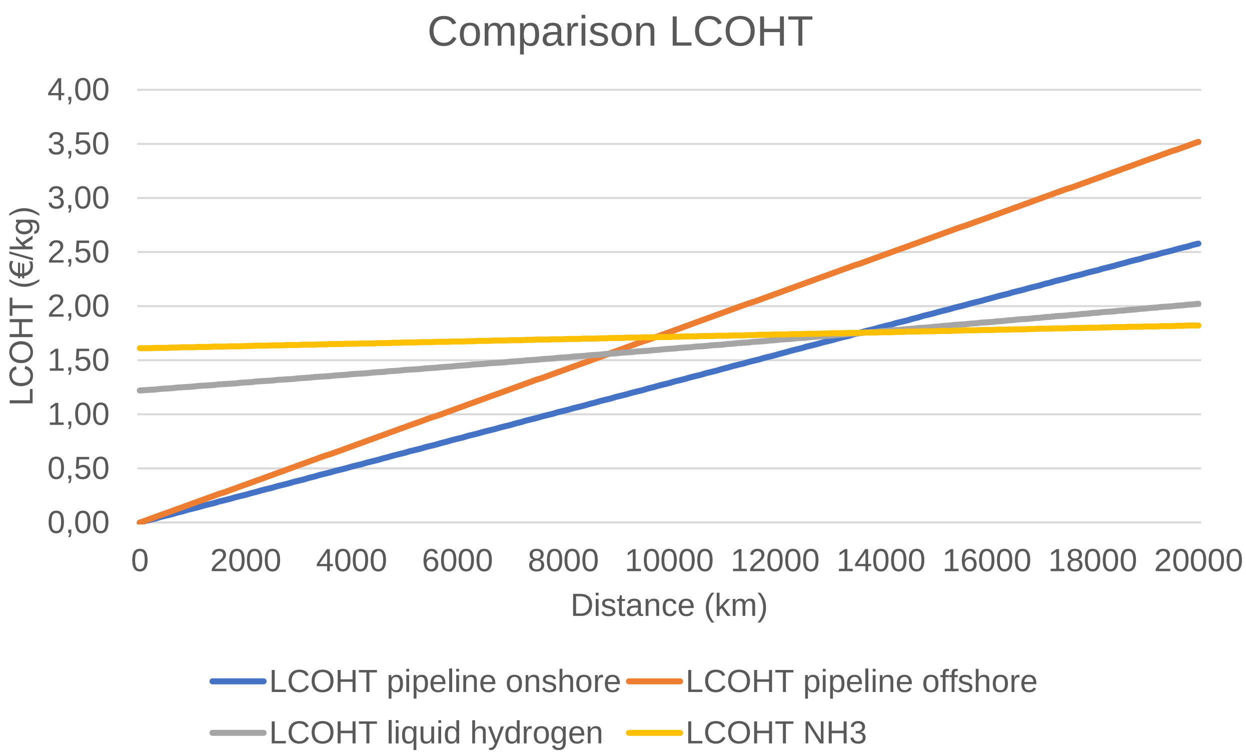
Technical assumptions seaborne transport

	Liquid	Ammonia
Capital costs ship (€/kg capacity)	16	7.28
Lifespan	15	15
Speed ship (km/h)	37	37
Loading/unloading (h)	36	36
Operating days	350	350
Hydrogen loss (%/day)	0.2	0
Maintenance costs (%/capex)	4%	4%
Labor costs (€/year/kg capacity)	0.22	0.13
Port charges (€/year/kg capacity)	0.31	0.19
Fuel use (kg h2/km)	12.4	-
Fuel costs (€/km)	Dependent on LCOHP	25

Sources: Al-breiki & Bicer (2020); IEA, the future of hydrogen (2019)

