LUT University

LAND OF THE CURIOUS

8.11.2022

Technological Perspectives on Hydrogen Economy

Jero Ahola, D.Sc., Professor, Energy Efficiency
Department of Electrical Engineering
LUT University
email: jero.ahola@lut.fi
twitter: @JeroAhola

Net-zero greenhouse gas emissions by 2050

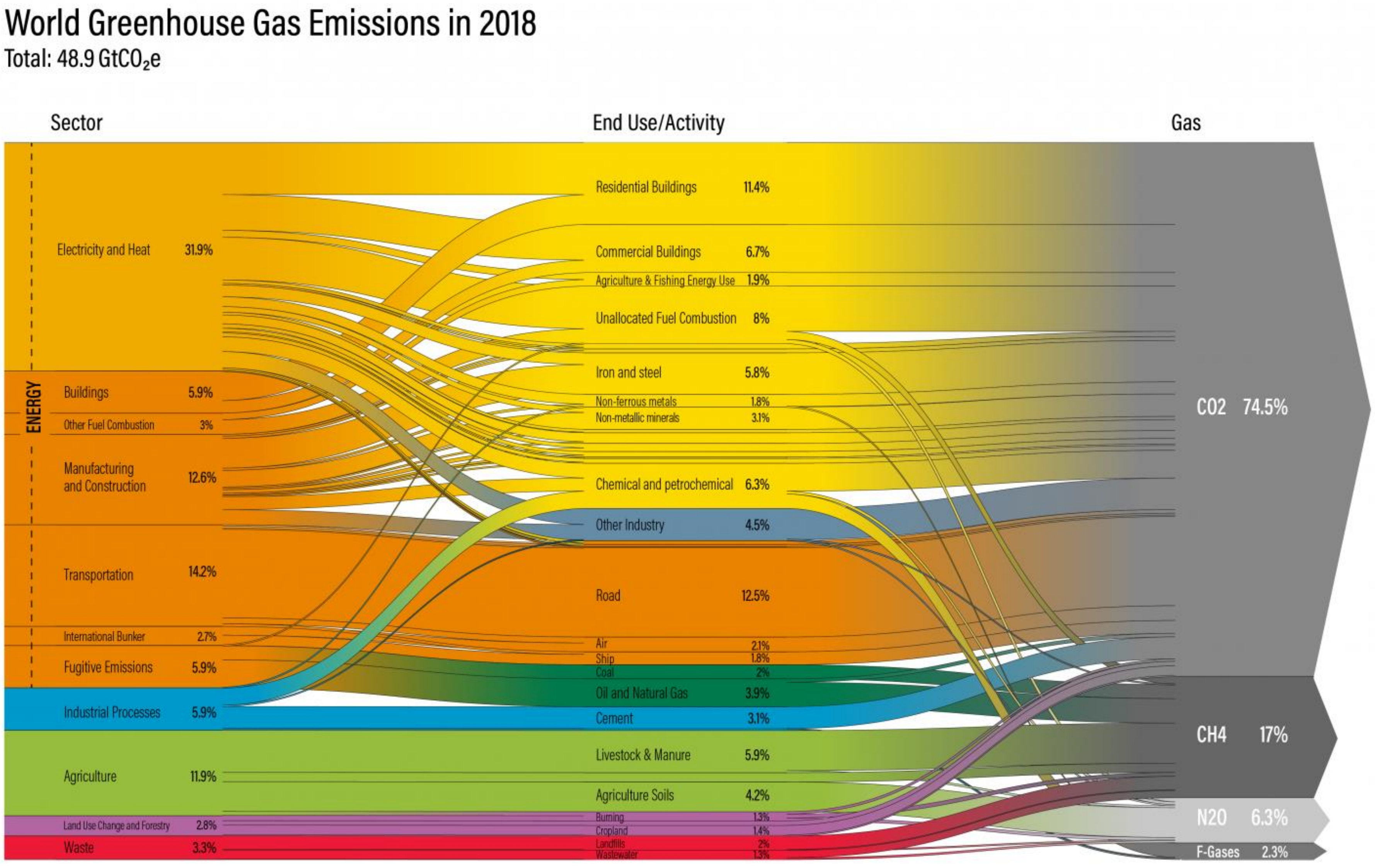
Electricity and heat (32%)

Industry (13%)

Transportation (14%)

Agriculture and land use change (15%)

ENERGIA (73 %)

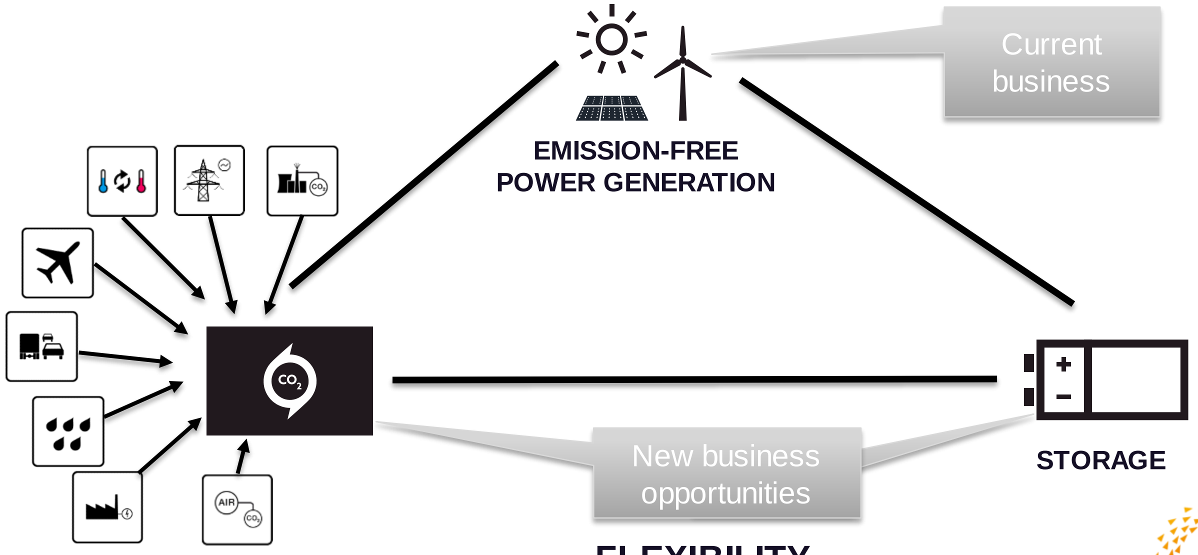


Source: Greenhouse gas emissions on Climate Watch. Available at: https://www.climatewatchdata.org

WORLD RESOURCES INSTITUTE

For < +2 ºC climate goal we have to have net-zero GHG emissions by 2050

Solution: Electrify everything directly or indirectly. This is power-to-X economy. Hydrogen economy is a part of it.



http://www.neocarbonenergy.fi/library/reports/

NEO CARBON ENERGY

Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared to 2030.

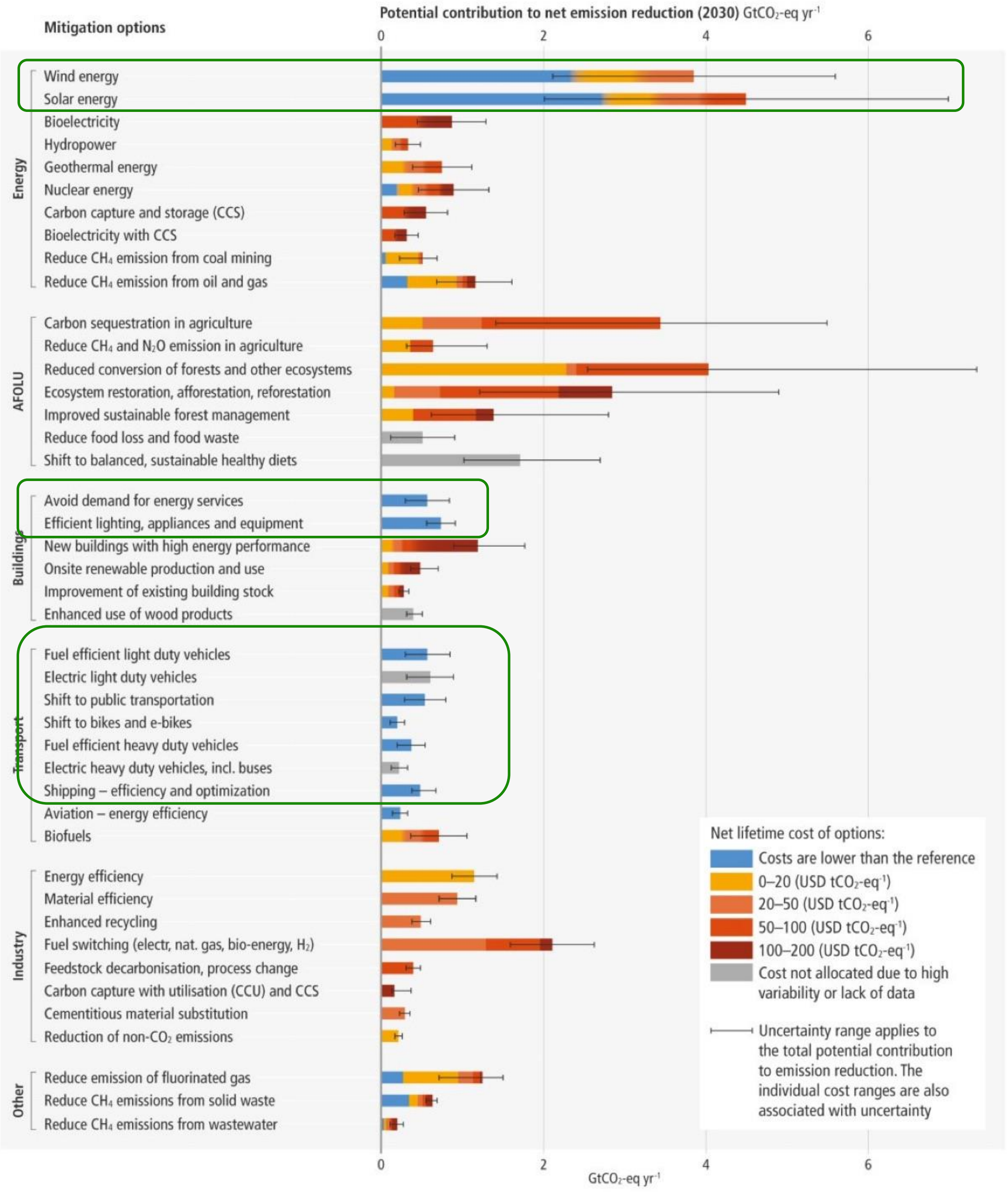


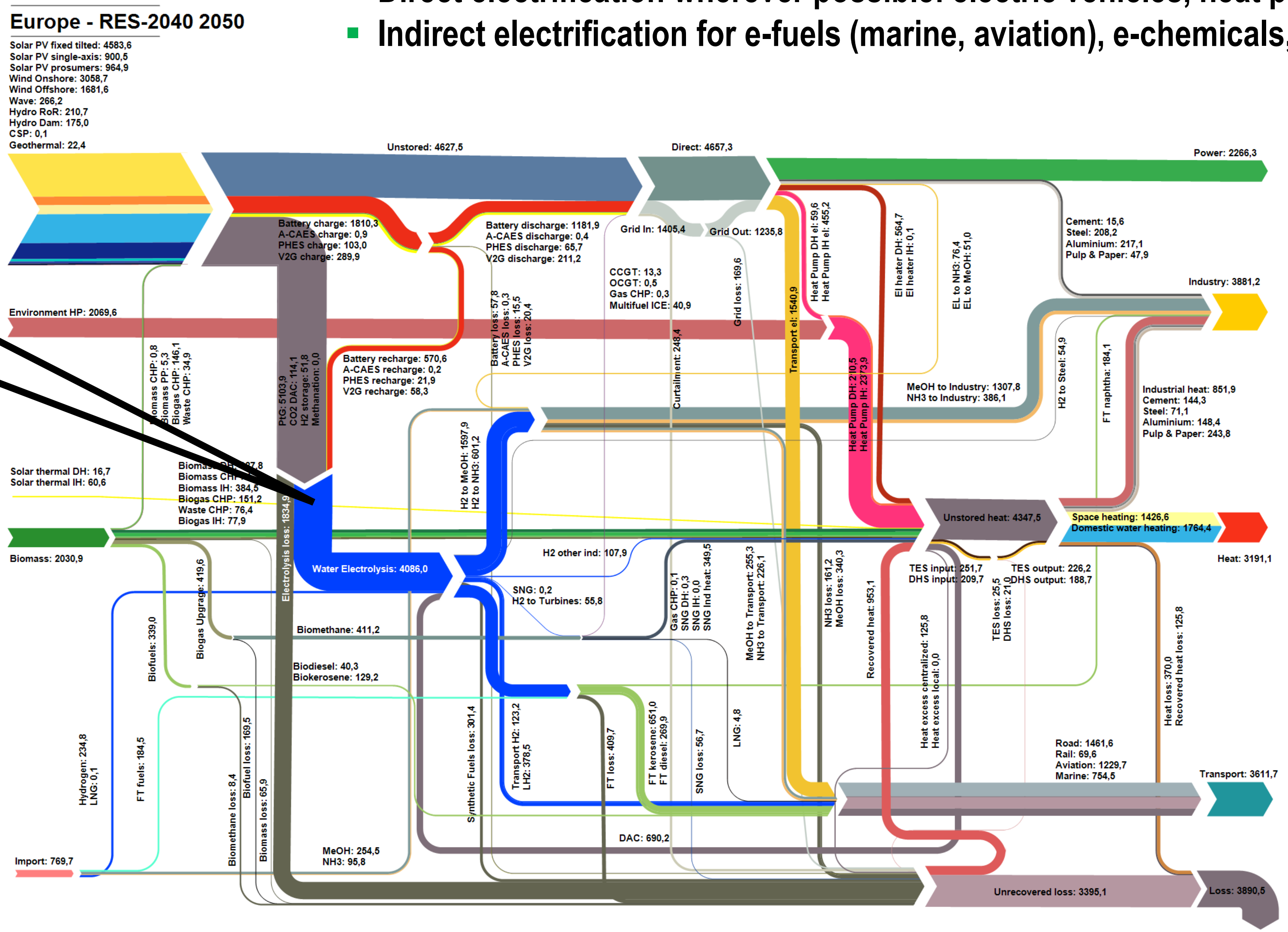
Figure SPM.7: Overview of mitigation options and their estimated ranges of costs and potentials in 2030.

