Economies of hydrogen production by electrolysis from wind and grid power

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Agenda

- Cost drivers of hydrogen production from electrolysis
- Evolution of renewable energy technologies
- Future cost of electrolytic hydrogen production
- Case study of hydrogen production in Texas in 2050

Reductions for investment cost of electrolysis

- Current investment cost of large-scale electrolysis:
  - Alkaline (AEL): about 500 €/kW
  - Proton exchange membrane (PEM): about 8-900 €/kW
- Expected to be reduced in the future
  - PEM closing the gap on AEL
  - Costs approaching 400 €/kW in 2030?

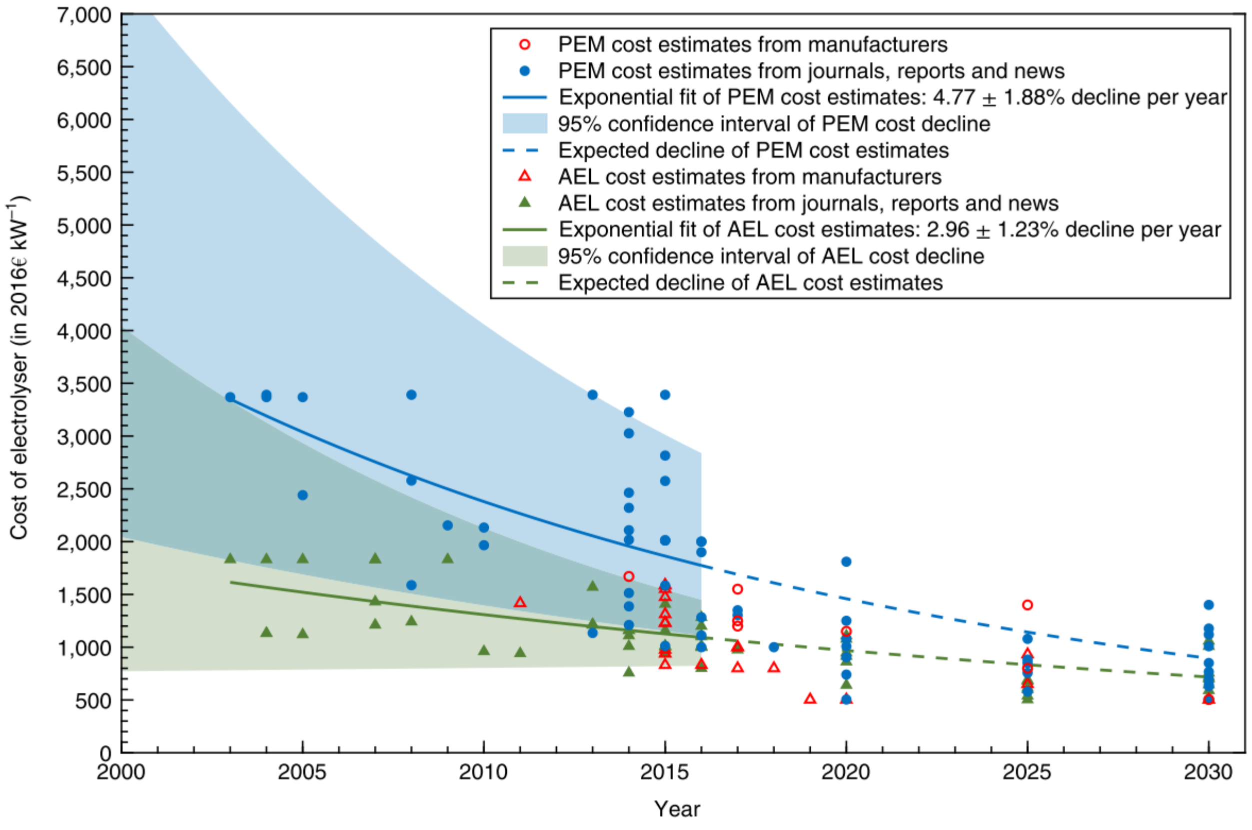
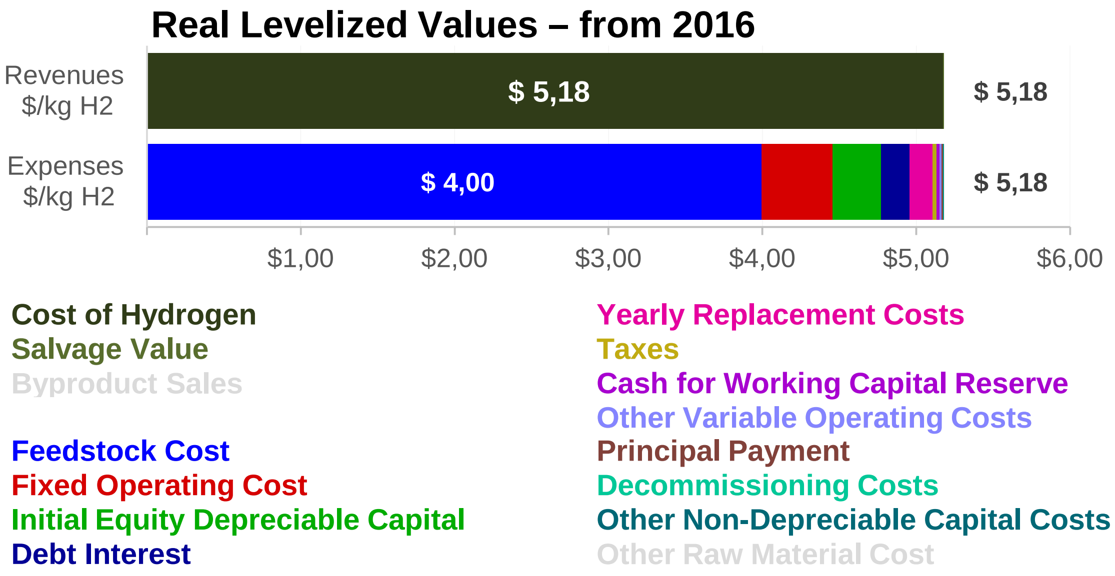


Fig. 2 | Cost of electrolyser technologies for PtG application. Cost data are from multiple sources for alkaline electrolysis (AEL) and PEM electrolysis (see Methods for details).

