The role of hydrogen to balance increased variable renewables

How can synthetic fuels complement direct electrification in low-carbon energy systems?

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HYPER Closing Seminar, Renaissance Brussels Hotel, Brussels
10 December 2019

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Energy Economics and System Analysis Group at Fraunhofer IEE uses market analysis tools and methods to answer a broad range of research questions

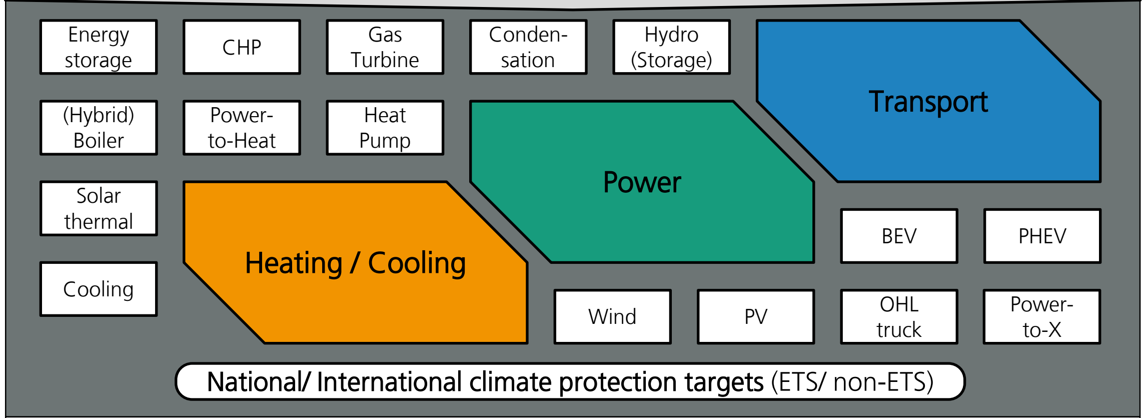
Research focus

- **Dynamic simulation of short- and long-term power markets** in Germany and Europe
- **Scenario development** for energy system transformation **towards decarbonisation and climate stabilisation scenarios**
- **Technology evaluations in future energy markets** particular focus on multivalent **sector integration interfaces** between power, building and industry heat, and transport sectors
- **Grid** (cross-border) and **storage expansion** analyses

Current and relevant projects

- **Value of Efficiency in the Building Sector**, AGORA, 2017-2018
  http://www.agora-energiewende.de/veroeffentlichungen/wert-der-effizienz-im-gebaeudesektor-in-zeiten-der-sektorenkopplung/
- **North Seas Offshore Network (NSON-DE),** BMWi, 2014 – 2017
  http://iee.fraunhofer.de/nson
- **RegMex – Energy System Model Comparison**, BMWi, 2015 – 2018
- **Greenhouse-Gas-Neutral Germany**, UBA, 2016 – 2018
- **Climate Impact of Electric Mobility**, BMUB, 2016 – 2018
  http://publica.fraunhofer.de/documents/N-439079.html
- **Heat Transition 2030**, AGORA, 2016
  http://bit.ly/2kDMHst

Market analysis tools and methods



- Planning models for analyses of **future energy supply systems with strong cross-sectoral integration and flexibility**
- **Mathematical optimisation models for energy system analysis** mainly formulated as large-scale LPs and MILPs
- **Modular** and **customisable techno-economic fundamental market models** (bottom-up) with **various configurations**
- **Extensive and continuously improving databases** for (geo-spatial) structural and time-series information
- Implementation in **self-developed MATLAB framework** and recently **Python**
- **Solver IBM ILOG CPLEX** (plus decomposition approaches) on Fraunhofer IEE-owned **High-Performance Computing Cluster**

Agenda

I	Low-carbon energy systems with high levels of cross-sectoral integration
II	Role of hydrogen in deep decarbonisation scenarios
III	Conclusions

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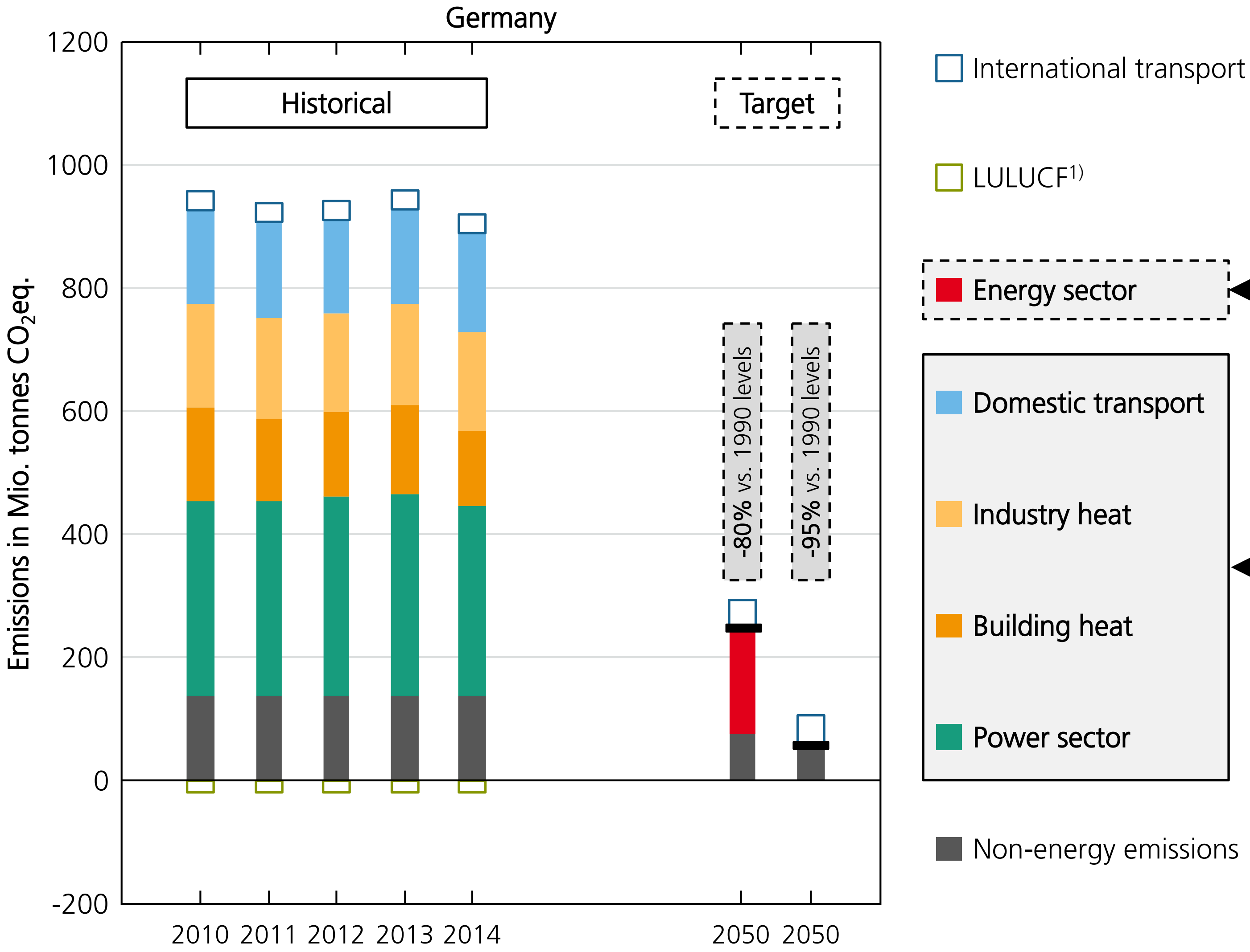
Long-term climate targets are very ambitious and decarbonisation challenges the energy sectors – promising solution via sector-integrating technologies based on maturing wind and solar power