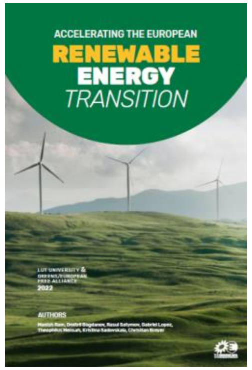
Power-to-X economy on the case of Europe

LUT University

- Zero CO_2 emission low-cost energy system is based on electricity
- Core characteristic of energy in future: Power-to-X Economy
  - Primary energy supply from renewable electricity: mainly solar PV and wind power
  - Direct electrification wherever possible: electric vehicles, heat pumps, desalination, etc.
  - Indirect electrification for e-fuels (marine, aviation), e-chemicals, e-steel; power-to-hydrogen-to-X

Hydrogen economy is a subset of power-to-x - economy





Europe

Source:
[Greens/EFA, 2022](#)

Net-zero emission energy system is possible and it is no more expensive than the current one

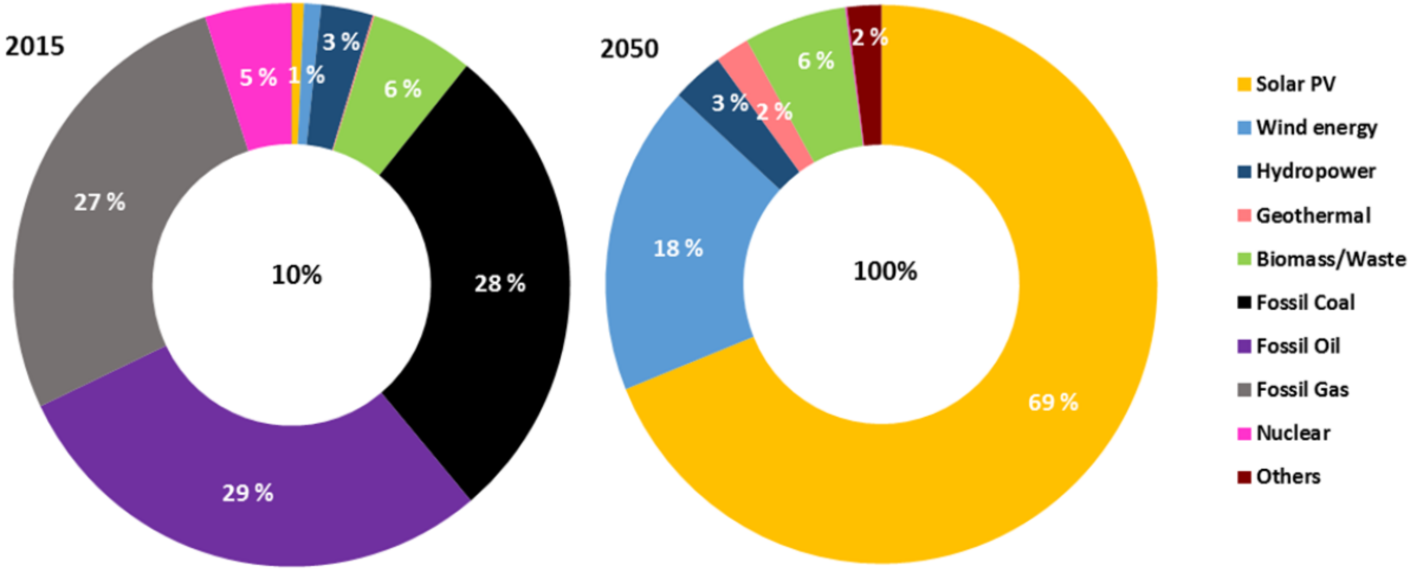
12 APR 2019 RENEWABLES, STUDY, UNCATEGORIZED

New Study: Global Energy System based on 100% Renewable Energy

The new study by the Energy Watch Group and LUT University is the first of its kind to outline a 1.5°C scenario with a cost-effective, cross-sectoral, technology-rich global 100% renewable energy system that does not build on negative CO2 emission technologies. The scientific modelling study simulates a total global energy transition in the electricity, heat, transport and desalination sectors by 2050. It is based on four and a half years of research and analysis of data collection, as well as technical and financial modelling by 14 scientists. This proves that the transition to 100% renewable energy is economically competitive with the current fossil and nuclear-based system, and could reduce greenhouse gas emissions in the energy system to zero even before 2050.

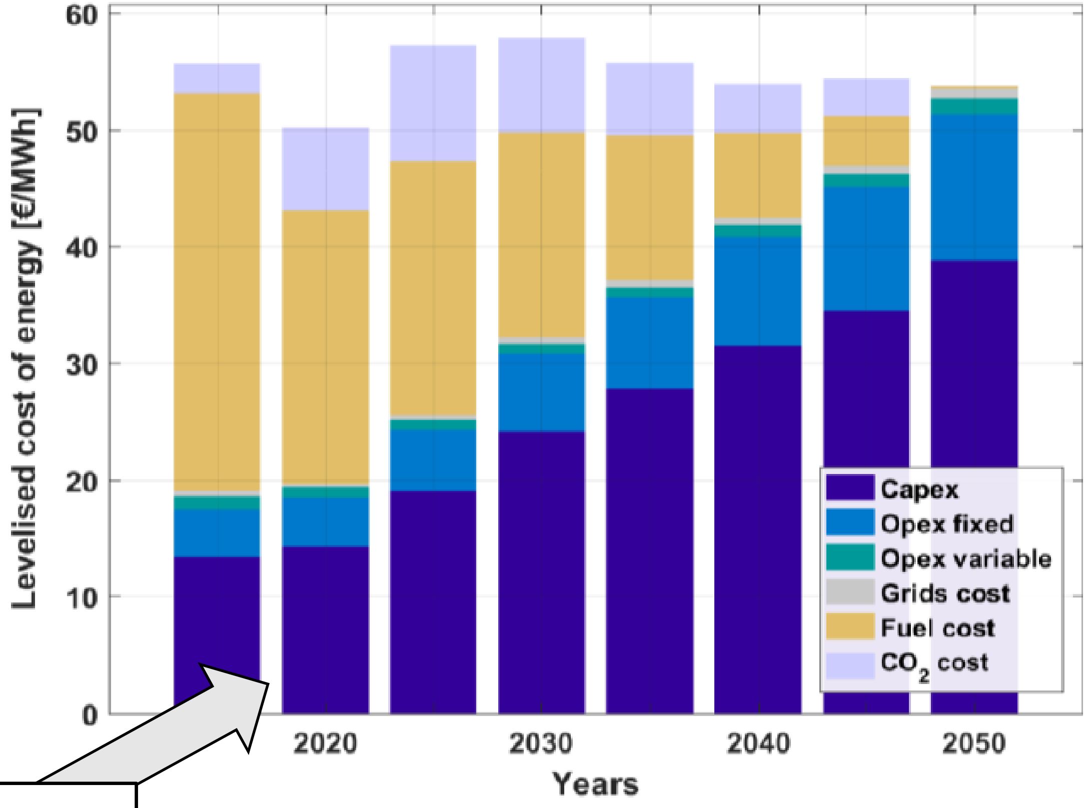
Total Primary Energy Demand Shares

Open your mind. LUT. Lappeenranta University of Technology



Key insights:

- TPED shifts from being dominated by coal, oil and gas in 2015 towards solar PV and wind energy by 2050
- Renewable sources of energy contribute just 22% of TPED in 2015, while in 2050 they supply 100% of TPED
- Solar PV drastically shifts from less than 1% in 2015 to around 69% of primary energy supply by 2050, as it becomes the least cost energy supply source



Source: http://energywatchgroup.org/new-study-global-energy-system-based-100-renewable-energy

Huge technology business opportunity

LUT University

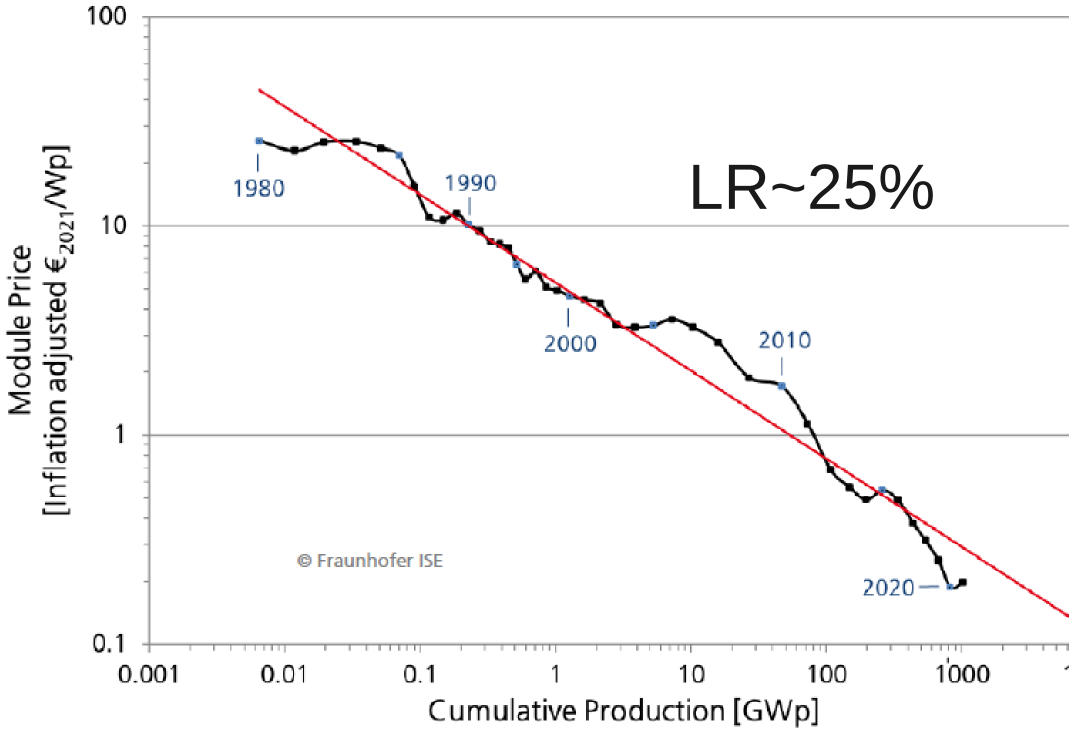
ENERGYWATCHGROUP

Transition from fossil fuels to series produced electricity-based technologies

Learning curves of series produced electrical energy technologies

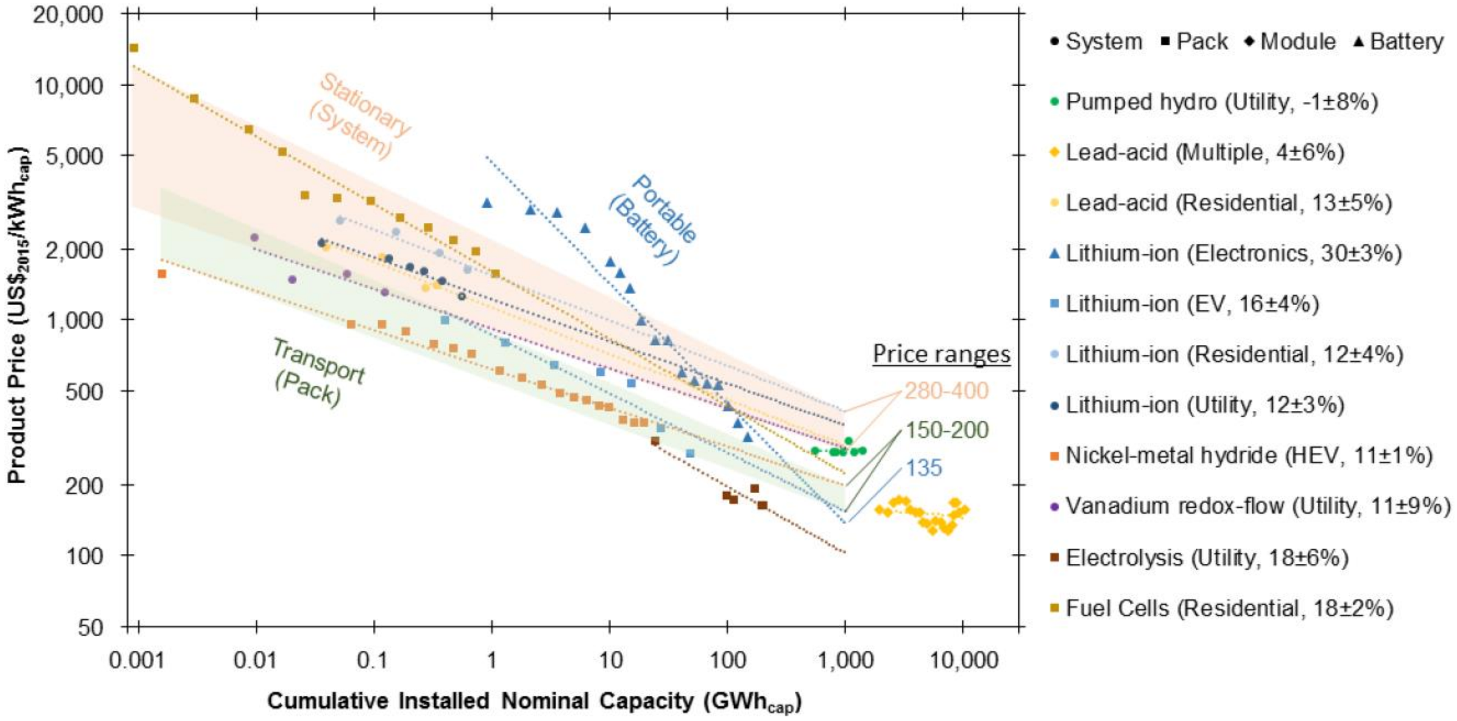
LUT University

Solar PV module learning curve



Source: Photovoltaics Report, Fraunhofer-ISE, Germany, 22.8.2022 https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Electricity storage/conversion technology learning curves

