Energy transitions at all scales
- an introduction to energy systems analysis and energy systems optimization models

Manuel Wetzel, Institute of Networked Energy Systems, Energy Systems Analysis

University of Canterbury, guest lecture

February 22nd 2024

DLR

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Deutsches Zentrum für Luft- und Raumfahrt

German Aerospace Center

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Institute of Networked Energy Systems

- Space Administration
- Research institution
- Project Management Agency

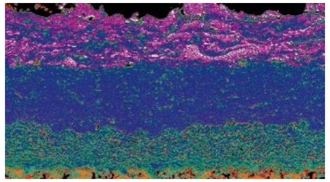
- Aviation
- Space
- Transport
- Energy
- Security (cross-topic)

Energy Systems Analysis

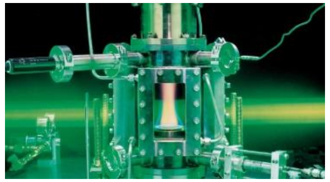
Energy System Technologies

Solar Energy

Wind Energy



Energy Storage



Energy Converters

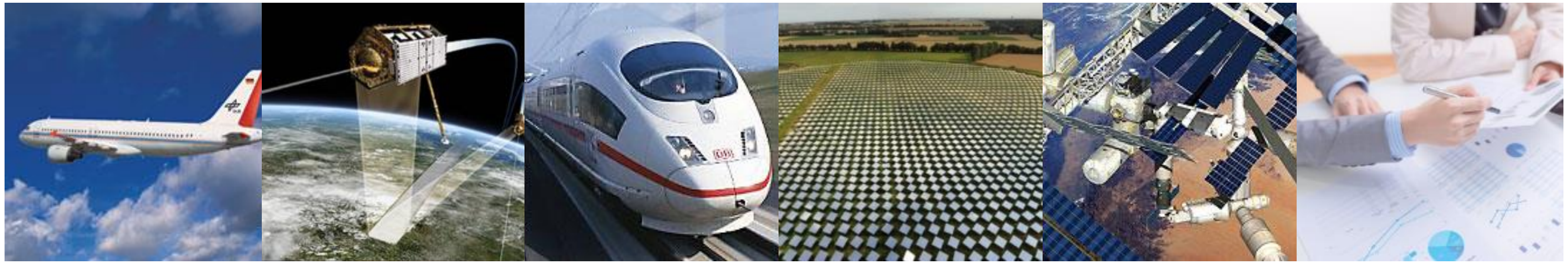


Image: Nonwarit/Fotolia

Institute of Networked Energy Systems

Buildings and districts

Technologies, operation and economics of small scale systems

Stable grids and markets

Technologies, operation and economics of large scale systems

Hydrogen in the energy system

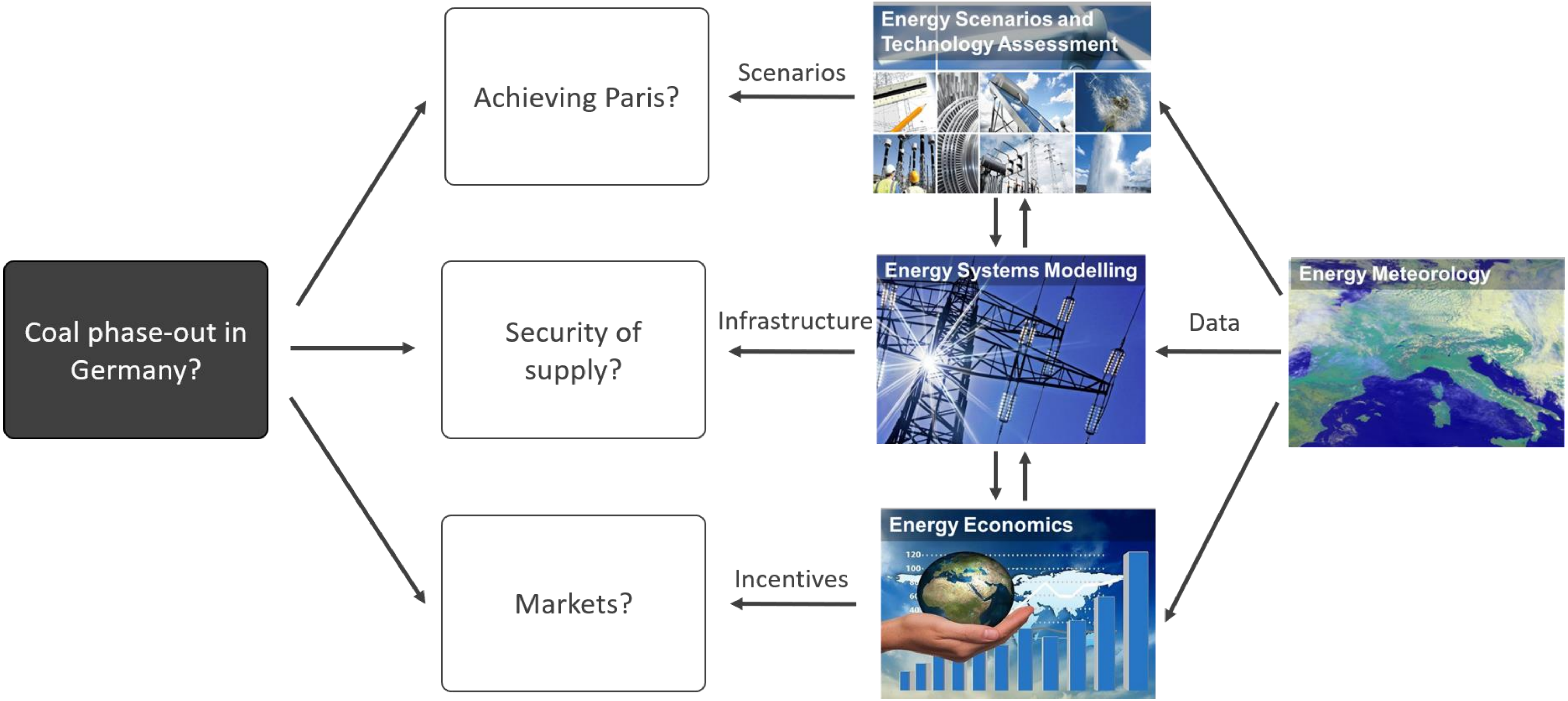
Hydrogen networks and storage for sector coupling

Sustainable supply systems

Systems modelling, transformation scenarios, technology assessment

Research and development of **technologies and concepts for future sustainable energy systems**

Energy Systems Analysis department

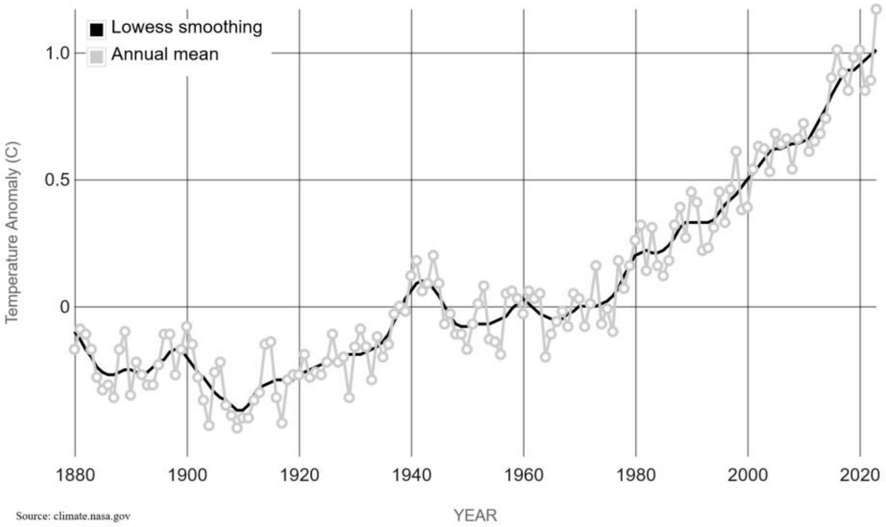


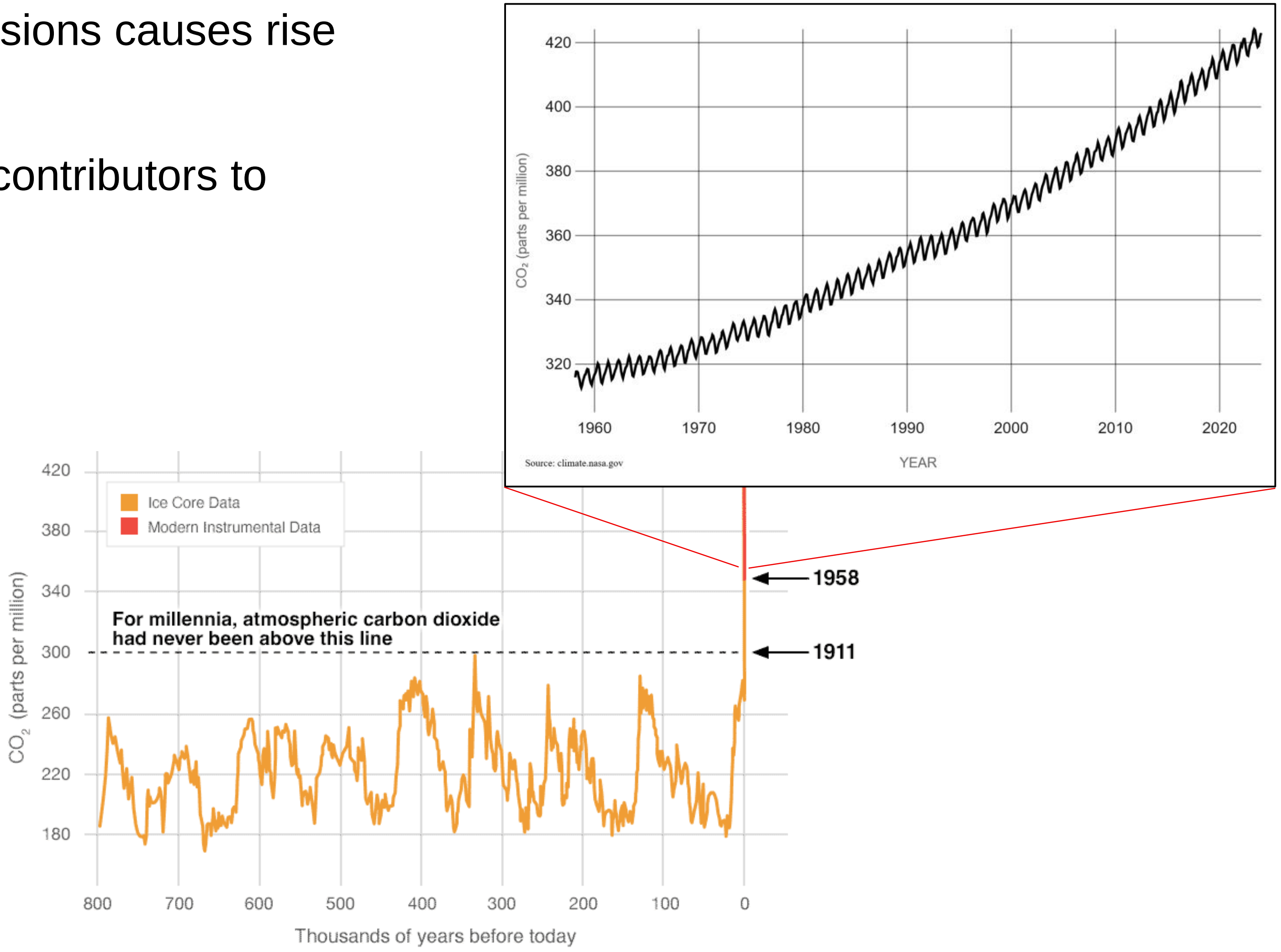
CLIMATE CHANGE AND THE ENERGY TRANSITION

Photo by Ella Ivanescu on Unsplash

Carbon dioxide and global warming

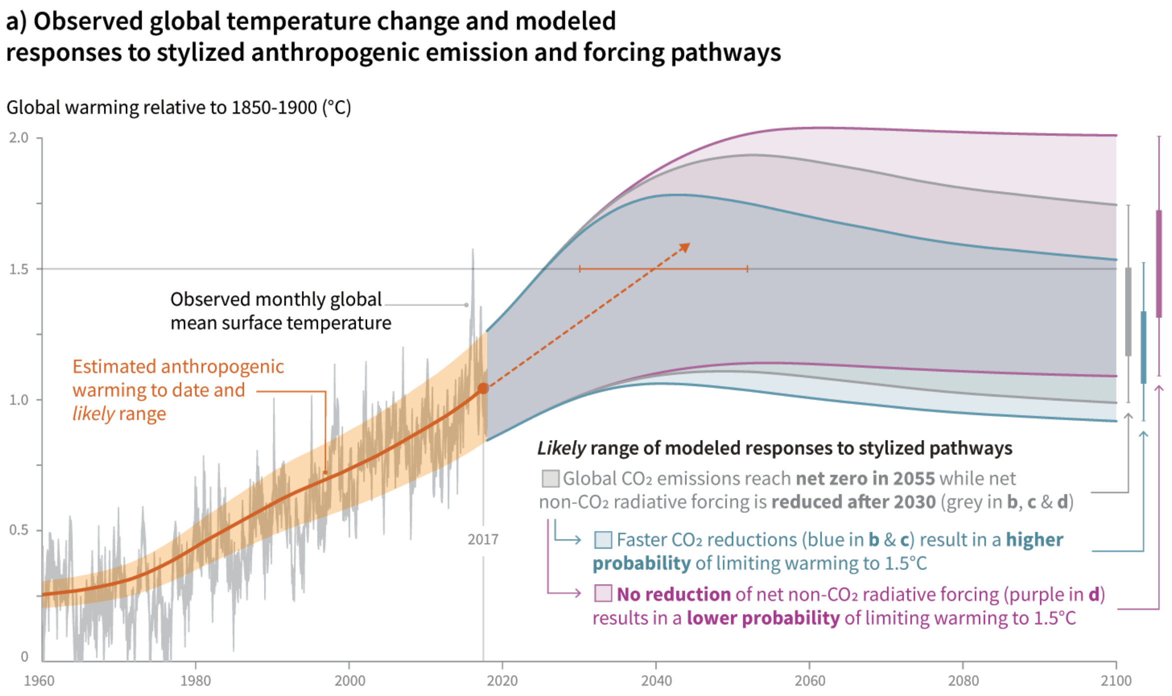
- Increase in green house gas (GHG) emissions causes rise in global temperature
- Carbon dioxide (CO_2) is one of the main contributors to GHG accumulation in the atmosphere