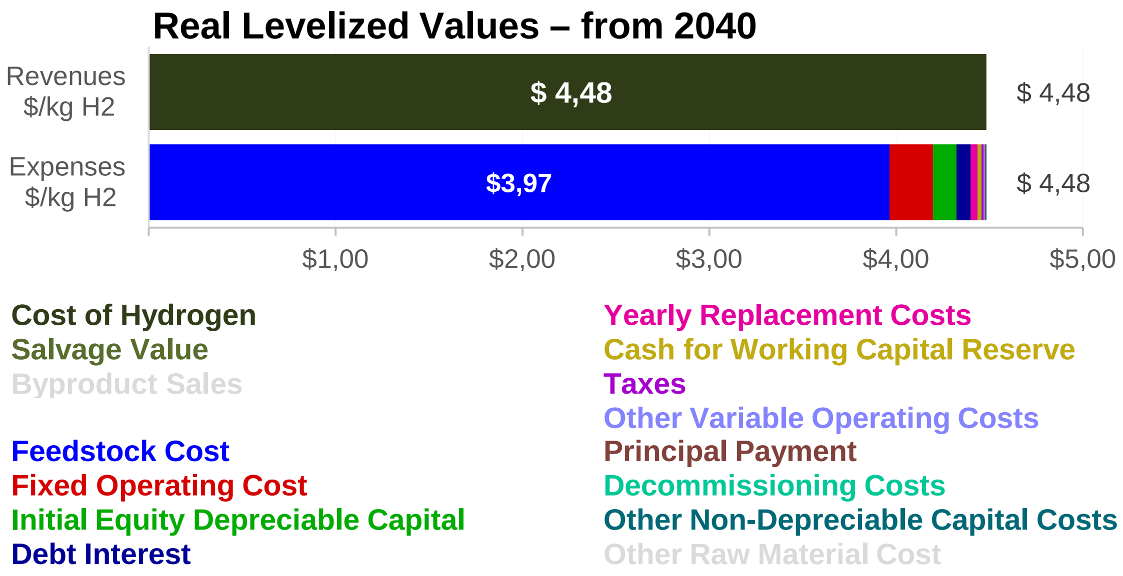
[1] G. Glenk and S. Reichelstein, "Economics of converting renewable power to hydrogen," *Nat. Energy*, vol. 4, no. 3, pp. 216–222, Mar. 2019.

Breakdown of hydrogen from electrolysis (PEM)
- Increased share of cost from electricity

900 $/kW



400 $/kW



- Feedstock cost is dominating the cost of hydrogen production from electrolysis
  - The cost of electricity consumption
  - Going to be even more dominating in the future due to reduced investment cost
- Key to reducing hydrogen production costs is to reduce the electricity price

Reducing cost of renewable energy technologies

- Onshore wind power

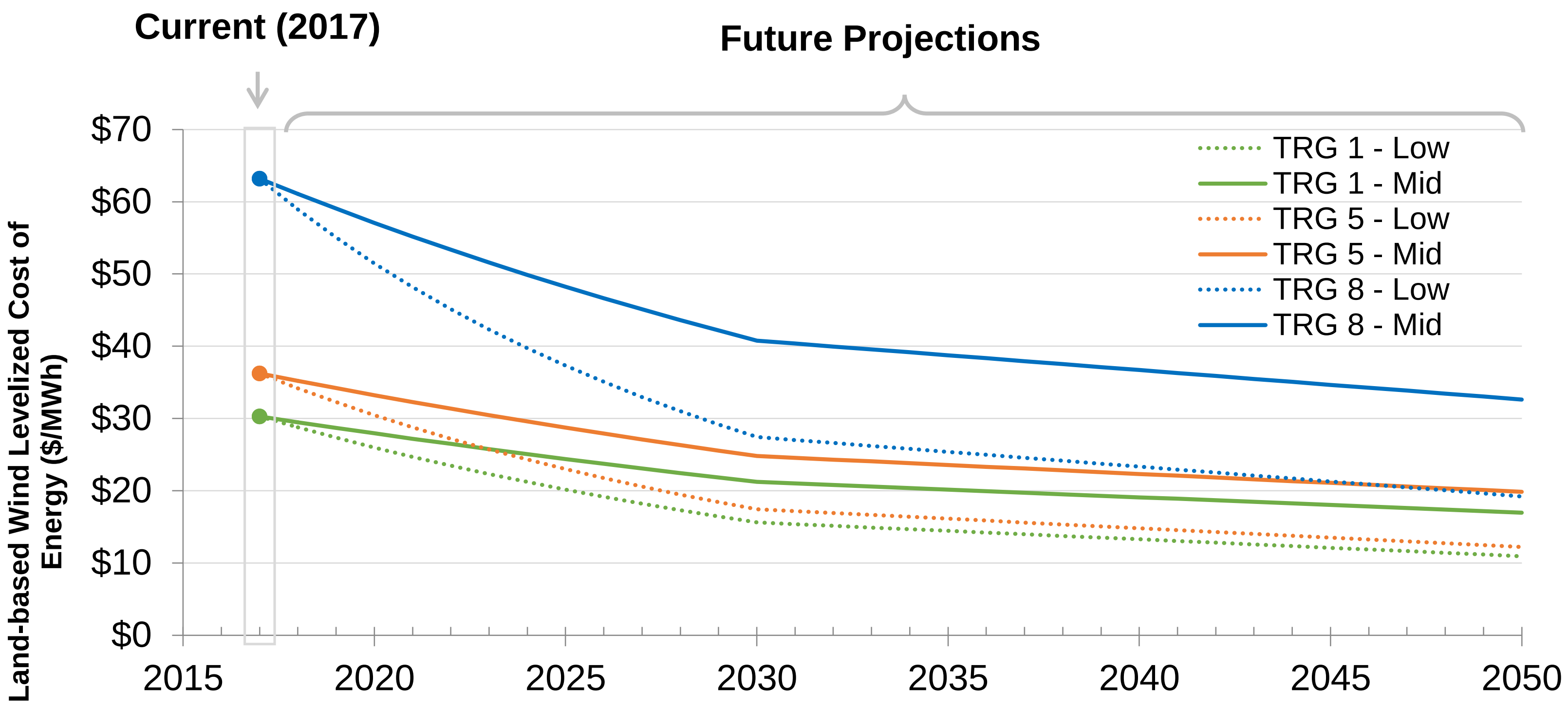


Fig: LCOE from wind power for wind resources by quality, high to low (1-10)