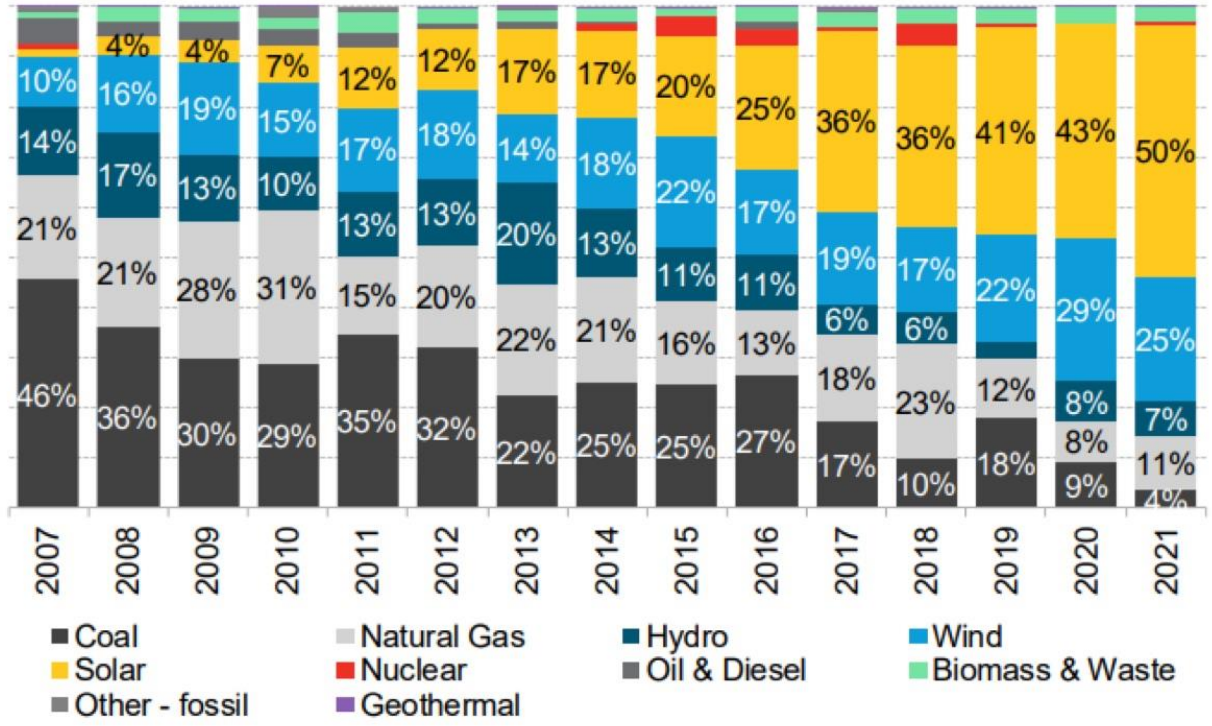


Source: O. Schmidt, A. Hawkes, A. Gambhir & I. Staffell, The future cost of electrical energy storage based on experience rates, Nature Energy volume 2, Article number: 17110 (2017)

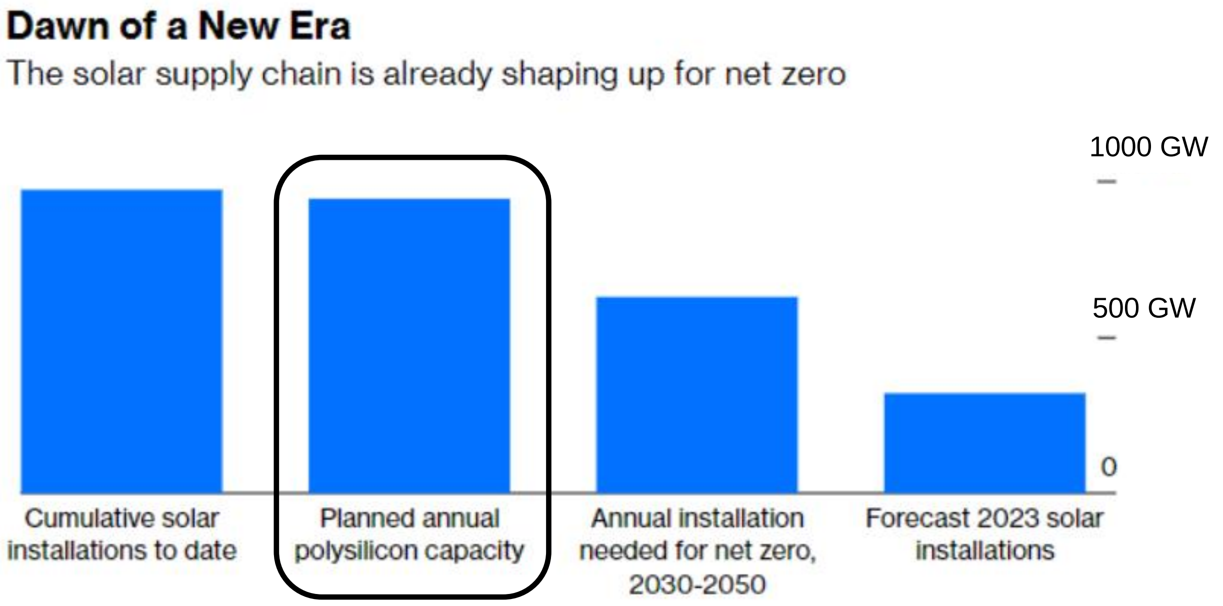
There is no doubt. The energy transition is ongoing.

- Cumulative solar PV installations reached 1 TW in March 2022
- During the next three years potentially additional 1 TW of solar PV capacity will be installed
- After 2025 global PV module manufacturing capacity will reach 1 TW/a

Share of global capacity additions by technology

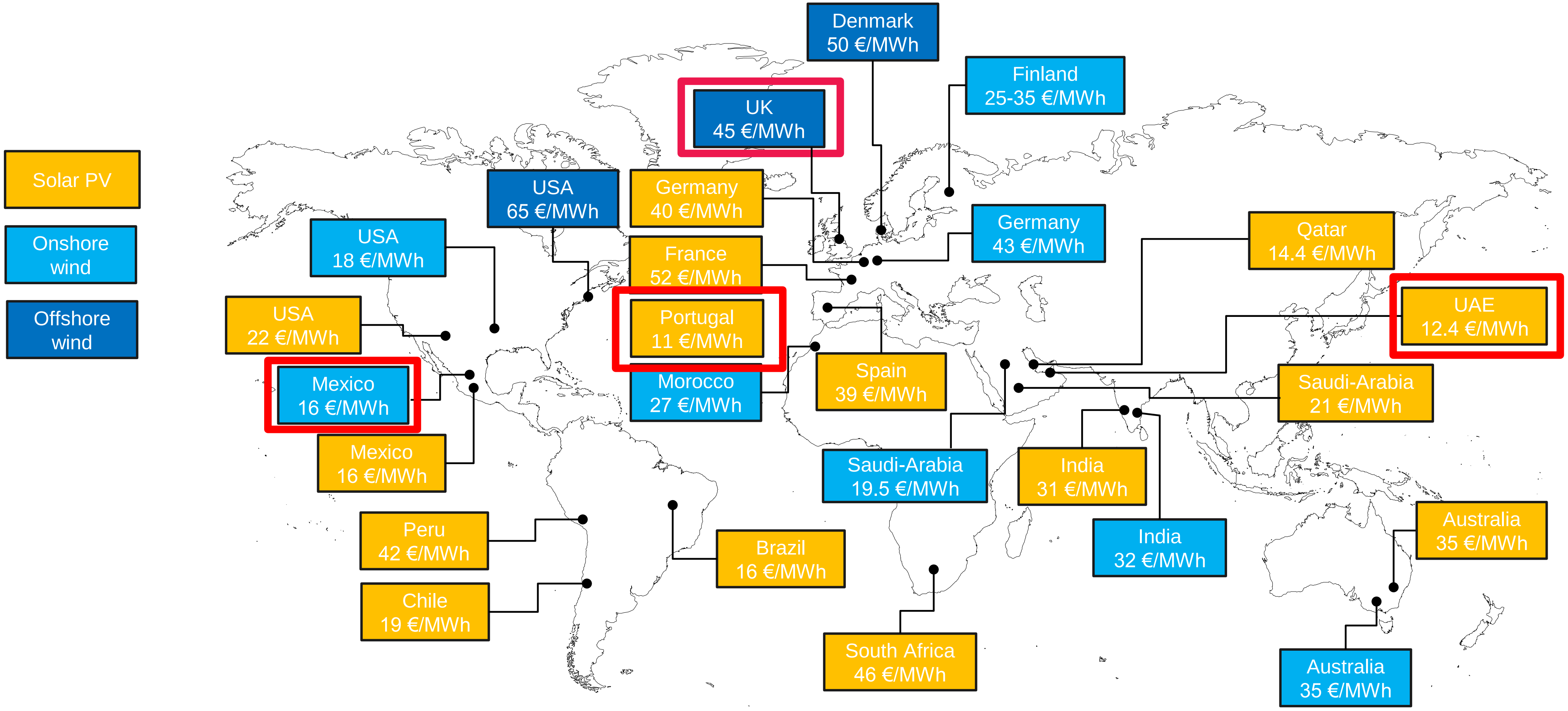


Source: BloombergNEF. Note: Share of global capacity additions excluding retirements.

