The Role of Green Hydrogen in a Solar Powered Energy Transformation

Open your mind. LUT.
Lappeenranta University of Technology

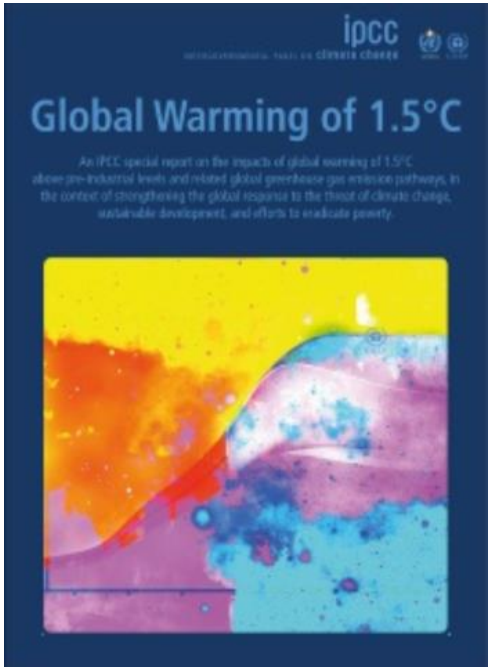
Christian Breyer
LUT University, Finland
IEA PVPS Workshop on
PV Powering the Energy Transition
November 10, 2020

Background

European Green Deal

Paris Agreement

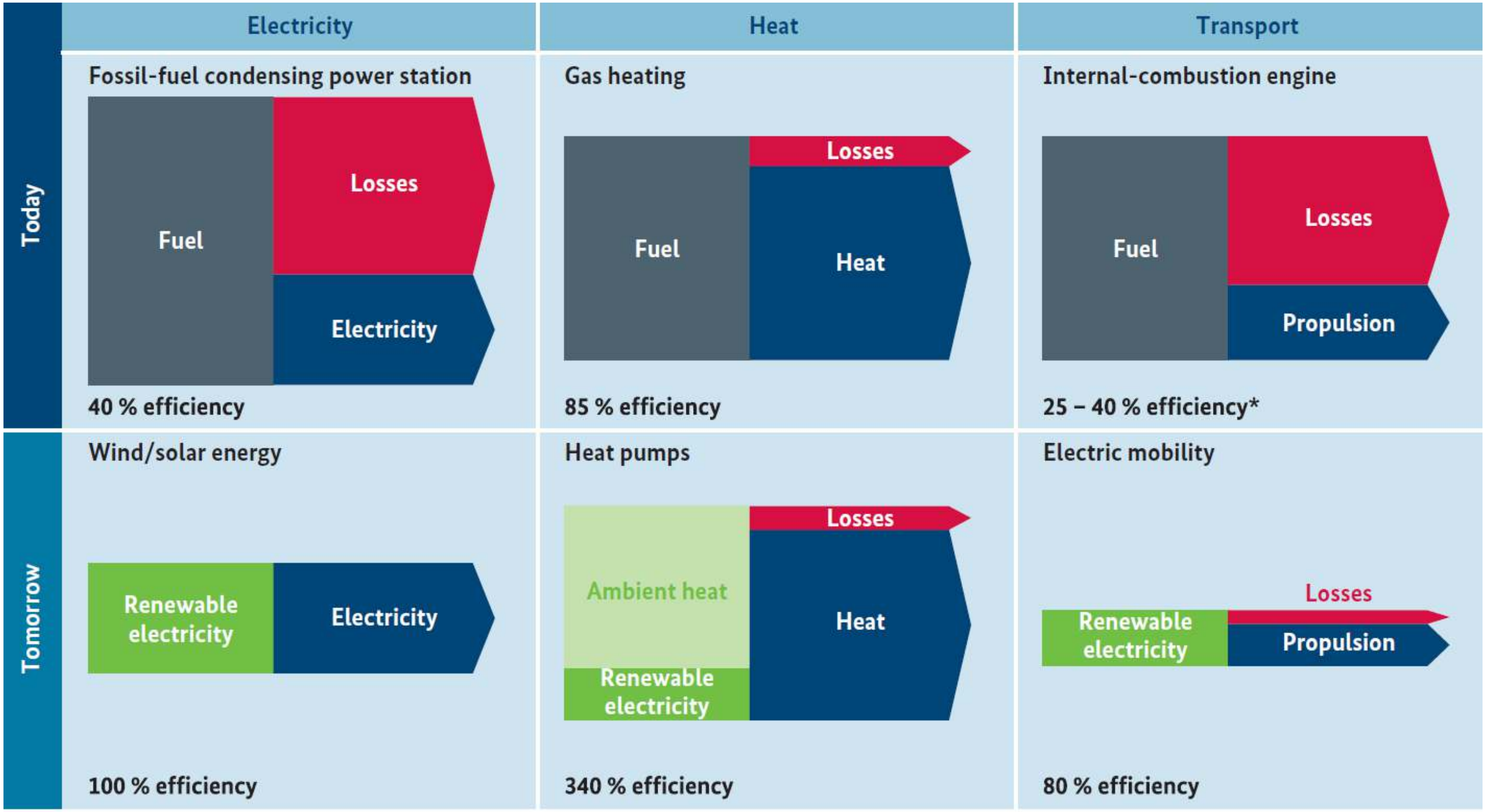
("well below 2ºC")



What does it mean?

- (net) zero greenhouse gas (GHG) emissions by 2050 are mandatory
- negative GHG emissions are costly, risky, with unclear responsibilities
- thus zero GHG emissions is the real target for the energy system

Key Rationale for Electrification: Efficiency



* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.

source: Brown et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847

Continued Milestones for Cost Decrease

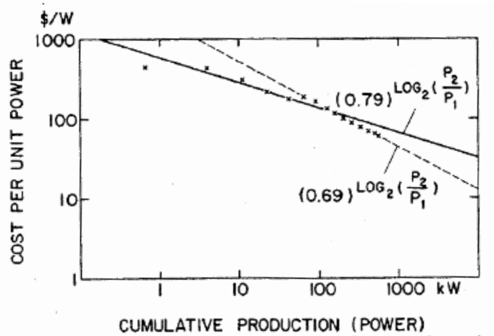
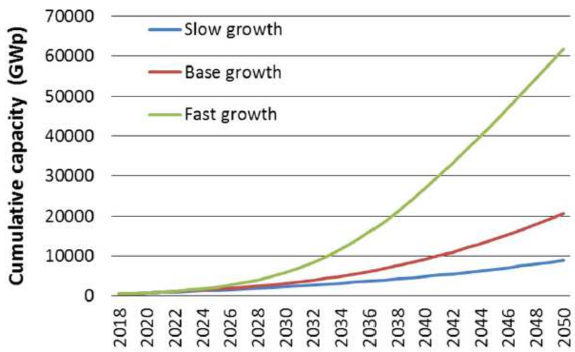
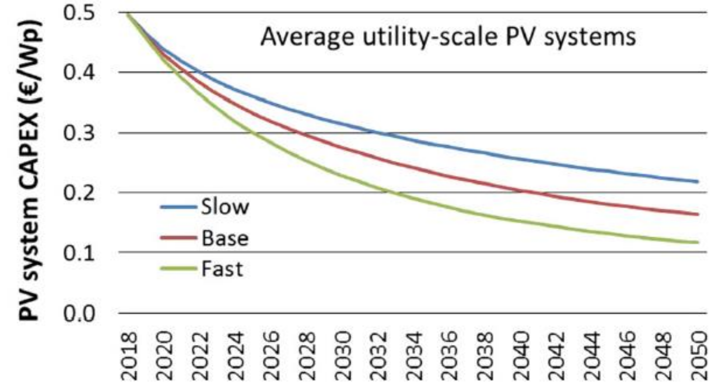
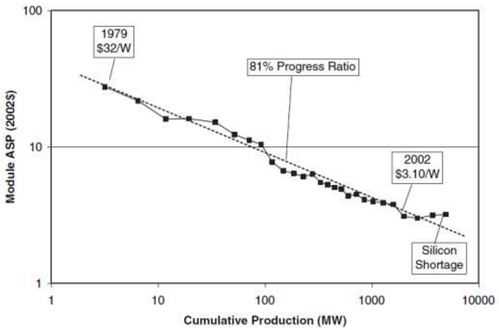
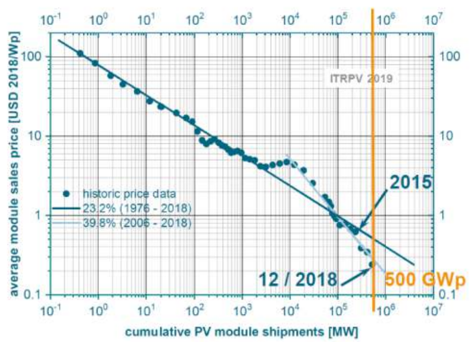


Figure 5. Cost of silicon solar cells plotted as function of cumulative production in term of potential power output (learning curve).





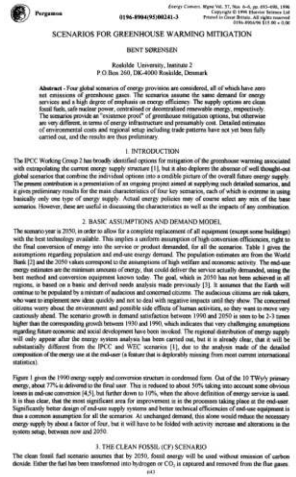


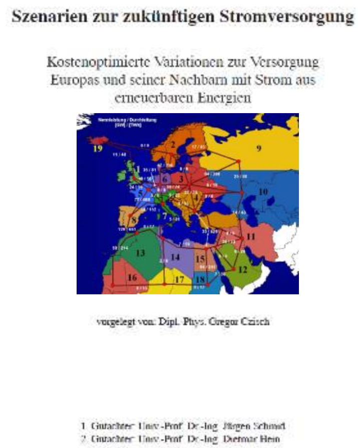


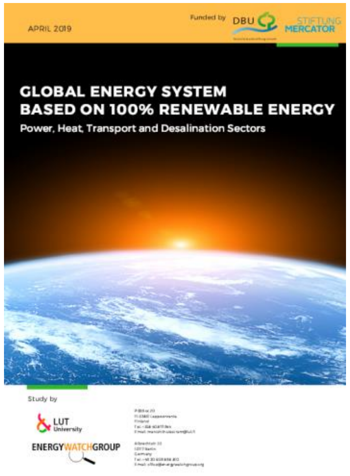
Key insights:

- earliest learning rates found to be 21-31% on cell level (Wolf, 1972)
- long-term learning rates found to be 21% on module level (Swanson, 2006)
- latest long-term learning rates found to be 23% and 40% for 2006-2018 (ITRPV, 2019)
- applying moderate learning rates and moderate efficiency increase leads to a cost level of PV utility-scale power plants of 110-210 €/kWp with 164 €/kWp in the base case (Vartiainen et al., 2020)
- summing up, learning rates are quite stable over long periods and recent PV module learning rates are comparable to the 40% benchmark of semiconductor devices as reported for DRAM and flat panels.