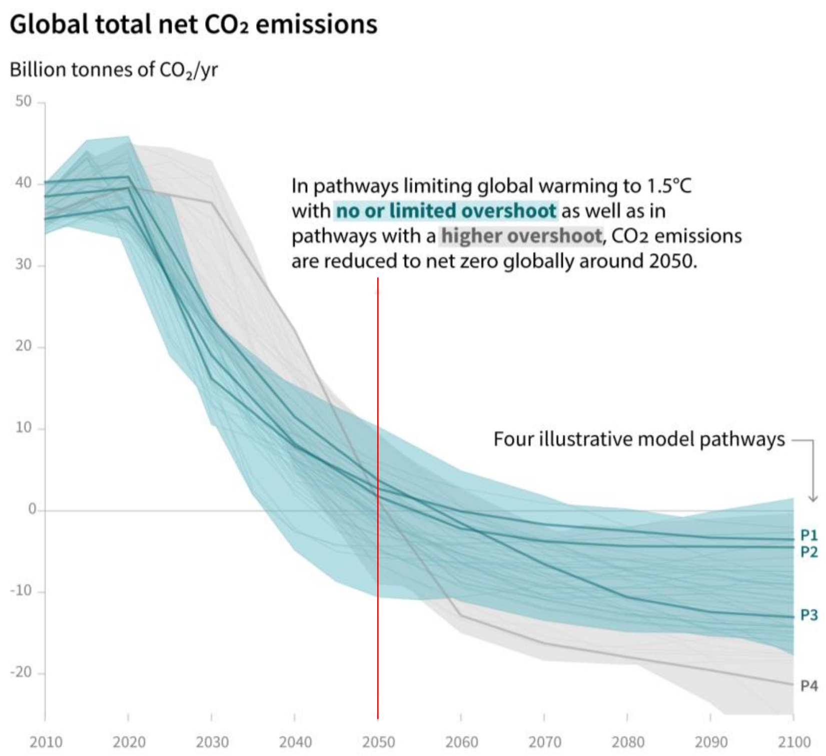




Sources: https://climate.nasa.gov/evidence
https://climate.nasa.gov/vital-signs

Reducing carbon emissions to net zero

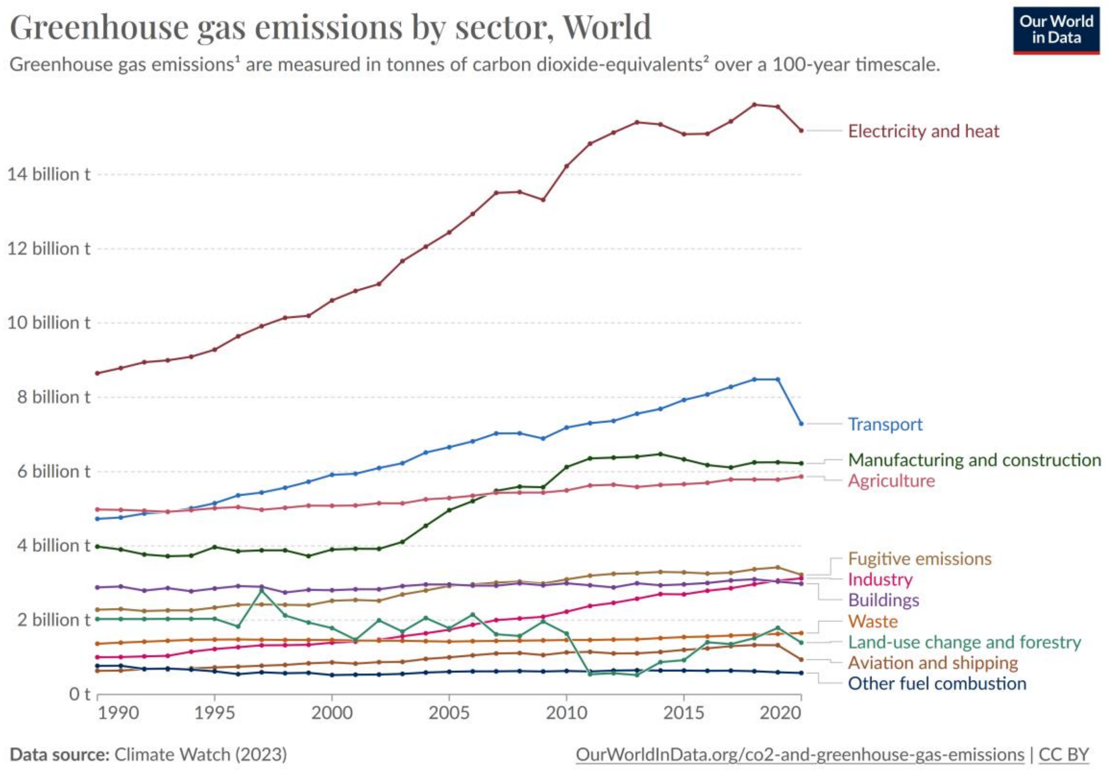


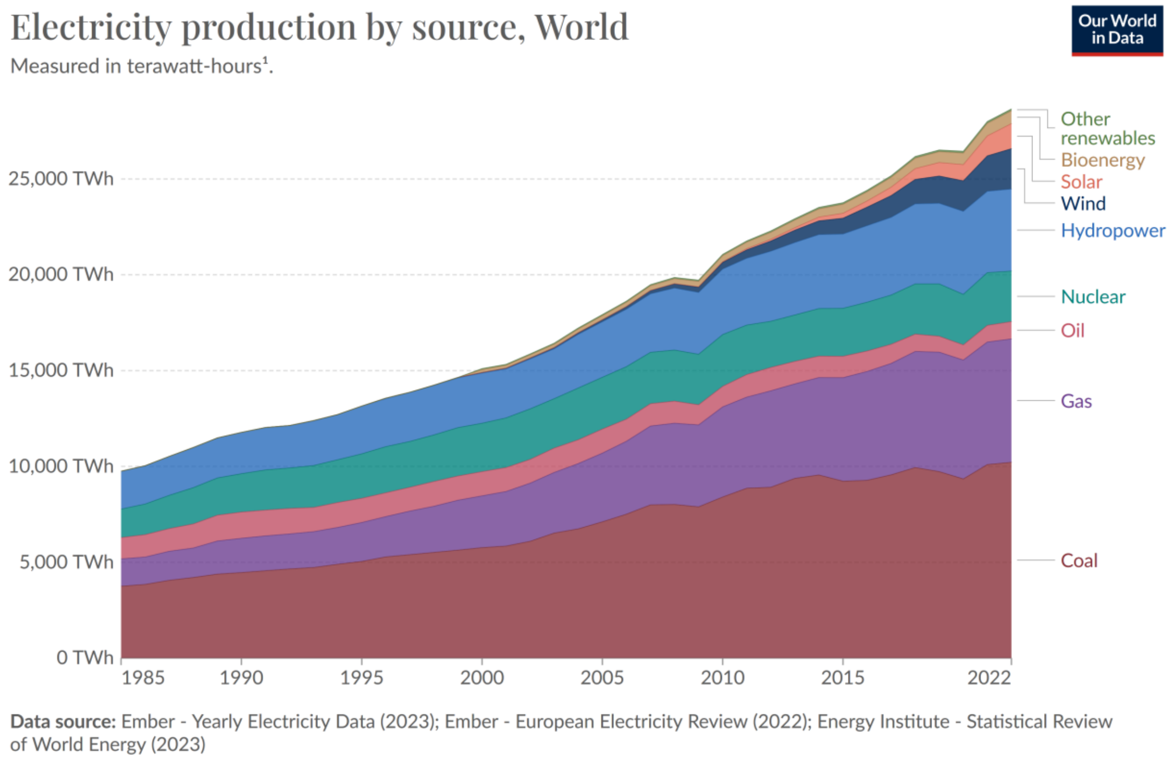


- Climate modelling allows scenario-based assessment of the future impact of GHG
- Reaching net-zero emissions by mid-century is a key milestone
- Paris Agreement as the first legally binding international treaty on global warming

Sources: https://www.ipcc.ch/sr15/chapter/spm

Where does it come from?

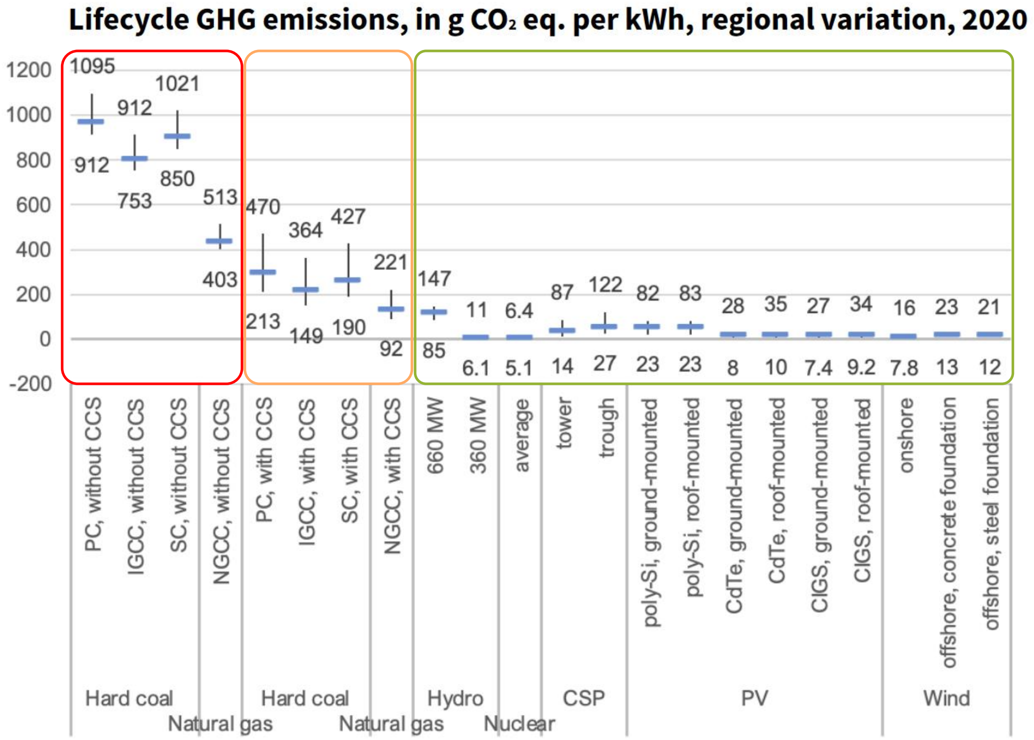


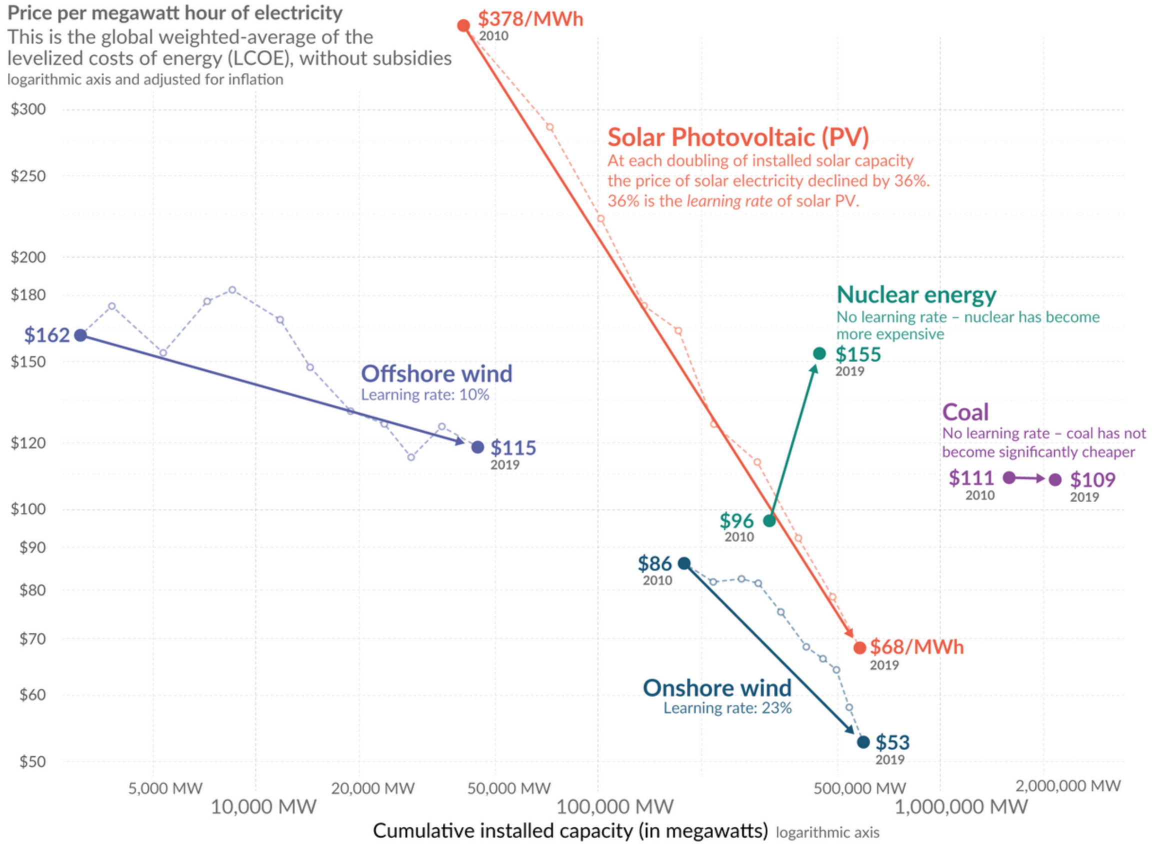


- Highest share of GHG comes from burning fossil fuels for electricity, heating, transport
- Reduction requires rapid and systematic transformation of these sectors

Sources: https://ourworldindata.org/emissions-by-sector
https://ourworldindata.org/energy