Challenge

Complying with **COP21 Paris** agreement **requires** emission **reductions** in the range of **80-95%** vs. 1990 levels, implying **consequences** for **the energy sector**:

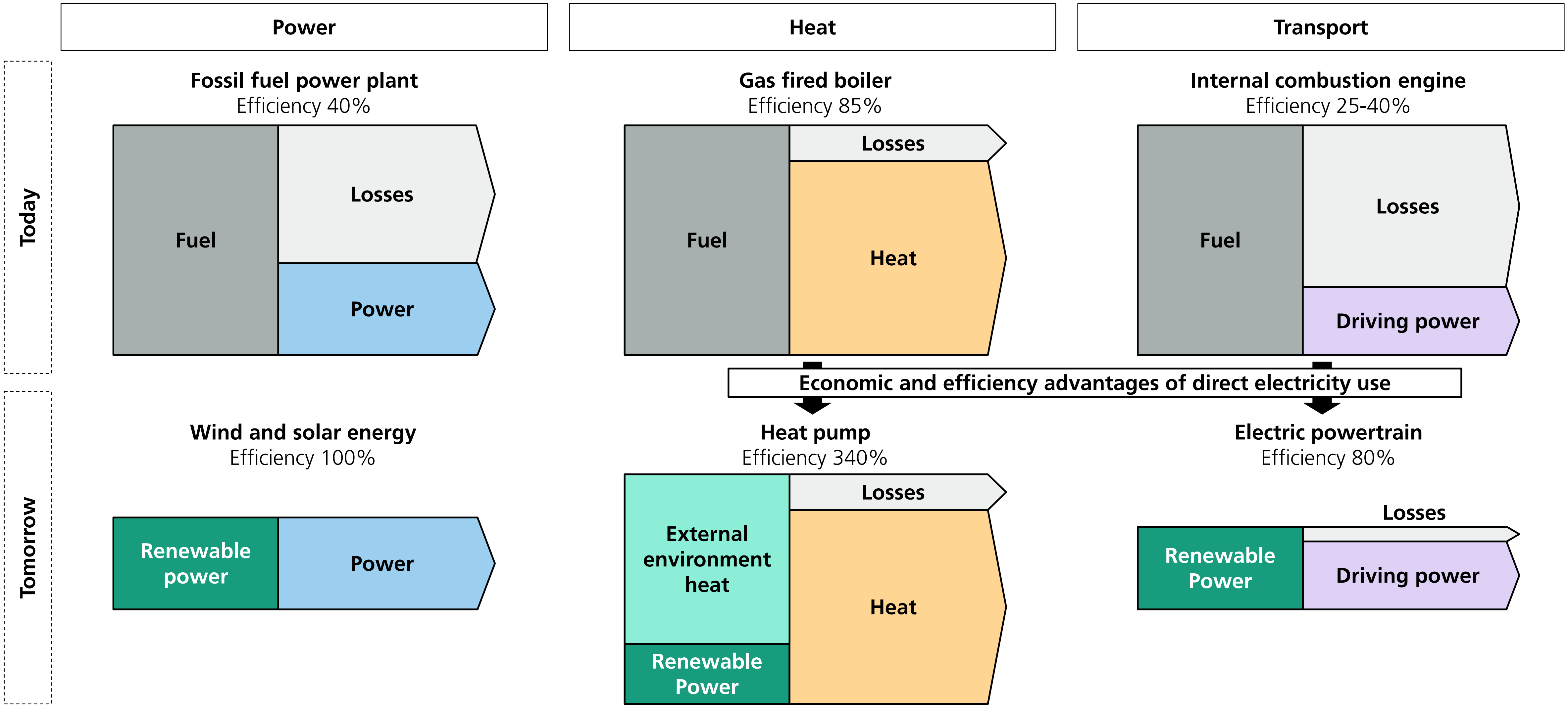
Power | Heat | Transport

Solution

Integration of energy sectors with key technologies **to use renewable power generation** (i.e. wind and solar) **as the main primary energy source** in the future

[1)] Land use, land-use change and forestry (LULUCF)

“Direct electrification” vital for largely decarbonising current fossil fuel-based energy systems in a cost-efficient manner – heat pumps and electric vehicles are key technologies for coupling of energy sectors



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SCOPE Scenario Development (SCOPE SD) is used for cost-optimised target scenarios of future energy systems with energy and emission targets – captures wide range of technology combinations

Input data

- Fuel costs (conventional & synthetic renew. import)
- Technology costs
- Potentials and restrictions
- Energy sector demand time series (power, heat, industry, transport)
- Technology-specific time series (wind, solar, natural inflow, COP, solar thermal, …)

Linear Optimization Model (LP)

Europe and/ or Germany

Objective is to minimise investment and system operation cost

subject to compliance with climate protection targets

full consecutive year,
hourly resolution (8760h)
historical climate reference years

Output data

- Optimised power generation mix
- Optimised heat generation mix
- Optimised transport mix
- Energy framework and installed capacities
- CO_2 emission price(s)
- …