Major Milestones on 100% RE Research

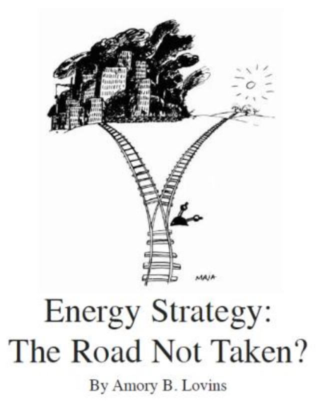


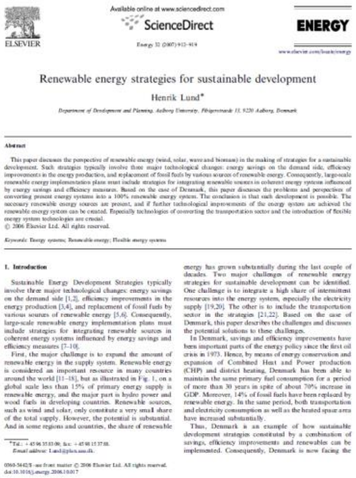


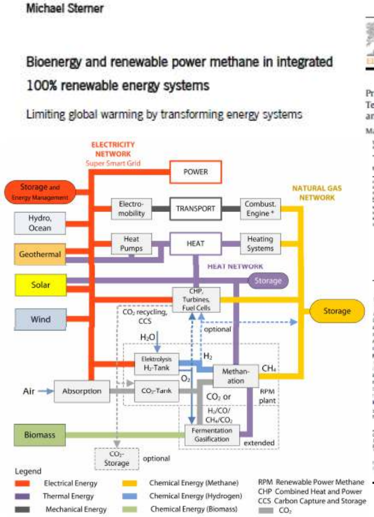


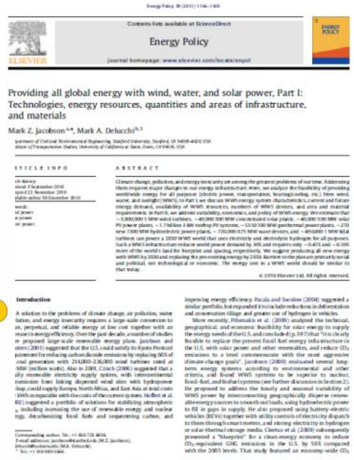
[Sørensen, 1975](#) [Sørensen, 1996](#) [Czisch, 2005](#) [Greenpeace, 2010](#) [LUT/EWG, 2019](#)

[Lovins, 1976](#) [Lund, 2007](#) [Sterner, 2009](#) [Jacobson, 2011](#) [Bogdanov et al. 2019](#)

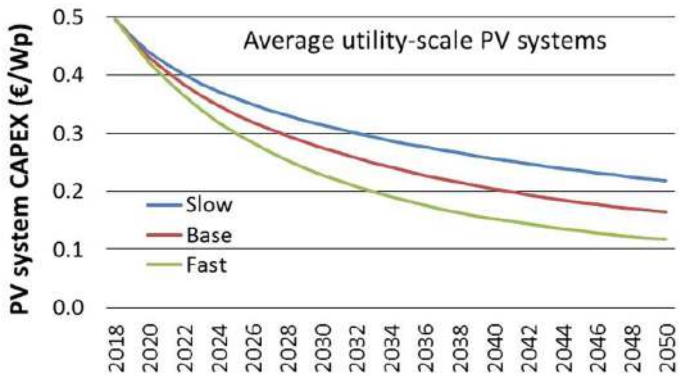


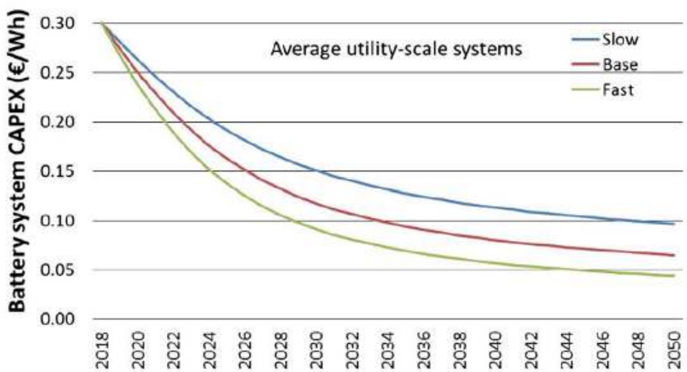


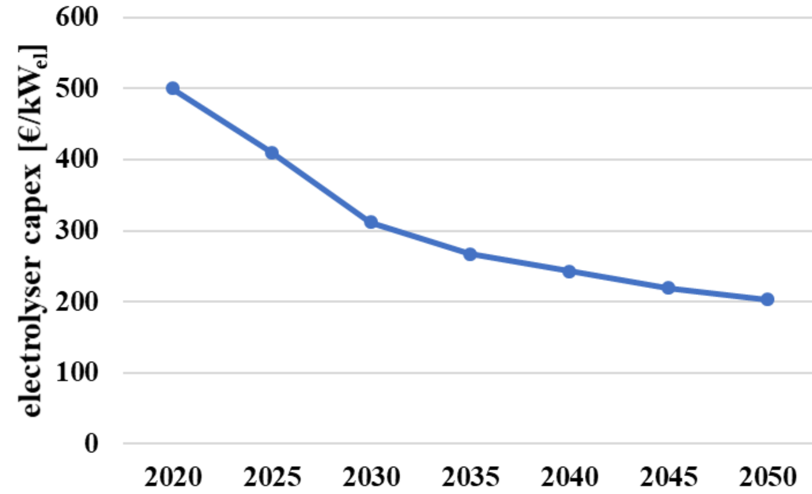


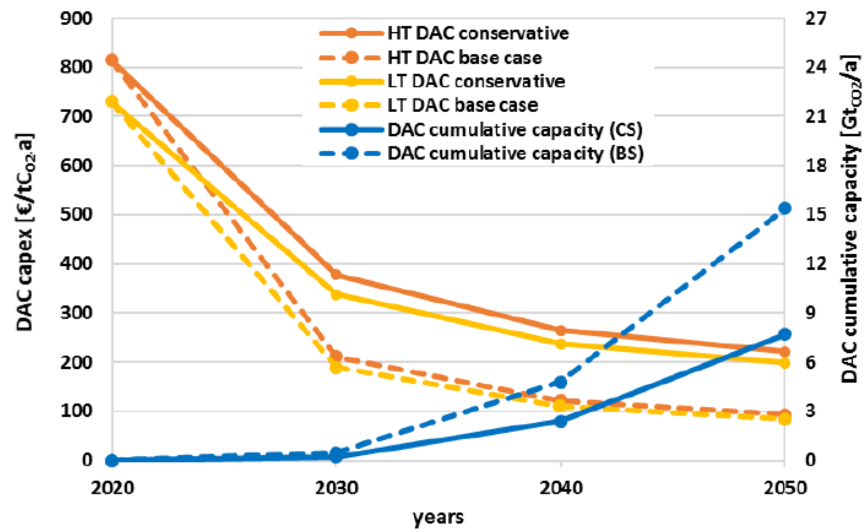


Basis for Change: PV enabling Green Hydrogen







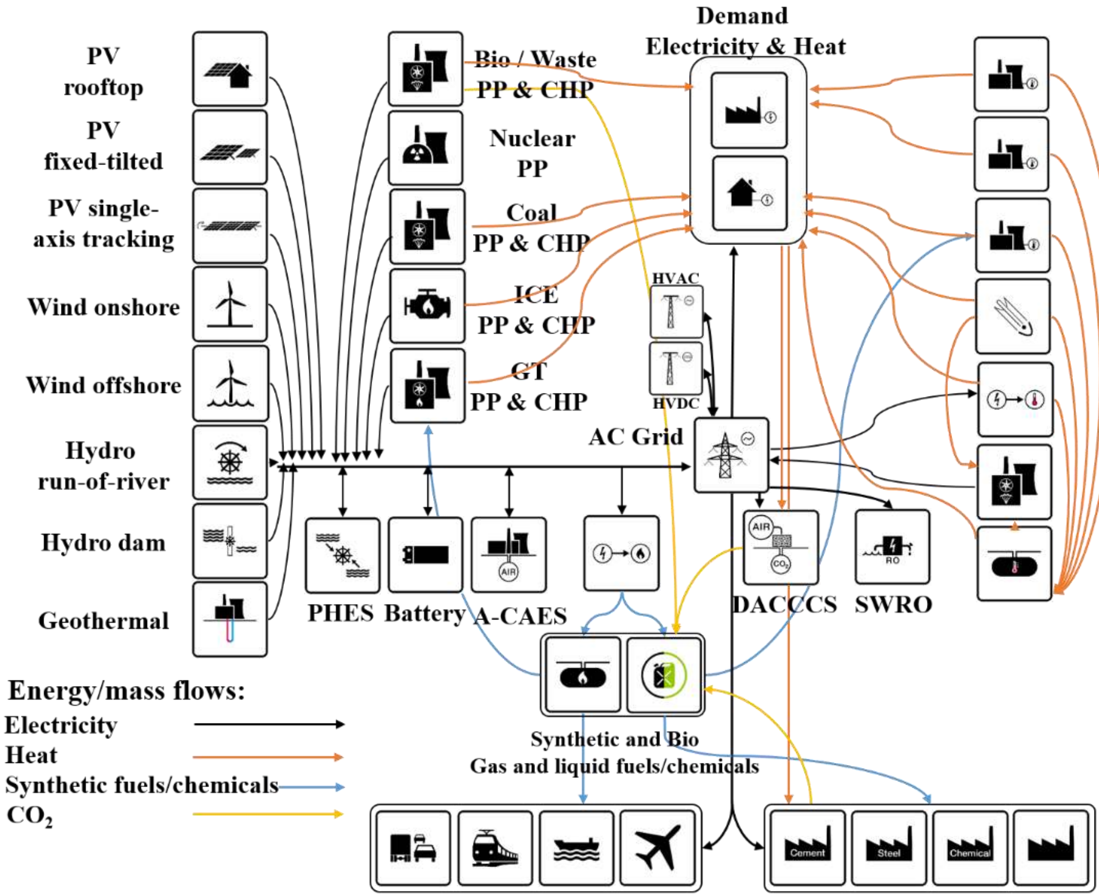


Key insights:

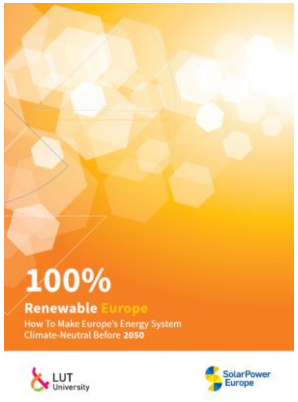
- massive continued cost decline for solar PV, wind, battery, electrolysers, CO_2 DAC
- massive pressure to eliminate all fossil fuels
- massive direct and indirect electrification of all energy sectors and non-energetic fossil fuel demand

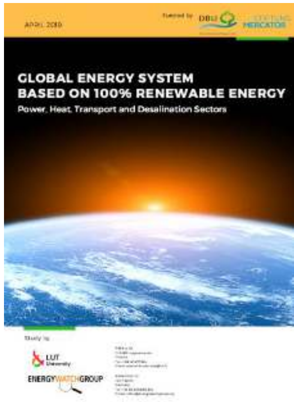
References:
PV, battery: Vartiainen et al., Progress in PV
Electrolyser: LUT model assumptio, Nature
CO_2 DAC: Fasihi et al., J of Cleaner Prod