LCOHT for different distances

Assuming optimal utilisation of transport methods



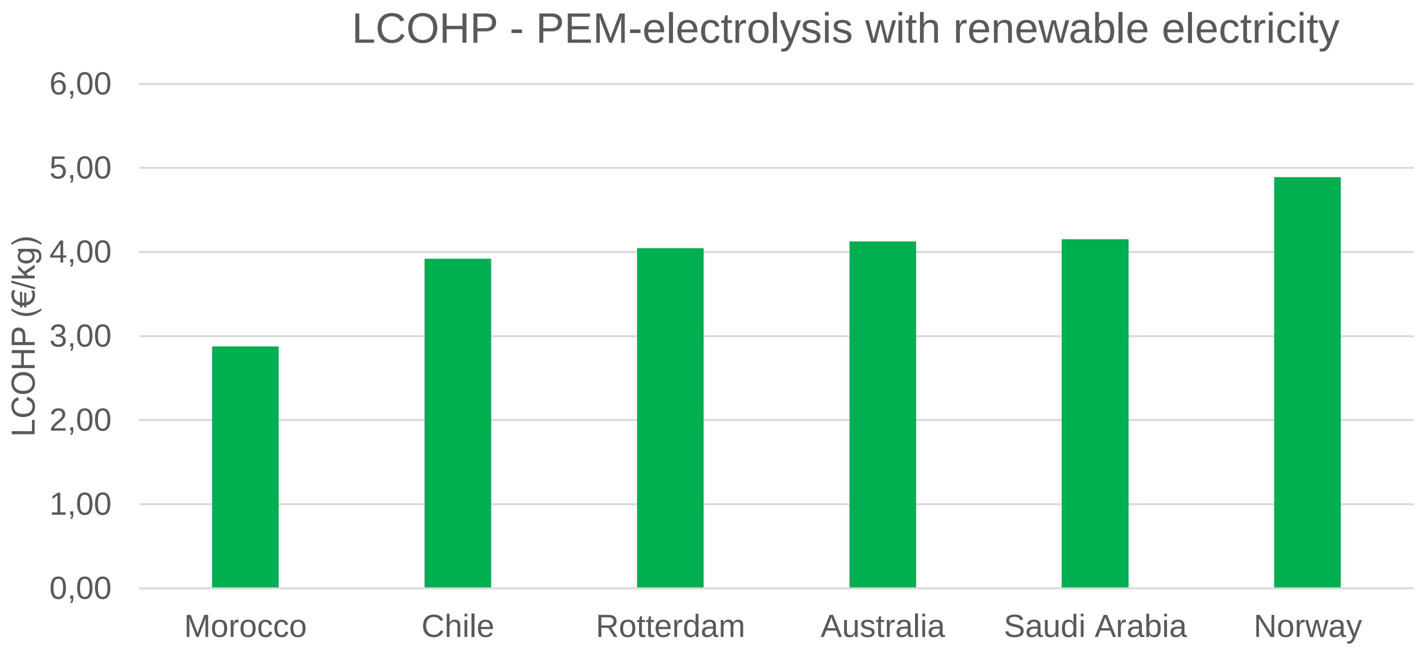
Based on:

Electricity price (€/MWh)	45
H2 price (€/kg)	3
Gas price (€/MWh)	20
Carbon price (€/ton)	40

Shipping of liquid hydrogen and ammonia have high upfront costs, but become competitive over larger distances

Levelised costs of hydrogen production (LCOHP)

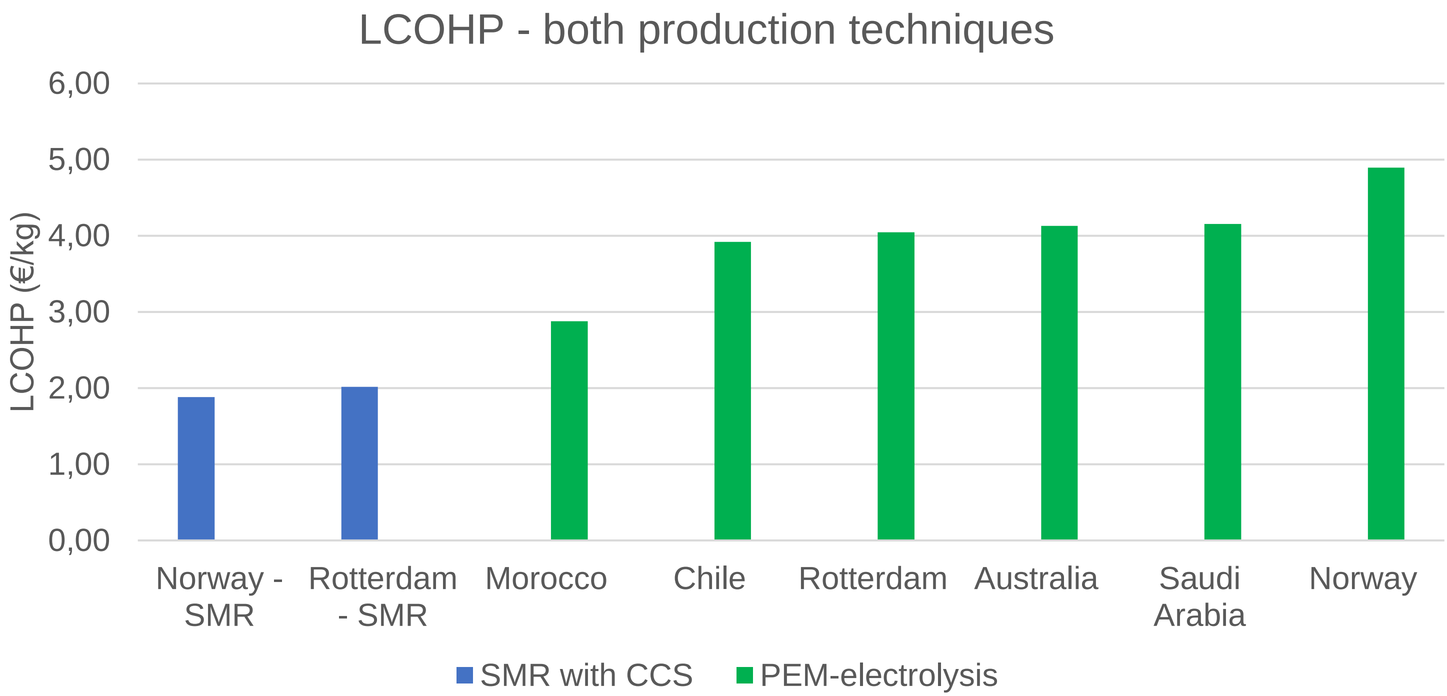
for PEM-electrolysis using renewable electricity