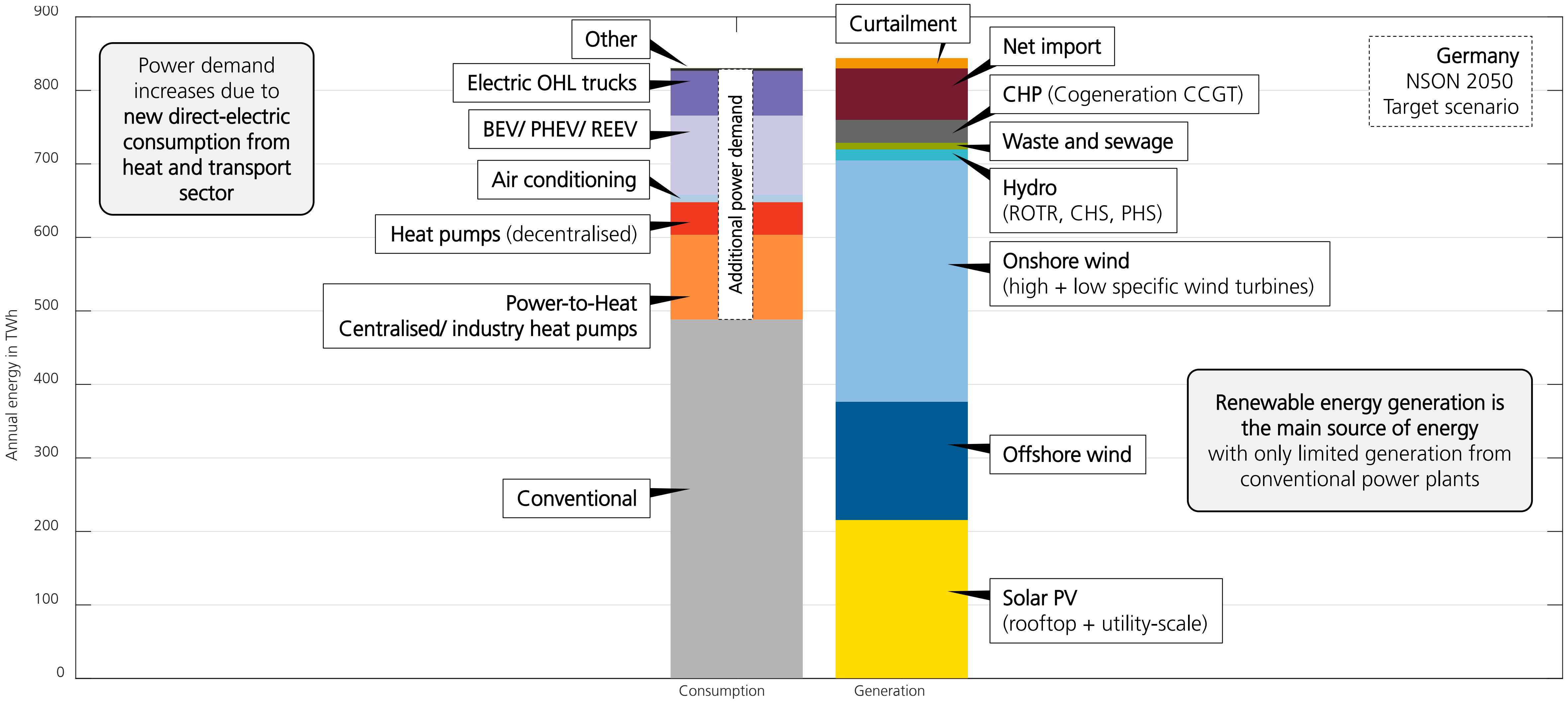
Markets

- Power market
- Heat markets (various building types and temperatures)
- Gas markets (national/ international)
- Transport demands (private, commercial, heavy goods)
- CO_2 markets (national/ international, sector-specific, ETS, non-ETS)

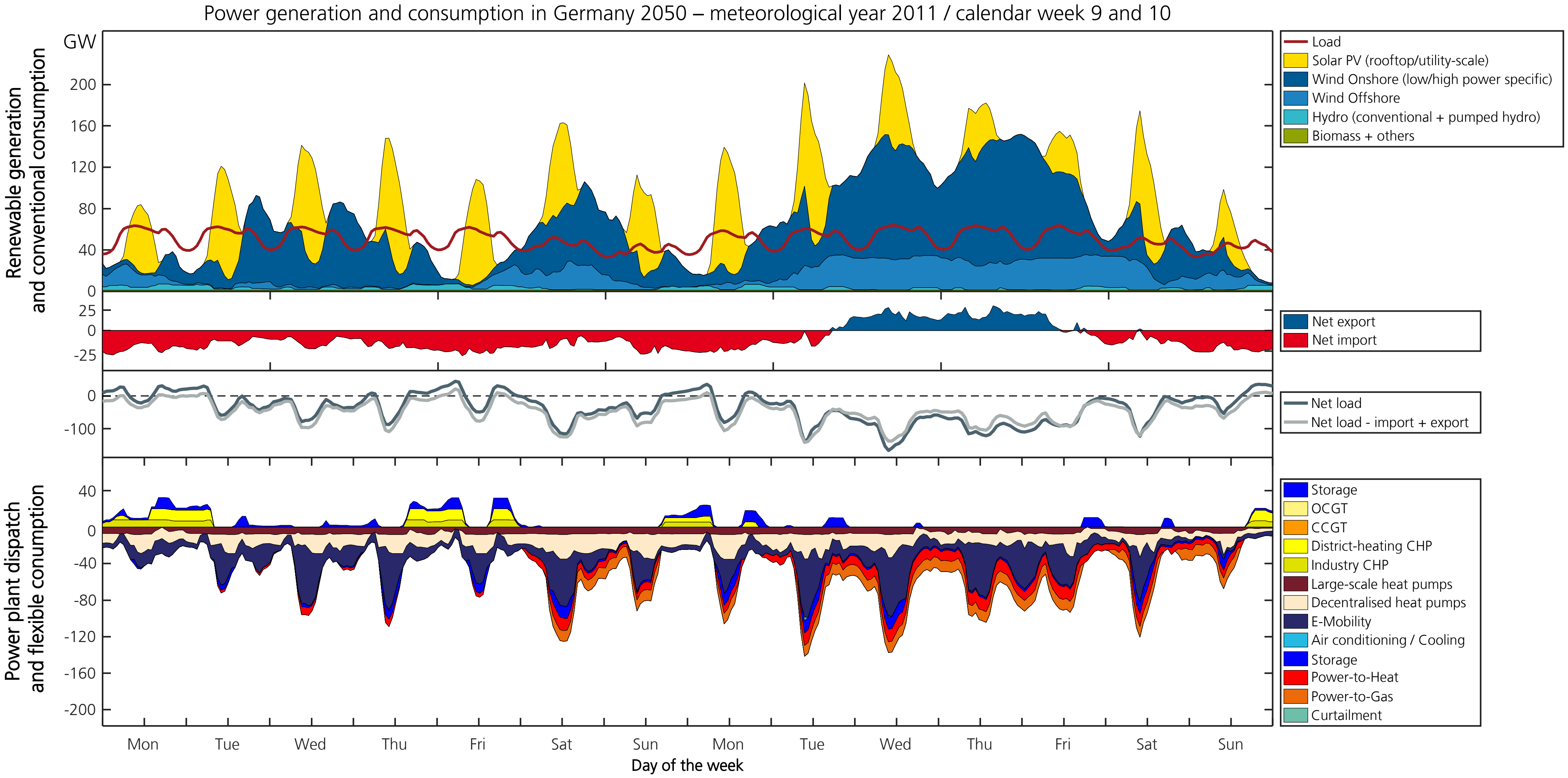
Technology options

Wind, Solar	Energy storage	Power-to-Gas	BEV	PHEV/ REEV
Hydro power	Cogeneration	Cooling process	Boiler	Electric truck (OHL)
Condensing Plant	Power-to-Heat	Heat pump	Solar thermal	Geothermal

Power sector sees higher volumes as it is expected to supply the heat and transport sector with electricity in order to fulfil overall energy sector climate targets (-80% carbon emissions vs. 1990 levels)



Exemplary week shows integration of renewable electricity through sector integration – heat and transport sectors directly use electricity and introduce flexibility – PtG provides additional balancing



Wind and solar PV are the primary energy sources – direct electrification favoured due to economic and efficiency advantages – power-to-X applications are still important and a challenge

General insights from modelling and analysing multiple configurations of low-carbon energy systems:

Electricity production from wind and solar PV is the primary source of energy
that can be facilitated by a high level of cross-sectoral integration