LUT Energy System Transition Model



recent reports





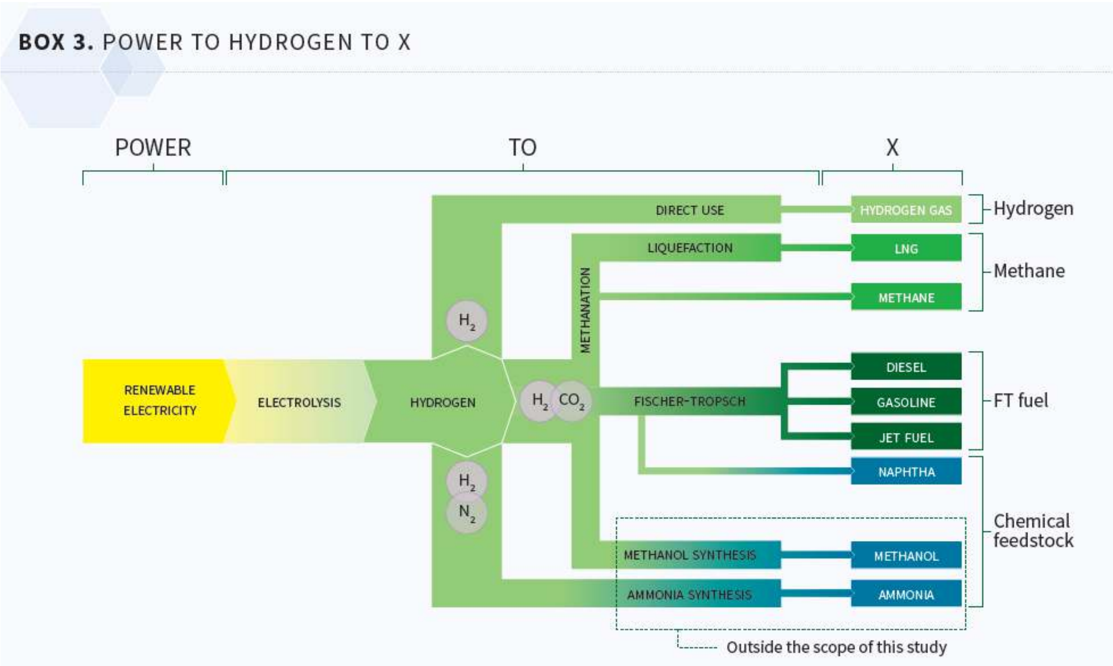
link to report   link to report

upcoming report on Powerfuels (fuels, chemicals) in a Renewable Energy World

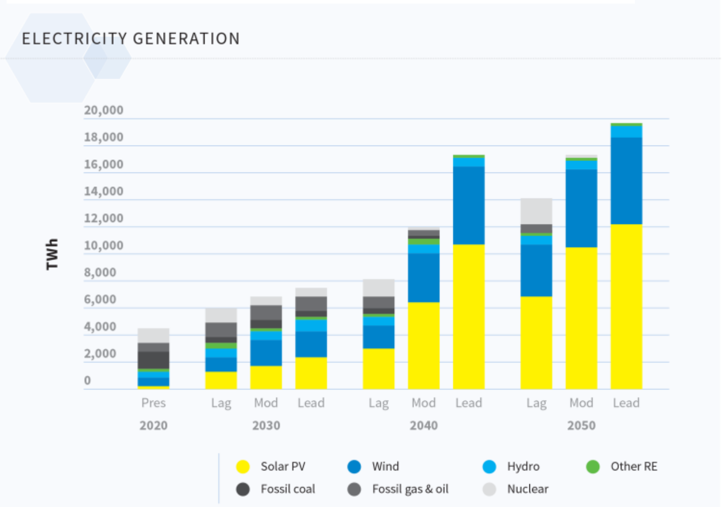
Key features:

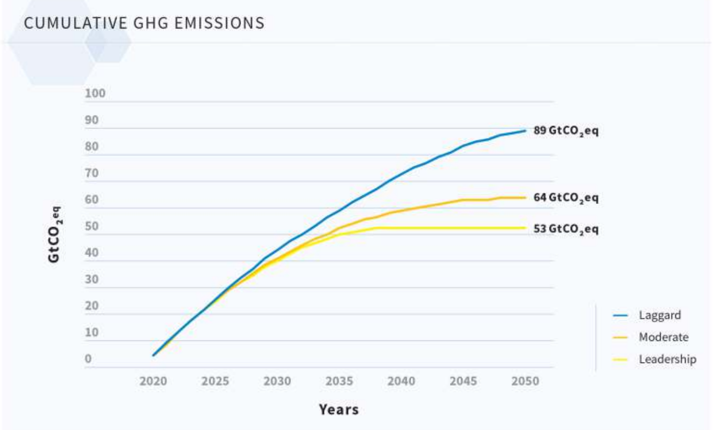
- full hourly resolution, applied in global-local studies, comprising about 120 technologies
- used for several major reports, in about 50 scientific studies, published on all levels, including Nature
- strong consideration on all kinds of Power-to-X (mobility, heat, fuels, chemicals, desalinated water, CO_2)

Power-to-X: the Core of Sector Coupling



Case: Sustainable Europe

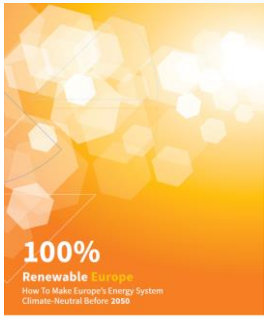




Source: SolarPower Europe.

Key insights:

- Power-to-X comprises: Mobility, Fuels, Chemicals, Heat, Steel, Desalinated Water
- Hydrogen is ONLY required, where direct electrification fails, e.g. chemicals, fuels for aviation/ marine
- Power-to-X is an essential core element for least cost zero GHG emissions and a booster for solar PV demand

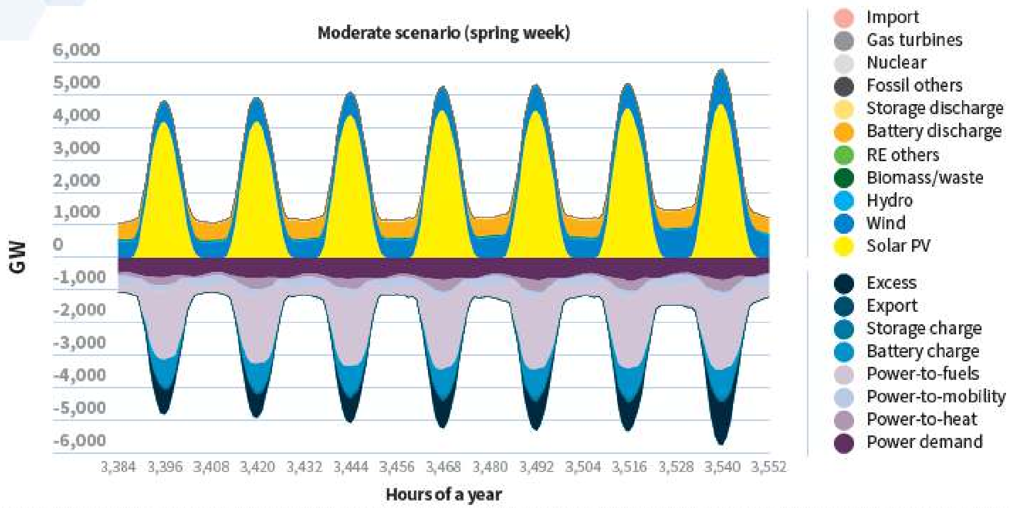


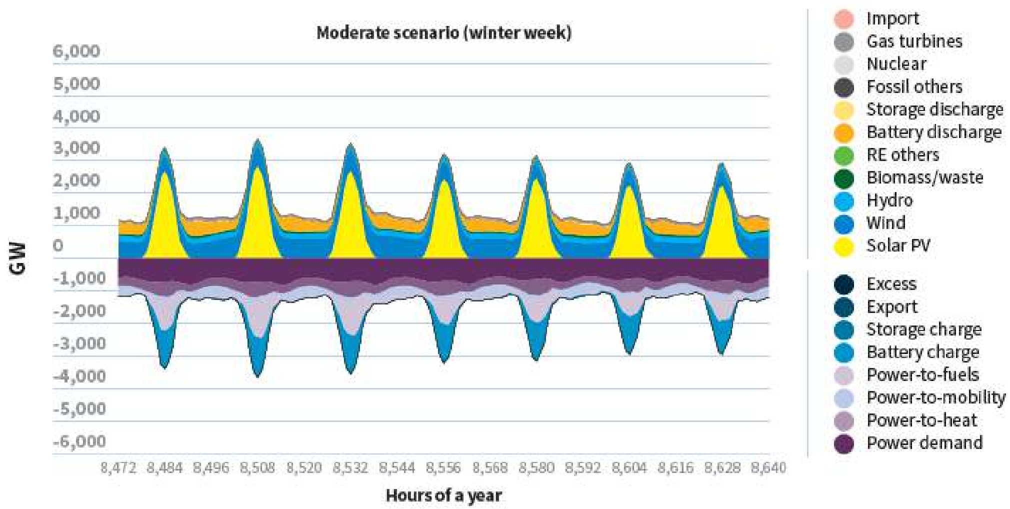
link to report

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe

Hourly Operation of the Energy System (Europe)

FIGURE 4.8 HOURLY OPERATION OF THE EUROPEAN ENERGY SYSTEM





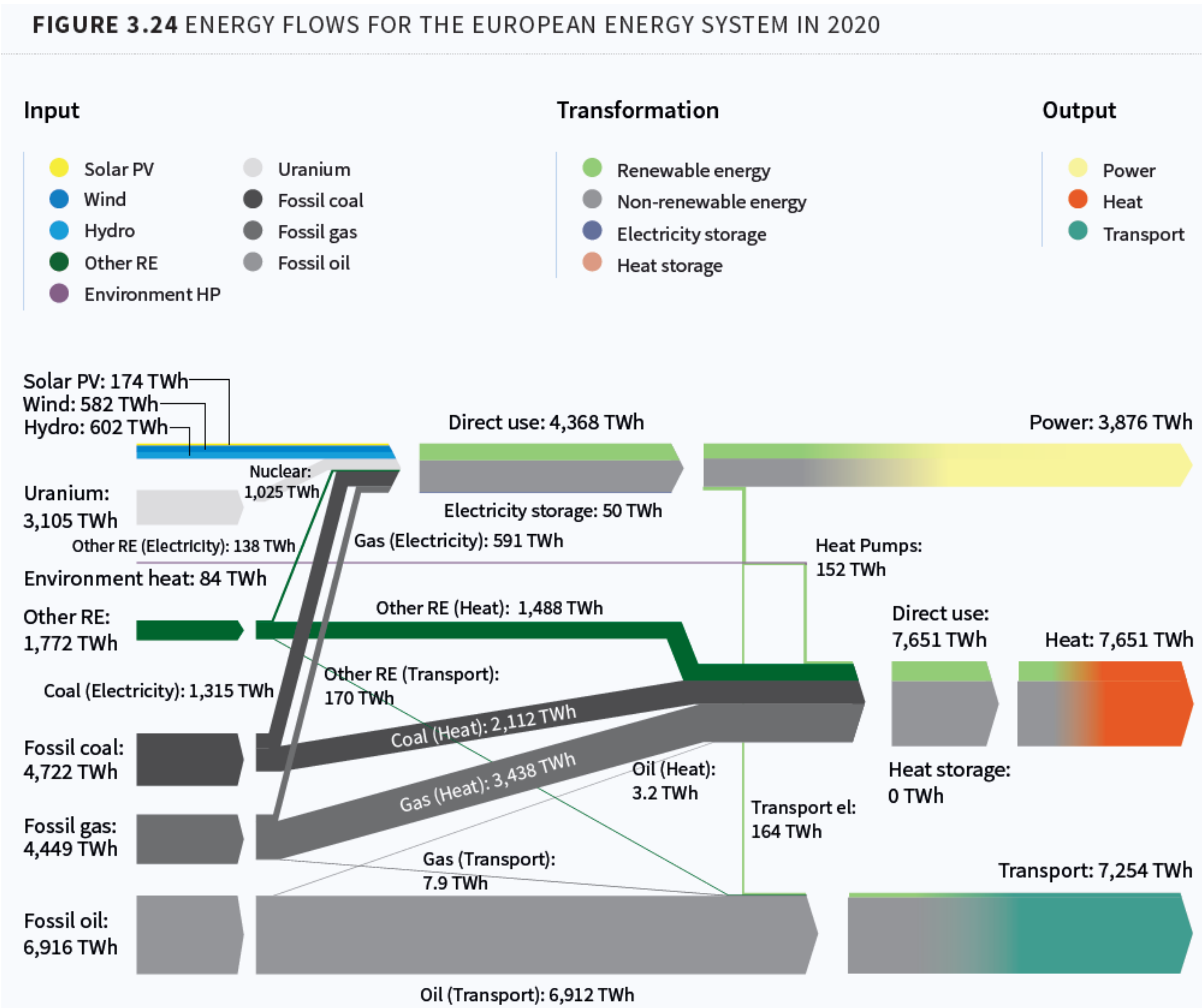
Key insights:

- Week of least renewables supply (winter) and most renewables supply (spring) is visualised
- A 100% renewables-based and fully integrated energy system in 2050 will function without fail every day of the year: Even in the dark winter days the region easily copes with energy demand
- Key balancing components are electrolysers (Power-to-fuels) which convert electricity to hydrogen, when electricity is available, but drastically reduce their utilisation in times of low electricity availability
- Massive ramp rates in the energy system have to be managed, as well as forecasting errors require balancing
- Collaboration with SolarPower Europe.