Production of hydrogen using renewable electricity is most competitive in Morocco, with a LCOHP of below 3 €/kg

Levelised costs of hydrogen production (LCOHP)

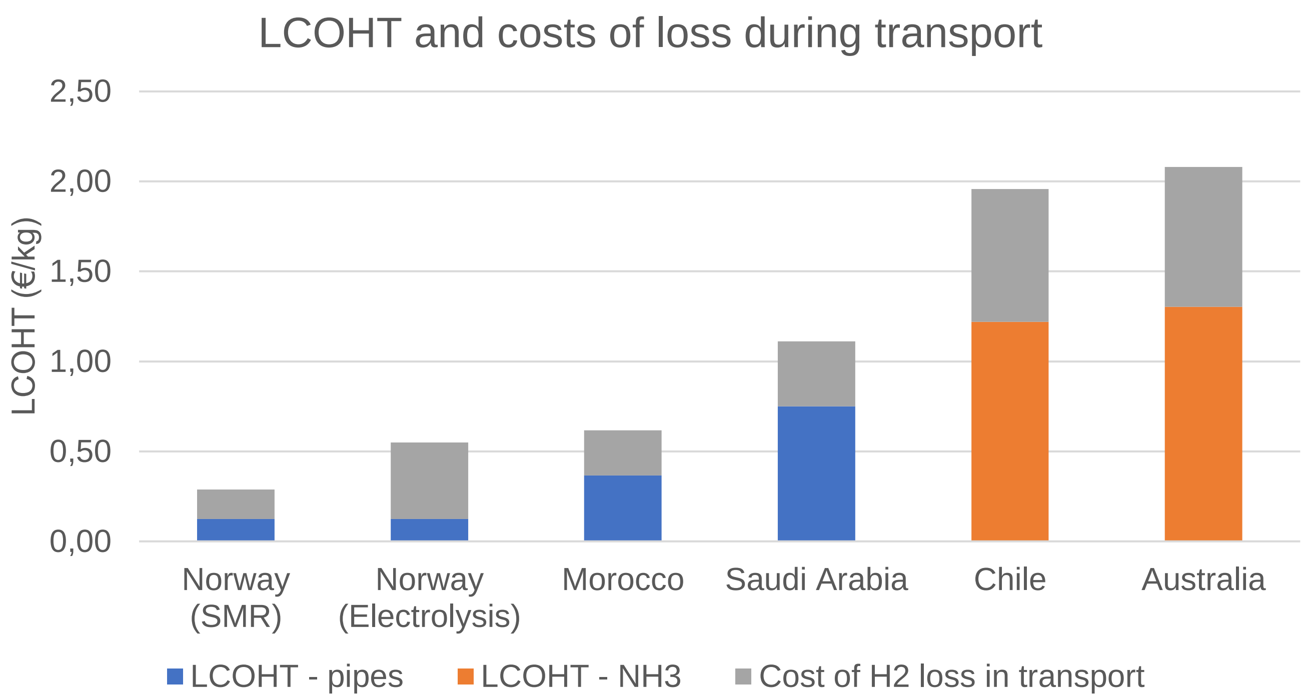
for both SMR with CCS and PEM-electrolysis