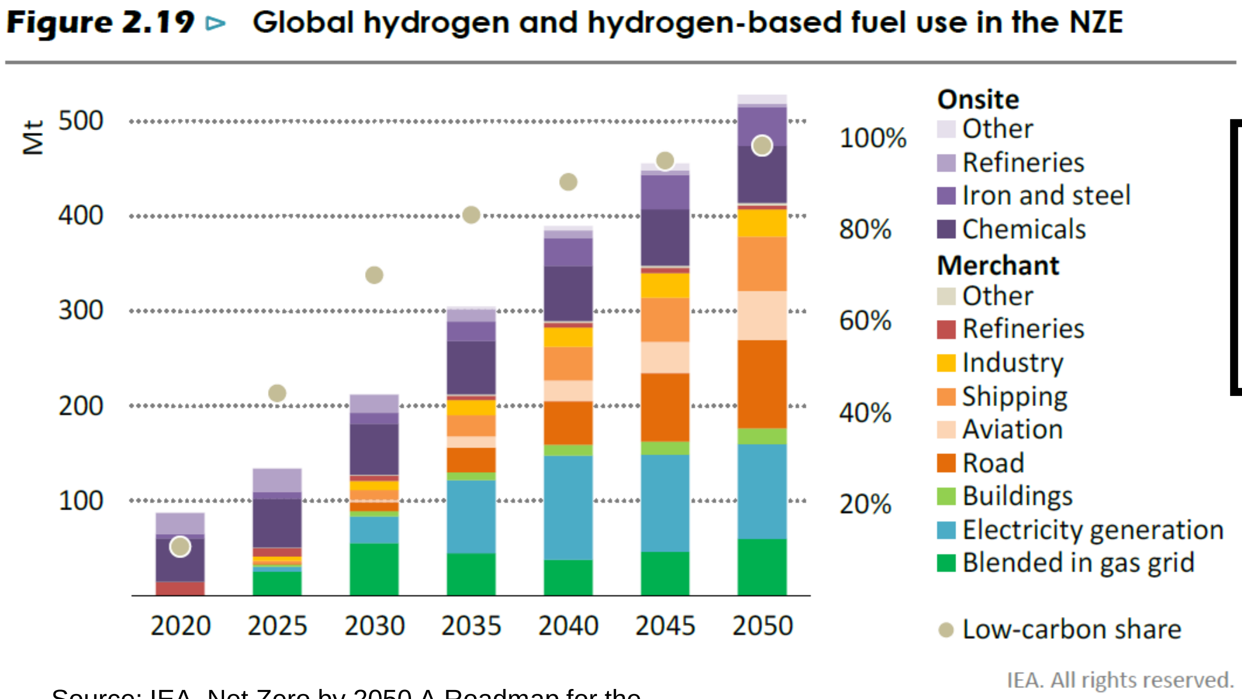


Source: BloombergNEF, International Energy Agency, JinkoSolar

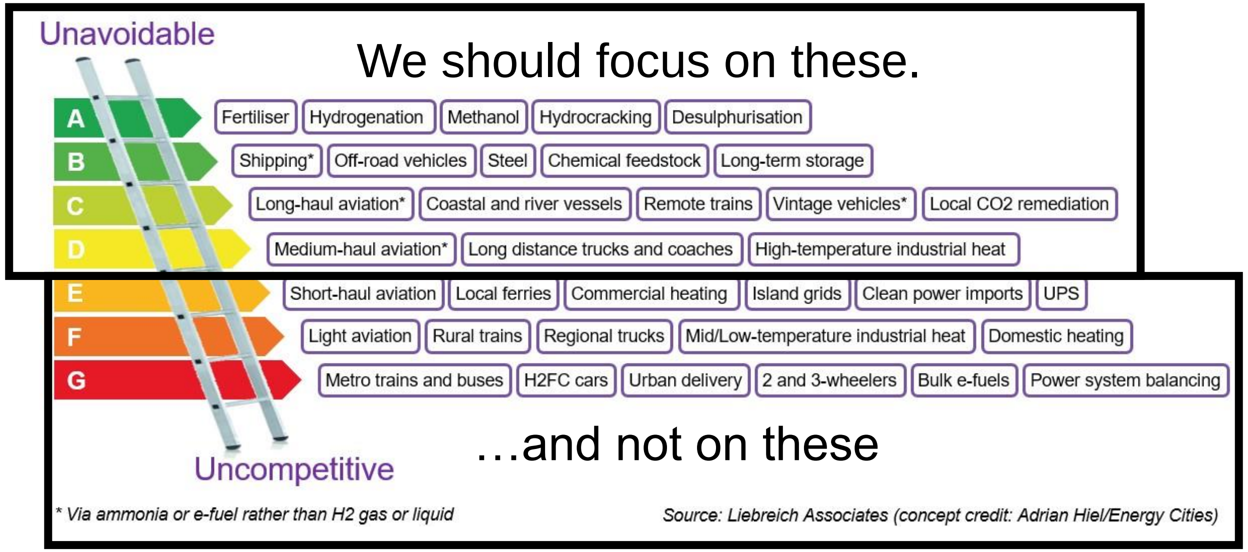
Some solar and wind PPA contract prices 2020->



IEA Net Zero by 2050: Demand of hydrogen

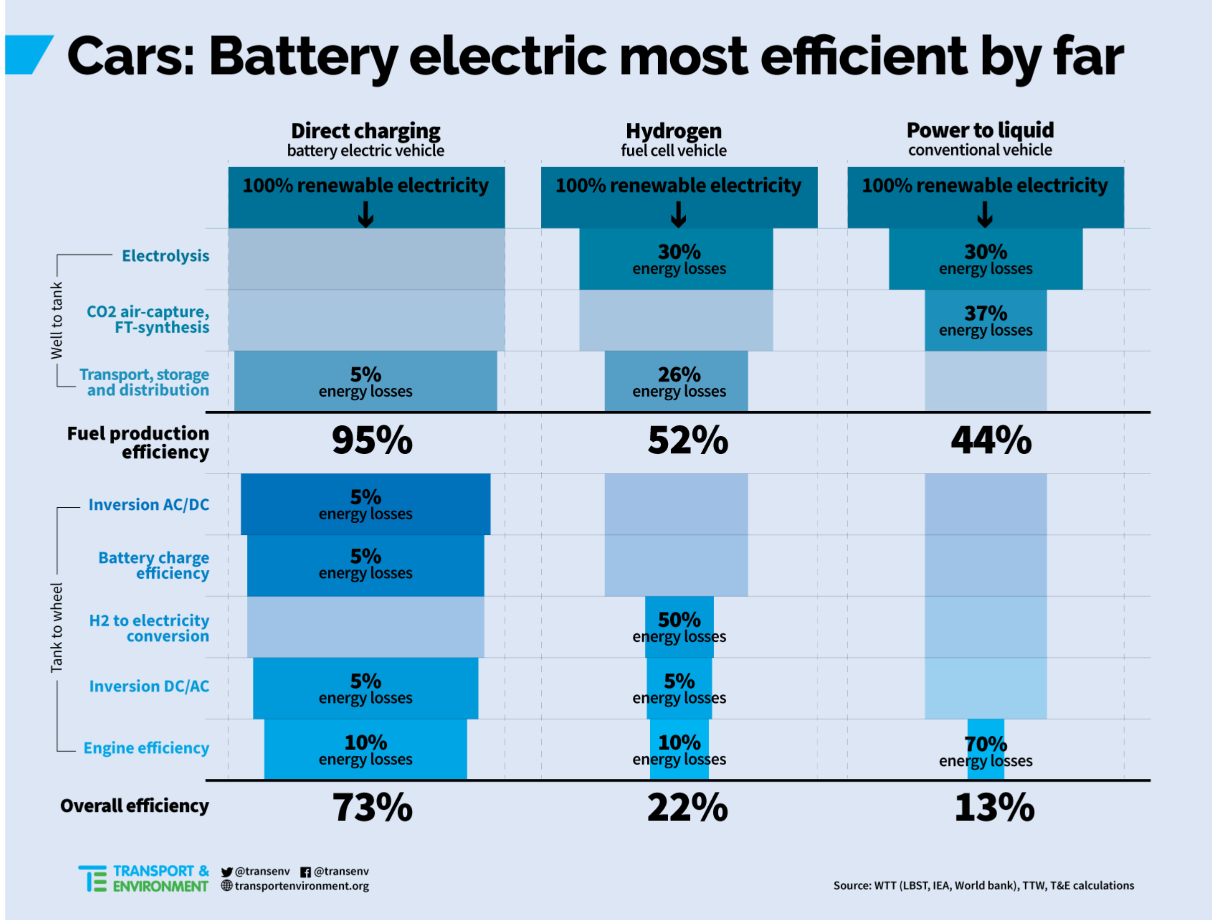


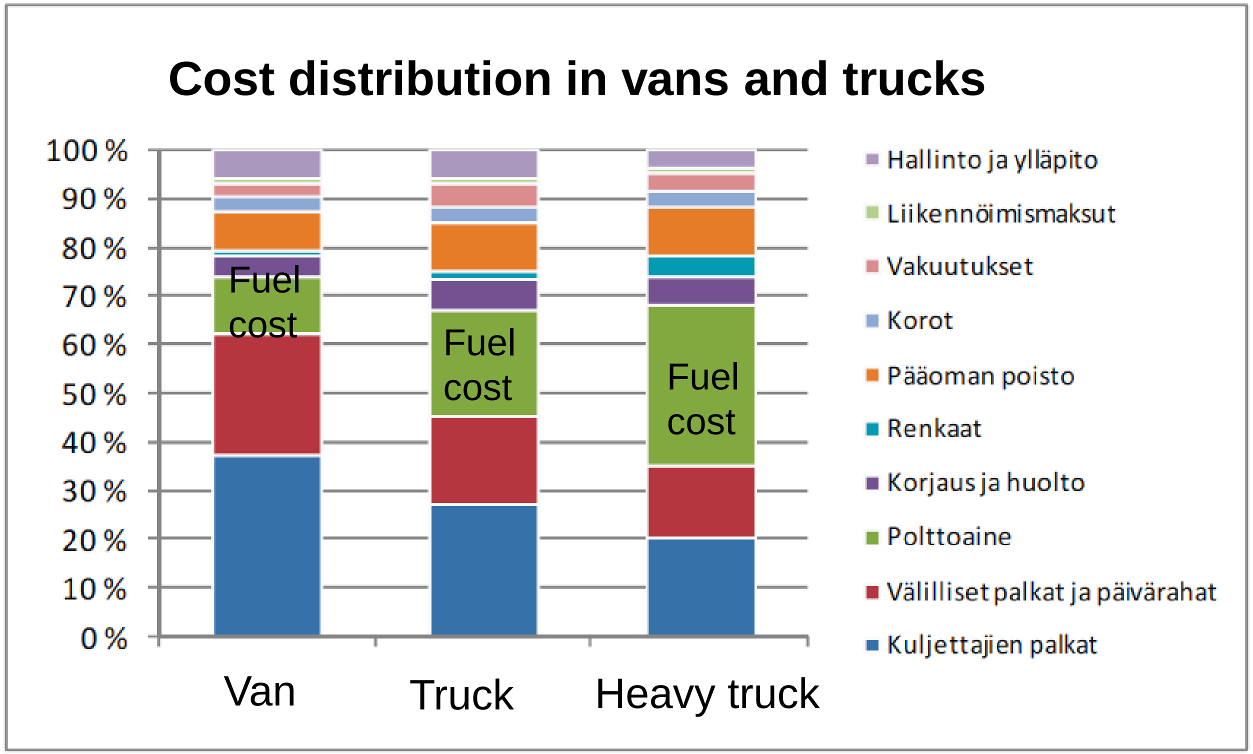
Source: IEA, Net Zero by 2050 A Roadmap for the Global Energy Sector, 2021 : https://www.iea.org/reports/net-zero-by-2050



- 7 TW of electrolyzers is needeed 500 Mt_{H2}/a capacity factor 4000 h/a (wind power)
- 14 TW of electrolyzers is needed if solar power is used (capacity factor 2000 h/a)

Example: Hydrogen in land transportation potentially makes no techno-economic sense





Lähde: Liikennemarkkinoiden nykytila, Liikenne- ja viestintäministeriö, 2009, https://julkaisut.valtioneuvosto.fi/handle/10024/78235

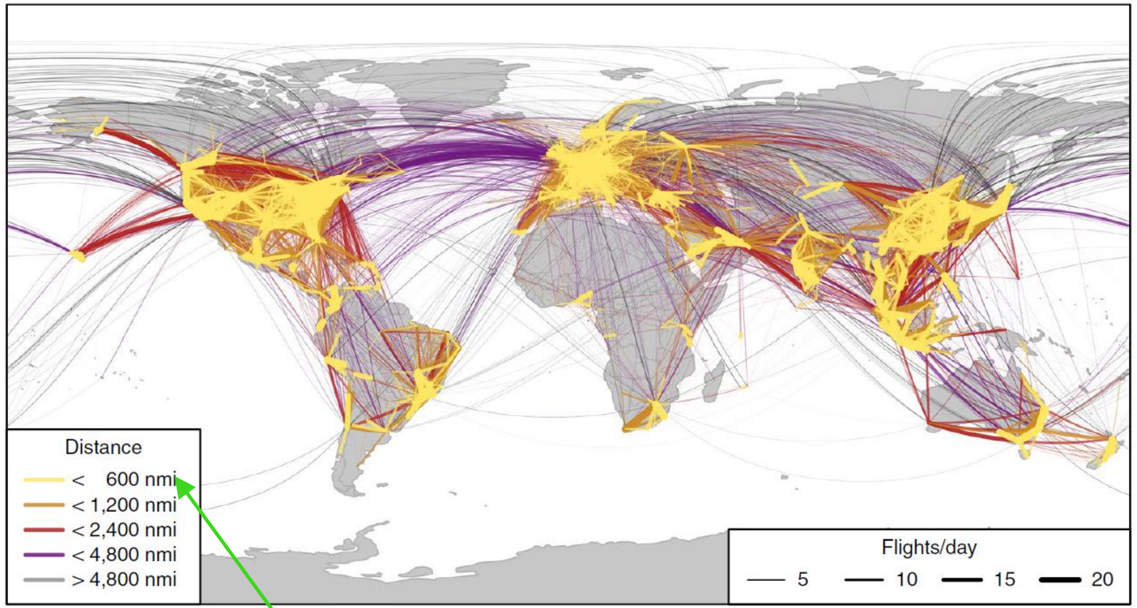
Chinese BEV truck and Geely battery-swapping station