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe

Energy System Structure: Present (Europe)

Open your mind. LUT.
Lappeenranta University of Technology



Key insights:

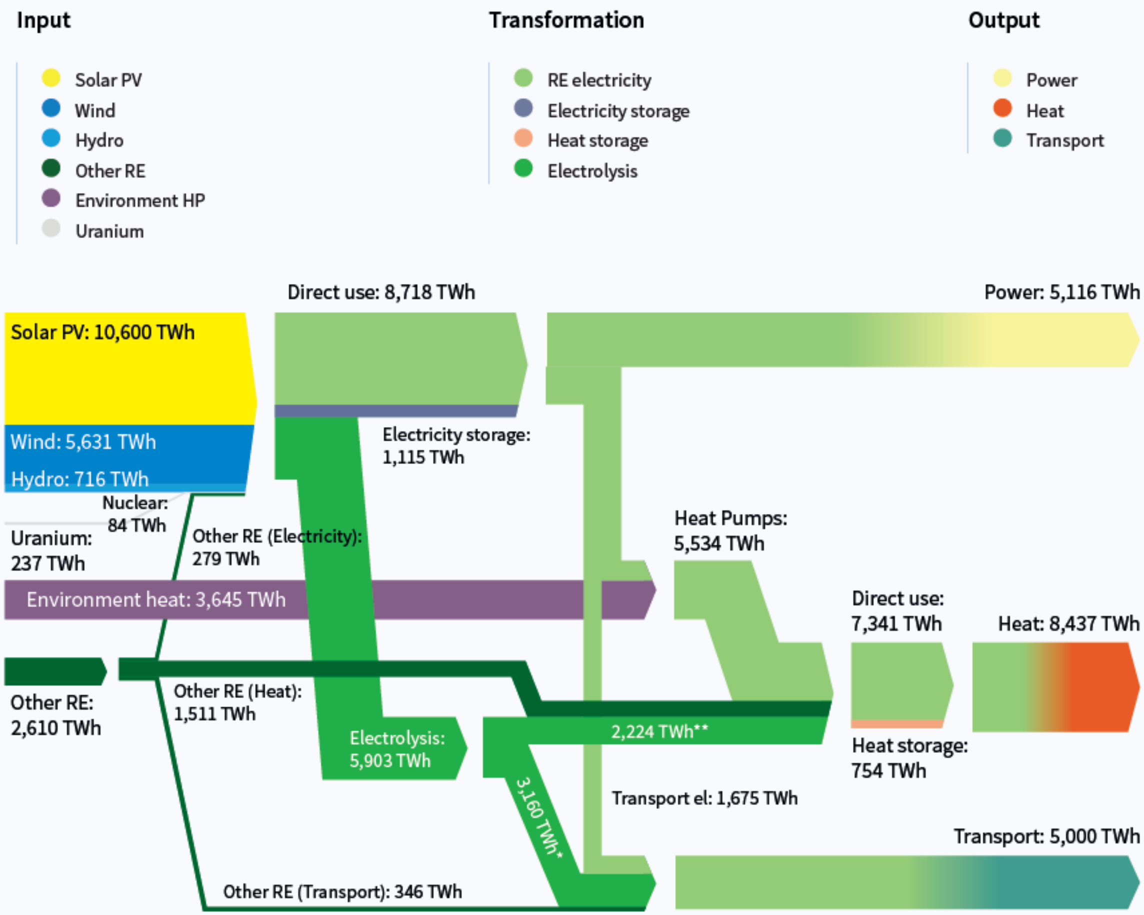
- Energy sectors (power, heat, transport) practically separated
- Dominating role of fossil fuels
- Transport sector has practically not yet started the transition

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe

Energy System Structure: Future (Europe)

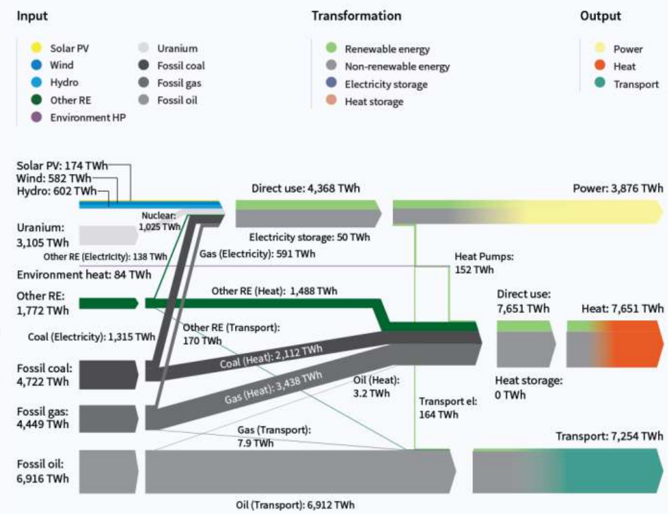
Open your mind. LUT.
Lappeenranta University of Technology

FIGURE 3.25 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN THE MODERATE SCENARIO IN 2050



*RE synthetic fuels for transport.
**RE synthetic fuels for heat, recovered heat.

FIGURE 3.24 ENERGY FLOWS FOR THE EUROPEAN ENERGY SYSTEM IN 2020

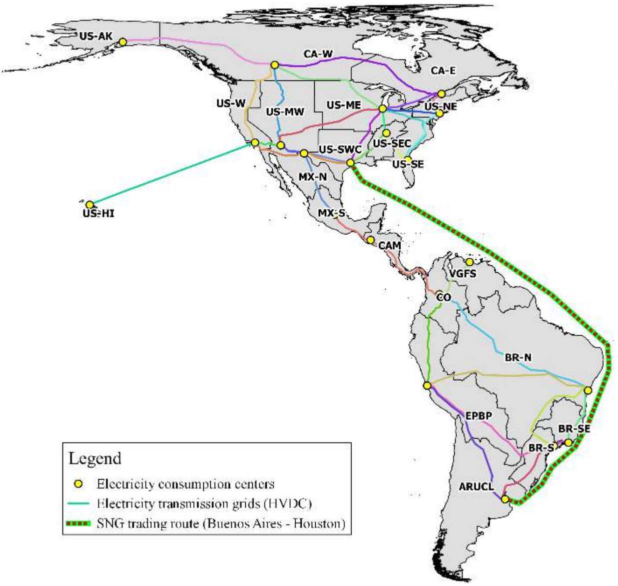


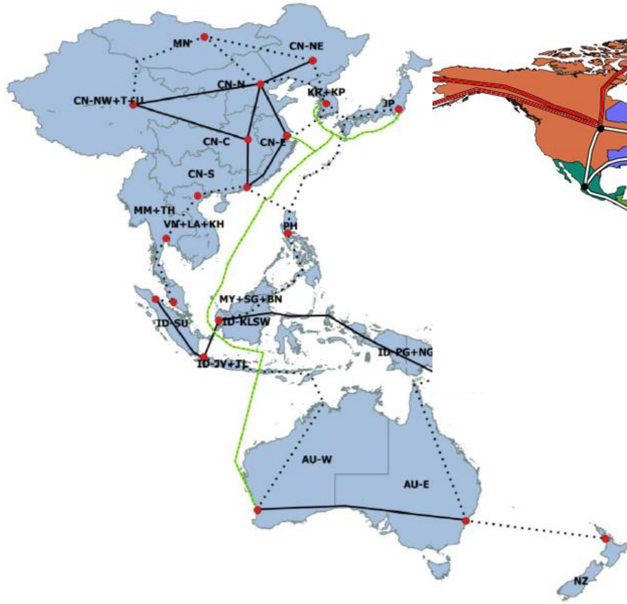
Key insights:

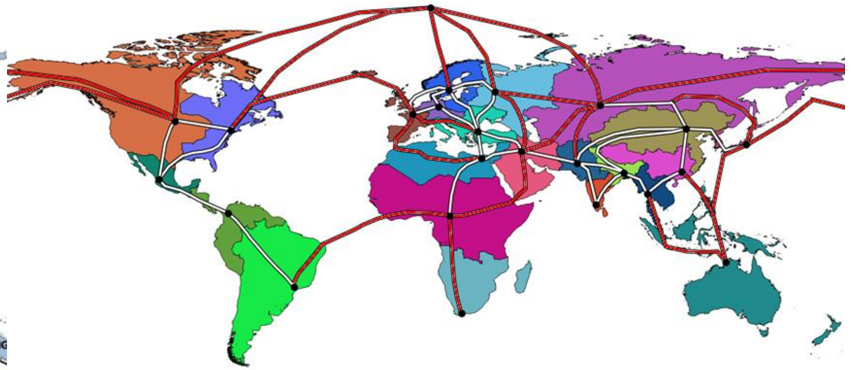
- 100% renewables will lead to strongly coupled energy system
- Most important energy carrier is electricity, while second most important is green hydrogen
- Fossil and nuclear fuels are not part of a sustainable and least cost energy system

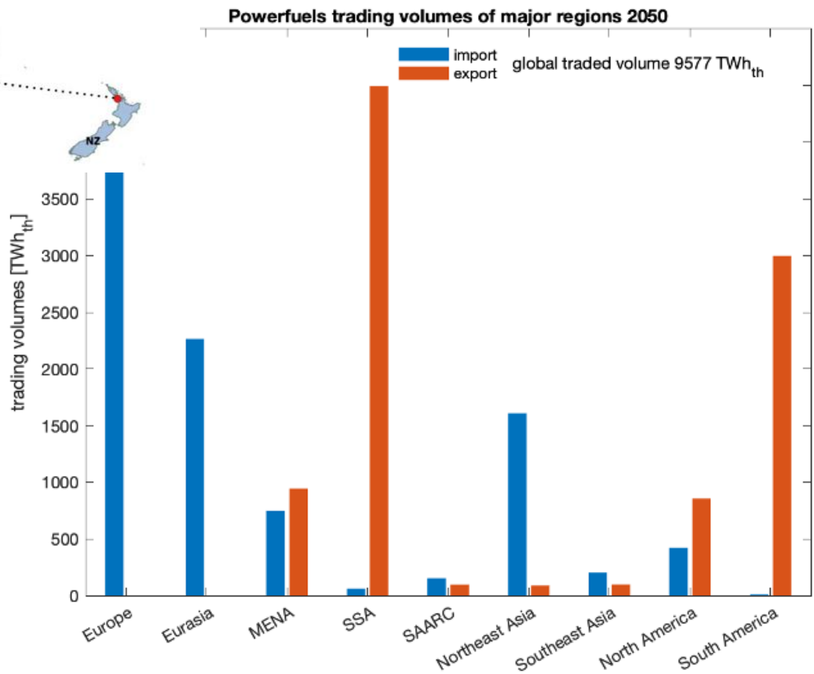
source: [SolarPower Europe/ LUT, 2020. 100% Renewable Europe]