Production of hydrogen using renewable electricity is not competitive compared to SMR with CCS production, which have a LCOHP of under 2 €/kg

Levelised costs of hydrogen transport (LCOHT)

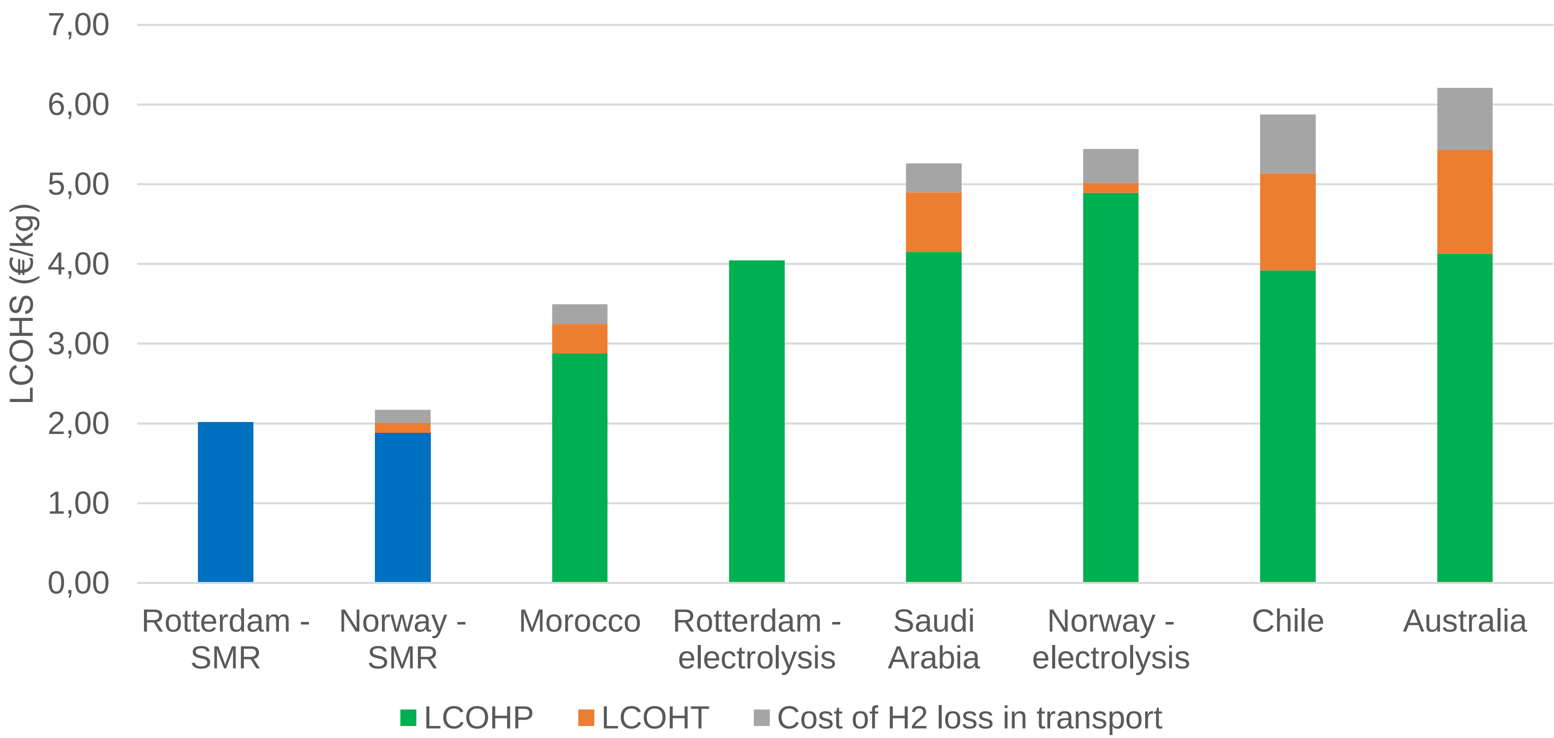
including costs of hydrogen loss during transport, per country



For the larger distances, transport as ammonia is most competitive for that region

High LCOHT for larger distances can potentially be a driver for global price differences