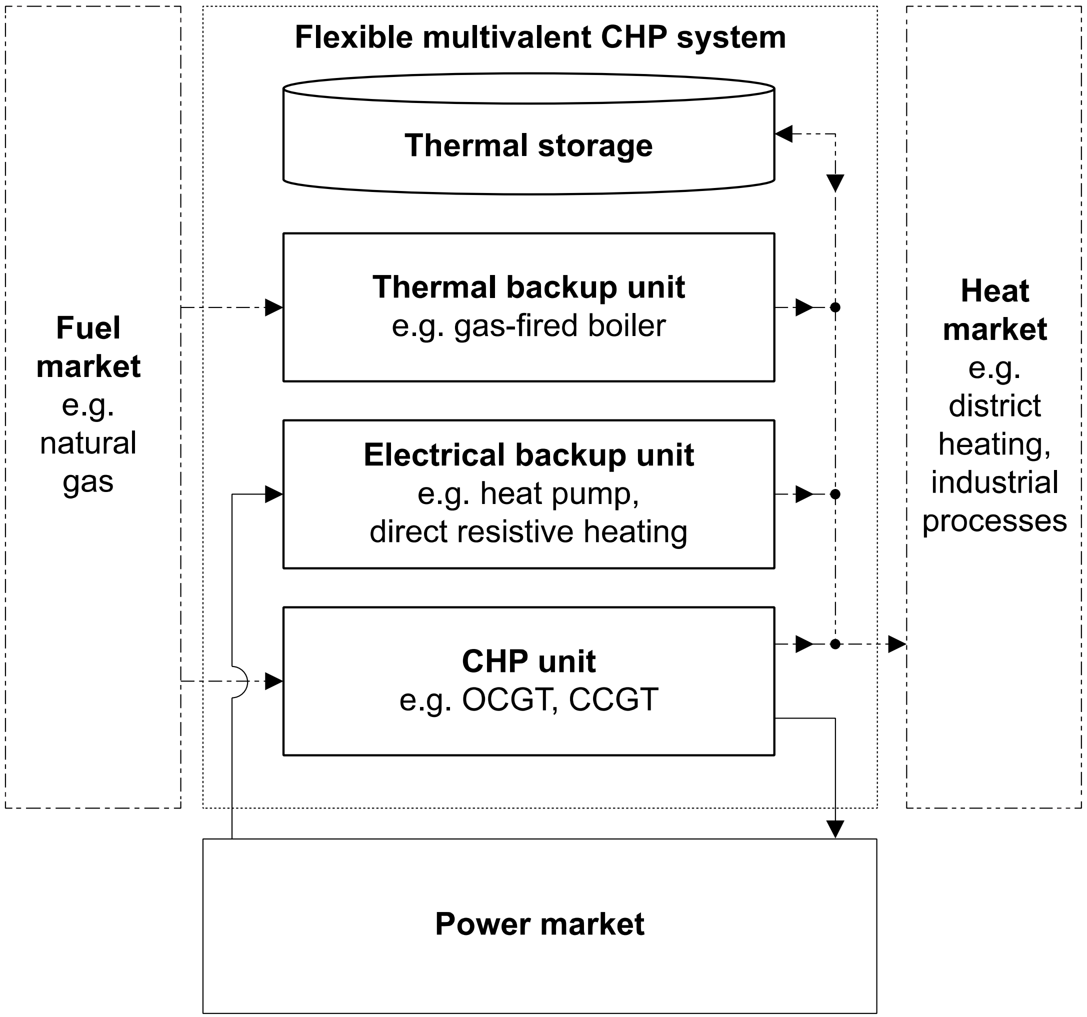
Efficiency disadvantages of using fuels exacerbated by the conversion losses of electricity to synthetic fuels ("PtX")
i.e. H_2, Power-to-Gas (PtG), and Power-to-Liquid (PtL)

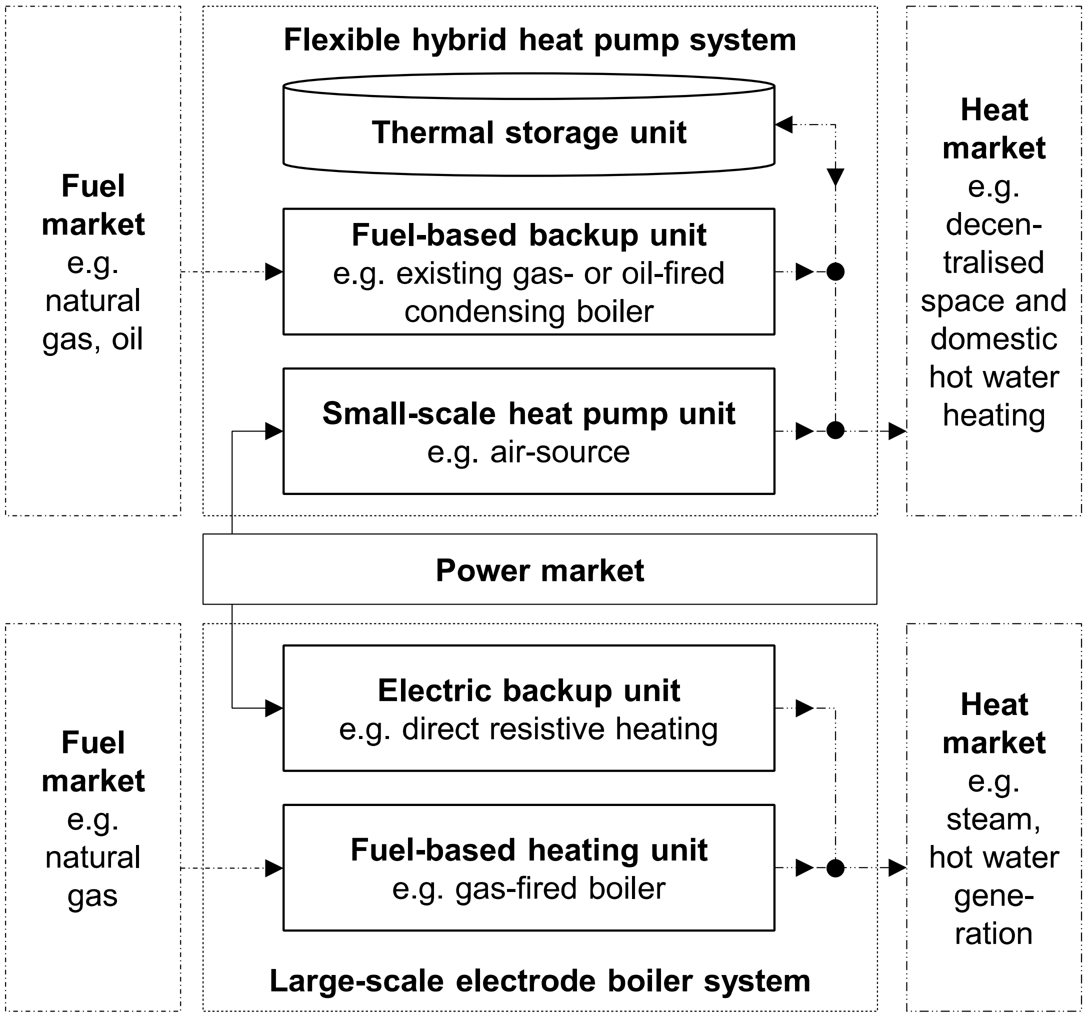
Despite of the efficiency drawbacks, PtX is an important pillar of carbon-neutral pathways
since Germany / Europe require large amounts of synthetic fuels even if maximum efficiency and electrification are achieved

Chemical industry, steel production, …?