Regional and Global Super Grids







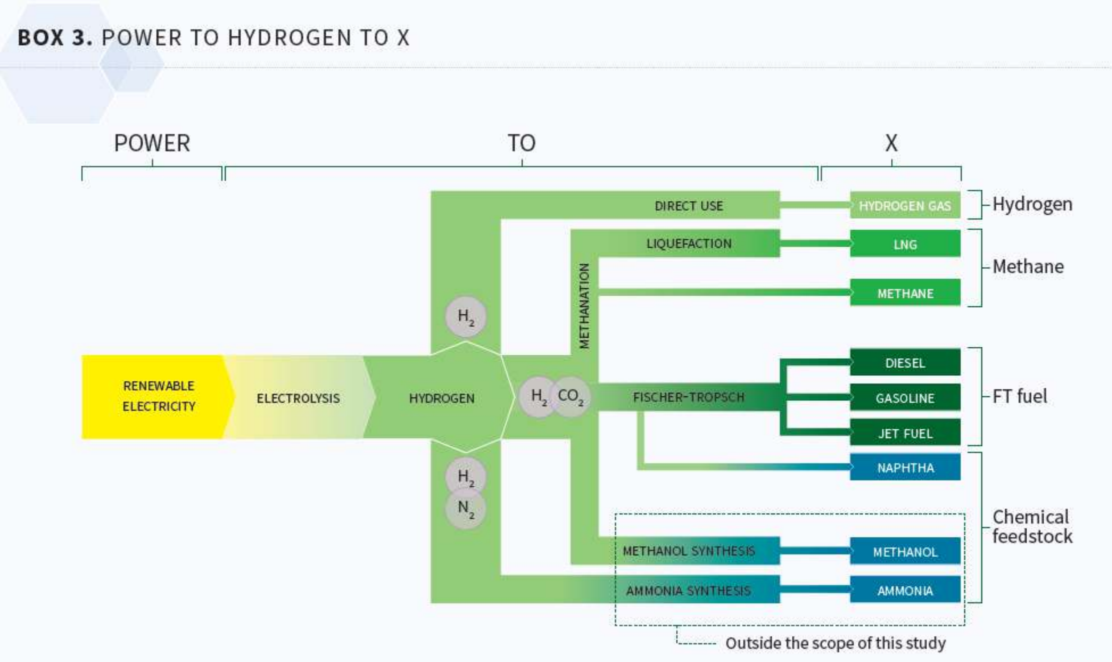


Key insights:

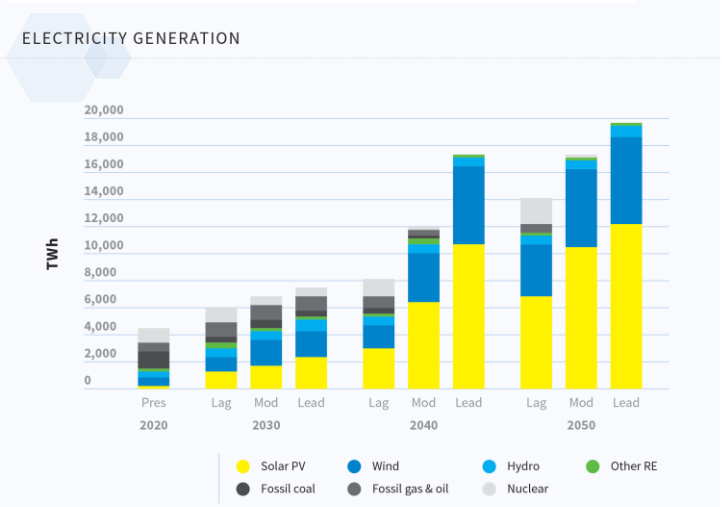
- What's the value add of very large Super Grids?
- Grids on a major region level (SAARC, Europe, etc.) reduce the system cost by about 10% by resource balancing, compared to state/ country level optimisation.
- The higher the solar PV share, the lower the balancing value.
- Integration beyond major region level, e.g. Americas North & South, Europe & Eurasia & MENA, Asia Northeast & Southeast, leads to negligible further cost reductions of about 1%.
- PtX powerfuels/ chemicals trade will generate substantial value.

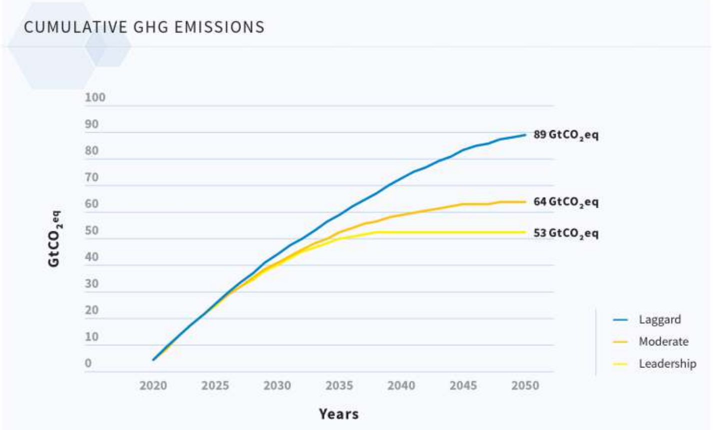
source: Aghahosseini et al., 2019. Renew Sustain Energy Rev 105, 187-205; Gulagi et al., 2017. Energies 10, 583; Breyer et al., 2020. EEEP 9, 83-102

Power-to-X: the Core of Sector Coupling



Case: Sustainable Europe

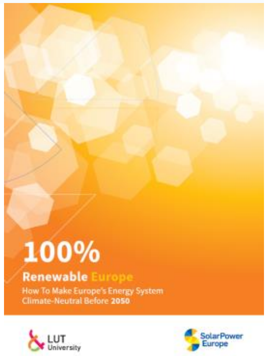




Source: SolarPower Europe.

Key insights:

- Power-to-X comprises: Mobility, Fuels, Chemicals, Heat, Steel, Desalinated Water
- Hydrogen is ONLY required, where direct electrification fails, e.g. chemicals, fuels for aviation/ marine
- Power-to-X is an essential core element for least cost zero GHG emissions and a booster for solar PV demand

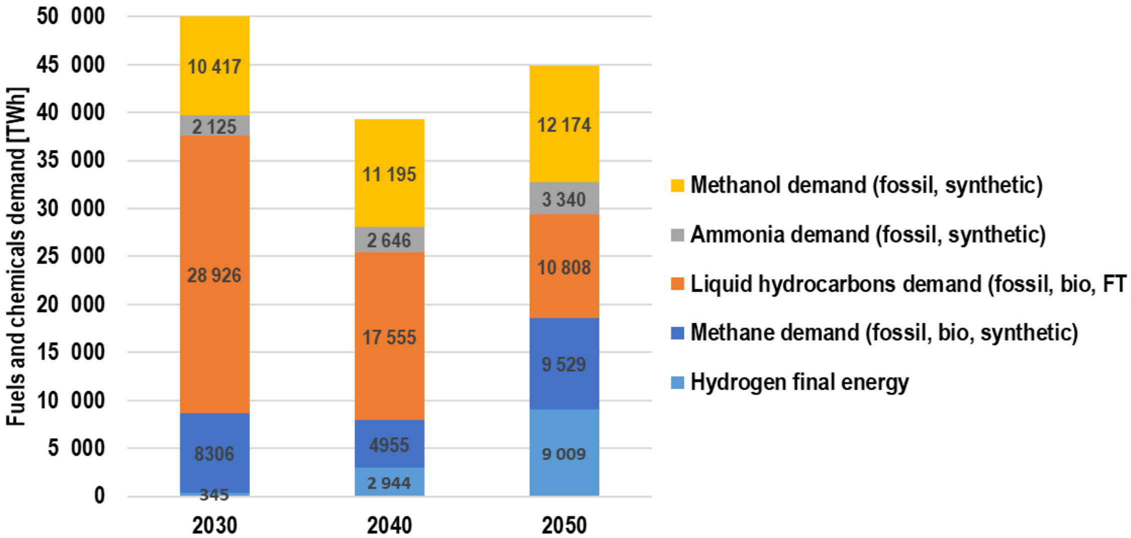


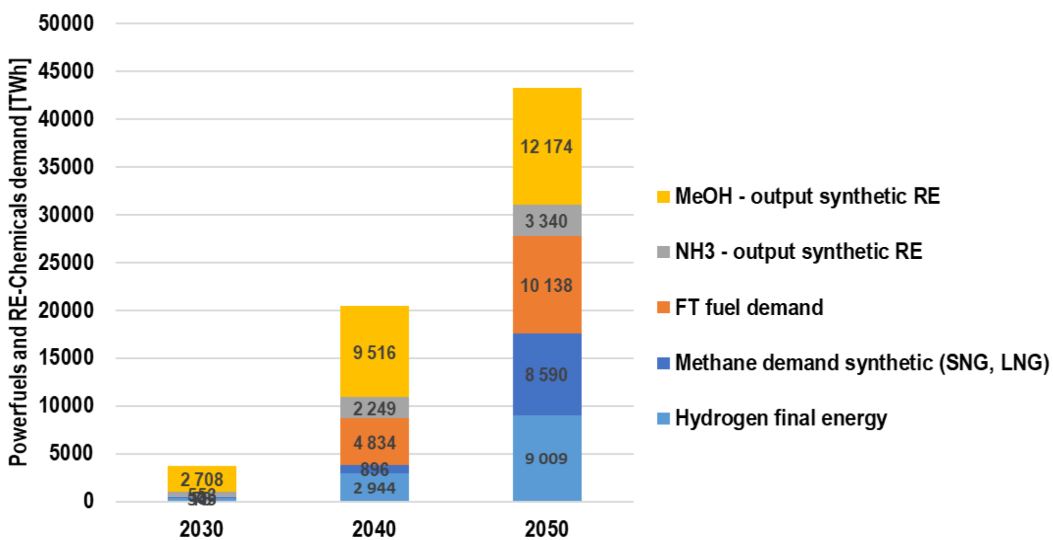
link to report

Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

source: SolarPower Europe/ LUT, 2020. 100% Renewable Europe

Results





Fuels and Chemicals in general:

- steady growth of chemicals, whereas Methanol represents non-Ammonia chemicals feedstock equivalent
- liquid hydrocarbons are in steady decline, mainly due to electrification of road transportation
- Methane demand in decline until 2040 with increase towards 2050, with some uncertainty for substitution of Methane by Hydrogen

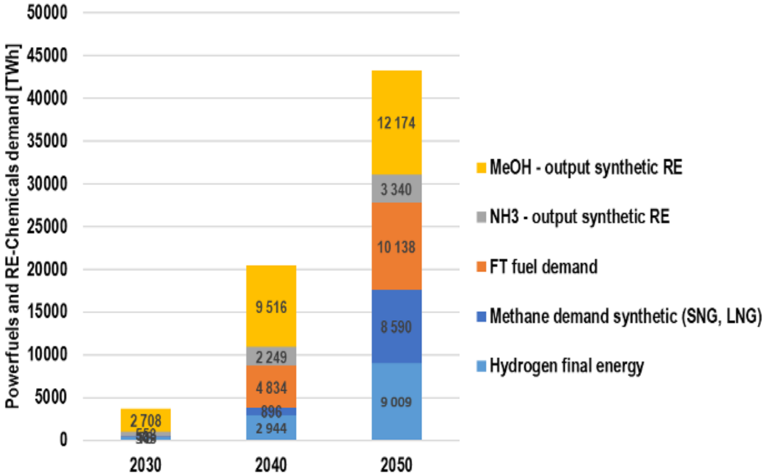
Synfuels and synthetic Chemicals:

- first markets in 2030
- strong growth until 2040, continued until 2050
- less uncertainty for synthetic Chemicals
- highest uncertainty for Methane demand due to substitution by Hydrogen (heat) and Ammonia/Methanol (marine)
- sustainable bioenergy for Fuels

Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE
source: dena/LUT, 2020. Powerfuels in a Renewable Energy World, upcoming report