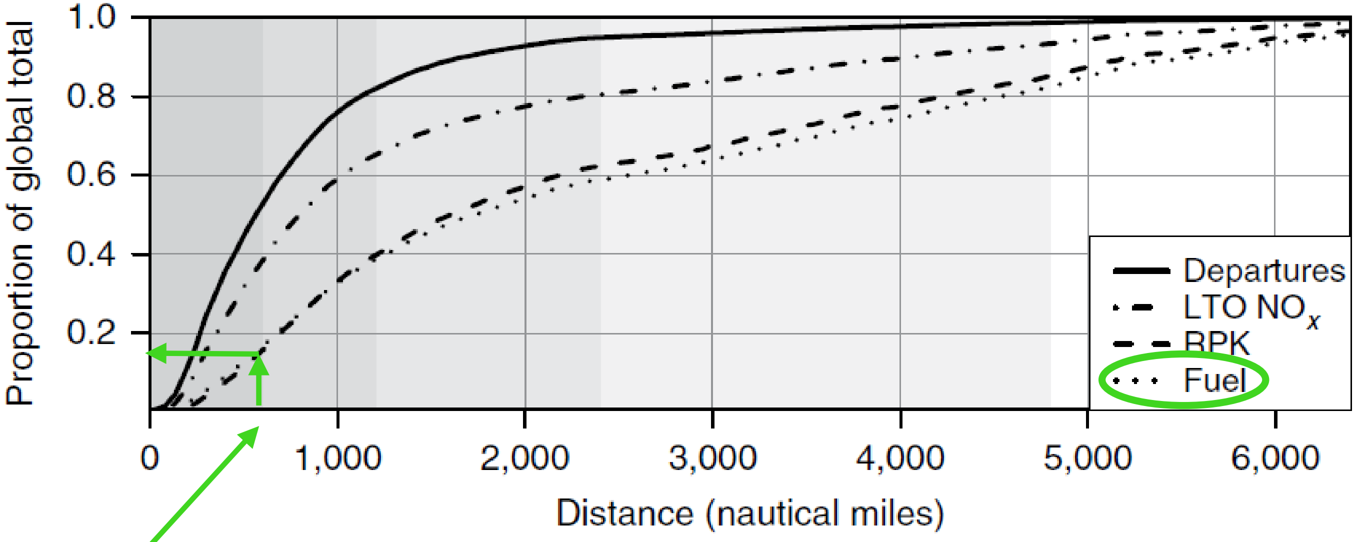
Description

- Battery pack is located behind the cabin of the truck. The capacity is 3-4 times of the capacity of EV car
- Battery weights 3.2 tons and it has a capacity of 280 kWh
- Battery gives around 150-200 km of electric range. It also powers other functions, such as the mixing of cement
- Used battery is transferred automatically to the battery warehouse and replaced with a charged one
- The whole operation takes about five minutes

Battery-swapping of a truck in operation

However, intercontinental aviation and marine transportation will need hydrogen-based fuels also in the foreseeable future





Electric flights at distances < 600 nmil (1100 km) ~15 % of total fuel consumption of battery energy density 800 Wh/kg will be reached

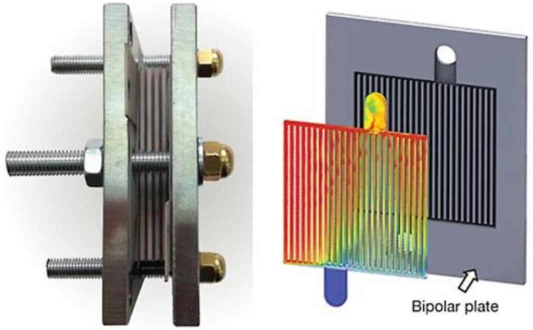
Source: Andreas W. Schäfer, et. Al., Technological, economic and environmental prospects of all electric aircraft, Nature Energy, Vol. 4, February 2019, pp. 160-166.

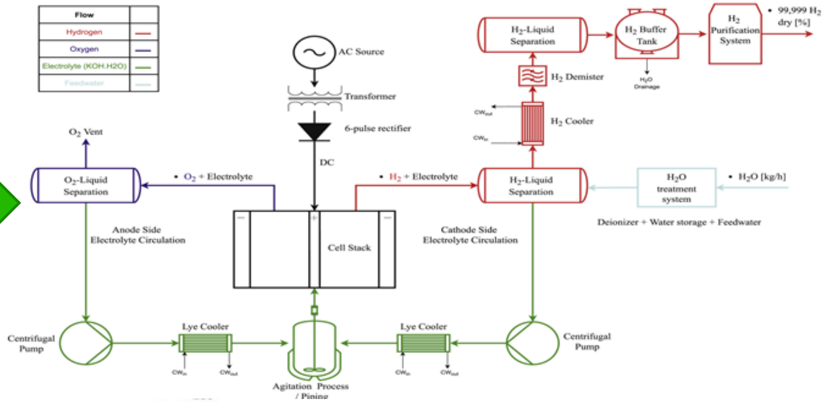
8.11.2022

Some recent findings from LUT PtX research

Multiscale-multiphysics modelling by LUT – Research objectives: system cost, dynamic performance and efficiency

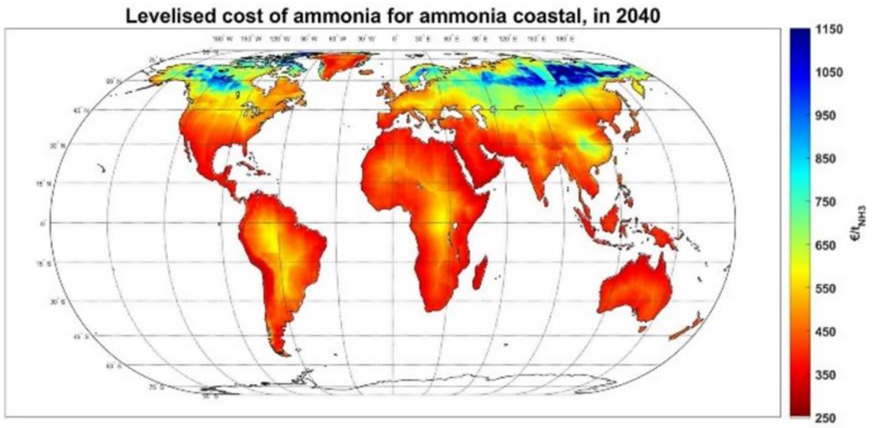
Cell and stack design

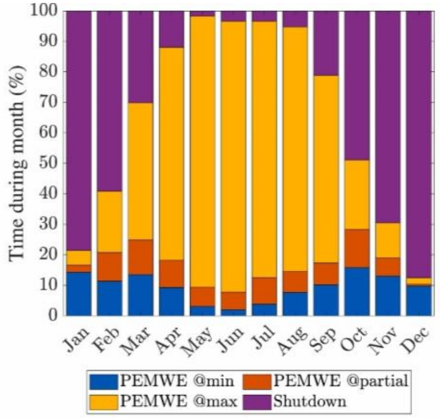




Electrolyser system operation

Global energy transition





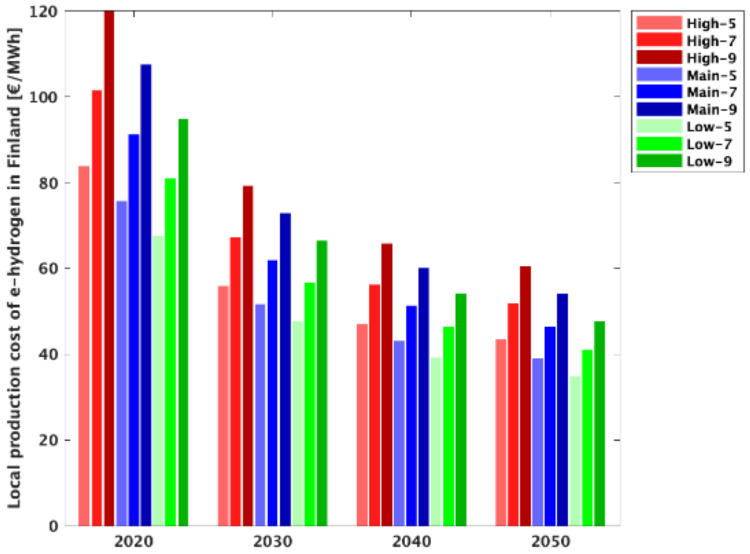
Optimisation of battery buffered solar PV and wind power-based production of green hydrogen

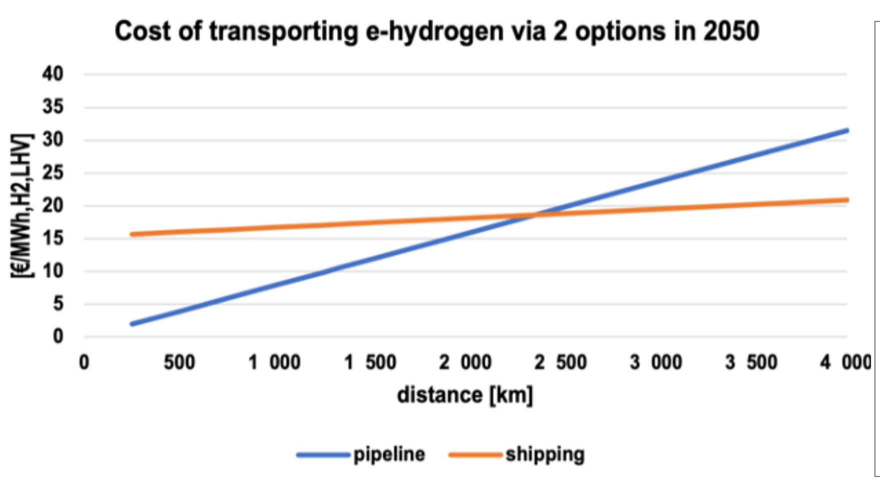
Local supply of hydrogen is more economic than long distance transport

source: Galimova et al., 2022. 8th International Conference on Smart Energy Systems, Aalborg, Denmark, September 13-14, under review at a journal

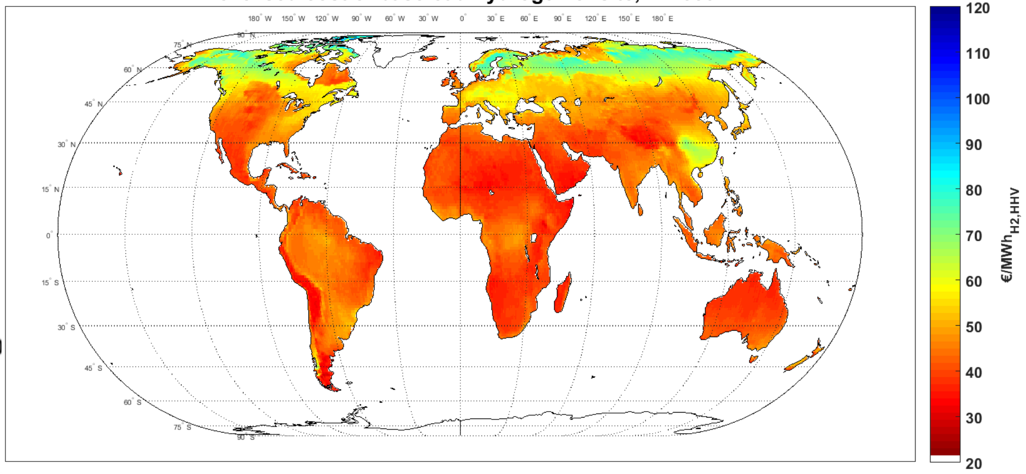
Key insights:

- Renewable-electricity based hydrogen can be produced at acceptable cost anywhere in the world
- To better assess attractiveness of imports transportation infrastructure needs to be considered
- Imported hydrogen costs were found to be significantly higher than H_2 produced domestically (case FI, DE)
- Local supply of H_2 is more economical across both cases and all years, since transportation costs are high
- Pipeline transport is lower in cost for short distances, whereas shipping is more economical for distances over 1500 km





Levelised cost of baseload hydrogen onsite, in 2050

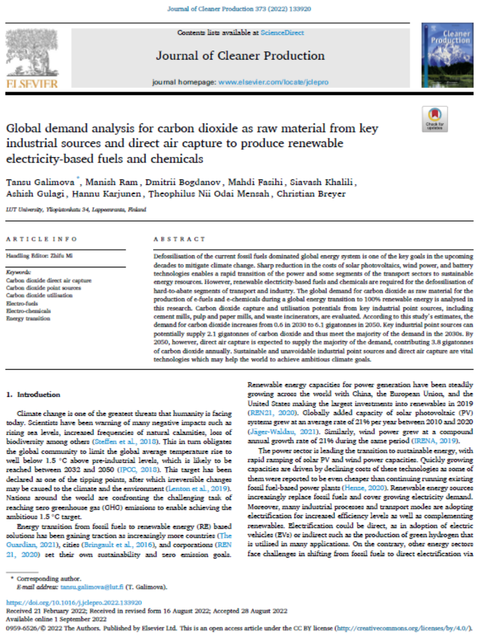


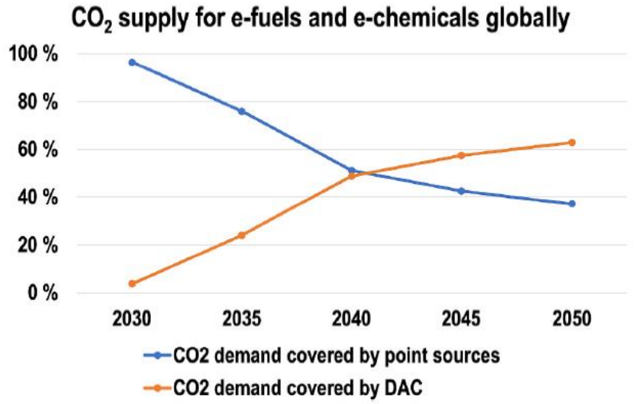
CO2 as raw material for e-fuels

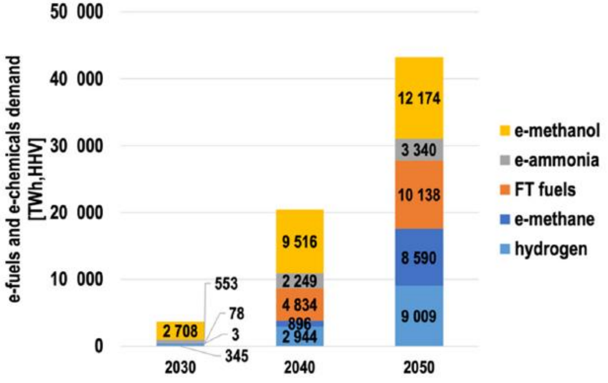
LUT University

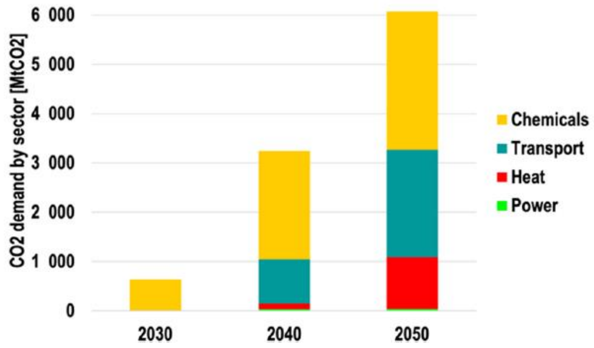
Key insights:

- e-fuels demand in order of 40,000 TWh
- key e-fuels are e-methanol and e-kerosene jet fuel, maybe some e-methane
- largest demand sectors: chemicals, transport, and maybe high-temperature industrial process heat
- hydrocarbon-based e-fuels require CO_2 as raw material
- sustainable or unavoidable point sources are usable, such as waste incinerators, pulp and paper mills, maybe cement mills
- largest source for CO_2 as raw material will be direct air capture





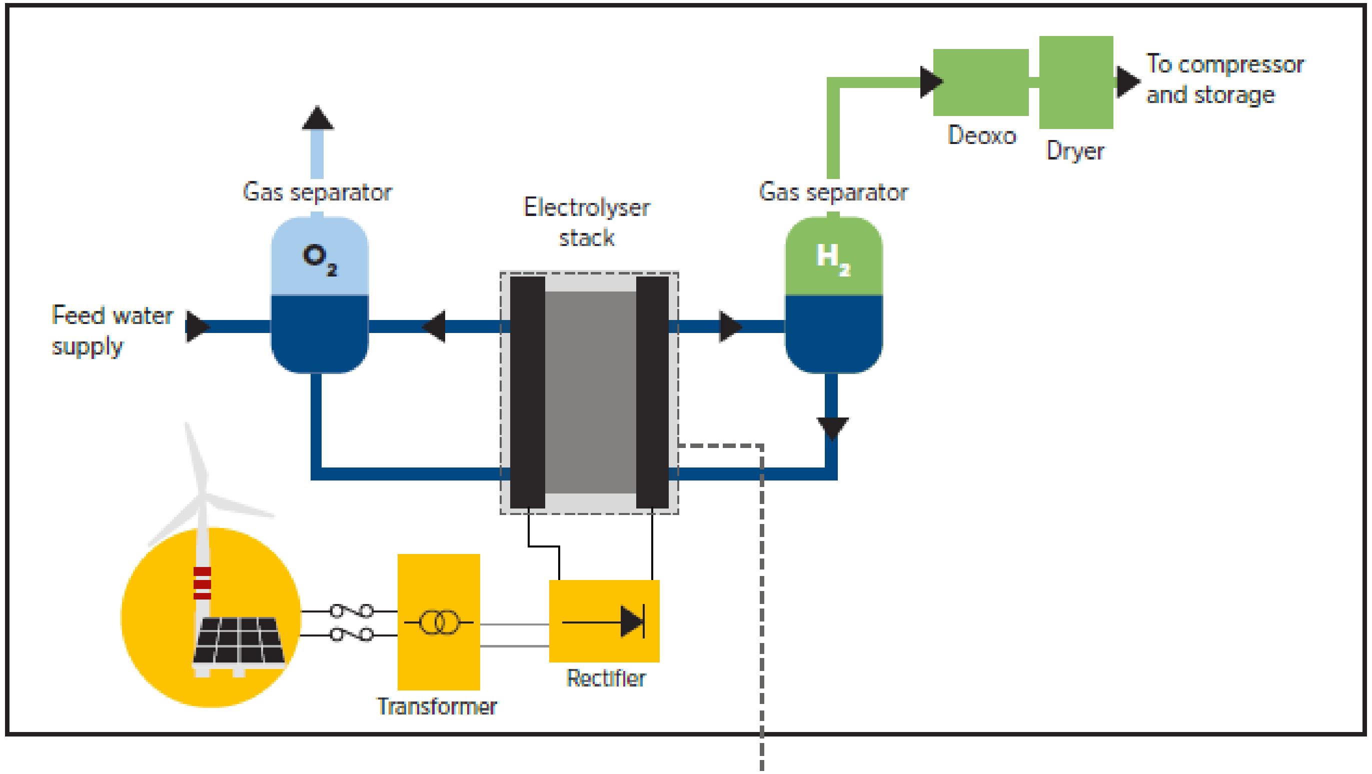




source: [Galimova et al., 2022. J of Cleaner Production, 373, 133920]

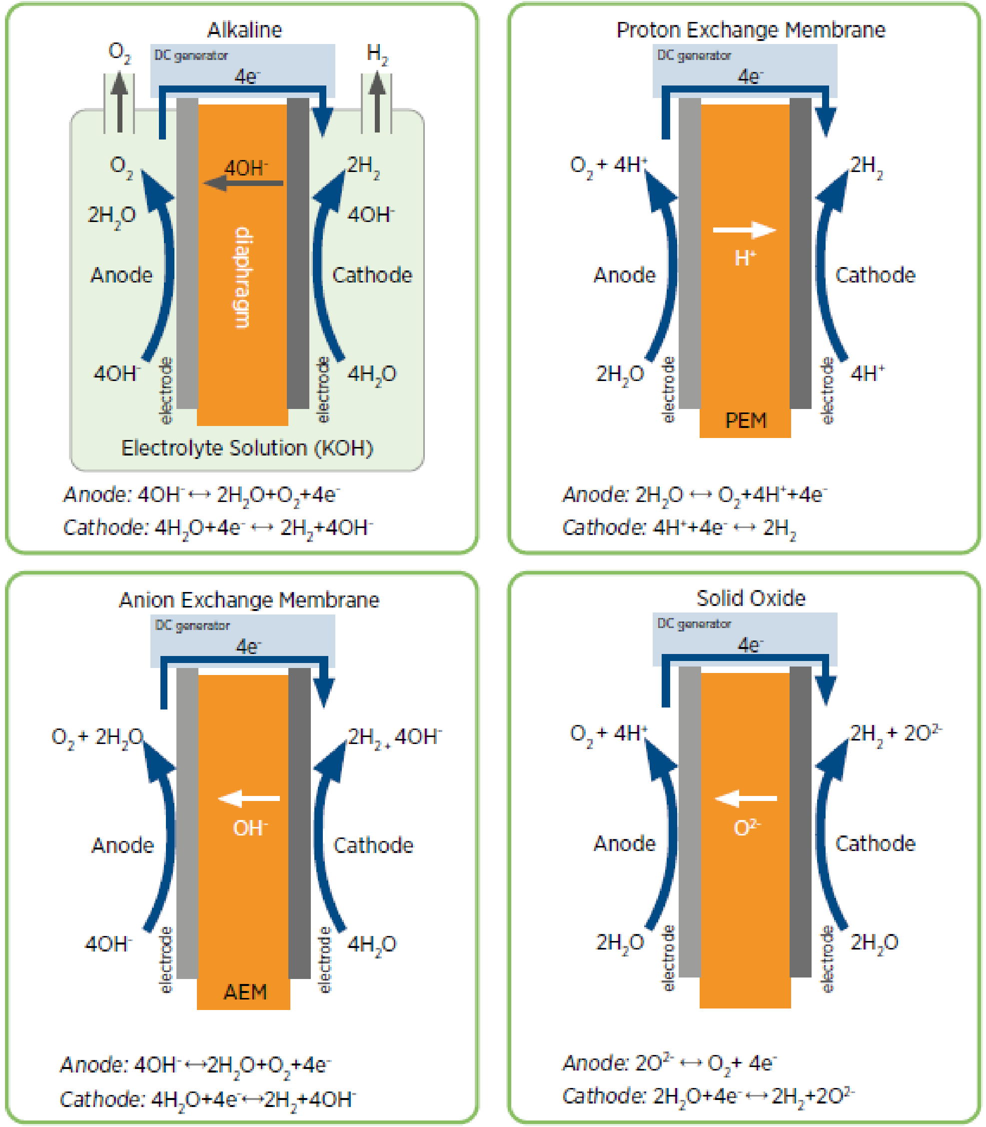
Green hydrogen production: Electrolysis process and most typical cell technologies

SYSTEM LEVEL



Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal,
International Renewable Energy Agency, Abu Dhabi

Different types of commercially available electrolysis technologies.



Industrial alkaline water electrolyzer plant in Finland in Kokkola (Woikoski Oy)

Summary:

- Located in Kokkola, Finland
- Power-to-Hydrogen: 1800 Nm^3/h (H_2)
- 3x3 MW pressurized alkaline water electrolyzers, 3x600 Nm^3/h, 16 bar (H_2)
- The main use of H_2 plant is at nearby Cobalt plant, hydrogen delivery by a pipeline
- The rest of H_2 compressed to 200-300 bar and stored in bottles for delivery with trucks

How to get low-cost green hydrogen?

Electrolyser cost

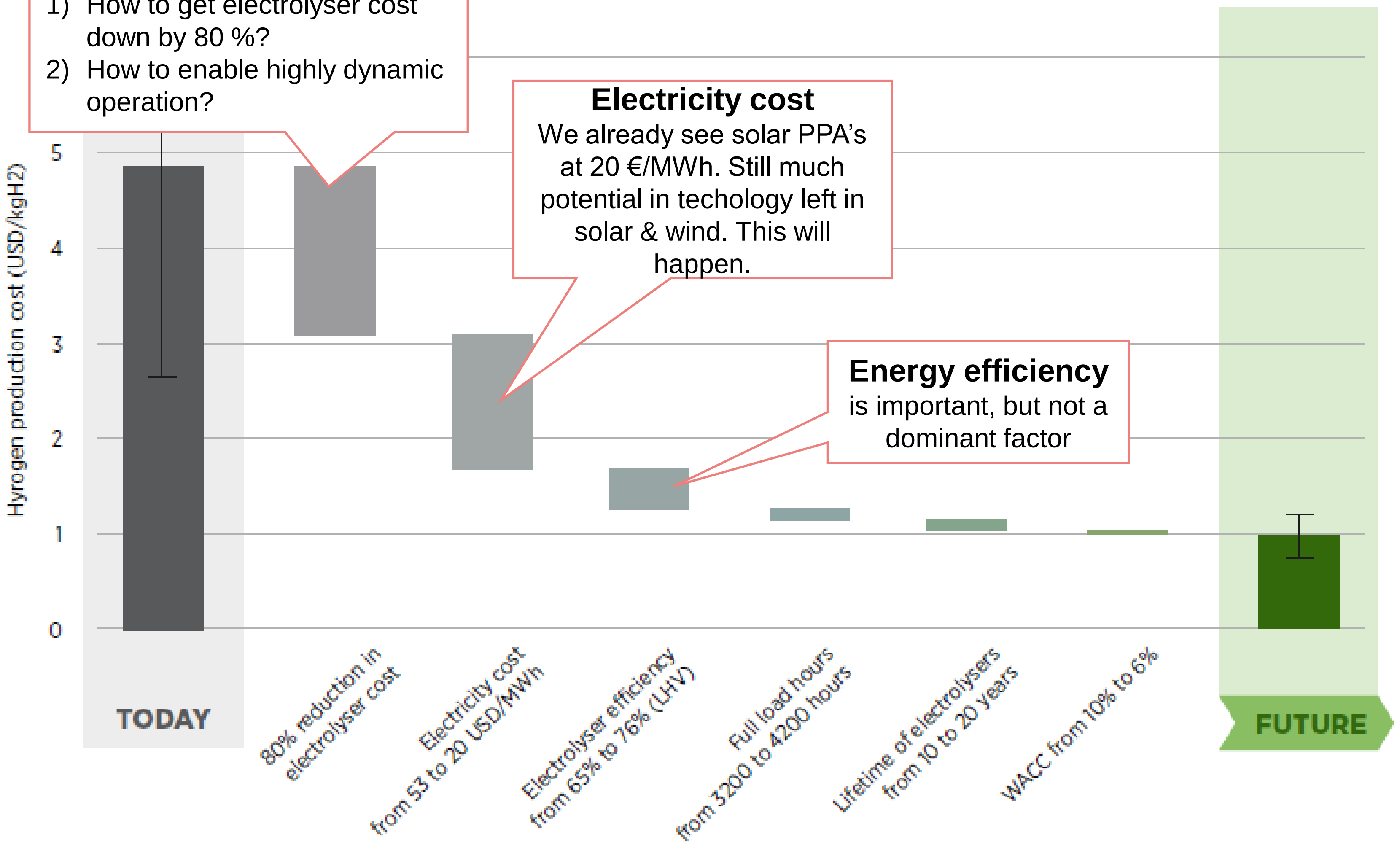
1) How to get electrolyser cost down by 80 %?
2) How to enable highly dynamic operation?