Challenge is a necessary market uptake for green hydrogen / PtX in Europe without the "surplus electricity from renewables"

Hybrid technology systems are vital for integrating renewable electricity into other energy sectors – e.g. flexible CHP, hybrid heat pump, and electrode boiler systems for the heat markets

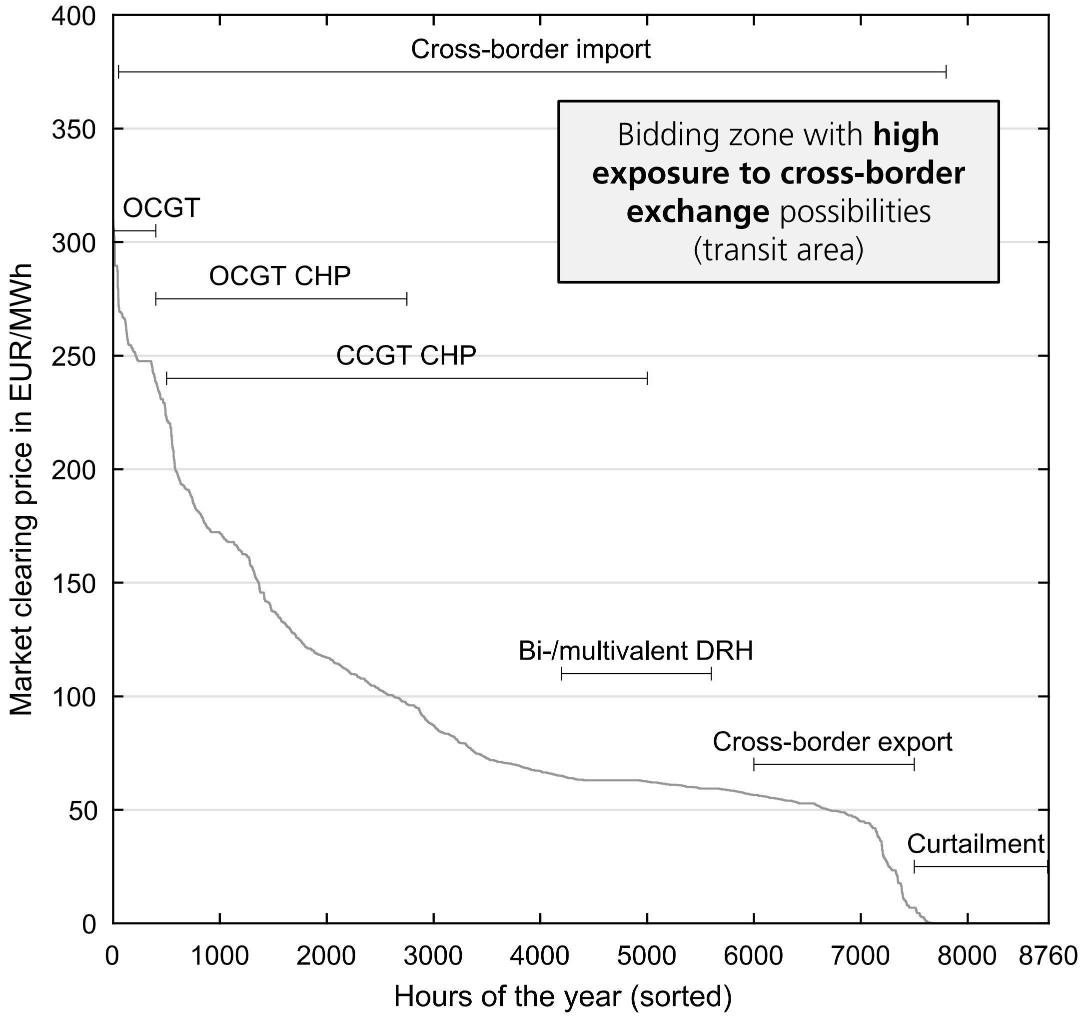


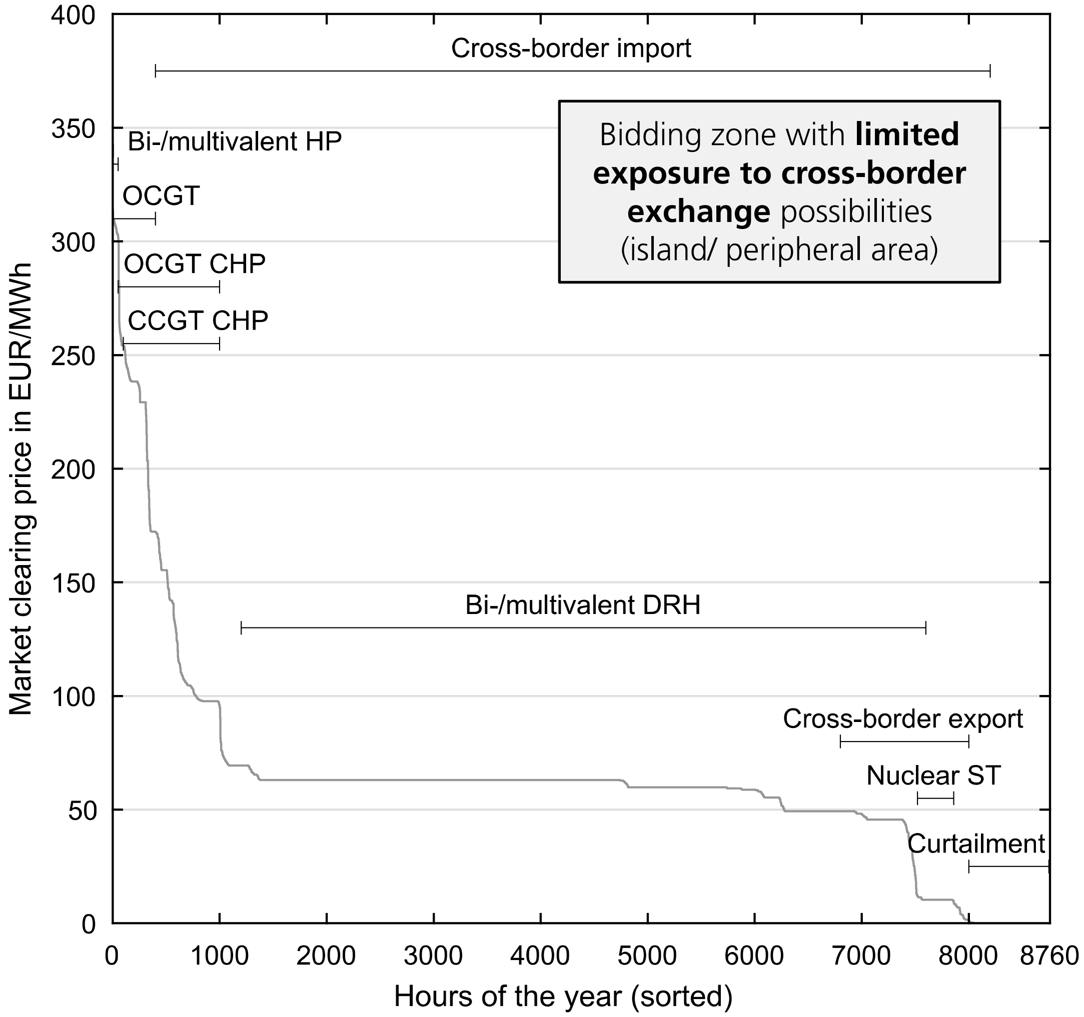


Preprint: Härtel & Korpås, Demystifying market clearing and price setting effects in low-carbon energy systems, Energy Economics (under review).