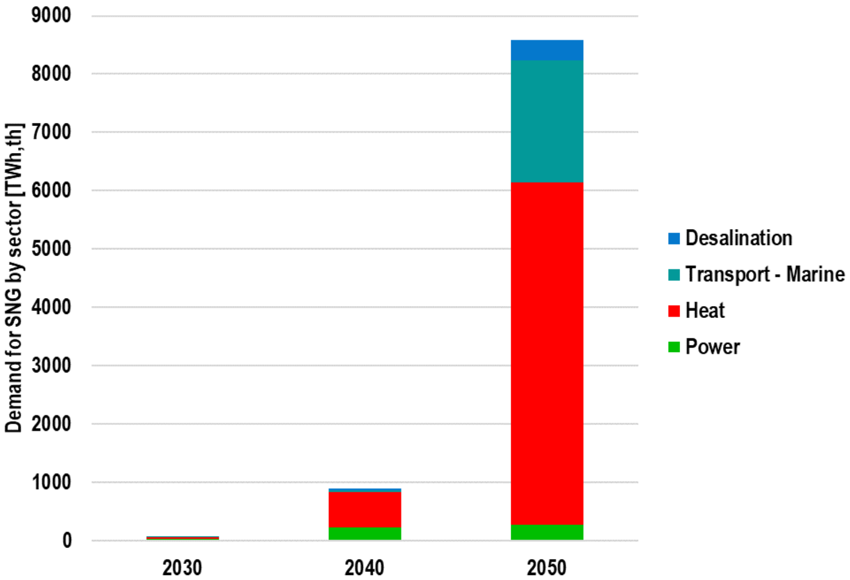
Open your mind. LUT.
Lappeenranta University of Technology

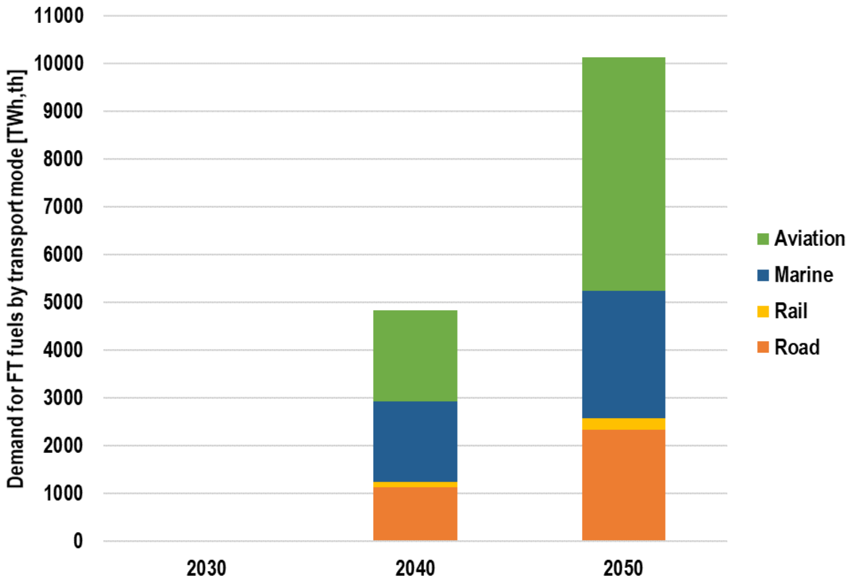
Details for Methane and FT fuels markets



Methane (SNG) and Fischer Tropsch markets:

- Phase-out of fossil gas does not necessarily lead to SNG phase-in, in particular not in the power sector
- High temperature heat demand requires SNG
- Marine fuel may require SNG/LNG, while ammonia and methanol may gain high shares
- Aviation requires highest share of FT fuels
- Marine and Road demand for FT fuels is more uncertain
- Green Hydrogen is the basis for these synthetic fuels

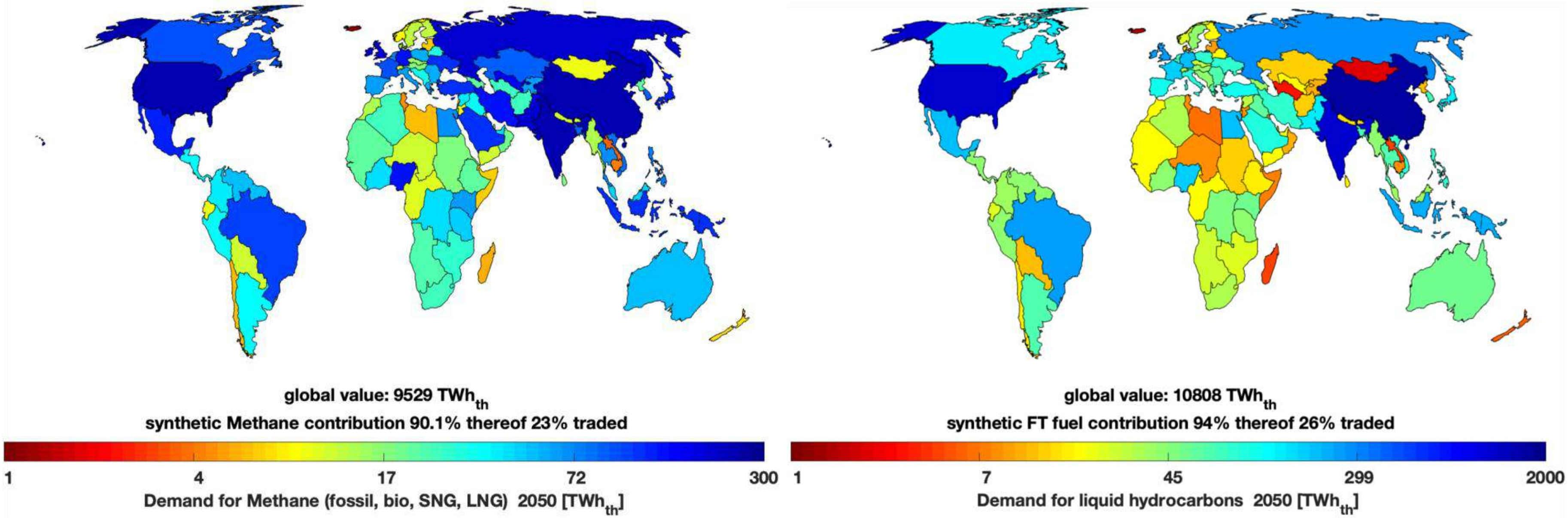




Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

source: dena/LUT, 2020. Powerfuels in a Renewable Energy World, upcoming report

Global demand distribution: SNG/FT fuels



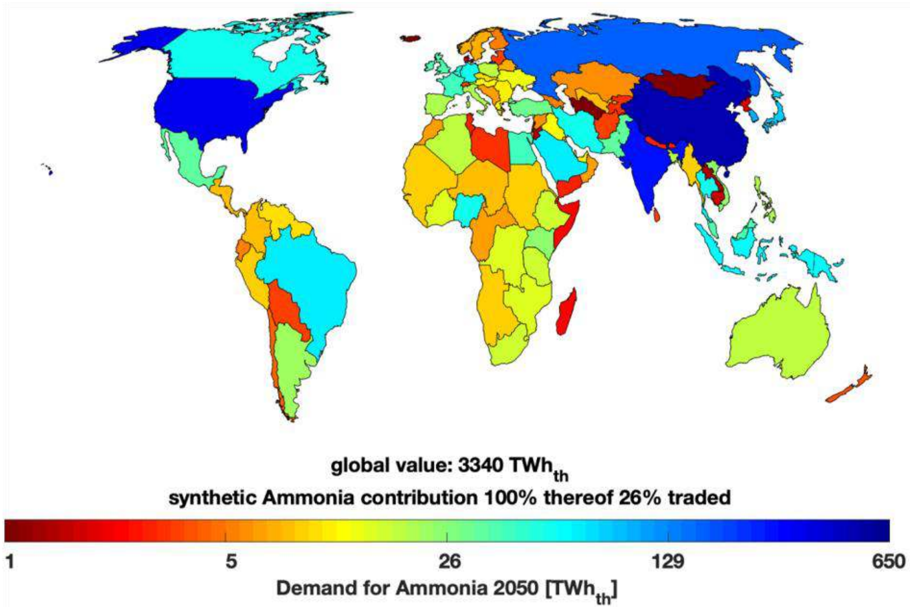
Key insights:

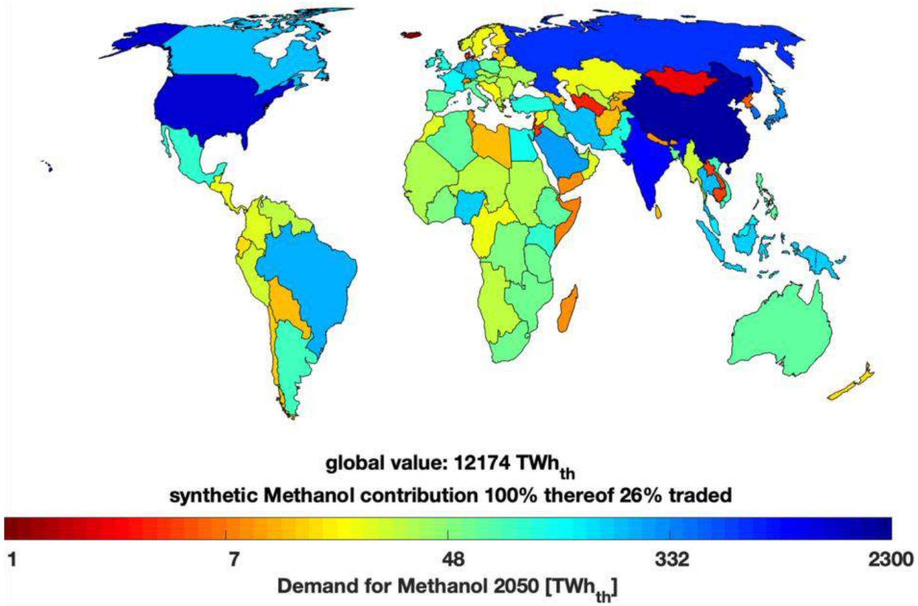
- **Dominant share (90%) of methane demand based on green hydrogen, thereof 23% traded, rest local**
- **Large green hydrogen based methane markets in North America, Europe, South and Northeast Asia**
- **FT fuels dominate the sustainable liquid fuels market (94% share), as biofuels are strongly limited**
- **Large green hydrogen based FT fuels markets similar to SNG**
- **Green hydrogen is the basis for these synthetic fuels**

source: dena/LUT, 2020. Powerfuels in a Renewable Energy World, upcoming report

Global demand distribution: Ammonia, MeOH

Open your mind. LUT.
Lappeenranta University of Technology



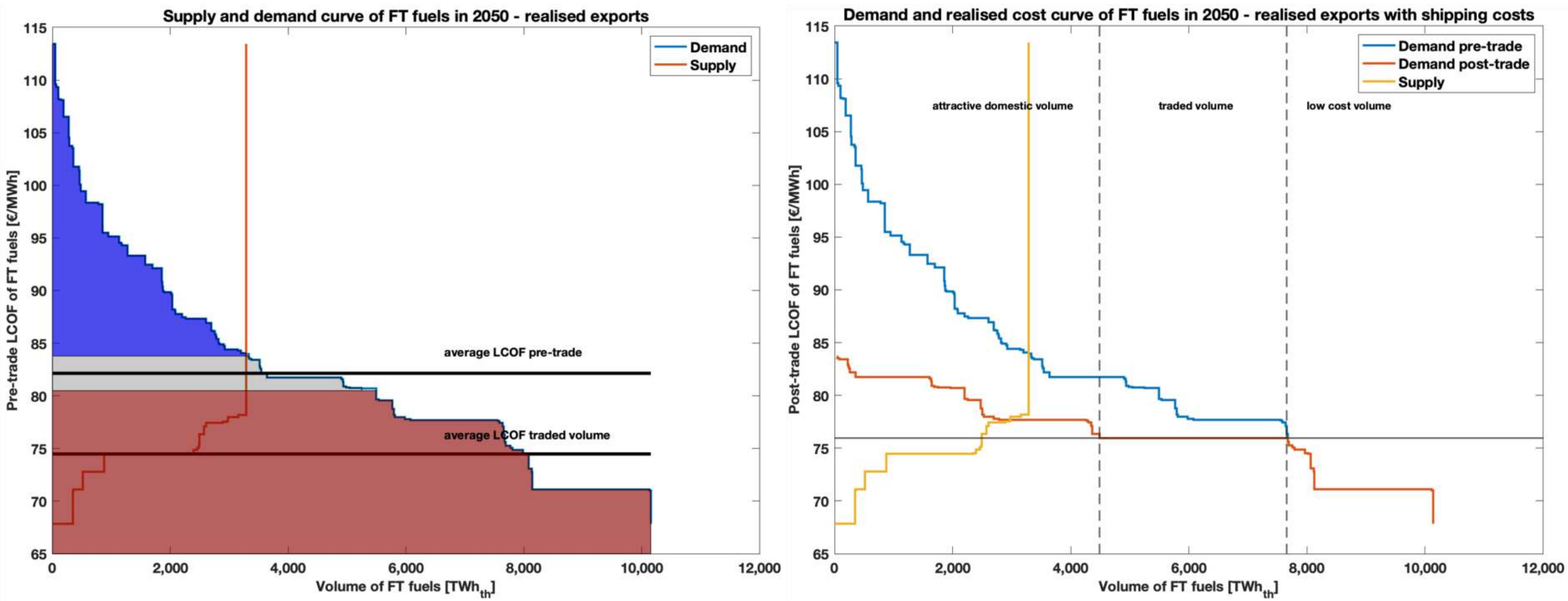


Key insights:

- **Ammonia is the basis for fertilisers, but can be also used as fuel, in particular for marine transport**
- **Methanol is expected to become the dominant new bulk chemical for multi-use, e.g. plastics, however, methanol could be also used as fuel, in particular for marine transport**
- **Similar to SNG/FT, about a quarter may be traded, thus most demand could be domestically supplied**
- **Demand distribution similar to SNG and FT fuels: North America, Europe, South and Northeast Asia**
- **Green hydrogen is the basis for these synthetic fuels**

source: dena/LUT, 2020. Powerfuels in a Renewable Energy World, upcoming report

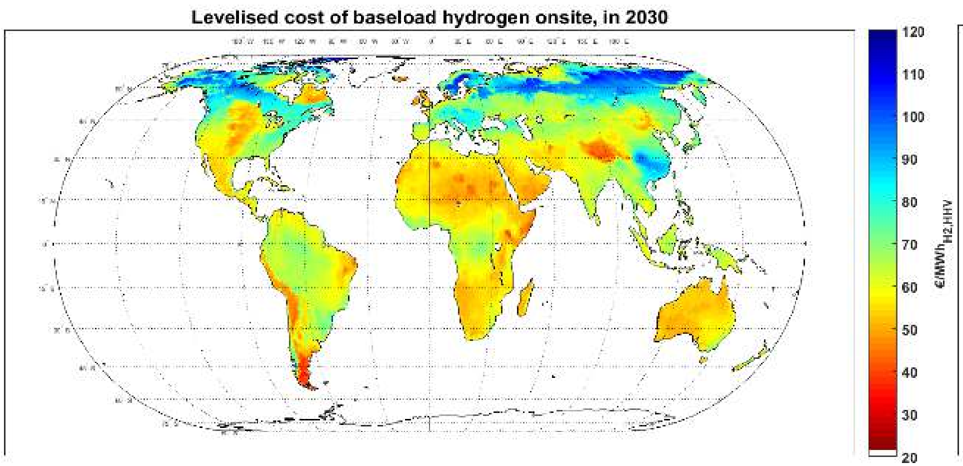
Global trading of synthetic fuels: case FT

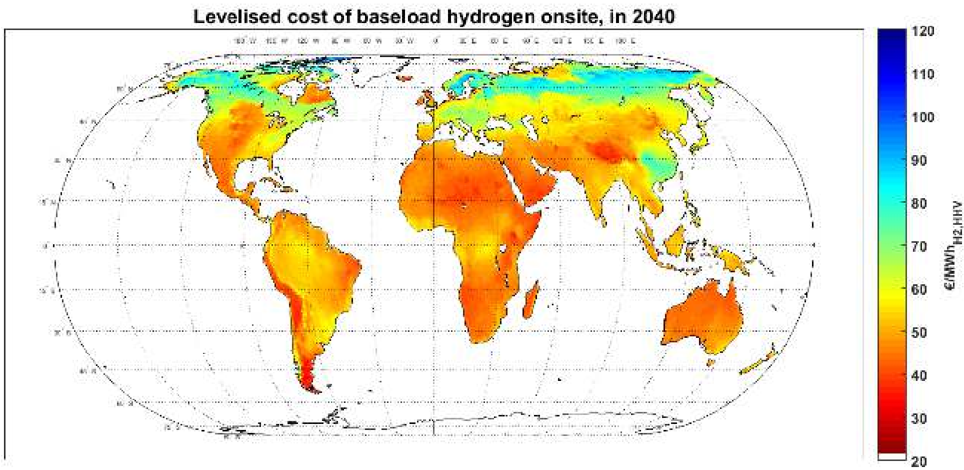


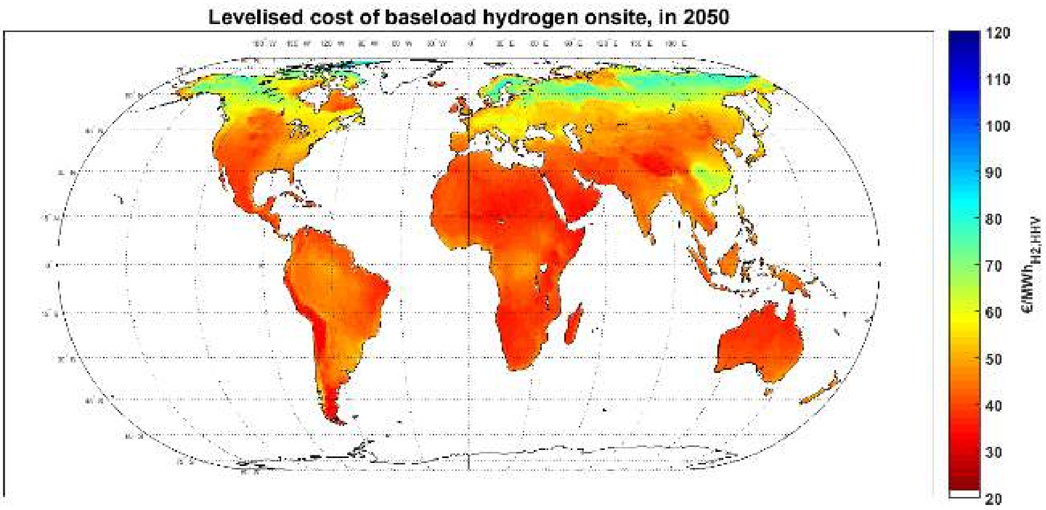
Key insights:

- Global trading model has been established, based on 145 regions, aggregated to 92 countries/regions
- Global average levelised cost of fuels has been defined as separator for imports and exports
- Exporter attractiveness has been introduced: cost, volume, political stability
- About a quarter of the global demand may be traded
    - Key importers: Europe, Japan, Russia, but even countries of the Sun Belt
    - Key exporters: South America, sub-Saharan Africa
- Most countries in the world can opt for domestic self-supply
- Green hydrogen is the basis for Fischer-Tropsch fuels

Green Hydrogen Cost Potential





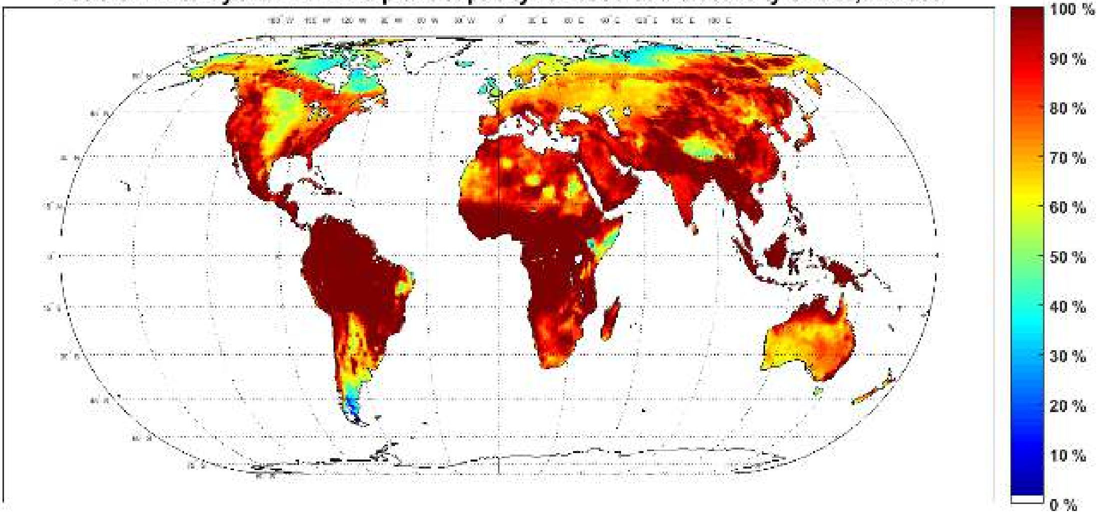


Key insights:
- Green hydrogen cost continuously decline
- Latest PV cost decline may lead to 10-20% lower cost as shown here
- 30-40 €/MWh$_{H2}$ green hydrogen cost may be available in many parts of the world
- Fossil gas price range assumed 15-25 €/MWh$_{th}$, thus CO_2 emission price needed

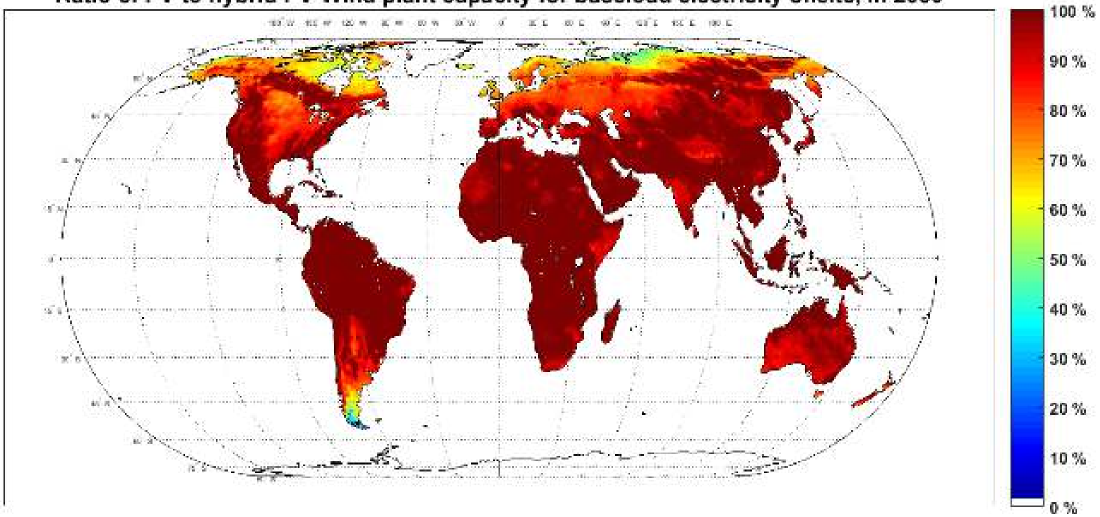
source: [Fasihi and Breyer, 2020. Baseload electricity and hydrogen supply based on hybrid PV-Wind power plants, Journal of Cleaner Production, 243, 118466]

Electricity used for Green Hydrogen

Ratio of PV to hybrid PV-Wind plant capacity for baseload electricity onsite, in 2030



Ratio of PV to hybrid PV-Wind plant capacity for baseload electricity onsite, in 2050