International merit-order of hydrogen supply

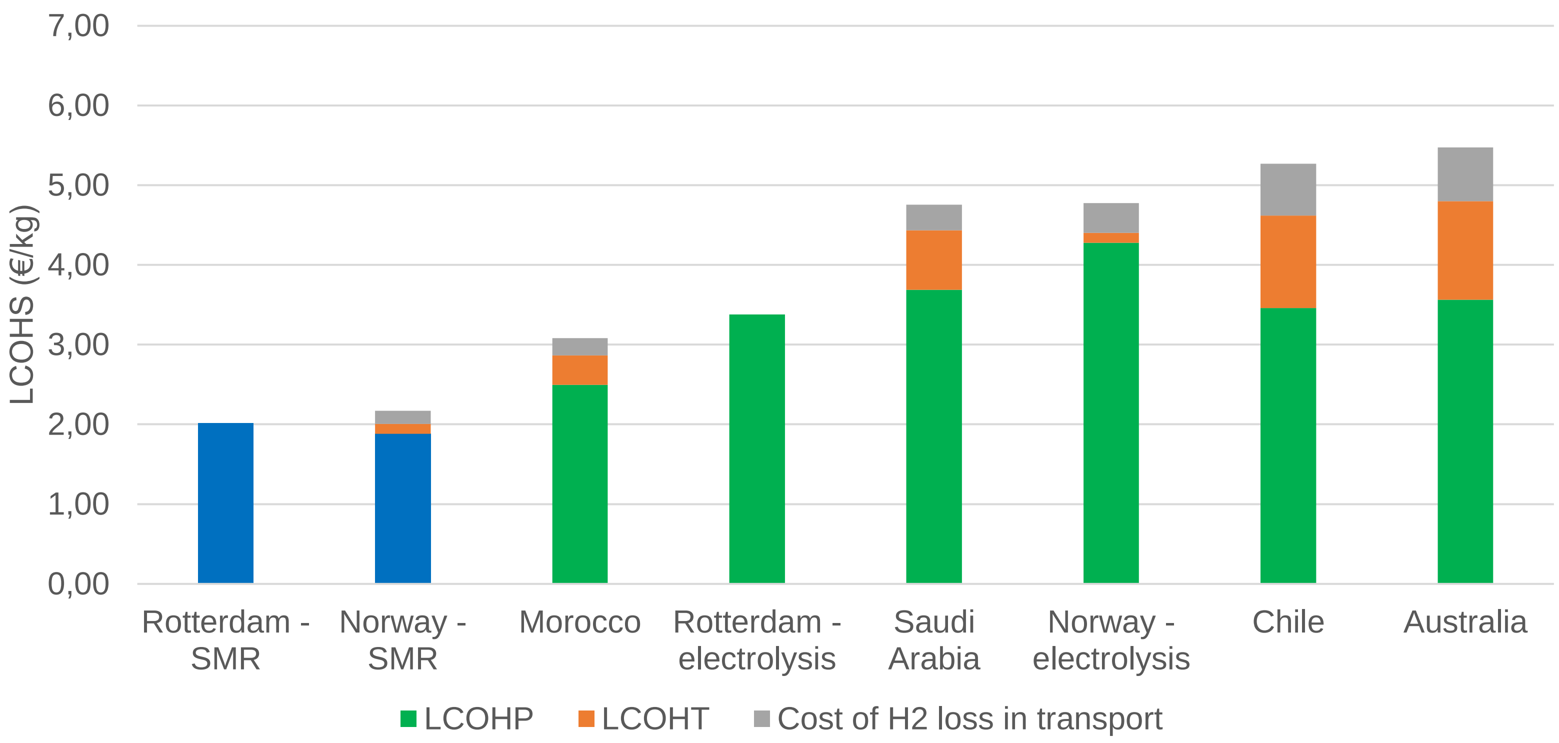


Hydrogen produced through SMR with CCS in Rotterdam is the most competitive

If one only considers PEM, supply from Morocco is cheaper than production in Europe