Sustainable energy technologies

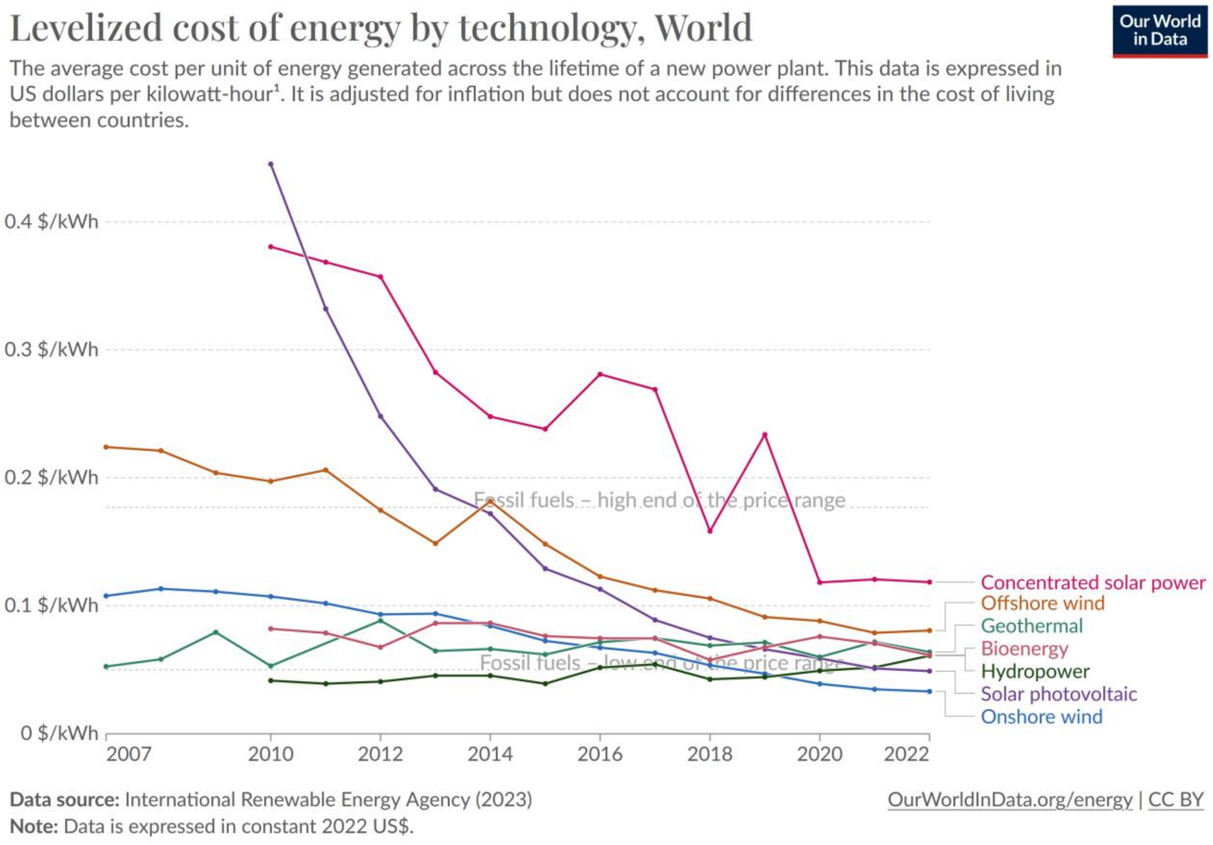


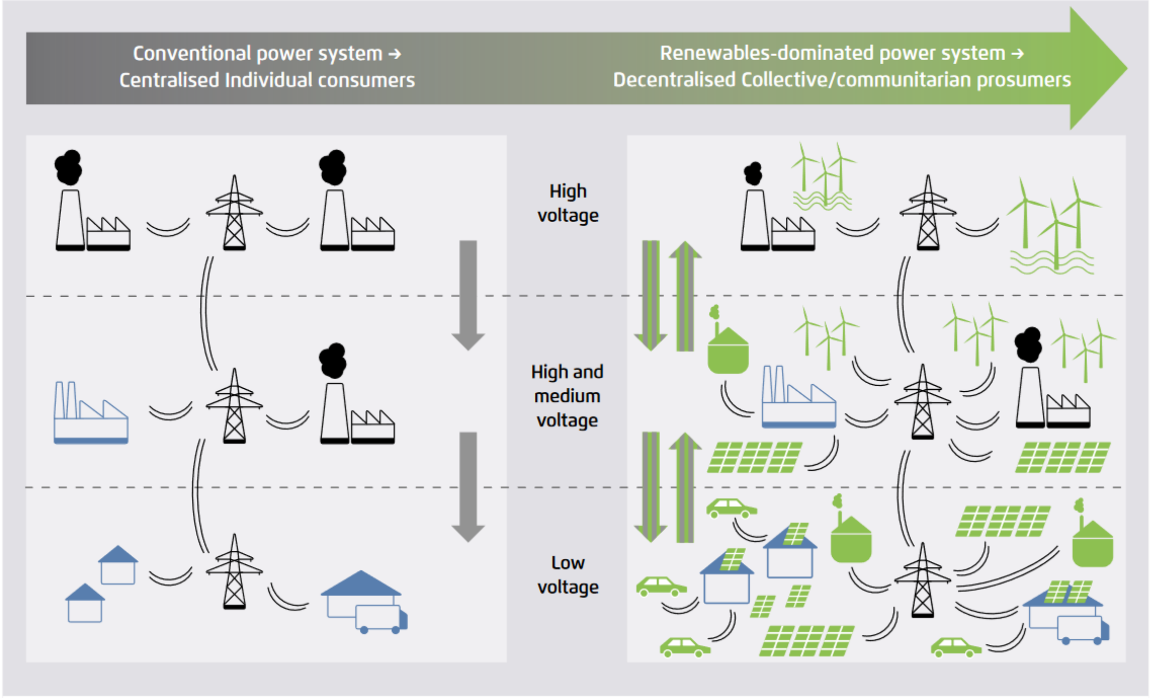


- Renewable energy technologies have no direct emissions and low indirect ones
- Feed-in tariffs have kick-started the learning rates for wind and PV

Sources: https://unece.org/sed/documents/2021/10/reports/life-cycle-assessment-electricity-generation-options
https://ourworldindata.org/cheap-renewables-growth

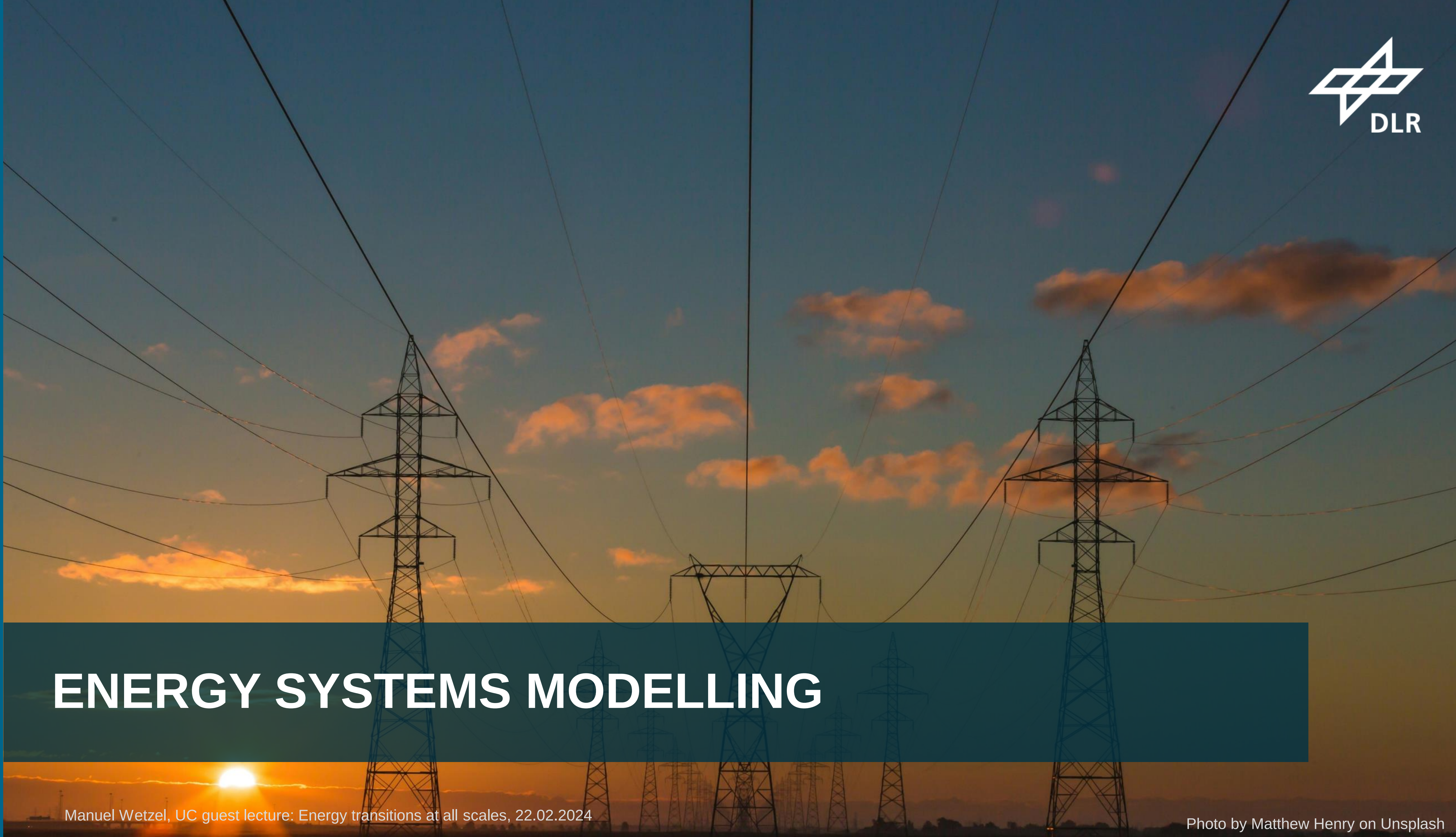
Bringing it all together





- Renewable energy technologies have become the cheapest option
- Capacity expansion and integration of renewables now the main challenge

Sources: https://ourworldindata.org/grapher/levelized-cost-of-energy
https://www.agora-energiewende.de/en/publications/european-energy-transition-2030-the-big-picture



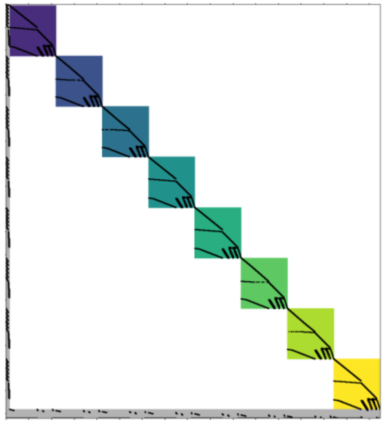
ENERGY SYSTEMS MODELLING

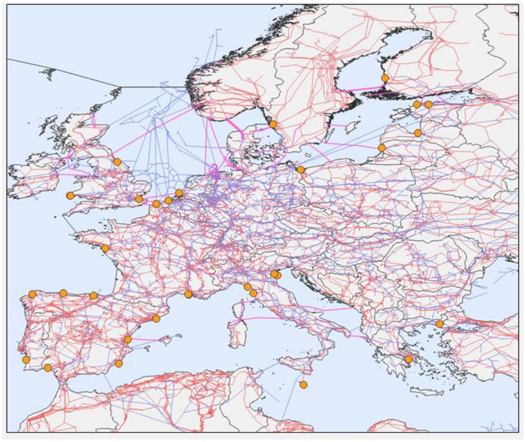
Photo by Matthew Henry on Unsplash

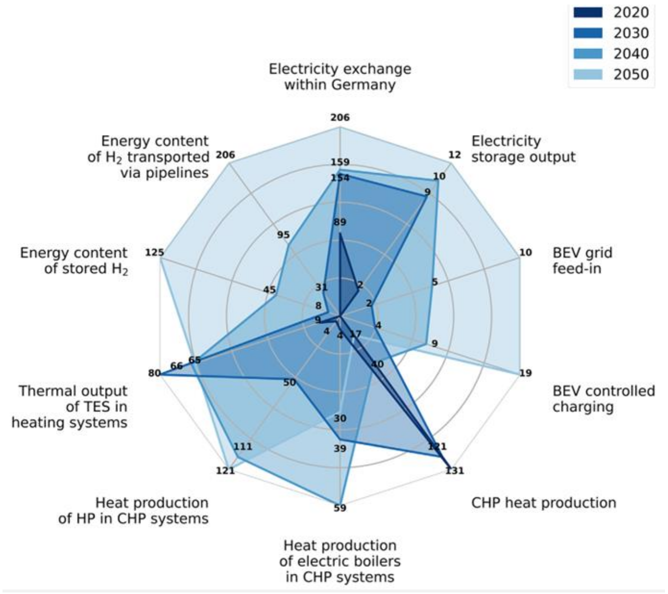
Focus of the Energy System Modelling group

Modelling robust pathways to a sustainable, economic and secure energy system

- Improving energy system models and data
- Comprehensively modelling sector coupling and flexibility
- Deriving policy recommendations for the implementation

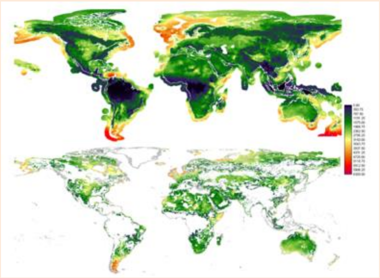


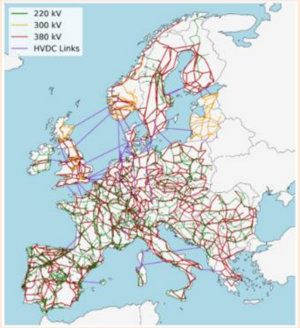




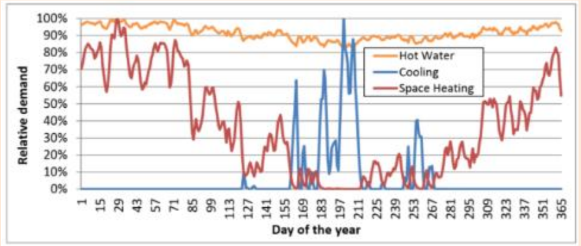
Research areas of the Energy Systems Modelling group

Improvement of the data basis for energy systems modelling

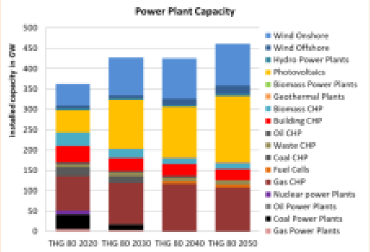


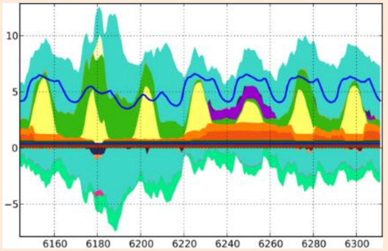


- Energy infrastructure data
- Renewable energy potentials
- Future energy demand profiles
- Demand side flexibility

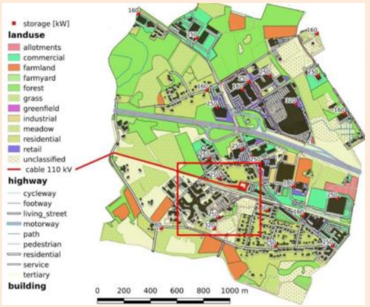


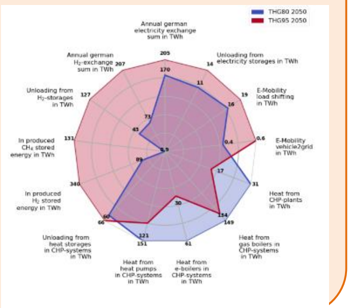
Investigation of energy system transformation pathways