- Levelized cost of energy (LCOE) for onshore wind by 2050
  - Mid scenario: reduction of 35-45 %
  - Low scenario: reduction of 65-70 %

Reducing cost of renewable energy technologies

- Utillity-scale solar power

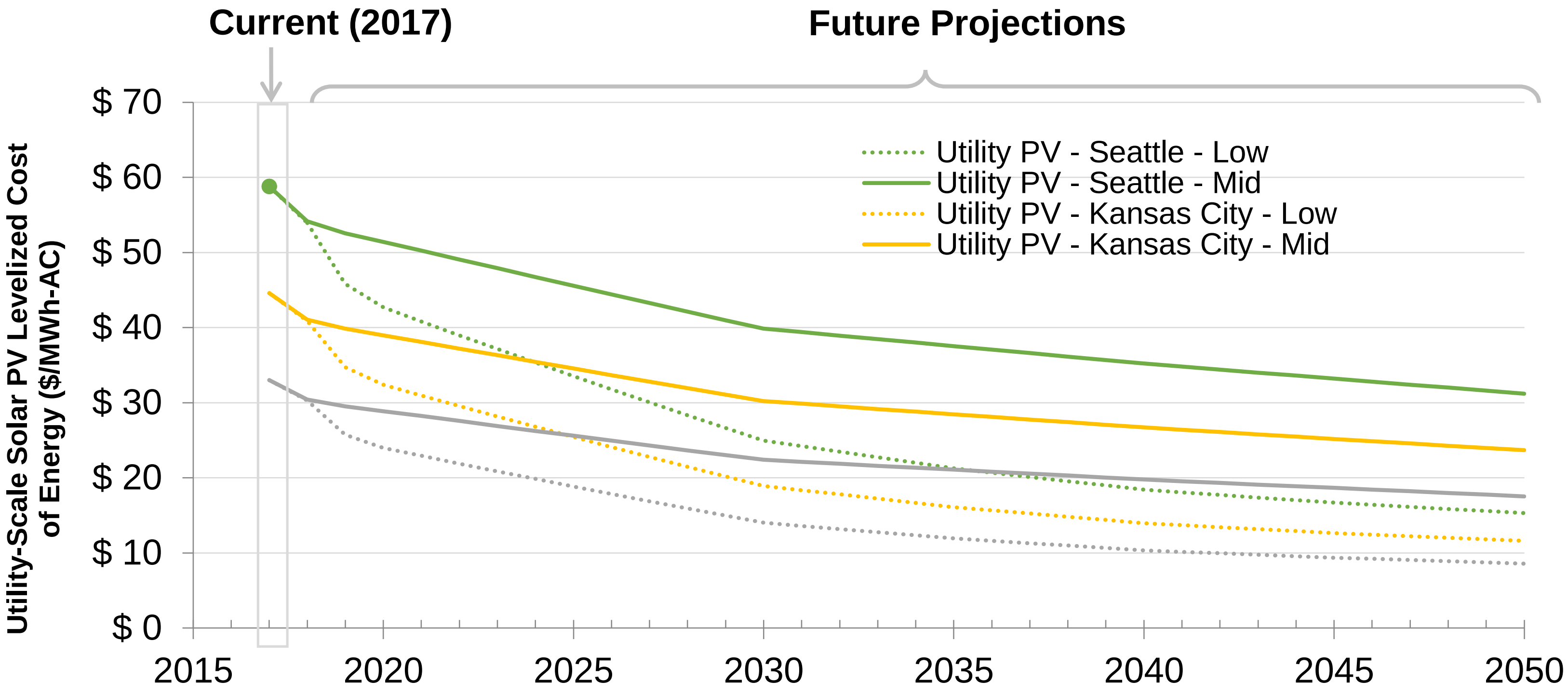


Fig: LCOE from wind power for wind resources by US city

- Levelized cost of energy for utility-scale solar by 2050
  - Mid scenario: reduction of 50 %
  - Low scenario: reduction of 70-75 %

Storage is needed to balance renewable variability

- Electricity is traditionally produced and consumed at the same time
- Electricity production from renewables cannot be controlled efficiently – thus we need storage!
- Different options for energy storage:
  - Hydro power – storing energy in water reservoirs
  - Batteries – goes well with solar
  - Flexible hydrogen production – storage on the demand side