Demand bidding from hybrid technologies, particularly power-heat sector units, might become very important for the formation of market clearing prices in low-carbon energy systems

Endogenous carbon price of 336 EUR/toCO_2-eq.
(dual variable of carbon budget constraints)





Preprint: Härtel & Korpås, Demystifying market clearing and price setting effects in low-carbon energy systems, Energy Economics (under review).; Direct resistive heating (DRH)

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"German government is currently at odds over hydrogen and electricity-based fuels" for its ongoing development of clean energy policy

Core question	**How much hydrogen and products based on it, e.g. synthetic methane, are needed for the energy transition?**

TAGES SPIEGEL

CDU/CSU parliamentary group ("Union")	SPD-led Federal Environment Ministry (BMU)
■ **Large quantities** needed, **as quickly as possible** ■ **7-point plan** for the promotion of hydrogen ■ Pressing for a **rapid implementation** of the **EU Directive on the Promotion of Renewable Energies** (RED II) into German law (target quota for regenerative fuels raised from 14 to 20%; sub-quota for green hydrogen and electricity-based fuels)	■ **Not in a hurry** – precious and expensive **hydrogen to be limited to a few applications** for which there are no other ways of reducing CO_2: heavy goods vehicles by water and air, chemical industry, steel manufacturers ■ **Private transport and trucks** no longer among those applications ■ **Electricity be used directly as far as possible**, e.g. in battery-operated electric cars or electric heat pumps

German government is at odds over national strategy for hydrogen and electricity-based fuels

Various ministries agree on import of hydrogen and synthetic fuels in Germany because of the limited domestic production potential for e-fuels

Taken from Der Tagesspiegel, "Wasserstoff spaltet die Bundesregierung", 5 December 2019.

Hydrogen's theory of colour shows carbon-free and low-carbon options for low-carbon energy systems

Grey H_2
Steam reformer
Natural gas

Green H_2
Electrolysis
Wind and solar PV

Pink H_2
Electrolysis
Nuclear

Carbon-neutral hydrogen

Low-carbon hydrogen

Turquoise H_2
Methane pyrolysis
Natural gas / biogas

- 83% natural gas + 17% electricity
  ⇨ 50% hydrogen + 40% carbon
- Methane slip
- Use of fossil carbon e.g. for steel production or graphite in batteries (pilot plants)
- Storage in a CO_2 sink implies higher natural gas consumption with higher methane slip than blue hydrogen

Blue H_2
Steam reformer with CCS
Natural gas / biogas

- 100% natural gas
  ⇨ ~75 – 80% hydrogren
- 90 – 95% of carbon emissions can be captured
- Methane slip

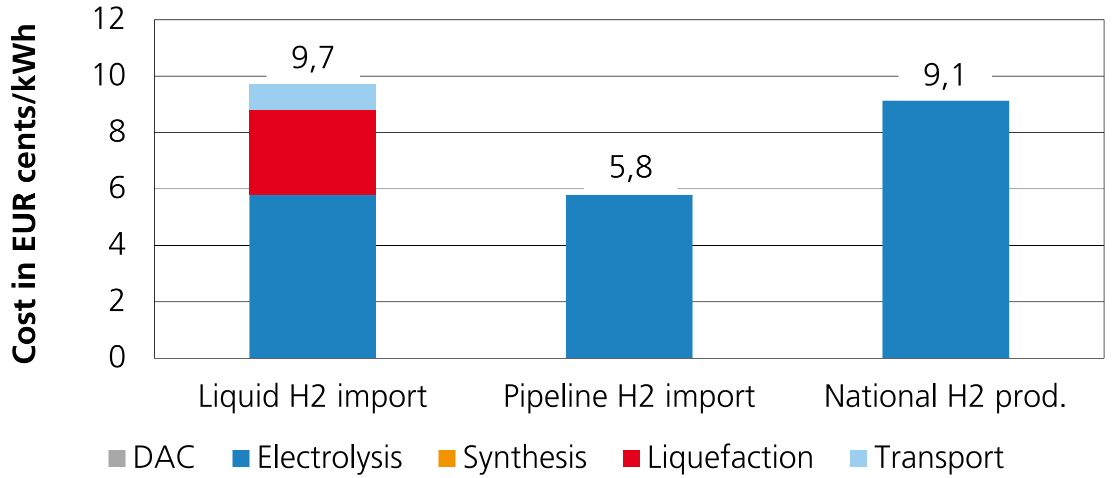
Long-term PtX cost comparison shows that a national PtL production (offshore wind based) is more expensive than all import variants – European H_2 production can be competitive with liquid H_2 imports

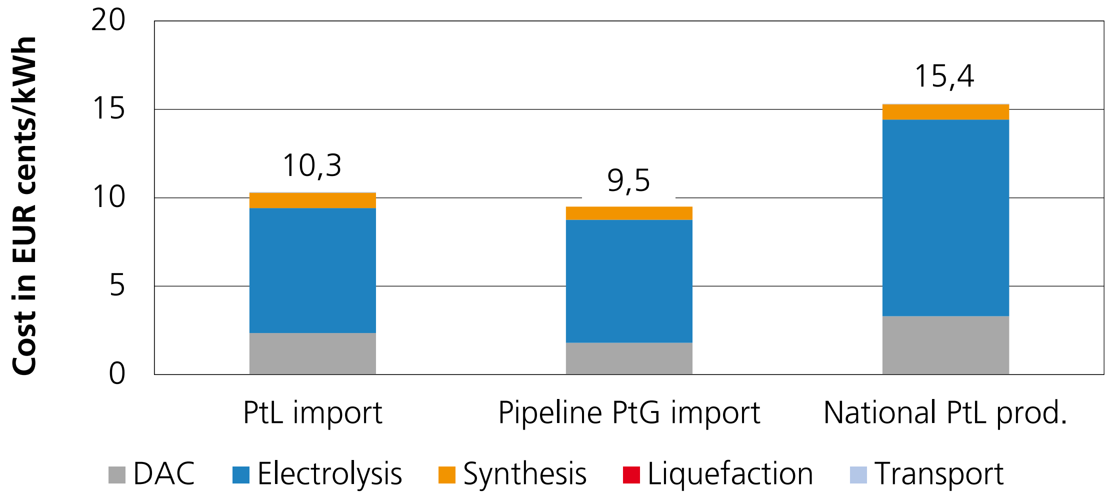
Import vs. national hydrogen paths (2050)	
Liquid H_2 import (Morocco)	9,7 ct/kWh
Pipeline H_2 import (Morocco)	**5,8 ct/kWh**
National H_2 production (offshore wind)	9,1 ct/kWh