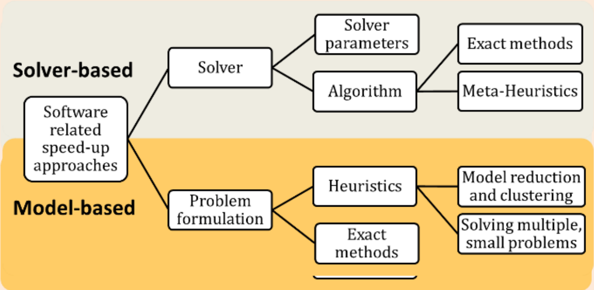


- Modelling systems: district to continental
- Storage, transmission, sector coupling
- Robust transformation pathways
- Resilience and security of supply
- Climate impact and system adaptation

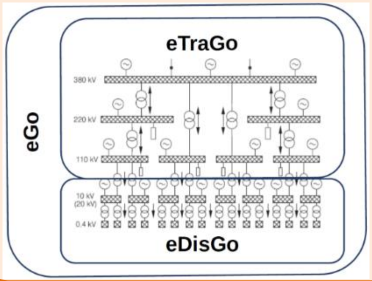


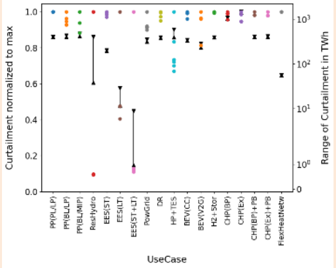


Enhancement of methodological competence



- Reduction of model solution times
- Model coupling and comparison
- Remote sensing and machine learning
- Data management (metadata, ontology)
- Quantum Computing

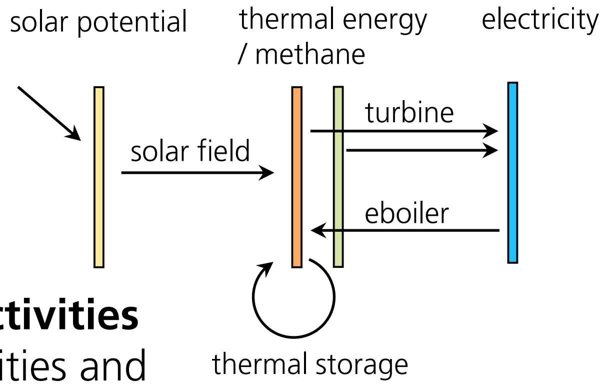




REMix
Renewable Energy Mix

- Algebraic modelling using GAMS
- Data management and interfaces using python
- Flexible spatial, temporal & technological scope
- Capacity expansions and dispatch of all infrastructures
- System integration of power, heat, gas, transport sectors

Multi-activity converters
- Linear combinations
- Partial and minimum loads



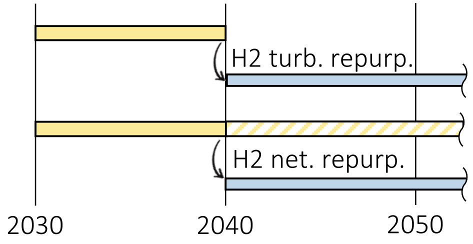
Multi-input multi-output activities
- Free definition of commodities and accounting variables

Multi-criteria optimization

Power grid
- LOPF power angles and Kirchhoff formulation
- Security-constrained transmission expansion planning

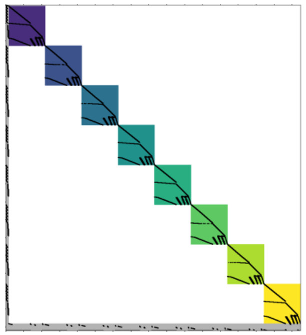
Gas sector modelling
- Pipeline and storage repurposing for H_2
- Hydrogen admixture for methane networks

System transformation pathways
- Limited and perfect foresight
- Carbon budgets



MIP capacity expansion and unit commitment

Resilience and outage modelling
- Rolling horizon with multiple outage events



Modelling to generate alternatives methods

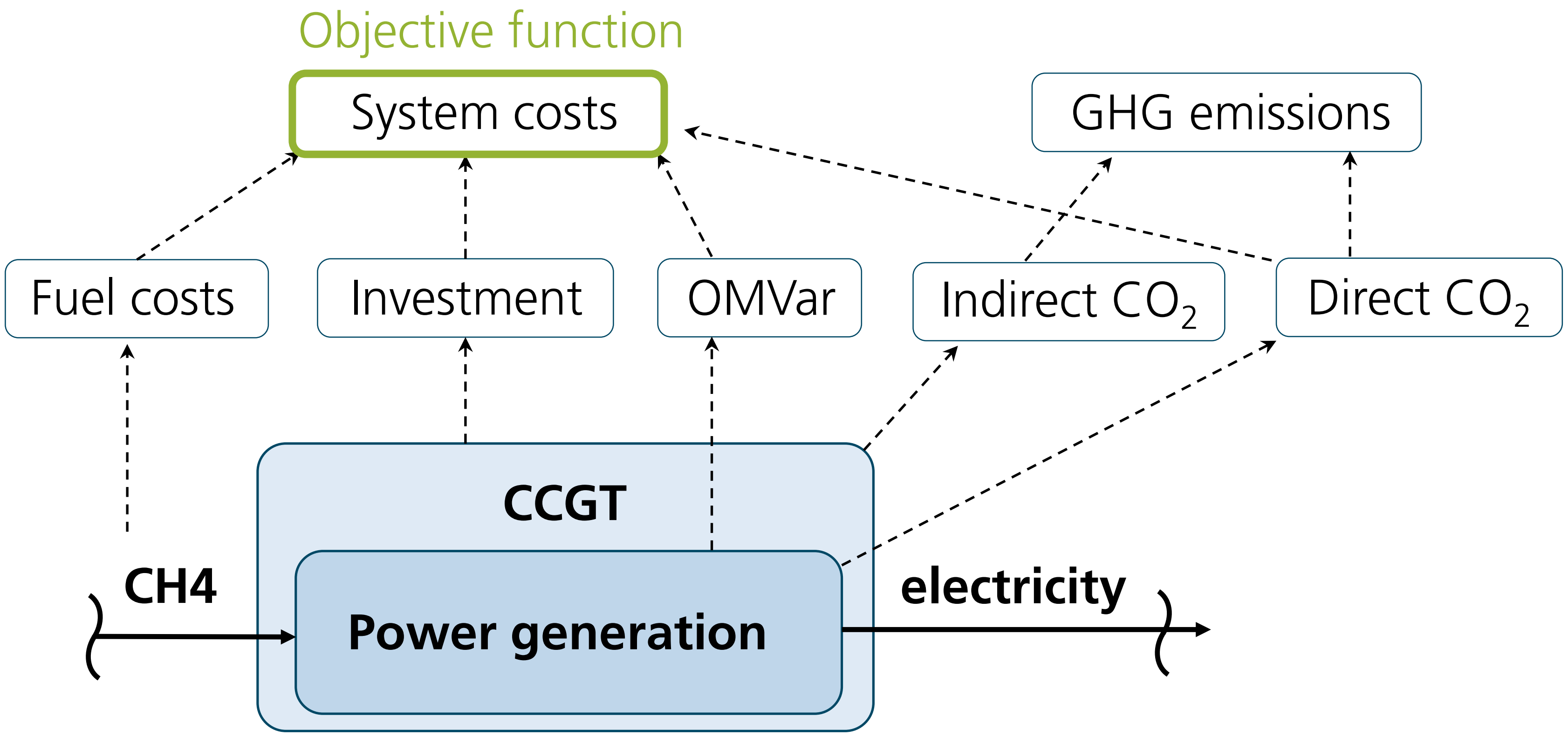
HPC ready via PIPS-IPM++ link
- EMP reformulation for stochastic optimization

open source code available here

Commodities and hierarchical indicators

Commodities trace physical flows in the system (e.g. fuels, electricity, heat, etc.)

Indicators account for additional information (e.g. costs, firmCaps, land use, CO_2, etc.)

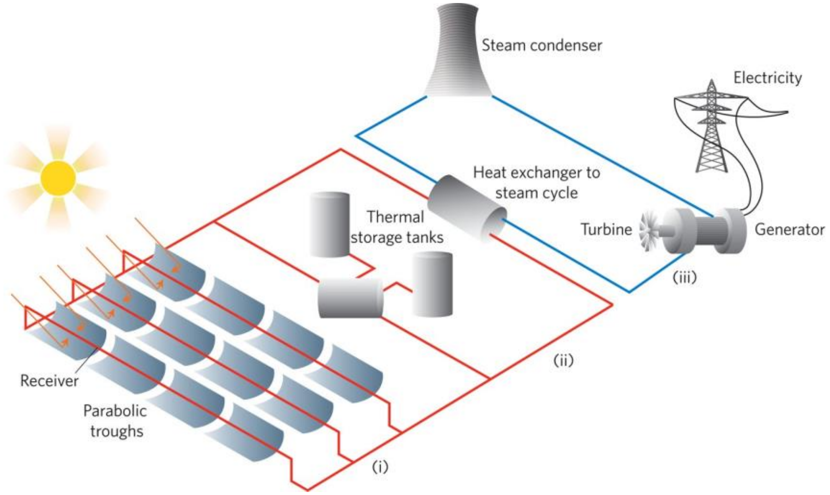


Modelling real systems

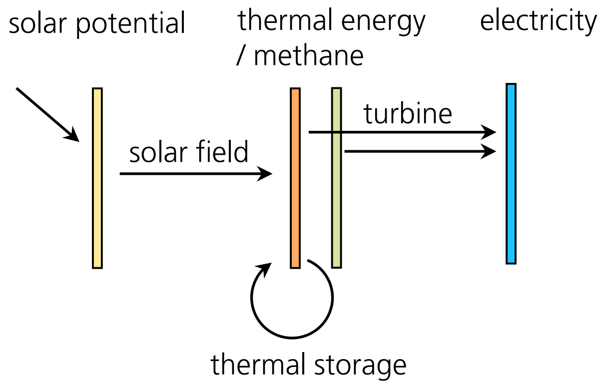
Real-world system

SENER

Plant design and engineering

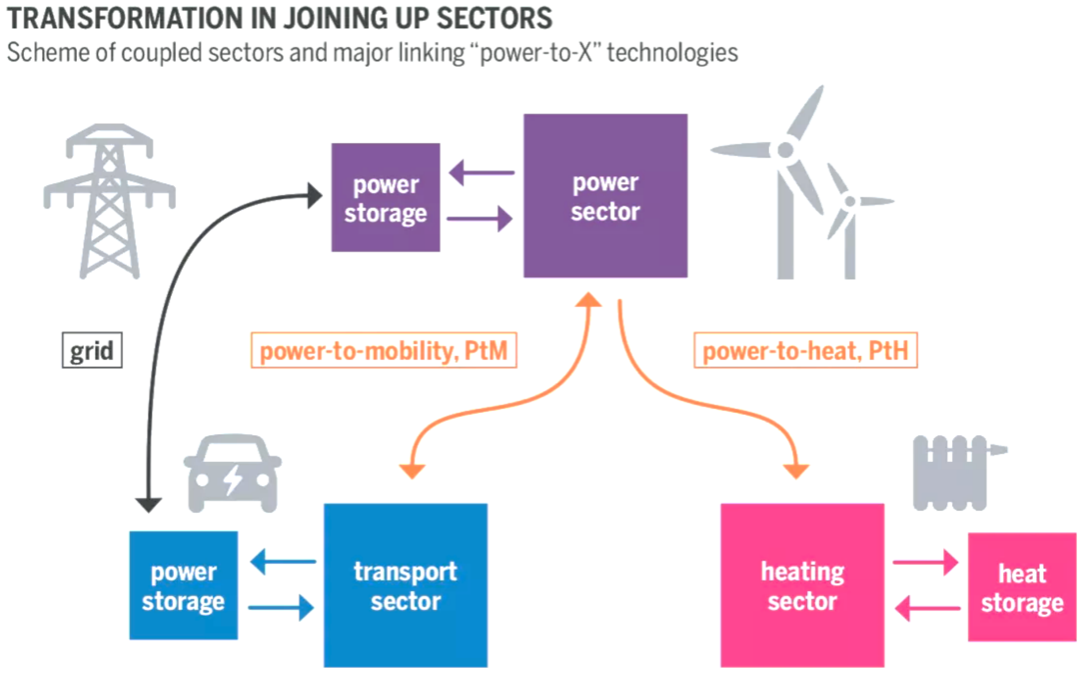


Energy systems analysis

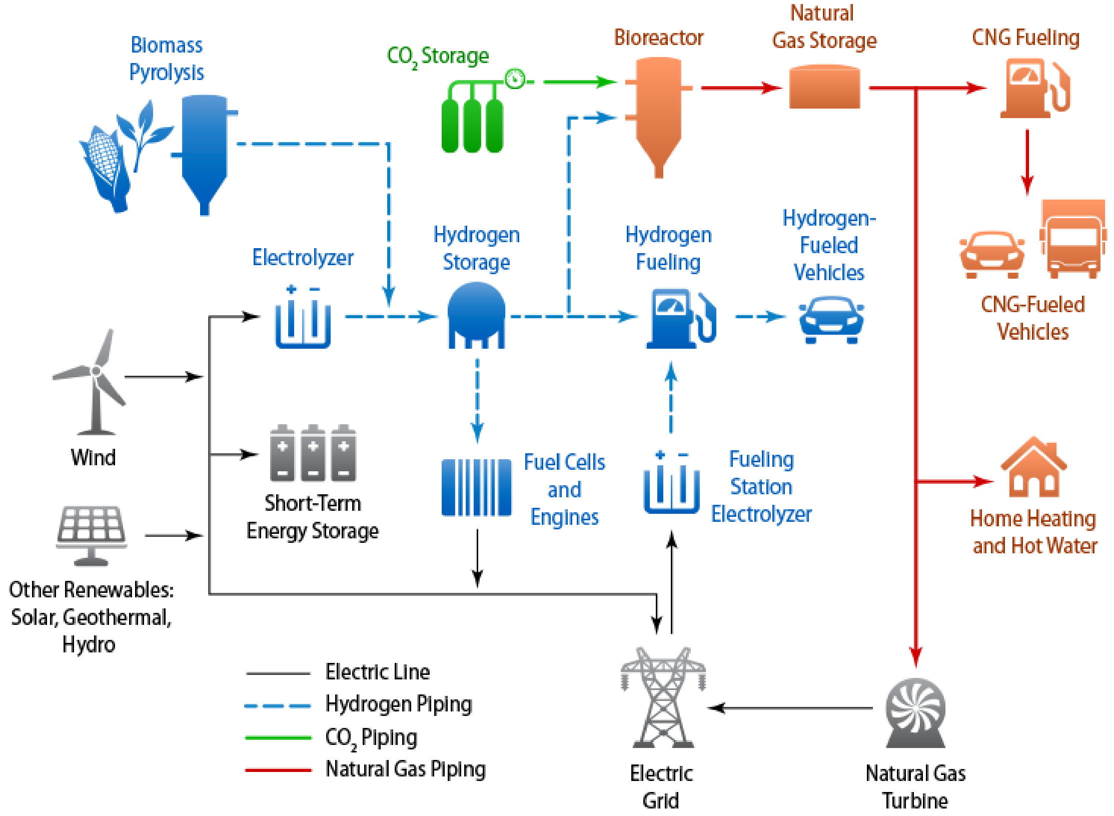


- The same system can be viewed from different perspectives
- Level of abstraction changes data requirements (cost, temperature levels, LCOE, efficiencies)