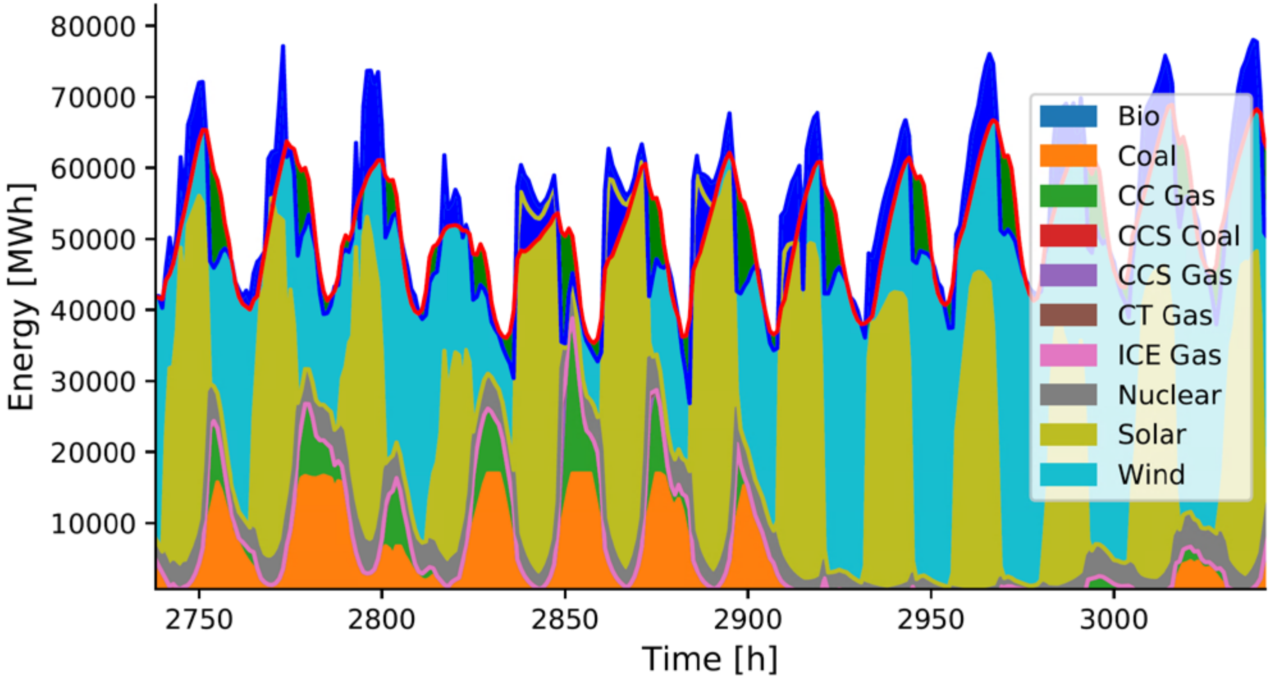


Fig: Electricity production by source, excess electricity is stored (dark blue) in batteries during peak hour and discharged (dark green) when needed to meet the electric demand (red line).

Energy storage can be provided by flexible hydrogen production

- Price fluctuations need to be large for hydrogen to be profitable as electricity storage, high prices must be 2X low price due to losses
- Hydrogen operate as a flexible demand by over sizing the electrolysis and adding hydrogen storage tanks
  - Hydrogen can be used to electrify and reduce emissions in sectors that is hard to electrify directly – such as several industrial processes, ships and trucks
  - Cheaper than batteries for large amounts of energy
  - Suitable to compliment wind power as there can be longer periods without significant electricity production

Using levelized cost of energy (LCOE) does not give a good estimate of the cost of electrolytic hydrogen

- Using LCOE in analysis does not take into account when electricity is used or produced
- Major cost reductions are gained from using electricity from the grid at the right time
  - Mismatch between production and consumption is a central issue when power systems have high shares of renewables and lead to periods with low prices
  - Transmission constraints also contribute to price fluctuations
  - Hydrogen storage can help to mitigate these issues and have to be included in the calculations

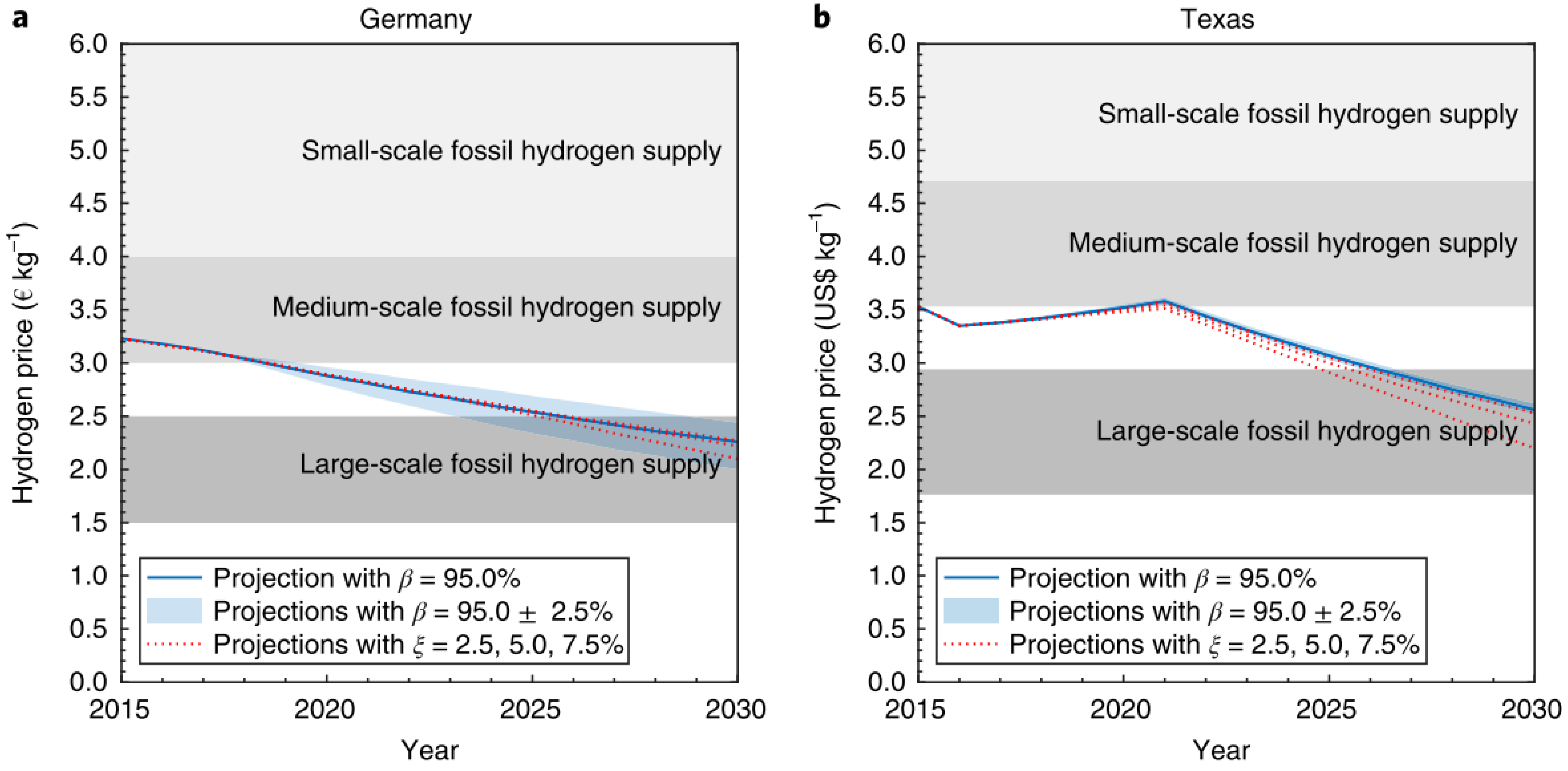


Fig. 3 | Prospects for renewable hydrogen production. a,**b**, The break-even price of renewable hydrogen for Germany (**a**) and Texas (**b**) relative to the benchmark prices for fossil hydrogen supply.