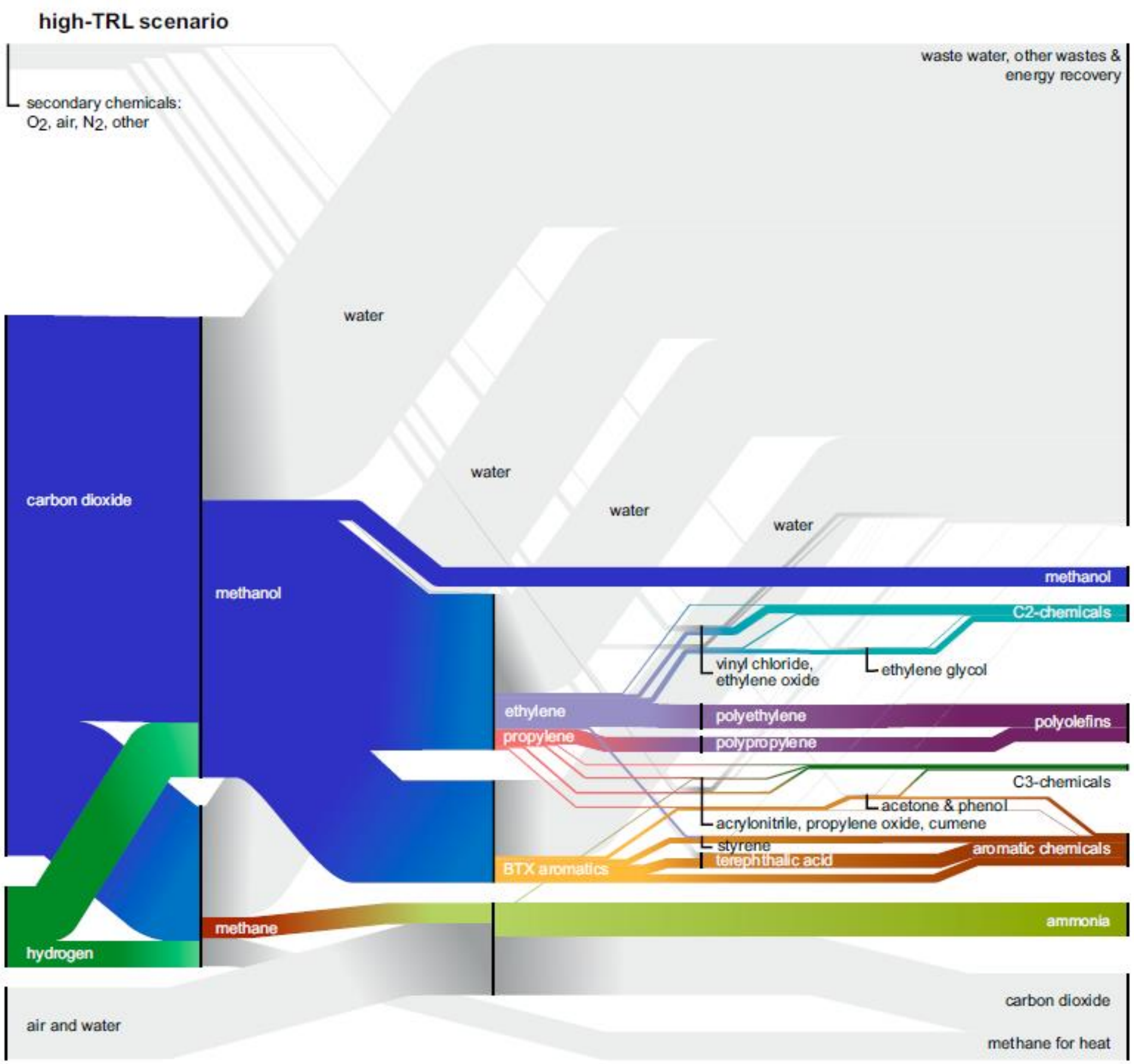
Key insights:

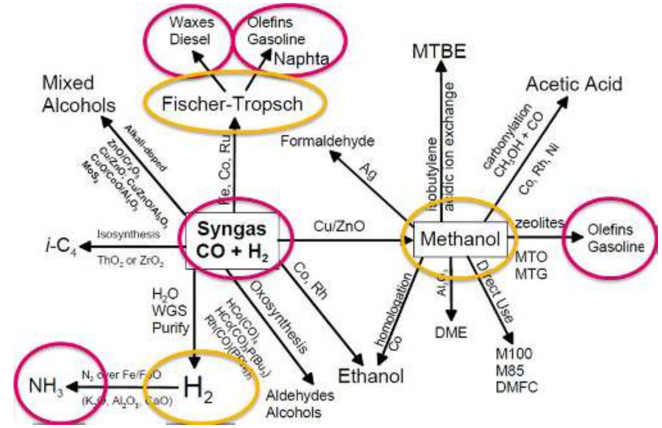
- Considered had been the scalable sources of electricity: PV and wind
- Area limitations have been factored in
- 2030: PV is already very strong in may parts of the world, typically contributing more than 50% for least cost green hydrogen
- 2050: most parts in the world are dominated by PV supply, while best wind sites contribute up to 30% for least cost green hydrogen, typically during winter and rainy seasons
- Bifacial PV is not yet factored in, but may push the shares further towards PV

- Summing up, PV emerge the THE low-cost electricity source for green hydrogen

source: Fasihi and Breyer, 2020. Baseload electricity and hydrogen supply based on hybrid PV-Wind power plants, Journal of Cleaner Production, 243, 118466

Green Hydrogen in industry: Chemicals



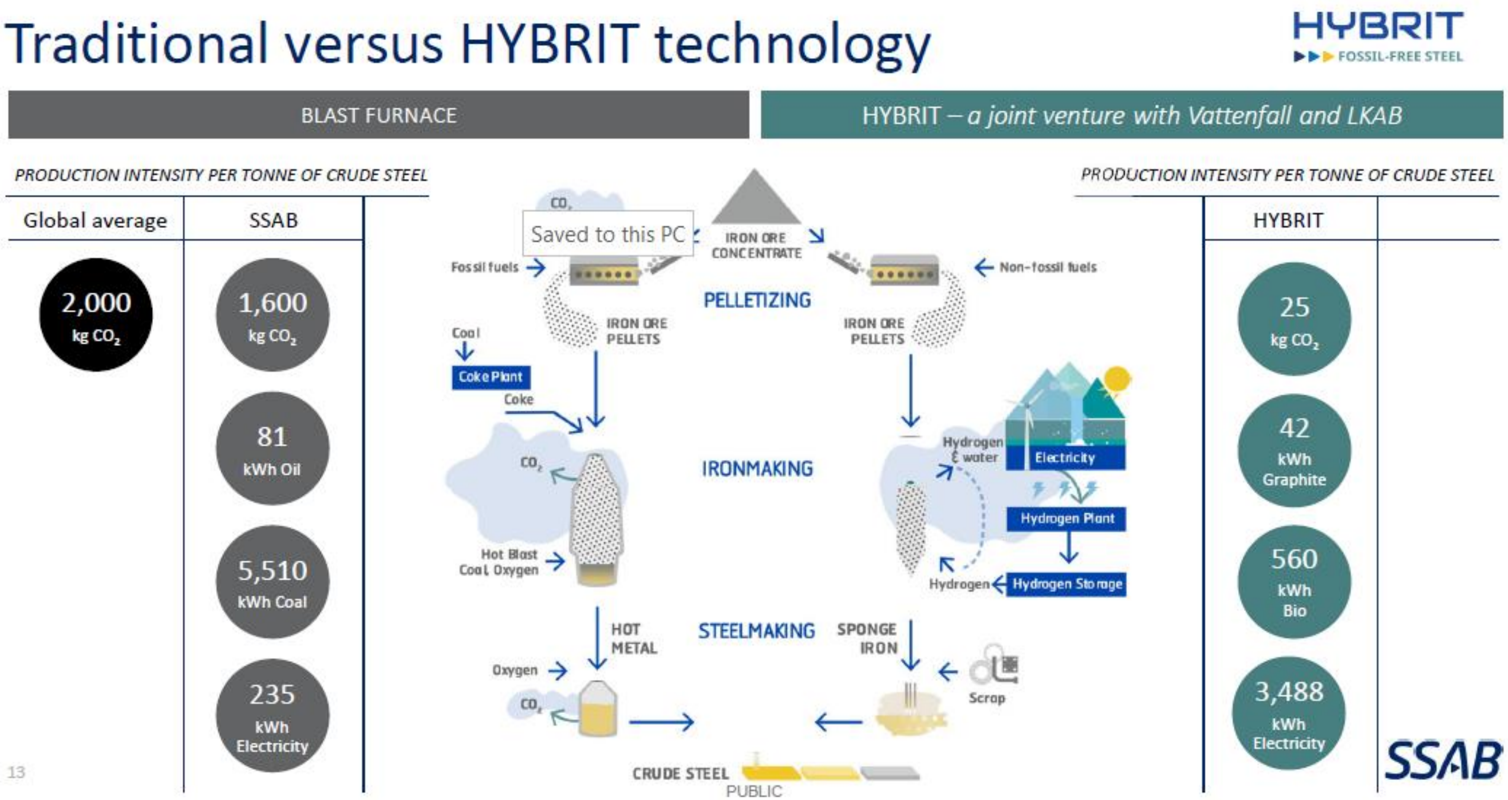


Key insights:

- Methanol seems to become the new key bulk chemical
- Ammonia can be produced with green hydrogen
- What's needed low-cost electricity, water (for hydrogen) and air (for CO_2)
- Global electricity demand for a sustainable chemical industry may be around 25,000 TWh_{el} in 2050

source: Kätelhön et al., 2019, PNAS.

Green hydrogen in industry: Iron & Steel



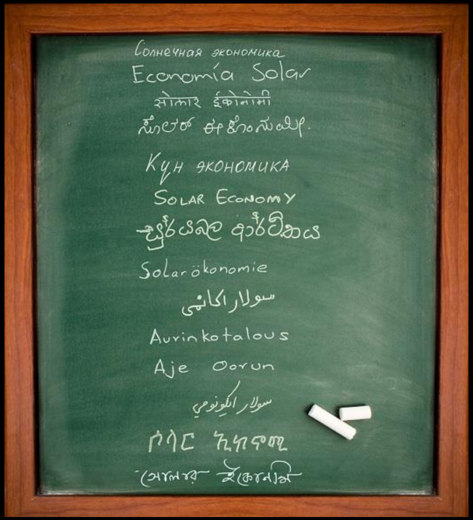
Key insights:

- coal is mainly substituted by green hydrogen
- electricity is needed for the Electric Arc Furnace process (as today's steel recycling), but also for green hydrogen
- little carbon is needed for steel as a material and can be taken from biomass or CO2 direct air capture
- global electricity demand for a sustainable steel industry may be around 5,000 TWh_{el} in 2050
- all GHG emissions can be avoided.

Summary

- Cost decline of PV is stable since 1950s
- Practically unlimited solar resource potential for energy supply
- Electrification of all energy sectors will boost PV demand
- 100% RE scenarios since 1975 and analytic global scenarios since 1996
- PV shares in global scenarios increases continuously: 70-80% may be the limit
- Key supporting technologies for PV are batteries, electrolysers and CO_2 DAC
- PV-based green hydrogen enables solutions for hard-to-abate sectors
- Green hydrogen is the basis for direct hydrogen use, but also in particular for further synthesis to SNG, Fischer Tropsch fuels, ammonia and methanol
- Strong sector coupling is a major driver for PV
- The Solar Age is a key opportunity to fix multiple issues, first of all climate change

Thank you for your attention …
… and to the team!



SCIENTISTS FOR FUTURE

NEO CARBON ENERGY
TRUST IN RENEWABLE.

all publications at: www.scopus.com/authid/detail.uri?authorId=39761029000
new publications also announced via Twitter: @ChristianOnRE

Open your mind. LUT.
Lappeenranta University of Technology