Electricity cost

We already see solar PPA's at 20 €/MWh. Still much potential in techology left in solar & wind. This will happen.

Energy efficiency

is important, but not a dominant factor



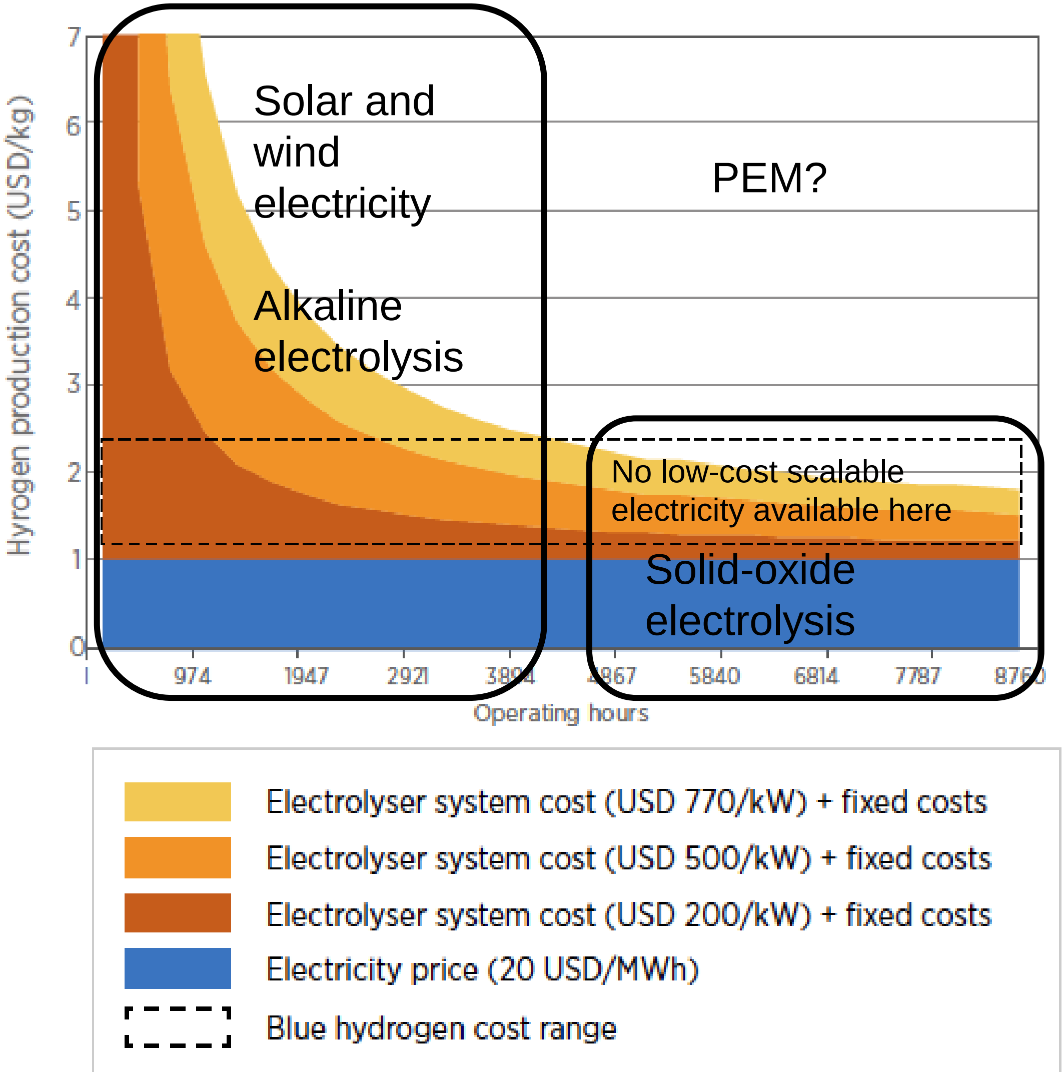
Source: IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi

Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Green hydrogen production will be based on solar and wind

LUT University

Effect of intermittency of electricity supply



Cost composition of alkaline water electrolysis

Electrolyzer plant size matters. 100 MW plant has significantly lower specific investment cost than 5 MW plant

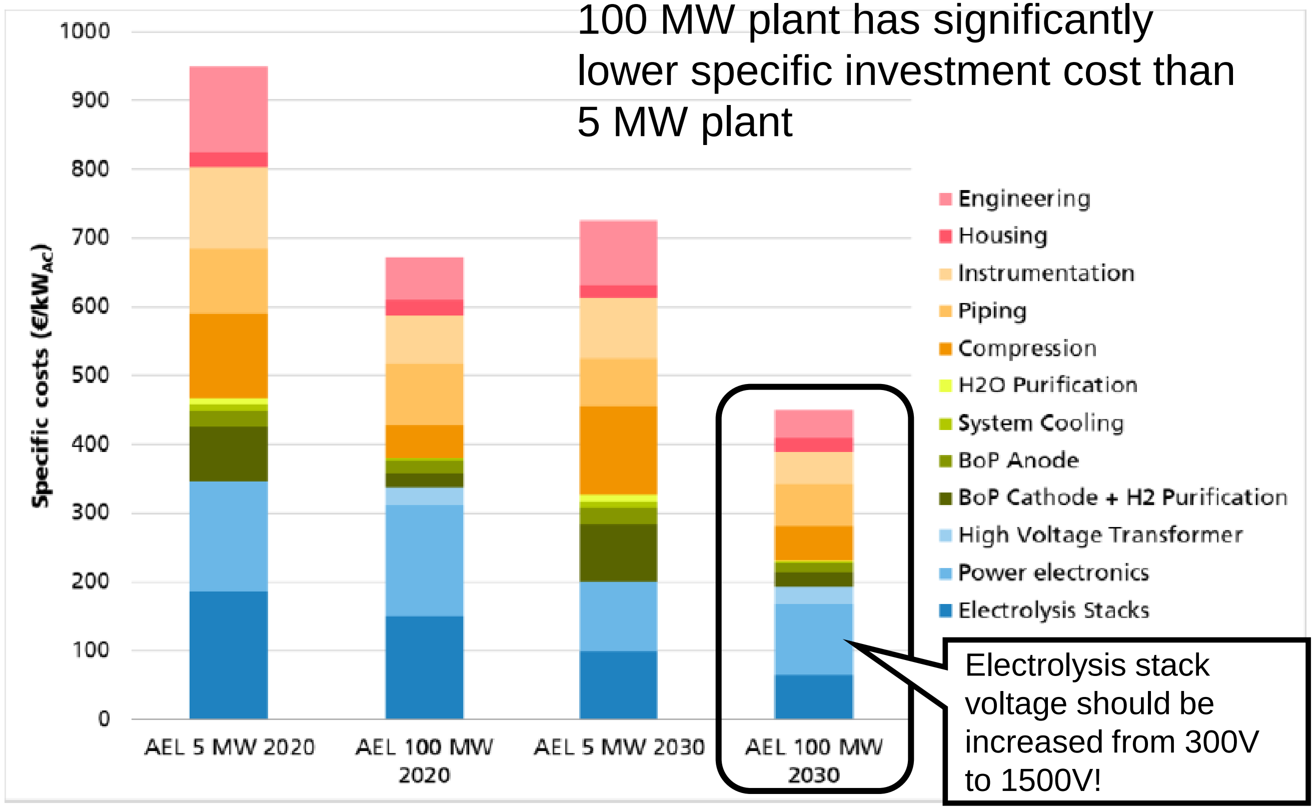


Figure 3-6: Specific costs of 5 MW and 100 MW next generation AEL systems (including mechanical compressors) for the design scenarios 2020 and 2030

Source: Marius Holst Stefan Aschbrenner Tom Smolinka Christopher Voglstätter Gunter Grimm, COST FORECAST FOR LOW-TEMPERATURE ELECTROLYSIS – TECHNOLOGY DRIVEN BOTTOM-UP PROGNOSIS FOR PEM AND ALKALINE WATER ELECTROLYSIS SYSTEMS, Frainhofer ISE, October 2021, https://www.ise.fraunhofer.de/en/press-media/press-releases/2022/towards-a-gw-industry-fraunhofer-ise-provides-a-deep-in-cost-analysis-for-water-electrolysis-systems.html

Dynamic mass and energy balance of industrial alkaline water electrolyzer plant

In this case, more than 10 % of current is leakage current -> It does not produce hydrogen. The problem gets even worse at partial loads or when more electrolyzer cells are connected in series.

Ovenpotentials can be reduced by better catalysts, membranes and increasing temperature. Overpotentials are reduced at partial loads.

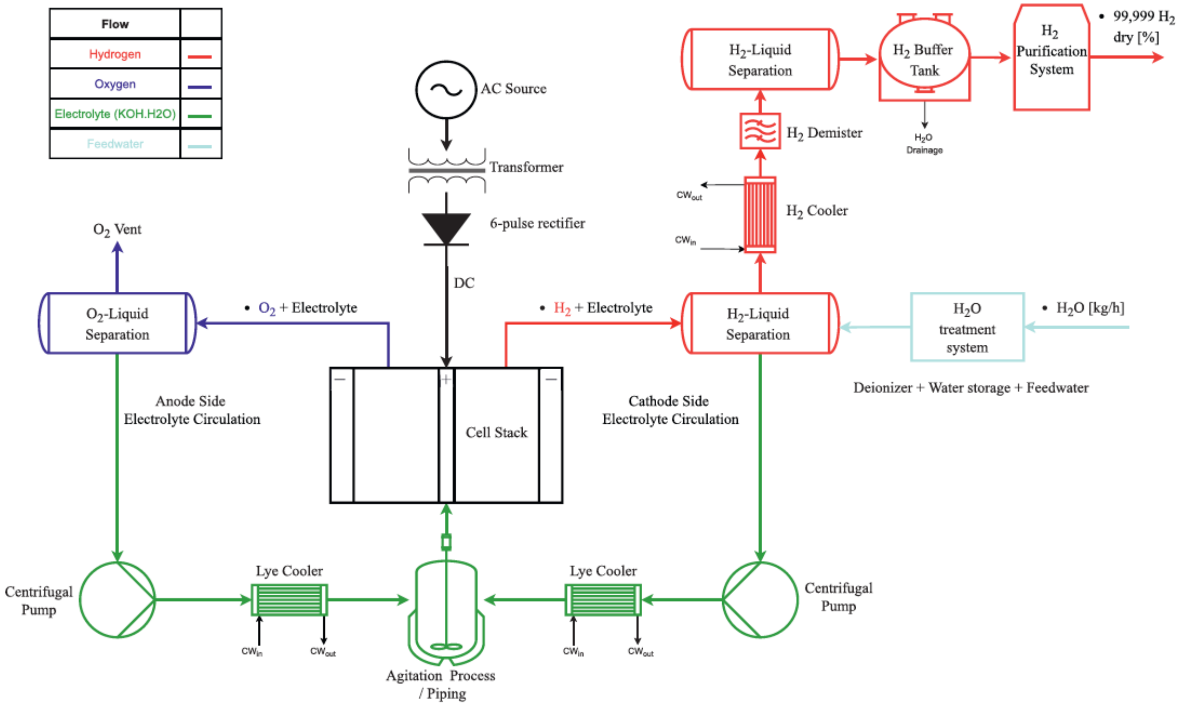


Fig. 1 — Formulated alkaline water electrolyzer plant process diagram.

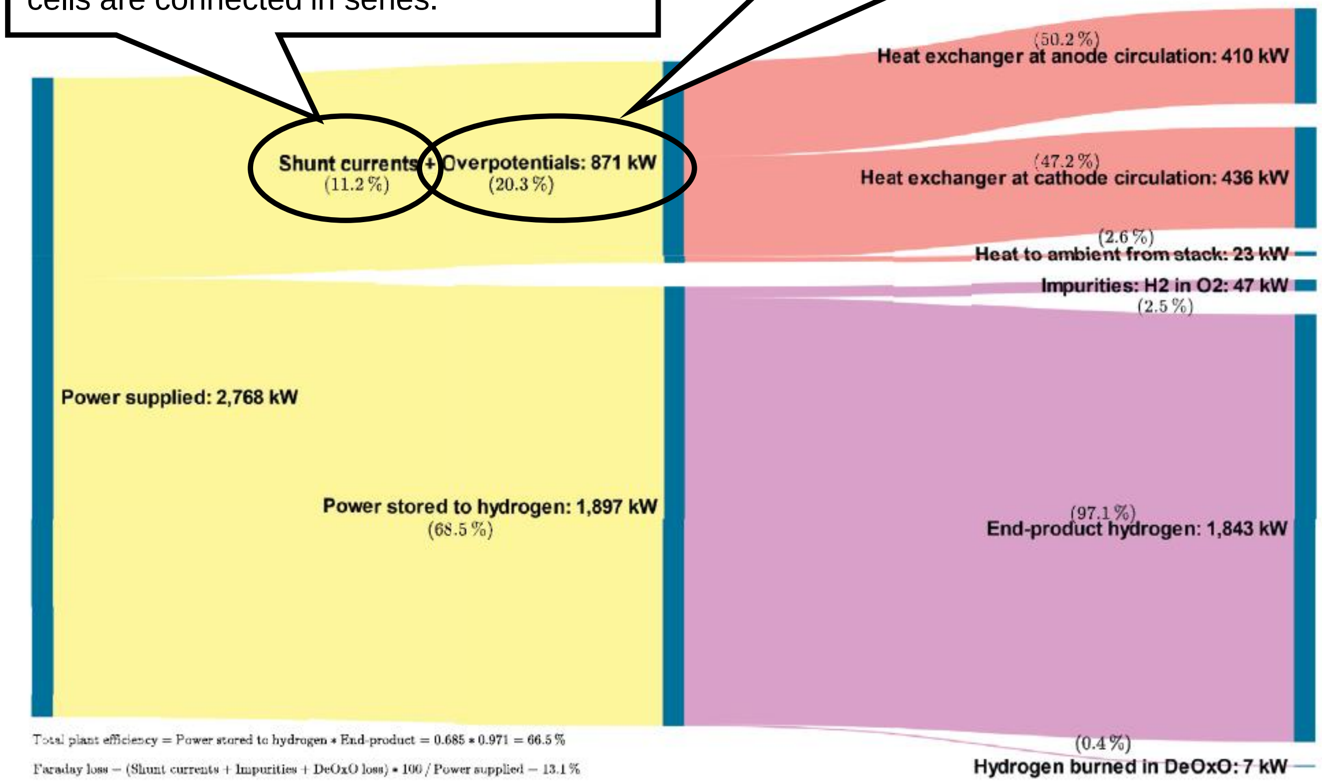


Fig. 9 — Supplied power consumption/distribution in the stack and system level.