- Study of hydrogen production from wind power shows that hydrogen production from renewables can be on the level of fossil sources for large scale applications within the next decade
- Wind is used to supply electricity demand or produce hydrogen
- Can be even lower if hydrogen storage or producing hydrogen from grid energy is included

[1] G. Glenk and S. Reichelstein, “Economics of converting renewable power to hydrogen,” *Nat. Energy*, vol. 4, no. 3, pp. 216–222, Mar. 2019.

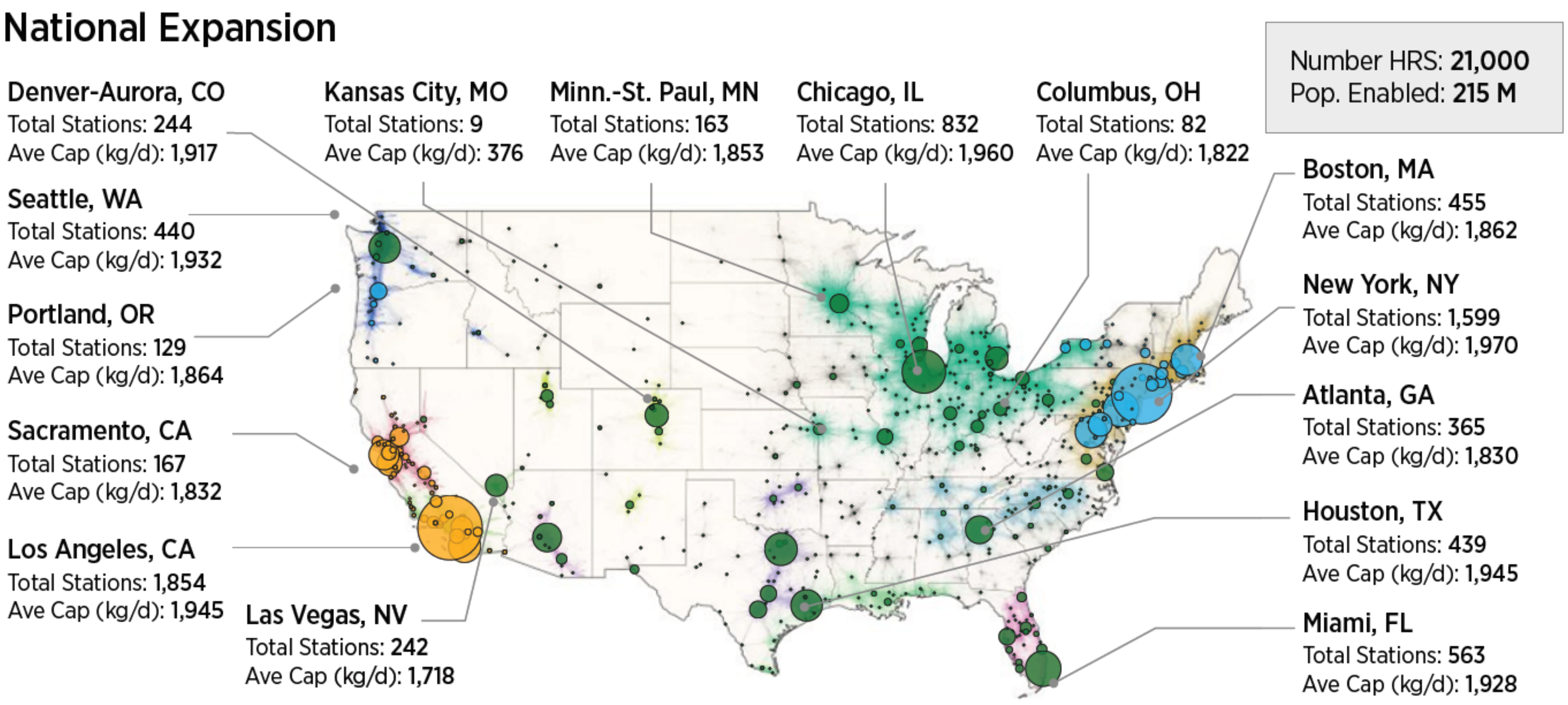


Figure 13. Number of stations and average capacity for select urban areas in 2050

Source: NREL

- Scenario for hydrogen demand in 2050 [2]
- Based on adoption of fuel-cell vehicles
- Texas is the most promising state in US for hydrogen production from renewable energy sources

[2] J. Z. and S. E. Melaina, M., B. Bush, M. Muratori, “National Hydrogen Scenarios: How Many Stations, Where, and When?,” no. October, p. 36, 2017.
[3] J. I. Levene, M. K. Mann, R. M. Margolis, and A. Milbrandt, “An analysis of hydrogen production from renewable electricity sources,” *Sol. Energy*, vol. 81, no. 6, pp. 773–780, Jun. 2007.