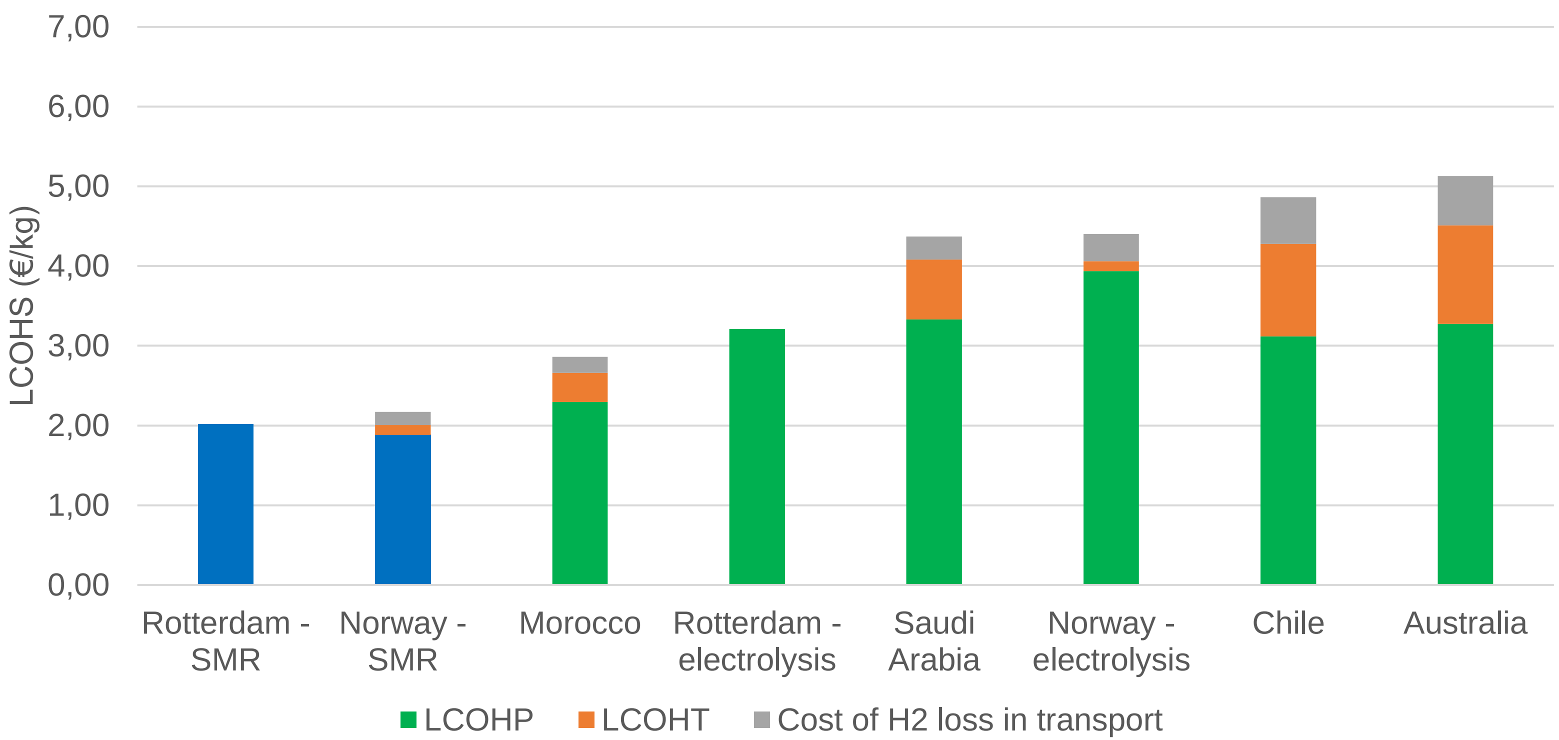
International merit-order of hydrogen supply

20% cost reduction installation costs renewables



International merit-order of hydrogen supply

20% cost reduction installation costs renewables and 20% cost reduction installation costs electrolyser



Both cost reductions combined are not sufficient to alter the international merit-order

Conclusions

- Production of hydrogen using renewable electricity is most competitive in Morocco
- Production of hydrogen using renewable electricity is not competitive compared to SMR with CCS production
- For larger distances, transport as ammonia is most competitive for that region
- High LCOHT for large distances can potentially be a driver for global price differences
- Hydrogen produced through SMR with CCS in Rotterdam is the most competitive
- If one only considers PEM, supply from Morocco is cheaper than production in Europe
- Cost reductions in renewable electricity generation and electrolysers combined do not alter the international merit-order
- Higher capacity factors of renewables could change the merit-order

Contact details

Peter Perey, MSc.
Centre of Energy Economics and Research (CEER)
Faculty of Economics and Business, University of Groningen
P.O. Box 800
9700 AV Groningen

email: p.l.perey@rug.nl
website: https://www.rug.nl/ceer/