Sector integration and the role of hydrogen



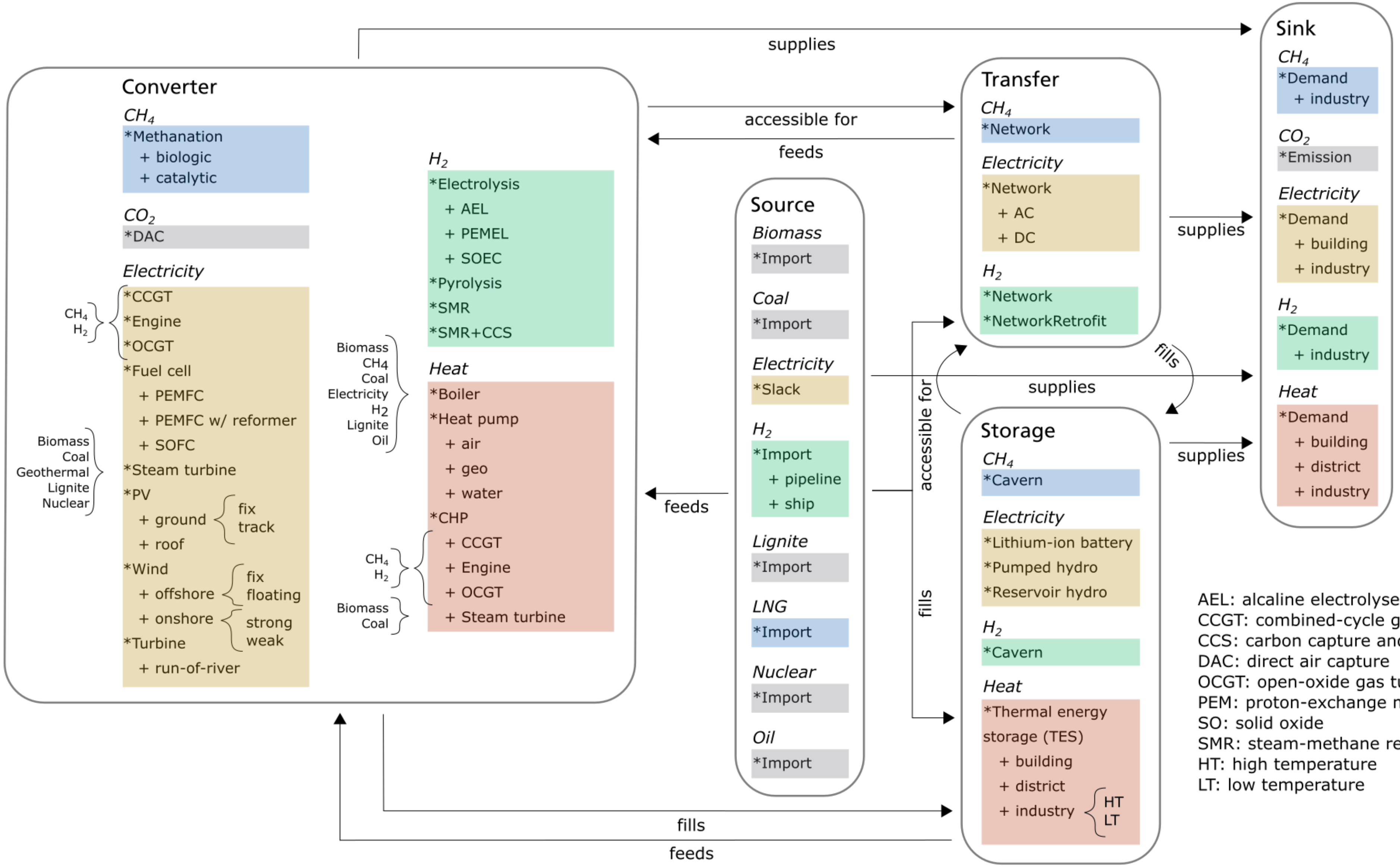
Agora Energiewende



NREL

- Direct electrification is the most efficient option, but energy can only be stored short term
- Hydrogen can provide long-term storage option and can be used in industrial applications

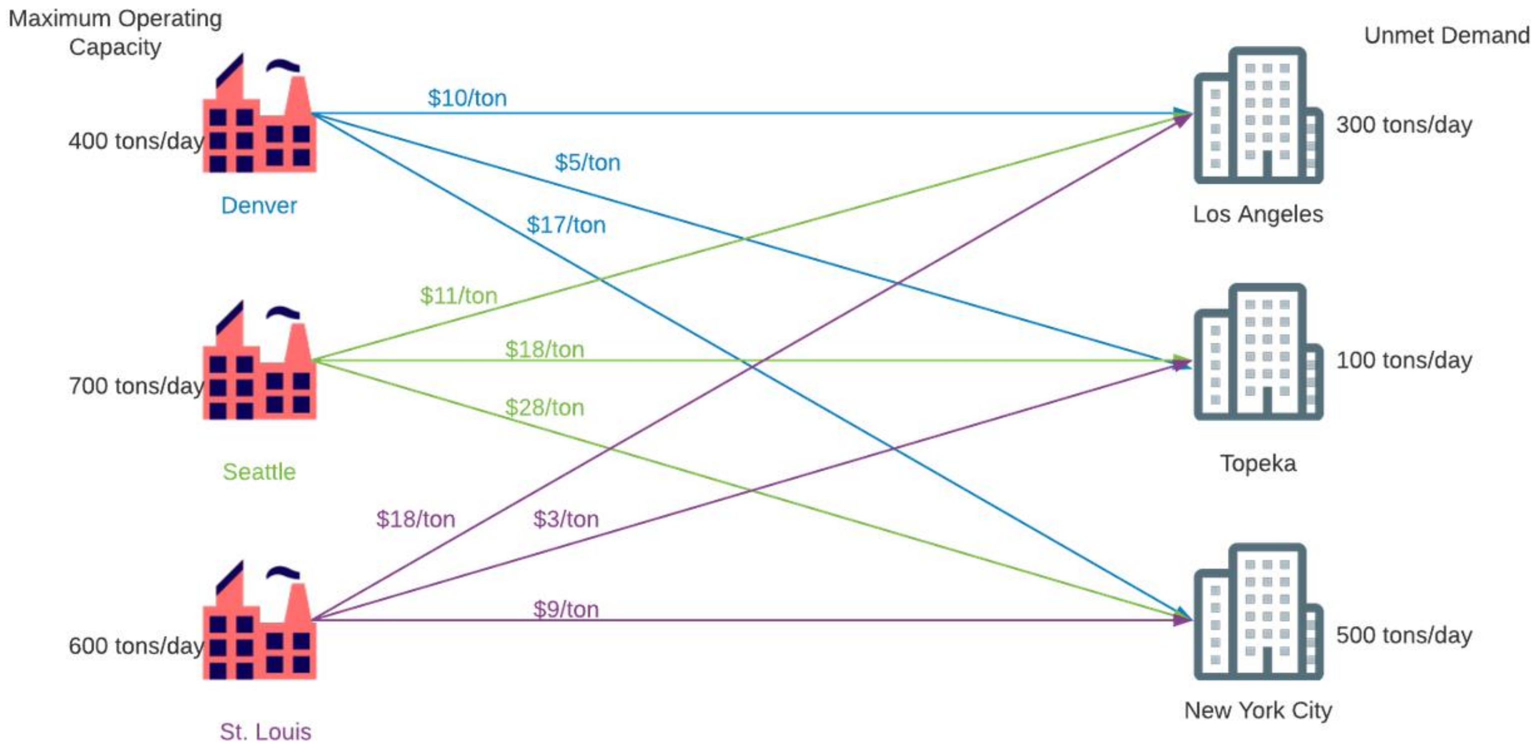
Modelling integrated energy systems



AEL: alcaline electrolyser
CCGT: combined-cycle gas turbine
CCS: carbon capture and storage
DAC: direct air capture
OCGT: open-oxide gas turbine
PEM: proton-exchange membrane
SO: solid oxide
SMR: steam-methane reforming
HT: high temperature
LT: low temperature

Linear Programming (LP)

$$\begin{aligned} \min \quad & c^T x \\ \text{s.t.} \quad & Ax = b \end{aligned}$$



https://optimization.cbe.cornell.edu/index.php?title=Facility_location_problem

- Linear programming can be used to solve large optimization problems
- “All models are wrong, some are useful” - George Box

Energy system optimization models (ESOMs)

DLR

Objective function

$$C_{total} = \sum_{y,r,p} c_{invest,y,r,p} * n_{build,y,r,p} + \sum_{s,t} c_{var,p}(act_{t,y,r,p,a} + flow_{t,y,r',r,p,c} + import_{t,y,r,c})$$

Capacity expansion planning

- Unit balance for converters, transport and storage

$$P_{y,r,p} = p_{rated} * n_{total,y,r,p}$$
$$n_{total,y,r,p} = n_{total,y-1,r,p} + n_{build,y,r,p} - n_{decom,y,r,p}$$

t	time step
y	year
r	region
p	type
a	activity
c	commodity

Economic dispatch

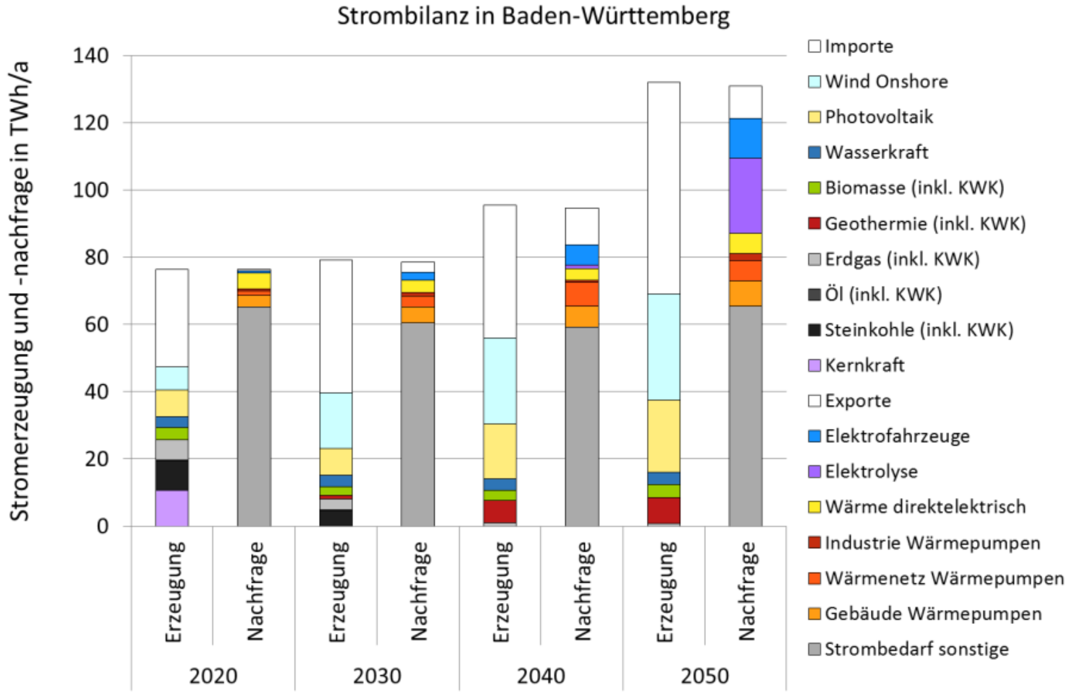
- Dispatch of power plants, transport and storage

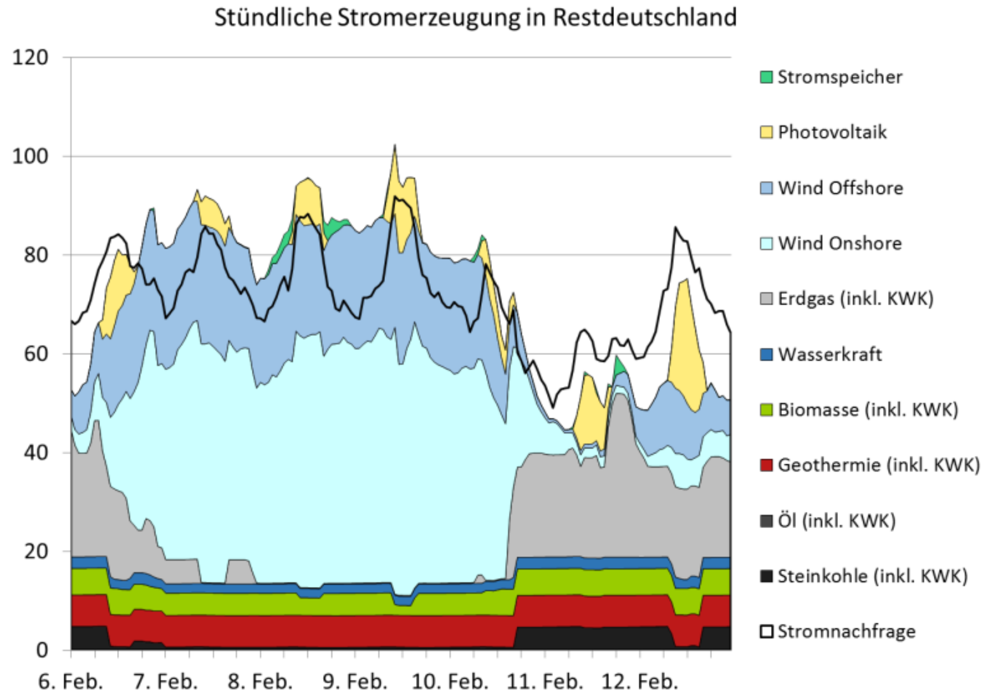
$$act_{t,y,r,p,a} \leq P_{y,r,p}$$
$$stor_{t,y,r,p,a} \leq P_{y,r,p}$$
$$flow_{t,y,r,r',p,a} \leq P_{y,r,p}$$