Import vs. national PtL / PtG paths (2050)	
PtL import (Morocco)	10,3 ct/kWh
Pipeline PtG import (Morocco)	9,5 ct/kWh
National PtL production (offshore wind)	**15,4 ct/kWh**
National PtL production (offshore wind, oxyfuel)	13,0 ct/kWh

Assumptions

- Cost projections for heat provision, direct air capture (DAC), electrolysis, and synthesis components from the current literature
- No cost for pipeline transport
- Offshore wind LCOE equal 5 ct/kWh

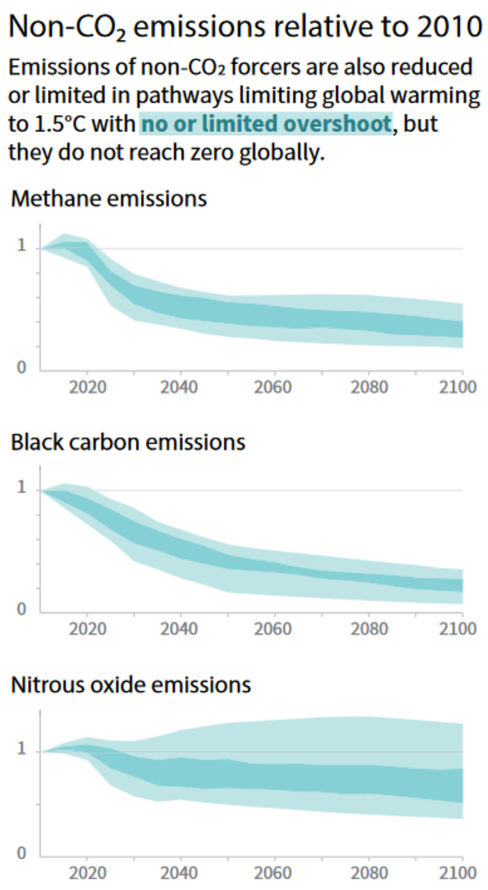




Based on work carried out by M. Pfennig & N. Gerhardt in the DevKopSys project; cost basis 2017; interest rates include inflation correction.

With non-CO_2 emissions, methane emissions increasingly become the centre of attention in climate policy-making

IPCC 2018 SPM SR15



Methane emissions
Estimated responsibility for about **17% of current anthropogenic climate warming**
Can have **short-term impact on the climate system** (concerning tipping points, e.g. permafrost)
Global Warming Potential (GWP) for 100 and 20 year time-scales: **GWP_{100} = 34 / GWP_{20} = 86**
Small emissions can have **big climate impacts**
Difficult data availability of status quo and improvement potentials
Relevant because of **methane slip** in **natural gas extraction, processing, transmission and distribution networks**
Today, methane emissions between 0.9 – 2.2 %
Increased focus in climate policy discussion

Fritsche, U. R. et al. 2006: Kurzstudie: Stand und Entwicklung von Treibhausgasemissionen in den Vorketten für Erdöl und Erdgas; Lechtenböhmer, S. et al. 2005:Treibhausgasemissionen des russischen Erdgas-Exportpipeline-Systems; Schütz, S. et al. 2015: Treibhausgas-Minderungspotenziale in der europäischen Gasinfrastruktur.

Role of hydrogen types depends on detailed evaluation of specific emissions – e.g. blue H_2 assessment is to include remaining CO_2 and methane slip emission compensation in a carbon-neutral world

Long-term levelised cost of blue H_2:

for 1 MWh H_2	MIN	MAX	Unit	Comment
Steam reformer	14,49	14,49	€/MWh H_2	
Natural gas consumption	1,25	1,33	MWh	80-75% Efficiency
Specific natural gas cost	19,90	19,90	€/MWh	WEO 2018 SD
Natural gas cost	24,88	26,53	€/MWh H_2	
CO_2-capture	0,24	0,24	t CO_2	95-90% capture rate
Cost for CCS	43	124	€/t CO_2	
Total w/o compensation	**49,62**	**70,93**	**€/MWh H_2**	
CO_2 remaining emissions	0,01	0,03	t CO_2	95-90% capture rate
CO_2-eq. methane slip	0,02	0,13	t CO_2-eq.	w/o transport;GWP_{100} / w/o distribution;GWP_{20}
Cost neg. emissions DAC	90	130	€/t CO_2	
Cost neg. emissions storage	4,00	51,00	€/t CO_2	CO_2 transport + storage
Compensation	2,99	28,65	€/MWh H_2	
Total	**53**	**100**	**€/MWh H_2**	

Comparison with other hydrogen import paths

- Liquid H_2 import (Morocco) — 97 €/MWh H_2
- Pipeline H_2 import (Morocco) — 58 €/MWh H_2
  plus pipeline transport — X €/MWh H_2

Cost of blue H_2 depend on climate policy assessment of methane slip

Based on work carried out by M. Pfennig & N. Gerhardt in the DevKopSys project; DAC assumed as cost benchmark with limited LULUCF and BECCS potentials.

Investigation of three carbon-neutral Europe 2050 scenarios with varying PtX import costs to better understand complex effects in the overall energy system

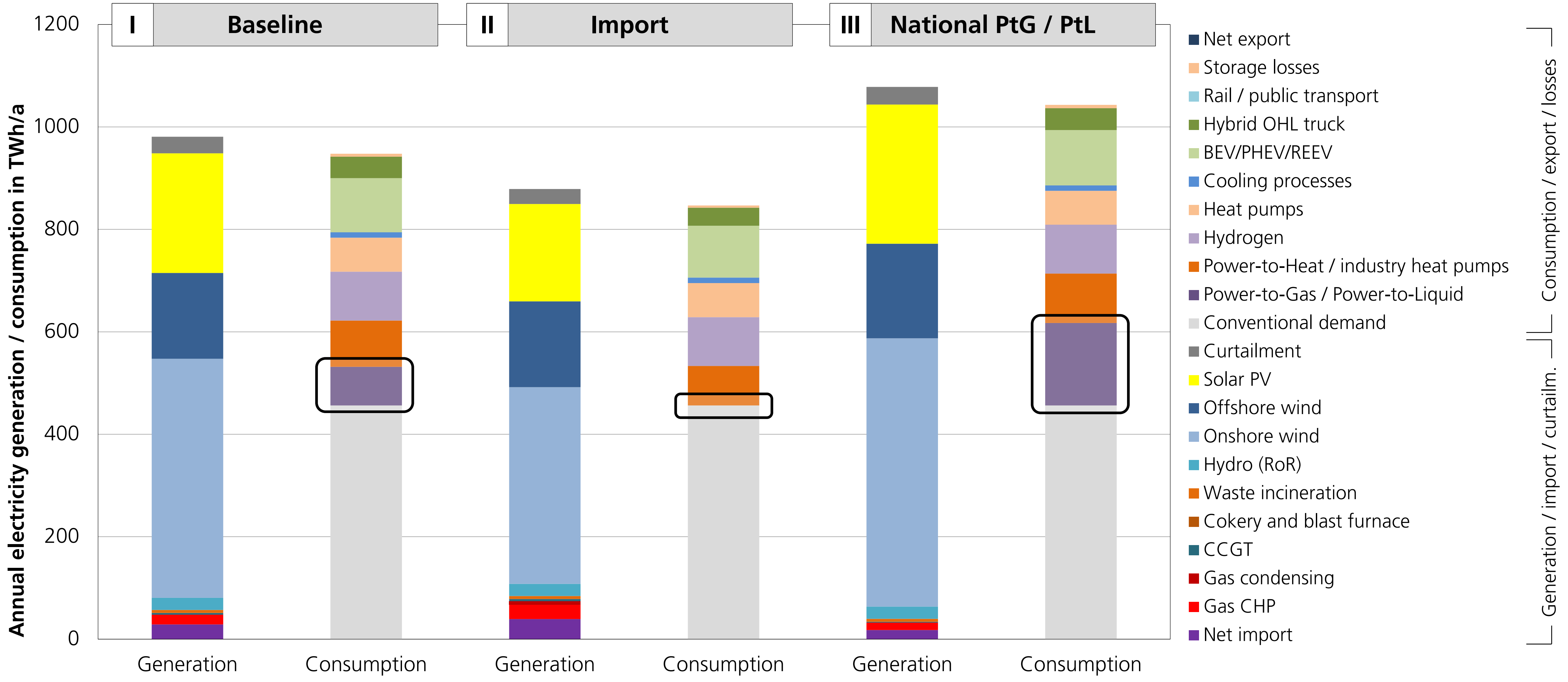
General assumptions for carbon-neutral Europe 2050