Hydrogen production in Texas - 2050

- We model the power system in Texas using 13 buses [3]
- Currently the system is largely based on natural gas (> 50 % of installed capacity)
- Recent years there has been a massive development of wind power
- Massive potential for further development of wind and solar in the north-west
- Load and population mainly in east
  - Estimated electric load for 2050 of 492 TWh/yr
  - Assumption: 1 % annual load growth from 2016
- Hydrogen load scenario of about 23.5 TWh/yr
  - 5% of electric load

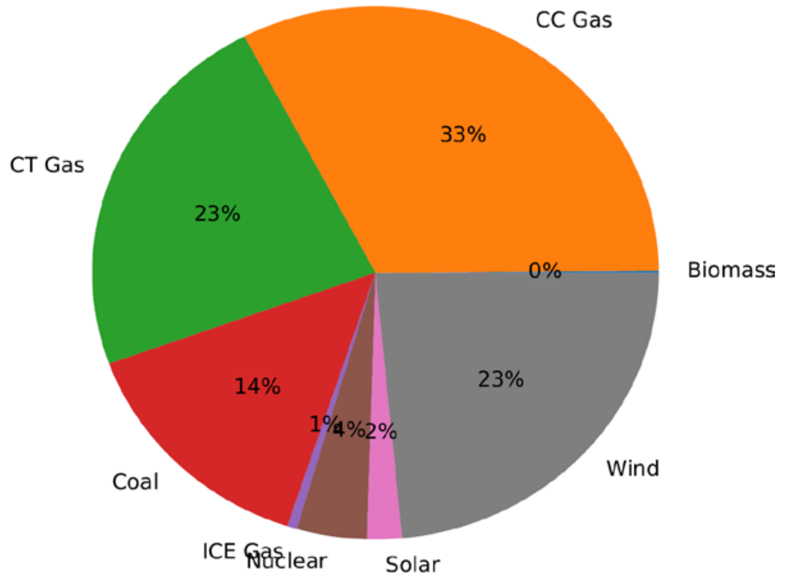


Fig: Aggregated representation of the electricity system in Texas using 13 buses (nodes). Transmission lines are colored by capacity in MW. [3]

[4] M. Majidi-Qadikolai and R. Baldick, “Stochastic Transmission Capacity Expansion Planning with Special Scenario Selection for Integrating n-1 Contingency Analysis,” *IEEE Trans. Power Syst.*, vol. 31, no. 6, pp. 4901–4912, 2016.

Sources of electricity production

- In 2050, electricity production in Texas is largely renewable based
- The renewable share grows with increasing CO_2-prices
- All coal will be faced out if a CO_2-price of 30 $/ton is implemented
- 150 $/ton CO_2 is needed to get electricity from natural gas with CCS