- Hourly energy and commodity balance

$$act_{t,y,r,p,a} * coef_{p,a,c} + stor_{t,y,r,p,c} - stor_{t-1,y,r,p,c} + flow_{t,y,r',r,p,c} - flow_{t-1,y,r,r',p,c} + import_{t,y,r,c} - demand_{t,y,r,c} = 0$$

Typical results from ESOMs





- Economically viable share of renewable energies
- Investment into new power plants, electrical transmission grid and flexibility options
- Annually transmitted energy on a European scale
- Impact of CO2 emission prices and annual limits

- Hourly dispatch of individual generation technologies as well as flexibility options
- Hourly security of supply and reserve capacities can be evaluated

ENERGY TRANSITION IN EUROPE AND GERMANY

Manuel Wetzel, UC guest lecture: Energy transitions at all scales, 22.02.2024

Photo by Nicholas Doherty on Unsplash

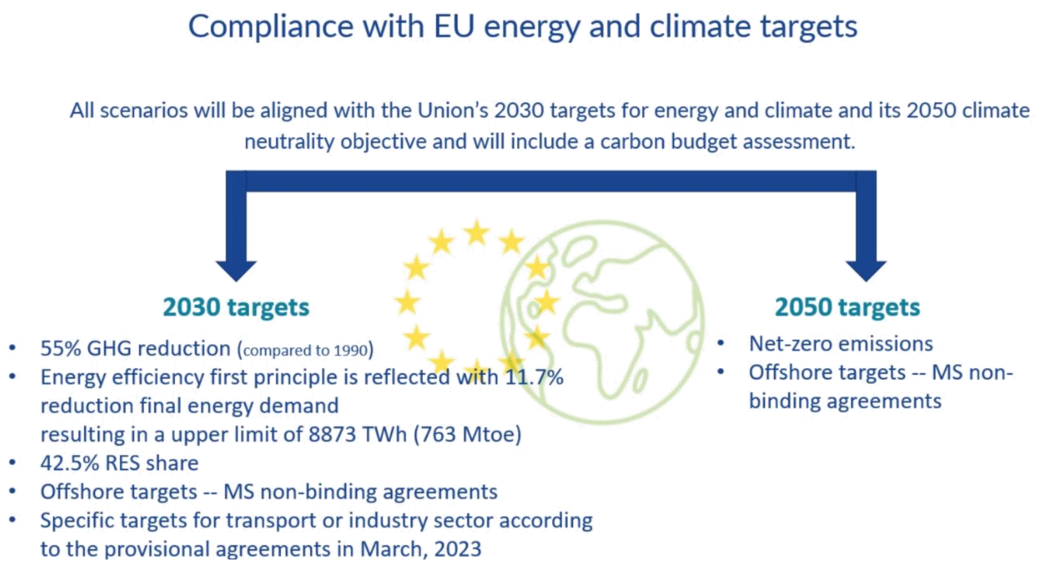
Challenges in European energy strategy

Climate risk and geopolitical crises drive the urgency for transformation:

- Decarbonizing the energy supply systems across sectors
- Providing security of energy supply

How can the system be transformed to reach these goals?

- What it the optimal timing for switching to hydrogen and green energy carriers?
- How can electrolyzers be ramped up efficiently for increasing demand of hydrogen?
- What are the implications for power grids and pipeline networks and their respective topology?



TYNDP2024 stakeholder consultation

Tab. 1 – Strategic choices in the European clean hydrogen value chain

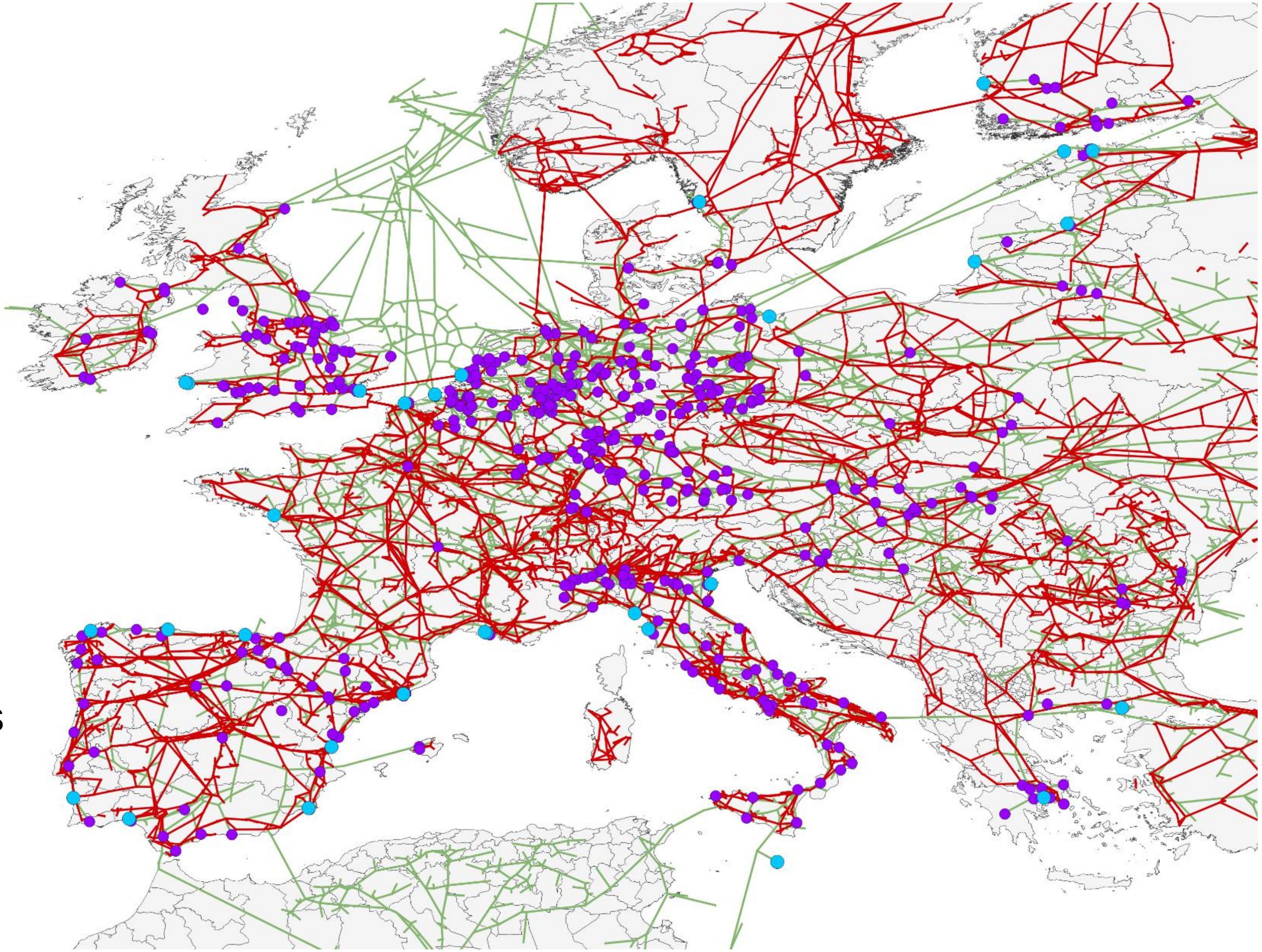
European Union	**40 GW** **10 MtH_2**	• Push for renewables • Promotes a "Hydrogen Valley" approach to facilitate local integration and growth • By 2024: **6 GW** electrolyzers, **1 MtH_2** • By 2030: **40 GW** electrolyzers, **10 MtH_2** • 2030-2050: large-scale deployment across all hard-to-abate sectors
Germany	**10 GW** **3 MtH_2**	• Push for renewables • Emphasis on imports of hydrogen (low-carbon hydrogen not excluded) • €8bn of public budget has already been allocated to 62 pre-selected projects • Up to €3.4bn to build refuelling stations

Deloitte 2022 The European hydrogen economy

European power and gas infrastructure

- One model region per country
- Increased spatial resolution
- Integration of high res power grid
- Integration of high res gas network
- Integration of LNG terminals
- Power and gas network with LNG terminals and gas power plants

→ European infrastructure modelling requires high spatial and temporal resolution



Own depiction based on ENTSO-E GridKit and SciGrid_gas IGGIELGN

Modelling toolchain

DLR

SciGRID Gas

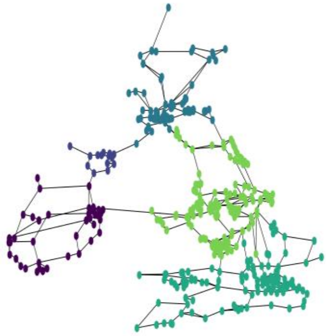
bdw/GridKit

GridKit is an power grid extraction toolkit

eGo^n

→

Topology reduction for networks



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Calculation of EEZs

- Area allocation based on coastlines or points

→

Renewable energy potentials and feed-in

↑

REMix
Renewable Energy Mix

Open source publication

- Source code release
- Python API and PyPI release

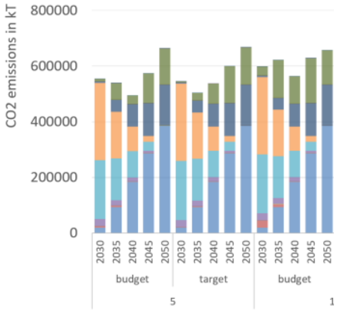
Model development

- Infrastructure repurposing
- Improved model formulation
- PIPS-IPM++ for pathways

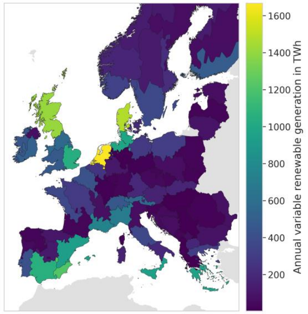
→

Results from the REMix model

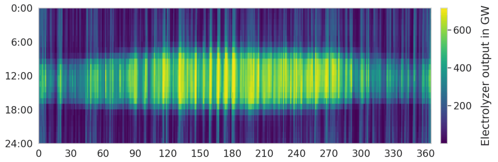
- Annual energy balances



- Spatial allocation of technologies

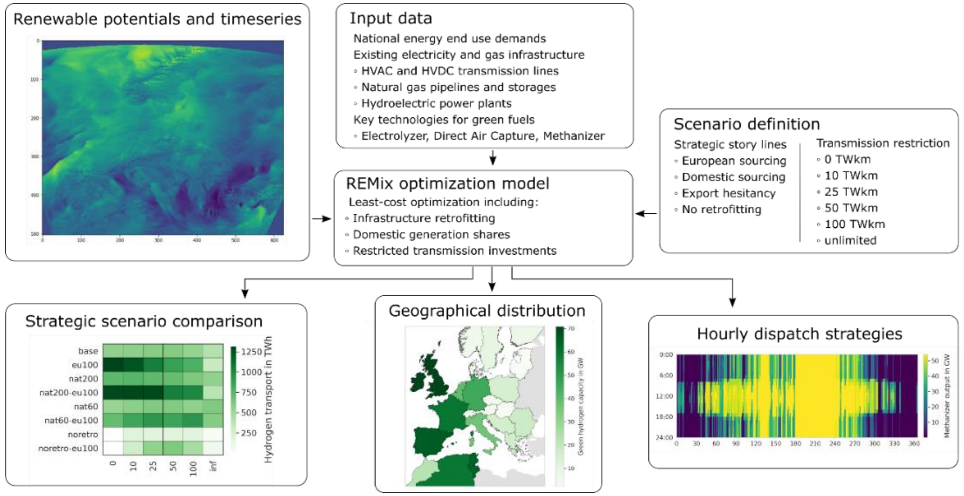


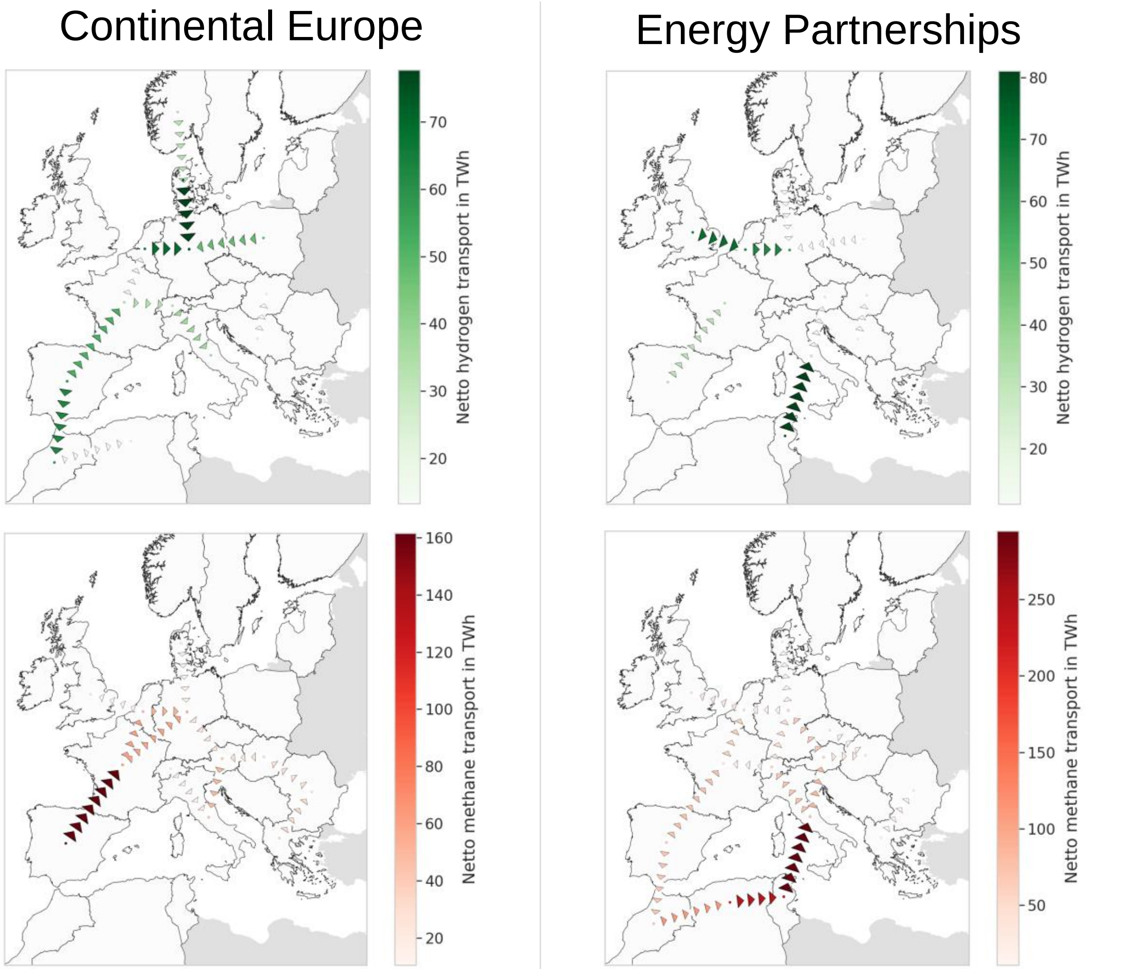
- Hourly interactions between technologies