- High transport sector traffic volumes
- Ambitious refurbishment levels for buildings, including exit from decentralised biomass heat generation and high district heating shares
- Restrictive use of biomass, implying negative emissions via LULUCF and other measures
- No CCS but CCU based on CO_2 sources from industry and biomass in Europe
- Direct air capture (DAC) outside of Europe
- Green H_2 for chemical industry and steel production
- Small share of pink H_2

I Baseline	II Import	III National PtG / PtL
PtG / PtL import price of 107 €/MWh	PtG / PtL import price of 97 €/MWh (20% reduction)	PtG / PtL import price of 118 €/MWh (10% increase); About 30% more offshore wind capacity across Europe
Moderate national production of PtG / PtL, i.e. about 75 TWh in Germany	**No national production of PtG / PtL**	**Very large national production of PtG / PtL, i.e. about 160 TWh in Germany**

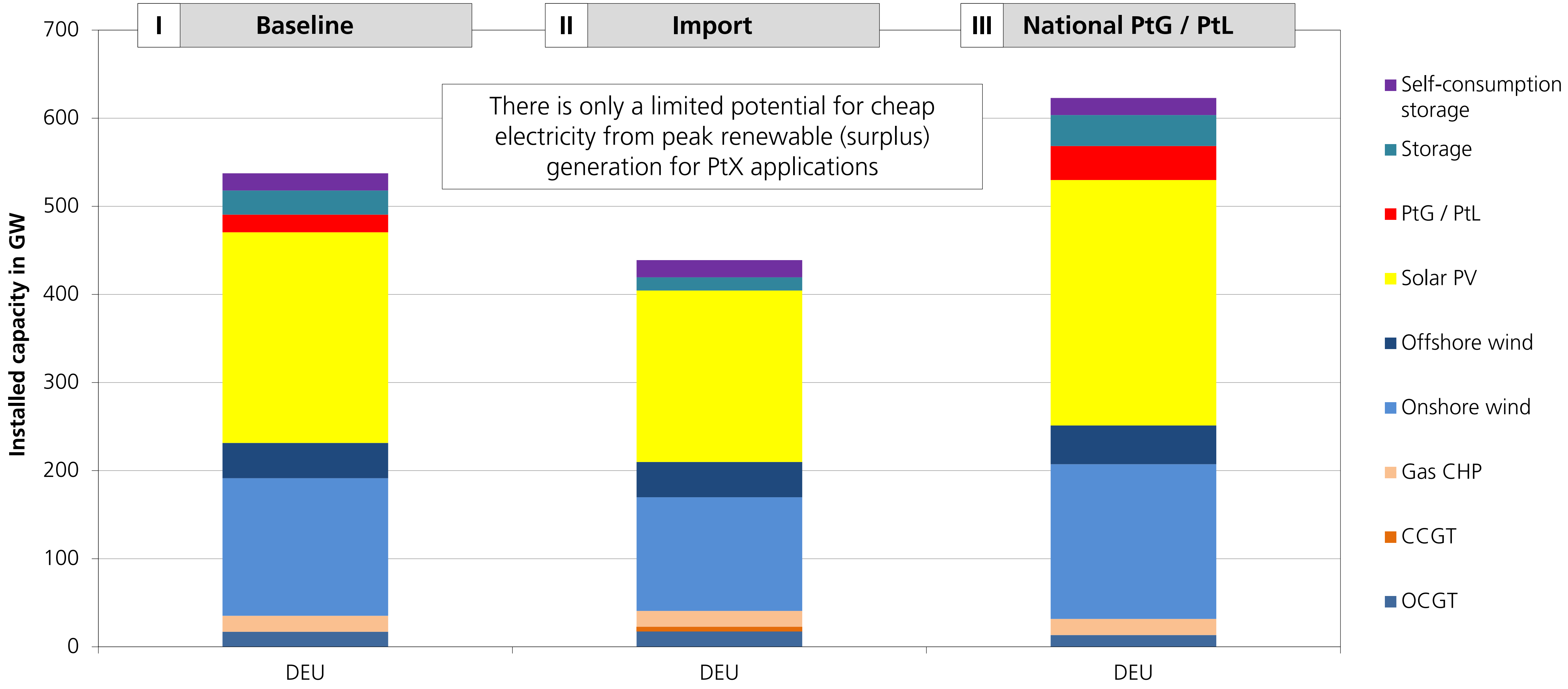
Based on work carried out by F. Frischmuth & N. Gerhardt in the DevKopSys project; scenarios were created with the cross-sectoral dispatch and investment model SCOPE SD at Fraunhofer IEE.

Electricity balances for Germany 2050 strongly affected by consumption for different Power-to-Gas / Power-to-Liquid production pathways



Based on work carried out by F. Frischmuth & N. Gerhardt in the DevKopSys project; scenarios were created with the cross-sectoral dispatch and investment model SCOPE SD at Fraunhofer IEE.

Installed capacities vary greatly for Germany in 2050 - Consumption for Power-to-Gas / Power-to-Liquid requires larger wind and solar PV production as well as electricity storage



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Some conclusions to take away!

Low-carbon energy systems

Direct electrification (if possible) of other energy sector applications most economic and efficient solution

Synthetic fuels / PtX play important role for achieving climate neutrality in Europe

Demand bidding from hybrid technologies highly relevant for price electricity price formation

Role of hydrogen in deep decarbonisation

National and different import options for low-carbon/carbon-free hydrogen / PtL

Climate policy evaluation of methane slip highly relevant for cost assessment of different options (long-term costs might be very high)

Natural gas stays cheap – displacing it might be hard and the role of existing pipeline infrastructure might be crucial

Potential lock-in effects of new hydrogen demand vs. industry CCS (relevance of time-scales)

Thank you very much for your attention!

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Questions?

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