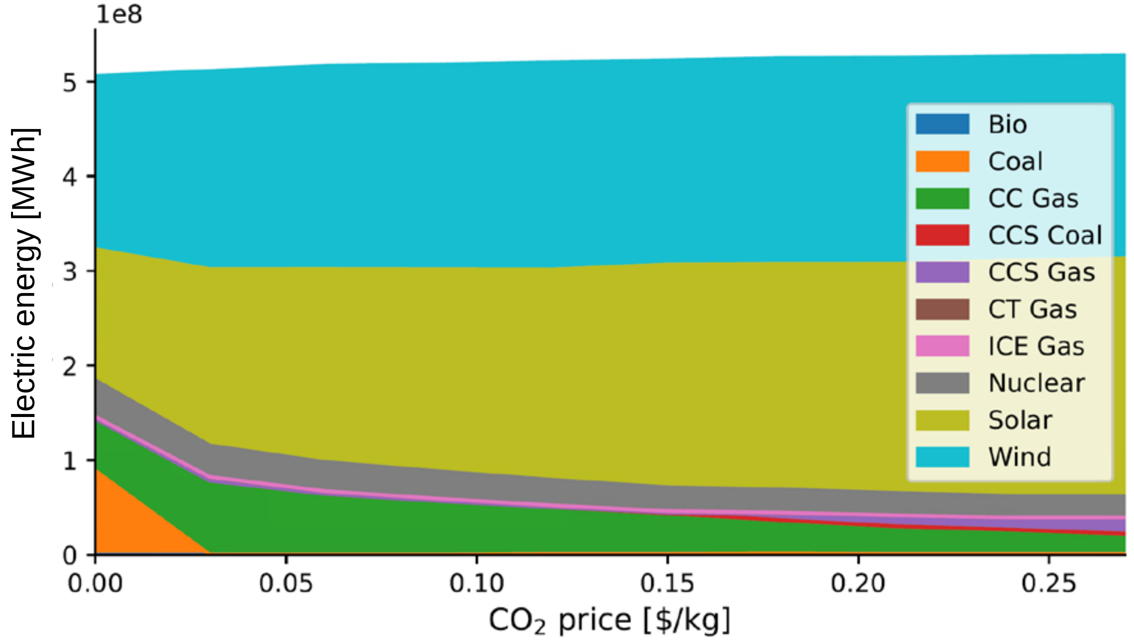


Fig: Electric energy from different sources as CO_2 prices increase

Hydrogen source by CO_2 price for H_2 demand cases

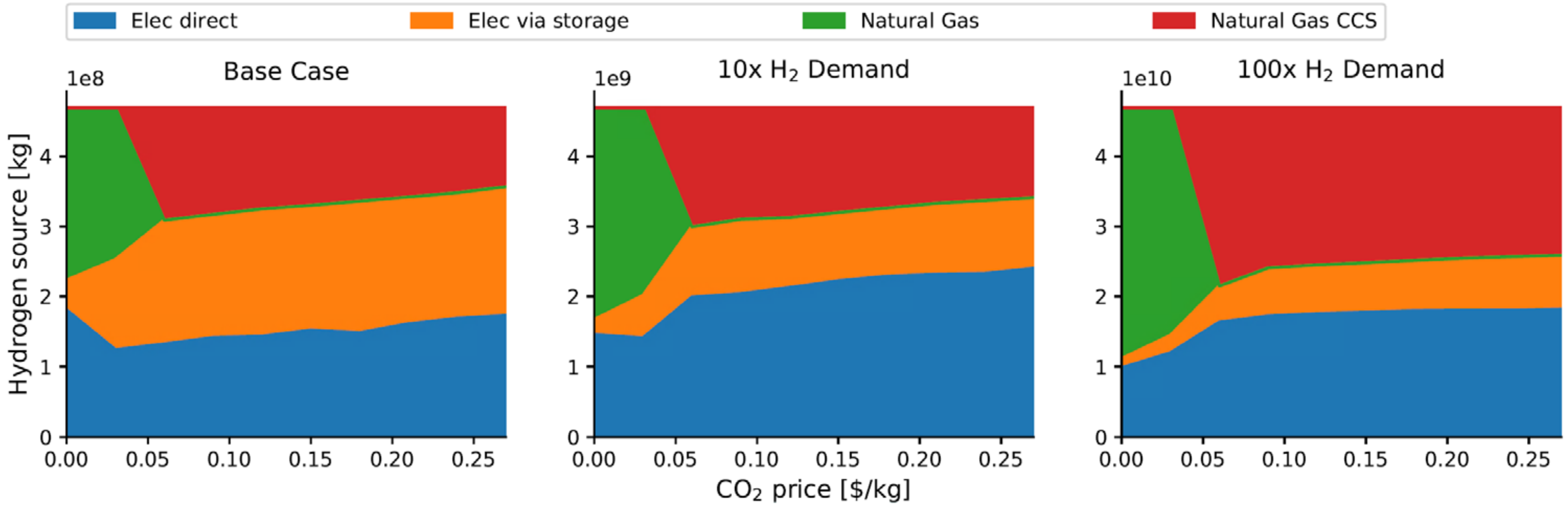


Fig: The source of hydrogen in the system, for increasing CO_2-prices and different hydrogen loads

- We run the model for the base case, but also when the hydrogen demand is scaled by 10 and 100 times
- At a CO_2-price of 60 $/ton hydrogen from natural gas includes CCS
- Hydrogen from electrolysis includes significant amounts of storage
  - The amount of storage increase with the CO_2-price and the integration of renewables

Relative CO2 emissions by CO2 price

- Total and by source

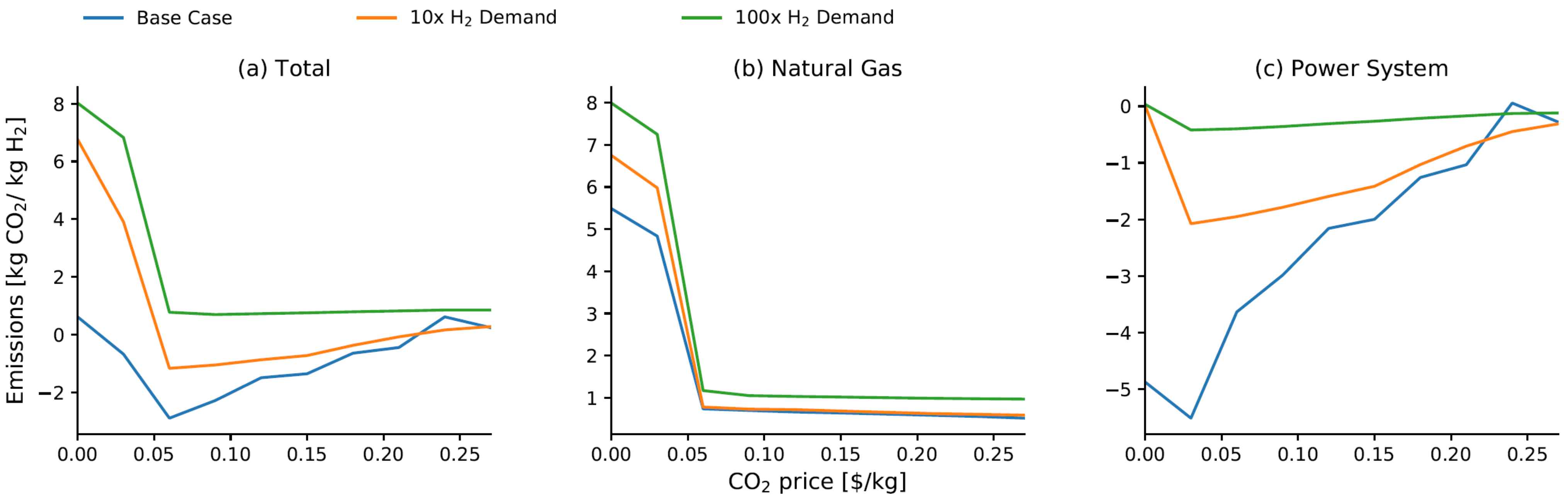


Fig: Total, natural gas and electricity related CO_2-emissions from hydrogen production

- We run the model without any hydrogen production and use those emissions as a baseline
- The total emissions related to hydrogen production are negative for the base case
- Emissions drop a lot for a CO_2-price of 60 $/ton as natural gas based hydrogen include CCS
- The emissions from the power system is negative for all cases as flexible hydrogen production replaces the flexibility otherwise provided from natural gas

Cost of hydrogen production

- The hydrogen production cost is in the lower range of current large scale costs
- With increasing CO_2-prices the hydrogen production cost increase until CCS is used for hydrogen from natural gas
- For CO_2-prices above 60$/ton, only the highest demand case shows a increasing price
  - A larger share of the hydrogen is from natural gas with CCS and has some emissions
- The hydrogen cost in the base case decrease for CO_2-prices above 60$/ton
  - The hydrogen is largely renewable based
  - Flexible hydrogen production helps mitigate electricity from natural gas with growing shares of renewables