The role of green hydrogen and methane

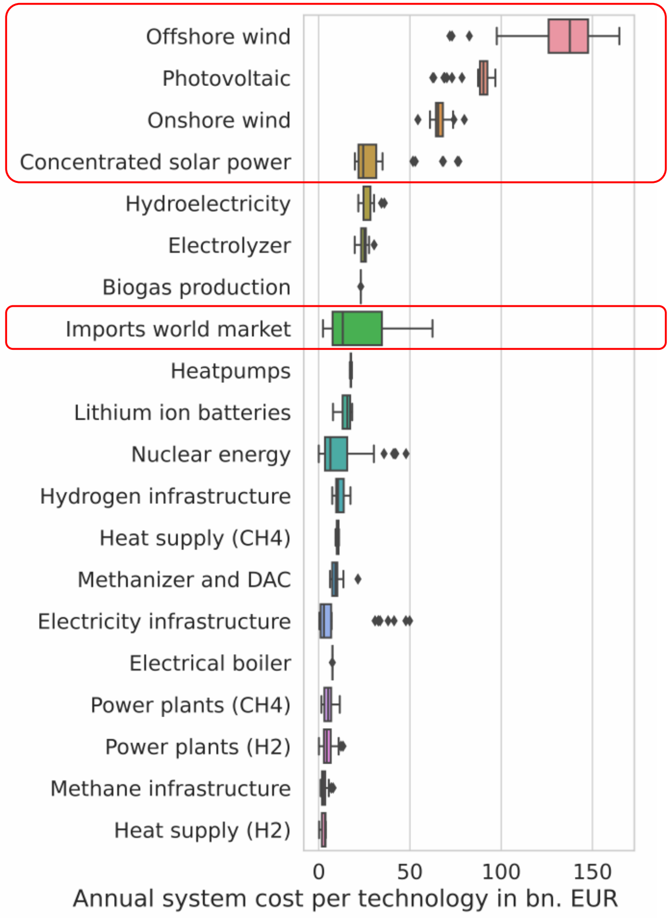
- Climate neutral energy system in 2050
- Scenarios on energy partnerships, domestic sourcing, network expansion limits





Wetzel, M., Gils, H.C., Bertsch, V., 2023, Green energy carriers and energy sovereignty in a climate neutral European energy system, Renewable Energy

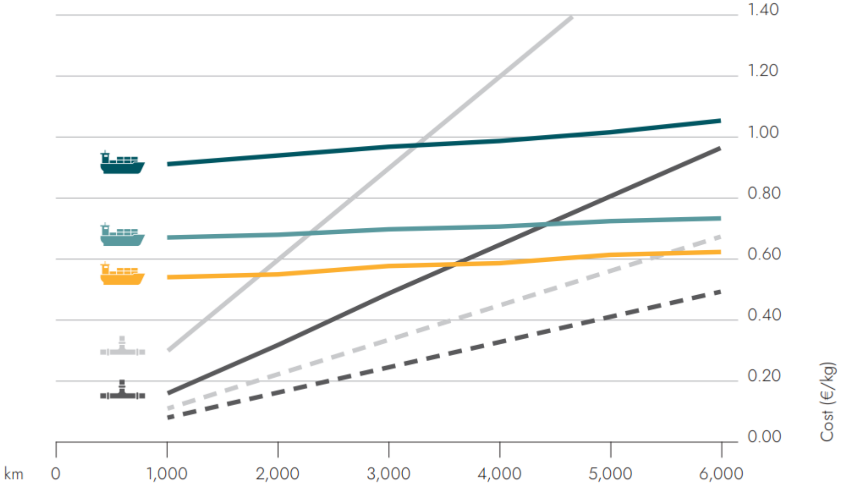
The uncertainty of future energy imports



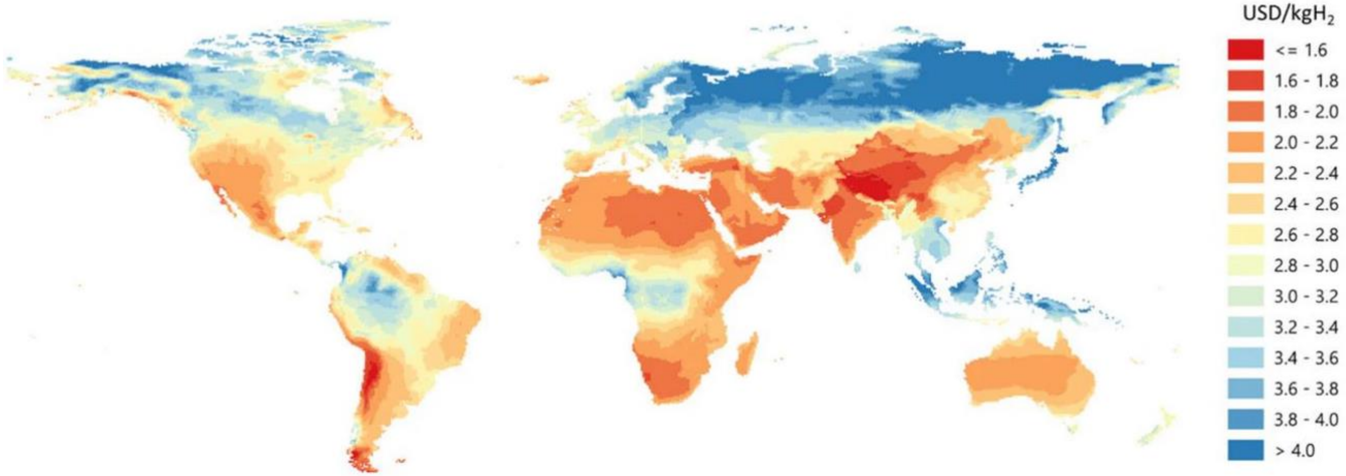
Wetzel, M., Gils, H.C., Bertsch, V., 2023, Green energy carriers and energy sovereignty in a climate neutral European energy system, Renewable Energy