Source: Georgios Sakas, Alejandro Ibáñez-Rioja, Vesa Ruuskanen, Antti Kosonen, Jero Ahola, Olli Bergmann, Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process, International Journal of Hydrogen Energy, Volume 47, Issue 7, 2022, Pages 4328-4345, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.11.126.

Specific energy consumption of alkaline water electrolysis

In order to run alkaline water electrolysis energy efficiently at partial load currents, we have to have a <u>low leakage current electrolyzer stack design</u>.

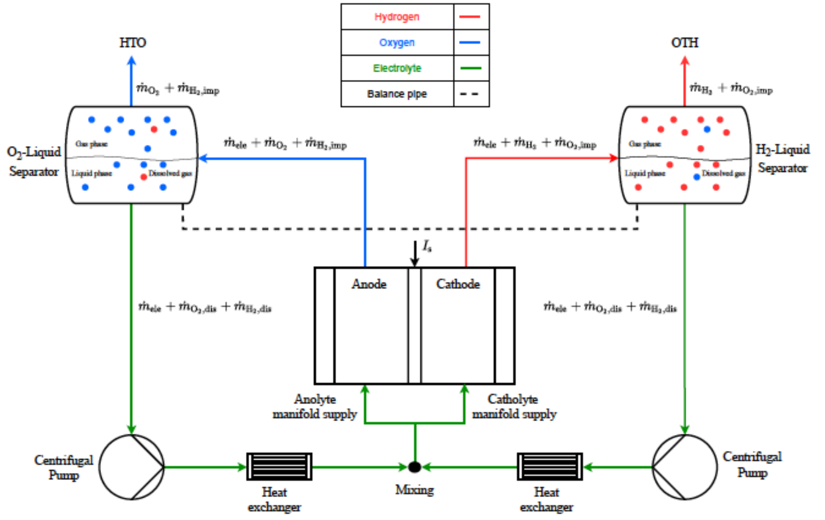
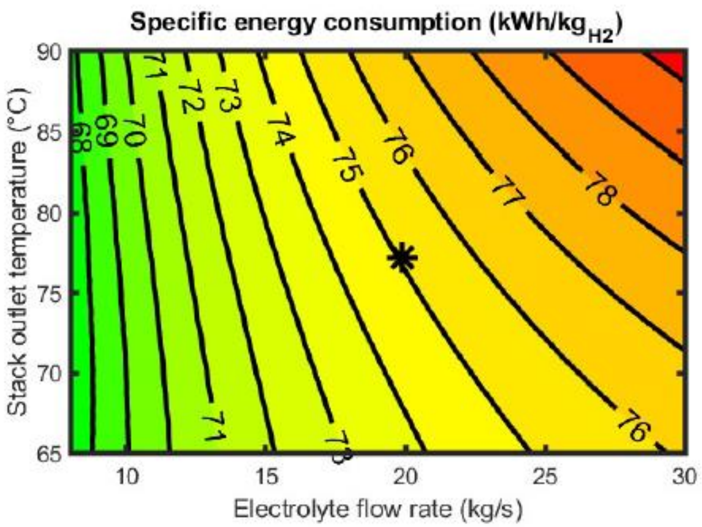
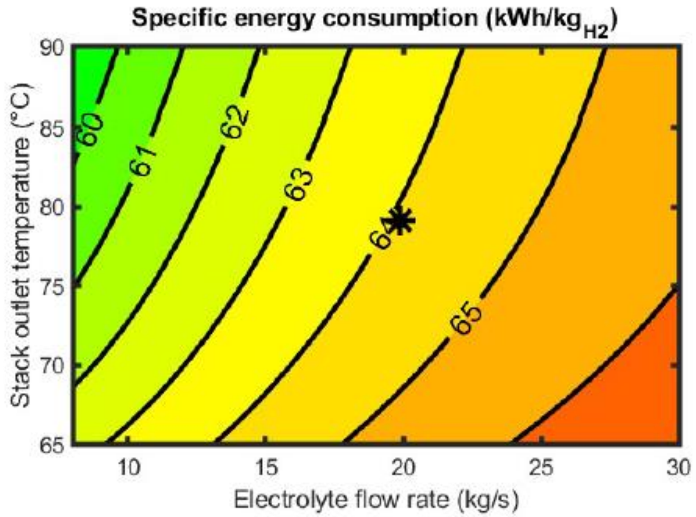


Fig. 2: Modelled process layout of the circulation loop of an industrial AWE and illustration of the gas crossover phenomenon resulting from the gas dissolution in the separation vessels.

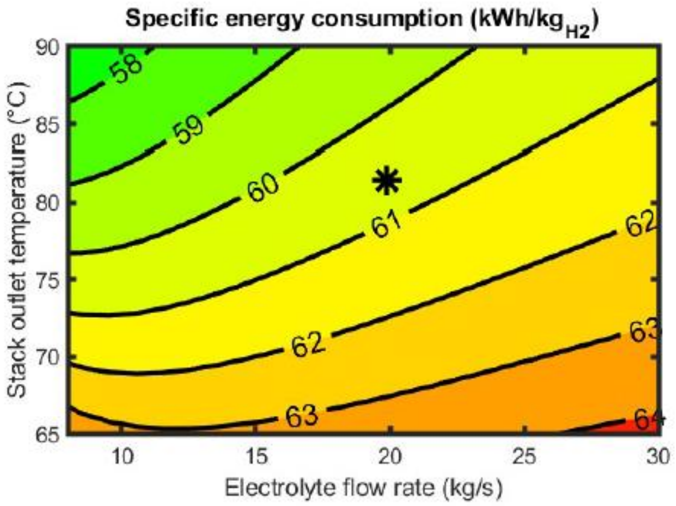
Source: Georgios Sakas, Alejandro Ibanez Rioja, Santeri Pöyhönen, Lauri Järvinen, Antti Kosonen, Vesa Ruuskanena, Jero Ahola, Sensitivity analysis of the process conditions that affect the shunt currents and the SEC in a bipolar configuration stack of an industrial-scale alkaline water electrolyzer process, manuscript under review.



50 % load current

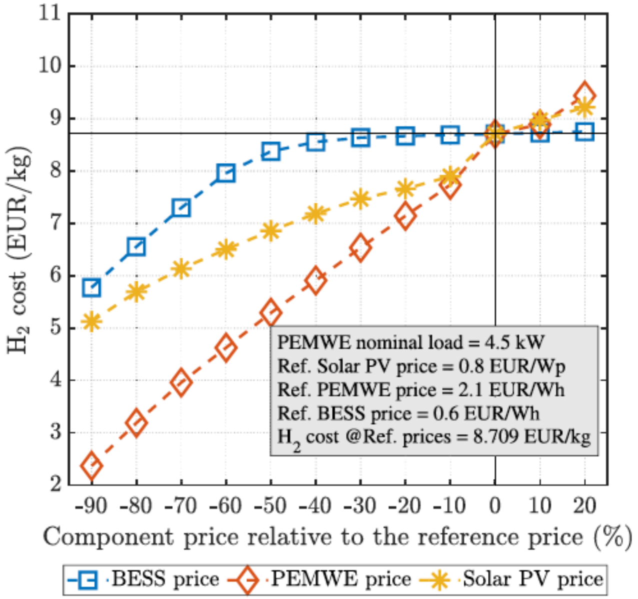


75 % load current

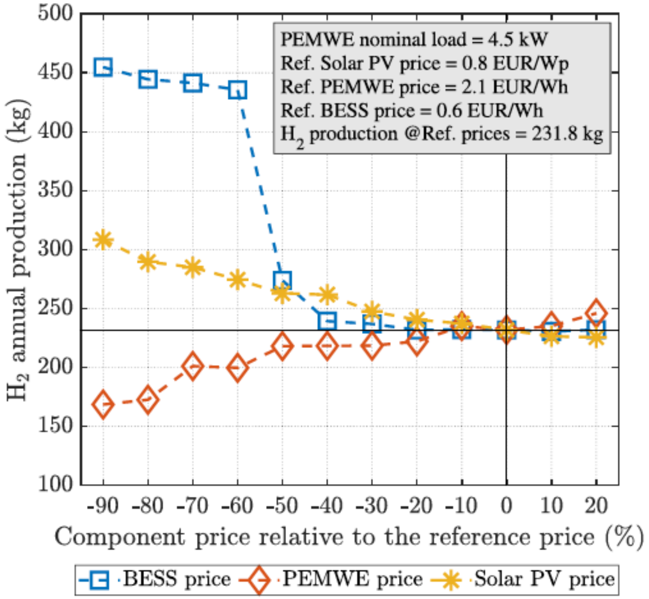


100 % load current

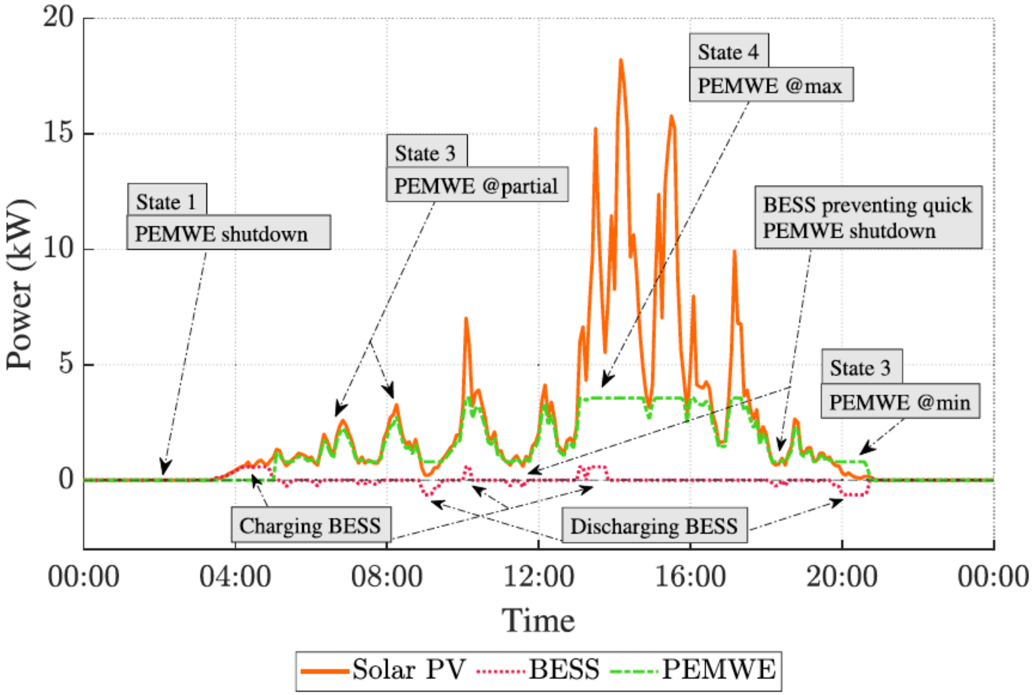
How to get low-cost green hydrogen: Co-optimization of component dimensioning and control in green hydrogen production



(a) Cost of the hydrogen produced.



(b) Total production of hydrogen



Source: Alejandro Ibáñez-Rioja, Pietari Puranen, Lauri Järvinen, Antti Kosonen, Vesa Ruuskanen, Jero Ahola, Joonas Koponen, Simulation methodology for an off-grid solar–battery–water electrolyzer plant: Simultaneous optimization of component capacities and system control, Applied Energy, Volume 307, 2022, 118157, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2021.118157.

LUT is one of the world's

TOP 10 UNIVERSITIES

in terms of climate actions – SDG 13

The Times Higher Education Impact Rankings 2021 assess the social and economic impact of universities against the UN's Sustainable Development Goals.

SUSTAINABLE DEVELOPMENT GOALS

13 CLIMATE ACTION