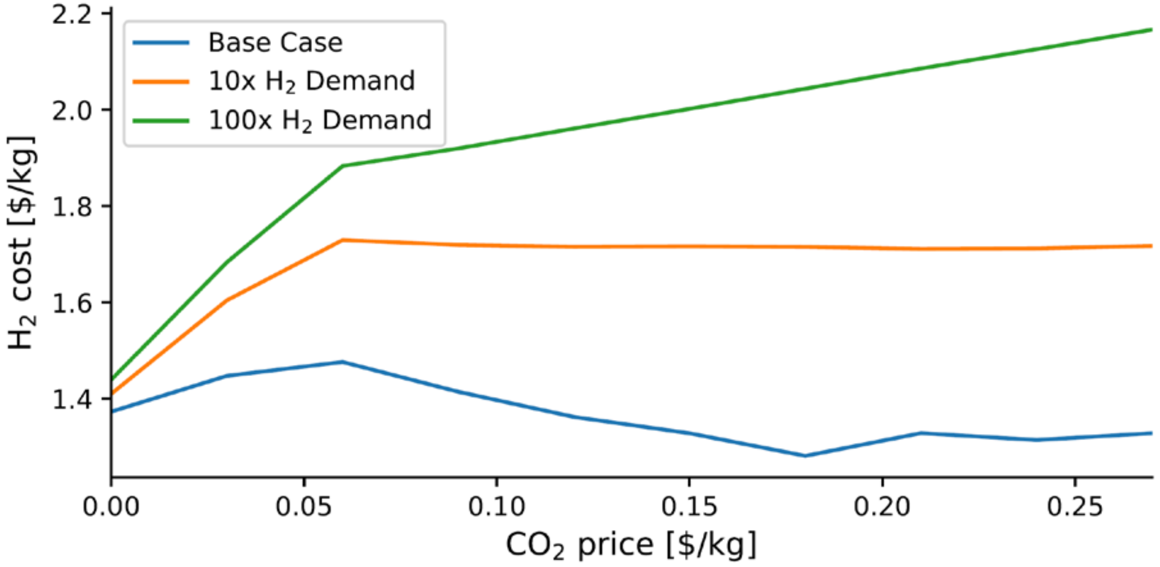


Fig: Weighted average marginal cost of hydrogen production in the system different CO_2-prices

Conclusions

- Reducing the electricity price is key for making electrolytic hydrogen competitive with natural gas
- Dropping costs of renewable energy technologies and the need for storage/flexibility reduced the electricity related costs significantly towards 2050
- The case study of Texas shows that:
  - Equal amounts of hydrogen is produced from natural gas and electricity in the base case with no CO_2-price
  - The share of hydrogen from electricity increase with increasing CO_2-prices
  - The share of hydrogen from natural gas increase with the quantity of hydrogen produced
  - Hydrogen storage replace the flexibility provided by natural gas based electricity and helps reduce emissions in the electricity sector
  - Hydrogen production from natural gas include CCS from a CO_2-price of 60 $/ton
  - Hydrogen cost increase with CO_2-price until 60 $/ton, for higher CO_2-prices the cost is dependent on the load case

Selected references

1. G. Glenk and S. Reichelstein, “Economics of converting renewable power to hydrogen,” *Nat. Energy*, vol. 4, no. 3, pp. 216–222, Mar. 2019.
2. J. Z. and S. E. Melaina, M., B. Bush, M. Muratori, “National Hydrogen Scenarios: How Many Stations, Where, and When?,” no. October, p. 36, 2017.
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4. M. Majidi-Qadikolai and R. Baldick, “Stochastic Transmission Capacity Expansion Planning with Special Scenario Selection for Integrating n-1 Contingency Analysis,” *IEEE Trans. Power Syst.*, vol. 31, no. 6, pp. 4901–4912, 2016.

Thanks for the attention!

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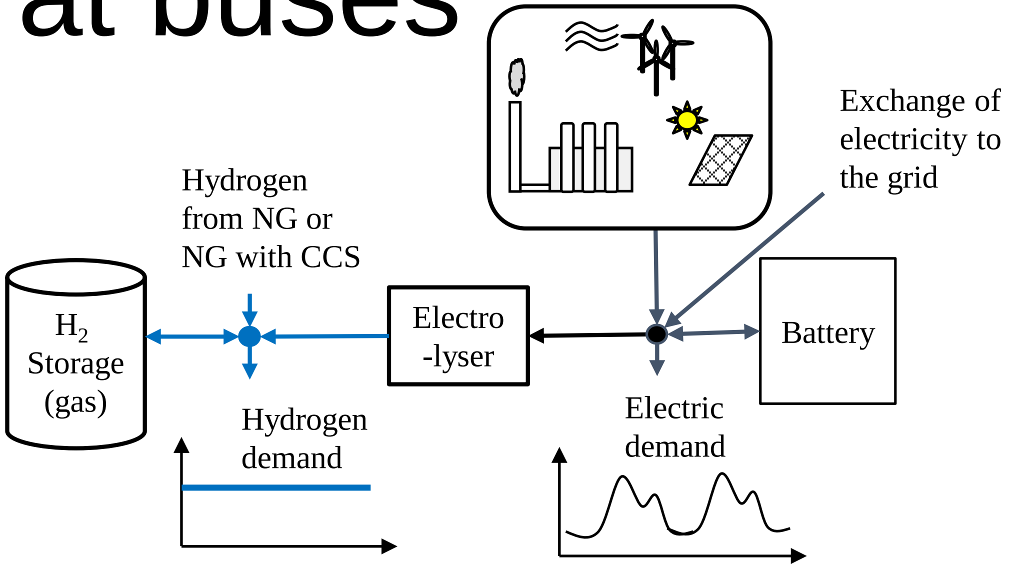
Model characteristics and assumptions

- Capacity expansion model – investment in new capacity and operations
  - Includes investment, fixed, variable and fuel costs
  - CO2 price included and used for marginal analysis
- Modelled as one big LP for a year with annualized investment costs
- Power balances for both electricity and hydrogen
- Linearized power flow representation of the transmission system (DC power flow)
- Hydrogen is produced locally by electricity or imported from centrally located natural gas reformation plants
- Modelled in python/PYOMO and solved using Gurobi Optimization solver

Energy balance at buses



Electricity balance

$$\sum_{i \in G} p_{ti} + p^{imp} - p^{exp} + \eta^{out} p^{disch} - \eta^{in} p^{ch} = D_{ti} + \eta^{elec} h^{dircet} + \eta^{storage} h^{storage}$$

Hydrogen balance

$$h^{dircet} + h^{h2\ disch} + h^{NG} + h^{NG\ CCS} = H_{ti}$$

- Two energy balances: Electricity and hydrogen
- Investment in generation units, transmission, electrolysis and storage
- Storage in forms of hydrogen gas or battery
- Battery is divided into power and energy investment decisions
  - Similar for hydrogen with storage tanks and electrolyzer