Investments into renewable energy becomes main driver of system costs

Large uncertainty about imports from global energy markets

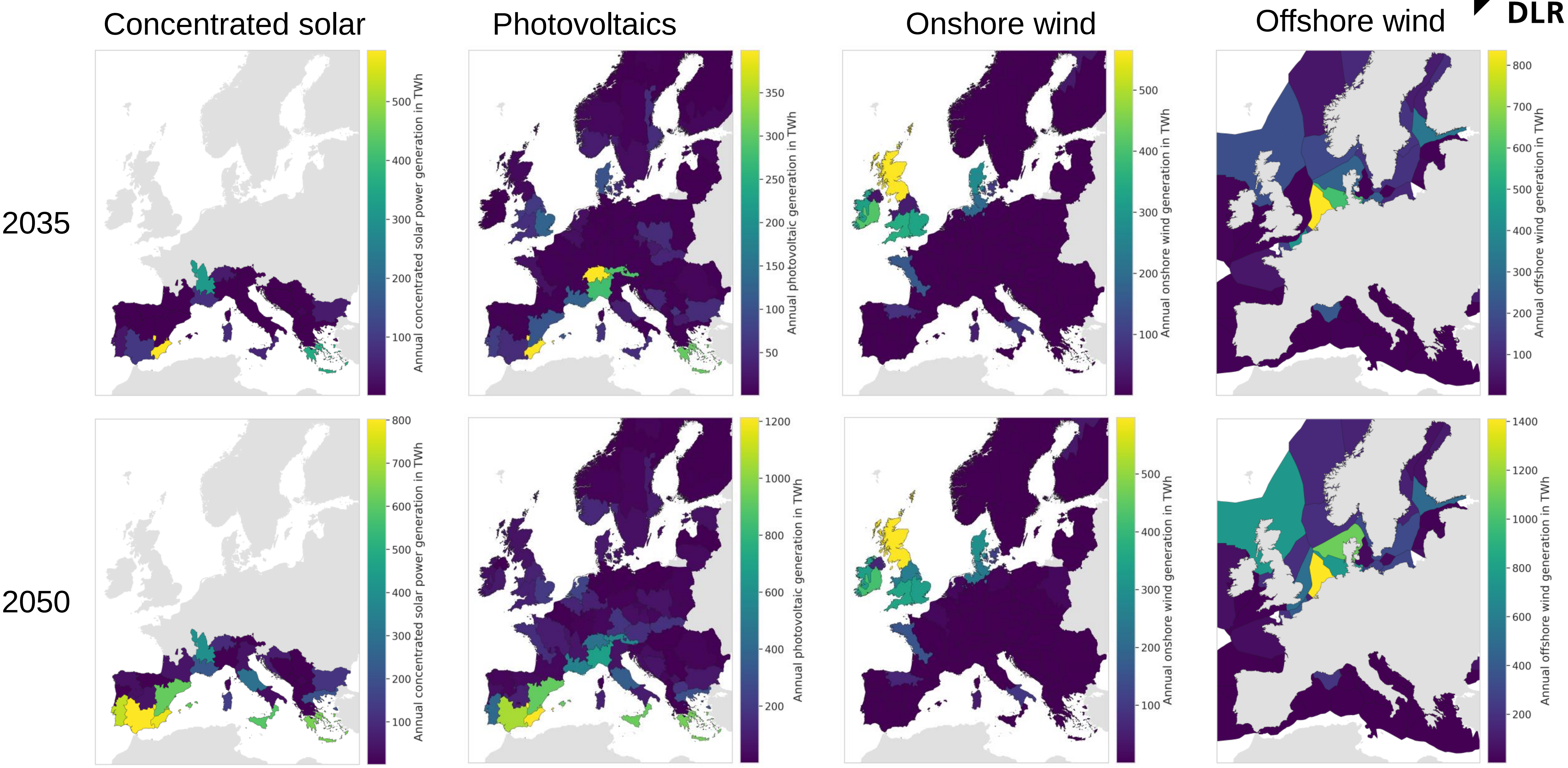


Guidehouse 2021, Future demand, supply and transport of hydrogen



IEA 2020, The Future of Hydrogen

Electricity production sites – preliminary results

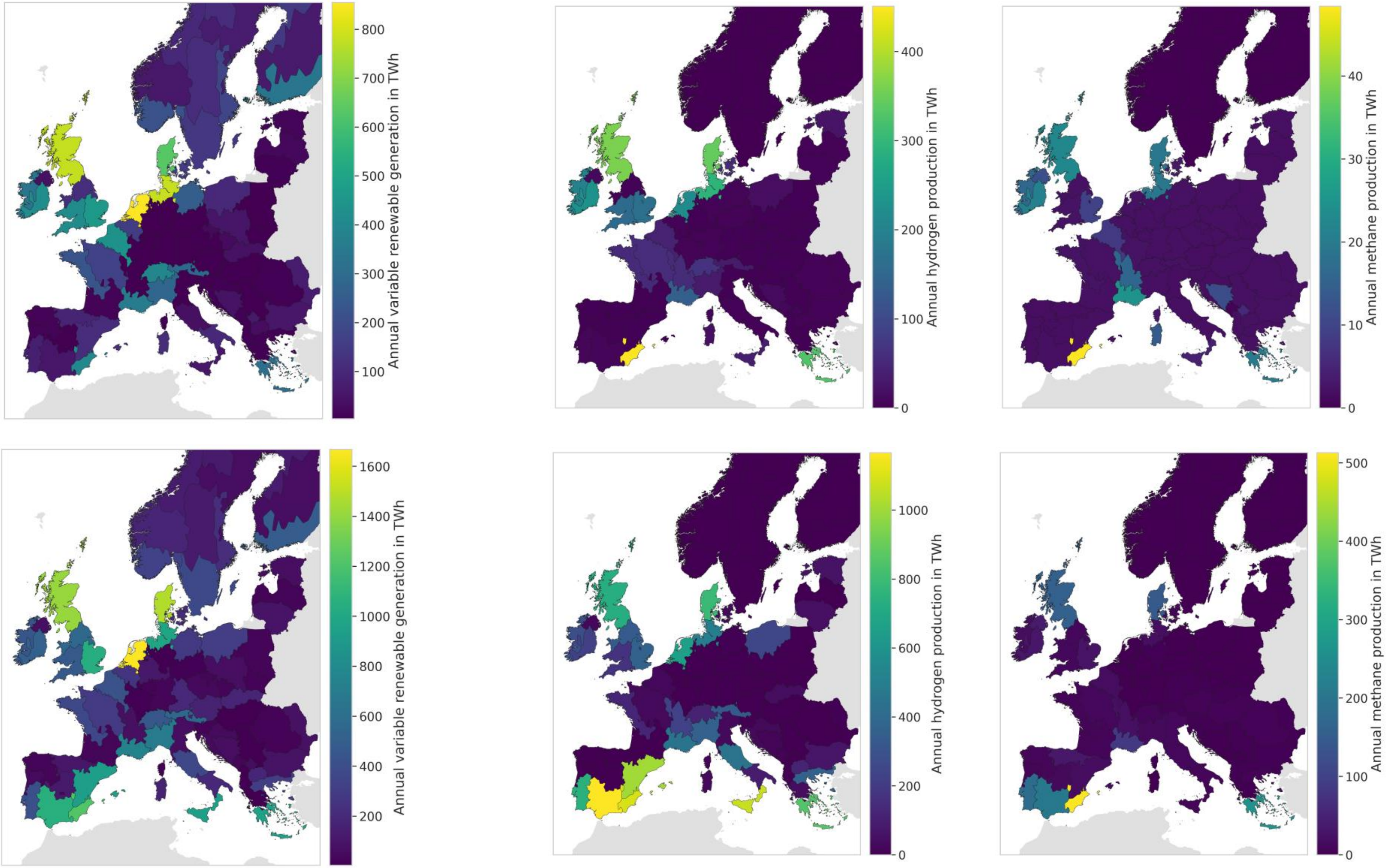


Hydrogen and methane sites – preliminary results

Variable renewable energy | Hydrogen production | Methane production

2035

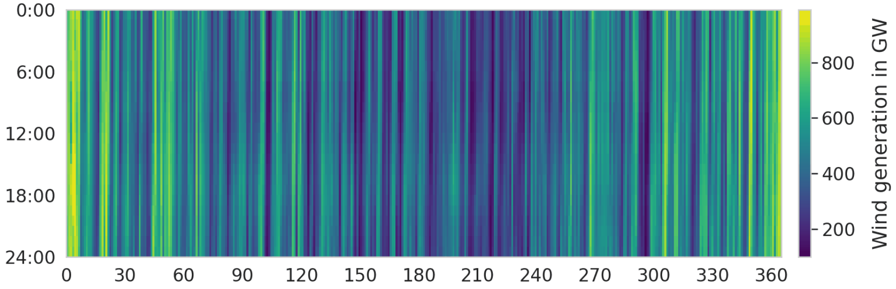
2050



Temporal technology correlations – preliminary results

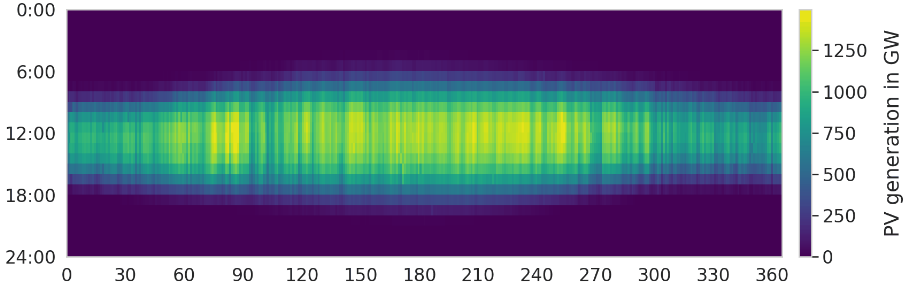
Onshore and offshore wind

pexels



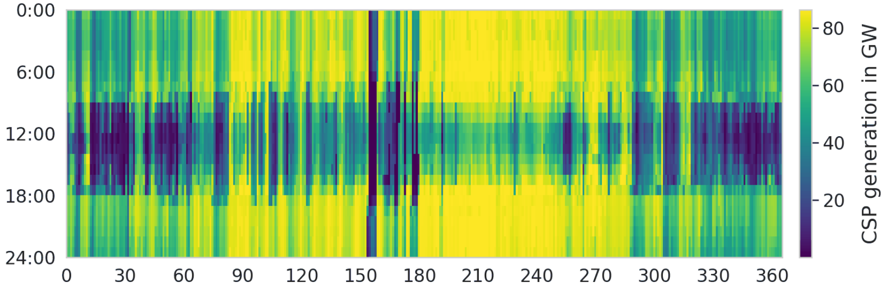
Photovoltaics

pexels

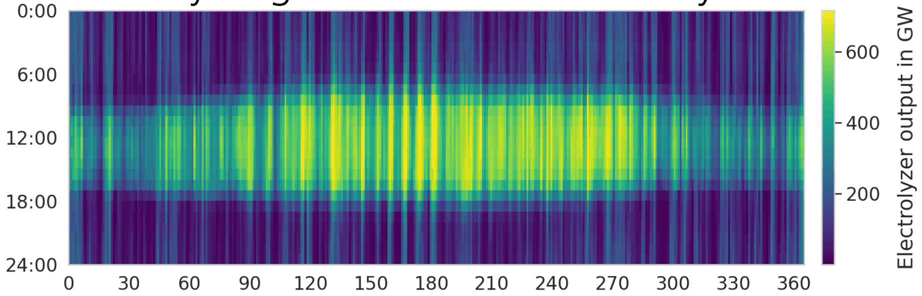


Concentrated solar power

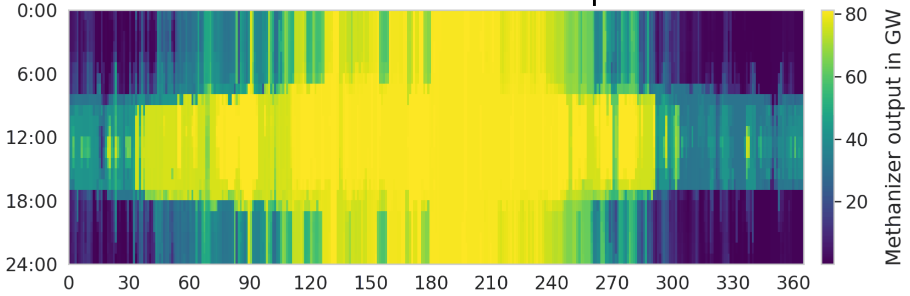
SENER



Hydrogen from water electrolysis



Methane from Sabatier processes

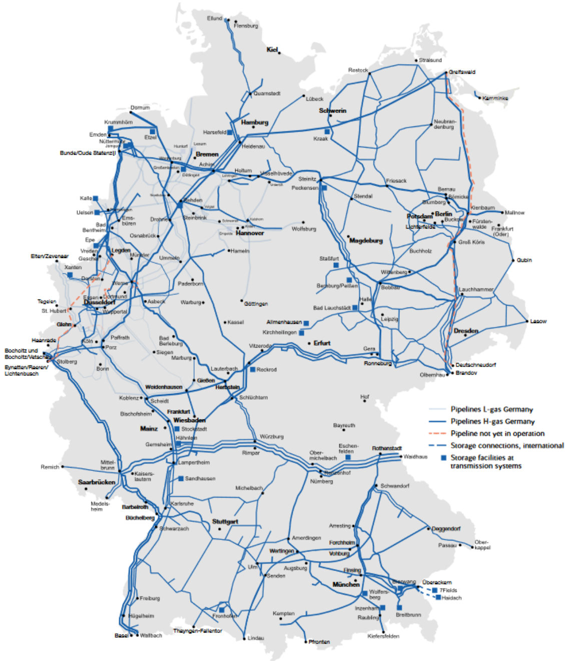


- Electrolyzers offer demand side flexibility
- Green methane requires seasonal storage

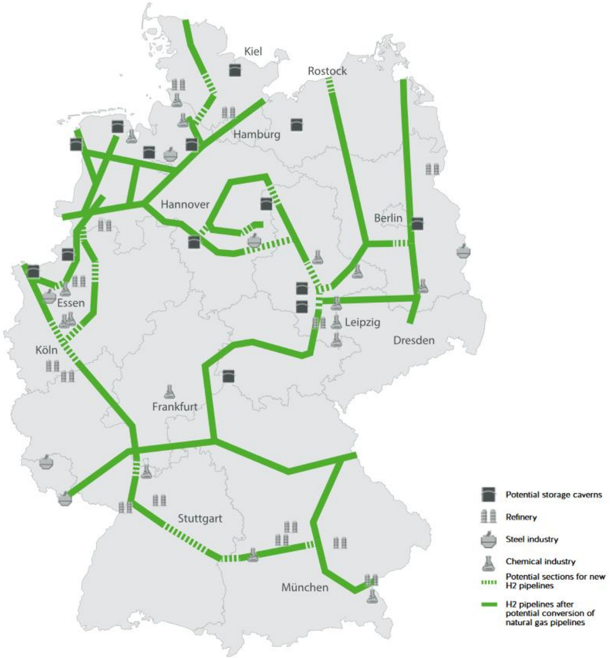
Infrastructure repurposing – preliminary results

- Integration of European infrastructure data
- Reduction of network topology for path optimization (myopic / perfect foresight)
- (Modelling of infrastructure repurposing)

Current H-gas network

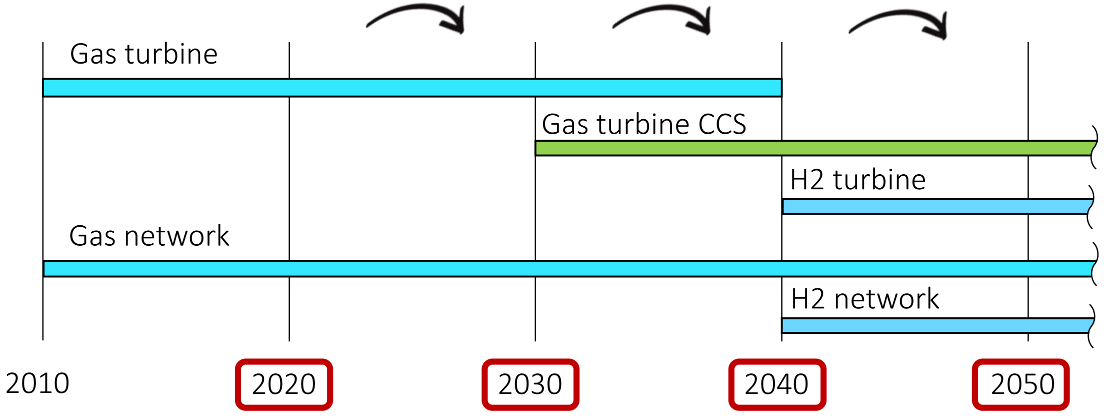


Envisioned hydrogen network

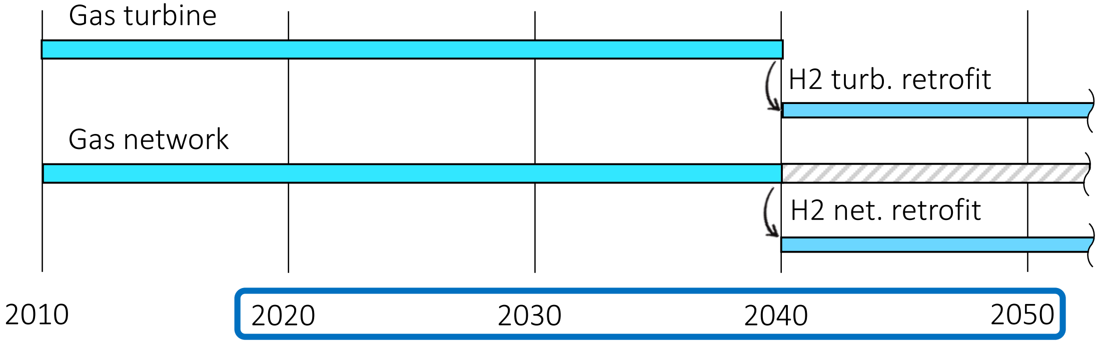


Gas Network Development Plan 2020 - 2030

Myopic foresight

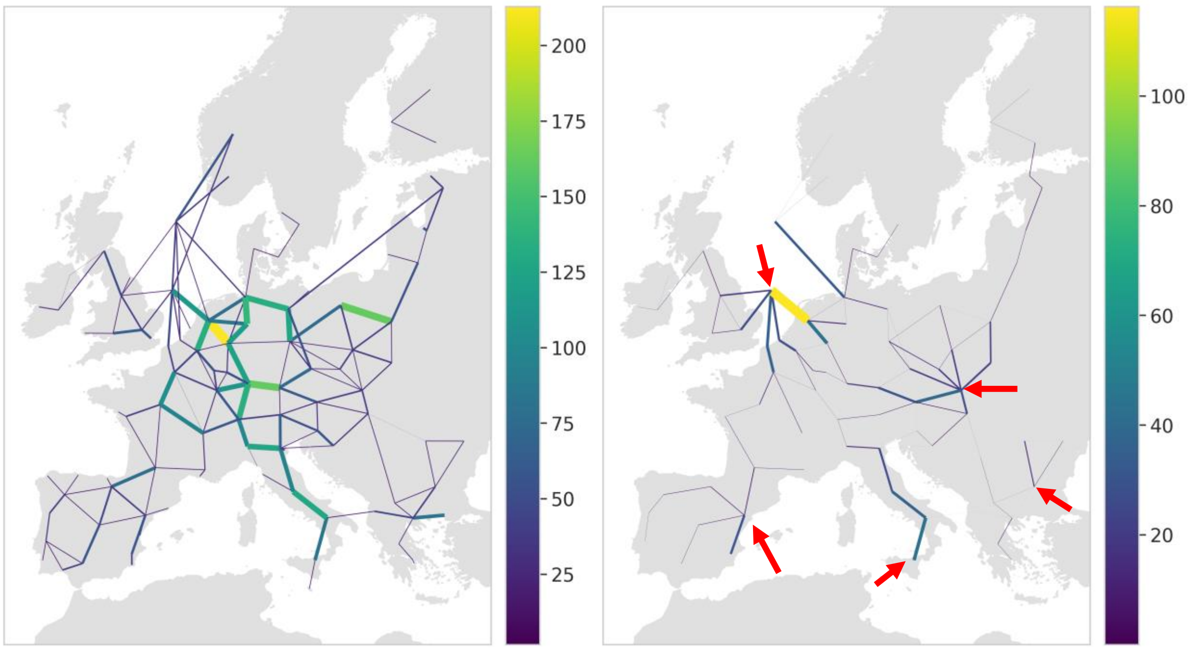


Perfect foresight

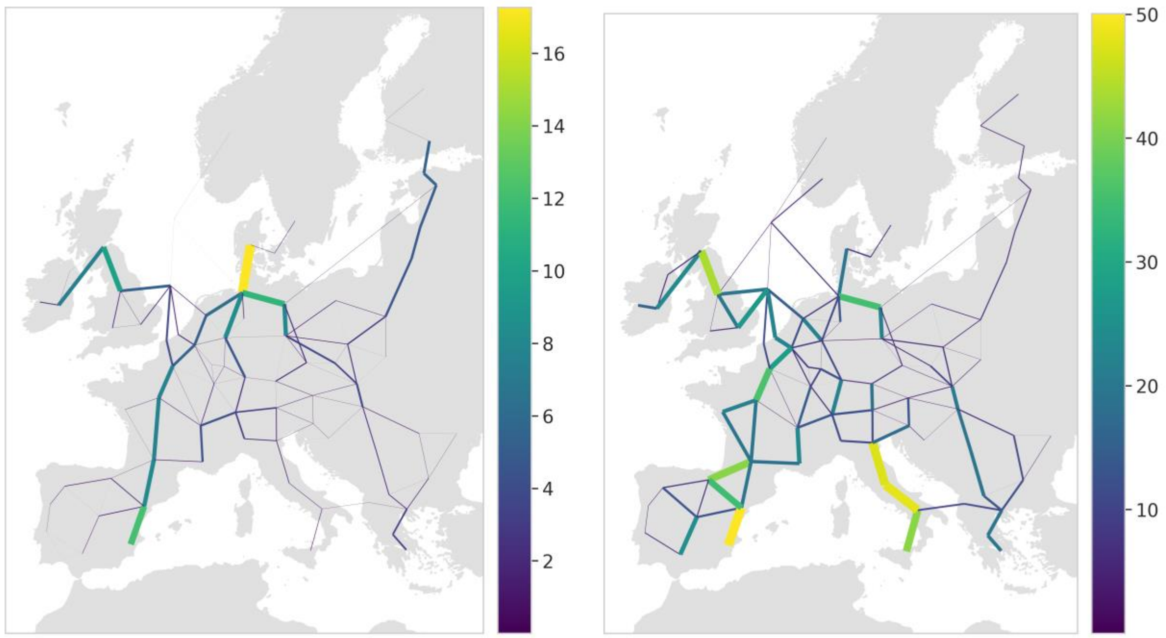


Future network topology – preliminary results

Methane network capacities 2025 - 2035



Hydrogen network capacities 2030 - 2050



- Current network topology is focused on imports from Russia, Turkey and North Africa
- Future network topology will be driven by linking centres of supply and centres of demand

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