universität freiburg

Net-zero Germany: Transitions paths to climate neutrality by 2045

791. WE-Heraeus Seminar

Bad Honnef
Mirko Schäfer

21.06.2023

ESYS Study
„Towards a Climate-neutral Germany“

Working group of the Academies‘ Project „Energy Systems of the Future (ESYS)“ (February 2023)

Methodology and focus

- Own **scenario modelling**
- Review of existing **scenarios**
- Expert discussions in an interdisciplinary working group

- Study (currently German only):

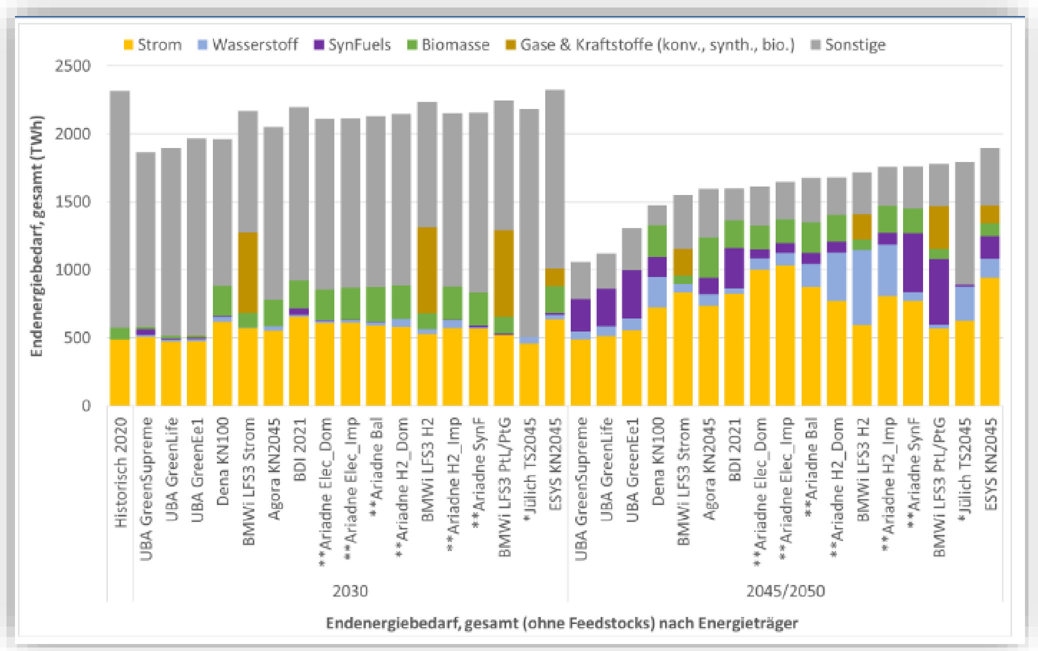
Energy system scenarios
Use and limits of scenarios of the energy transition

Purpose and use

- Identification of feasible pathways
- Options for achieving given targets
- Assessment of trade-offs, sensitivities and cost-efficient interplay between different technologies

Limits

- **Scenarios are no forecasts**
- Often optimization under boundary conditions, not an explicit simulation of decisions, policies, technological development, …



[ESYS 2023]

Common modelling approach: Linear optimization
Example PyPSA-Eur

- Objective function: usually cost minimization

$$\min z = \sum_{n,s} c_{n,s}\bar{g}_{n,s} + \sum_{n,s} c_{n,s}\bar{h}_{n,s} + \sum_{l} c_l F_l + \sum_t w_t \left[\sum_{n,s} o_{n,s,t} g_{n,s,t} + \sum_{n,s} o_{n,s,t}\, h_{n,s,t}\right] + \sum_t \left[suc_{n,s,t} + sdc_{n,s,t}\right]$$

Investment costs

(hourly) Operational costs

- Boundary conditions

$$\sum_s g_{n,s,t} + \sum_s h_{n,s,t} - \sum_s f_{n,s,t} + \sum_l K_{nl} f_{l,t} = \sum_s d_{n,s,t}$$

Nodal power balances (hourly)

$$\tilde{g}_{n,s,t} \cdot \bar{g}_{n,s} \leq g_{n,s,t} \leq \bar{g}_{n,s,t} \cdot \bar{g}_{n,s}$$

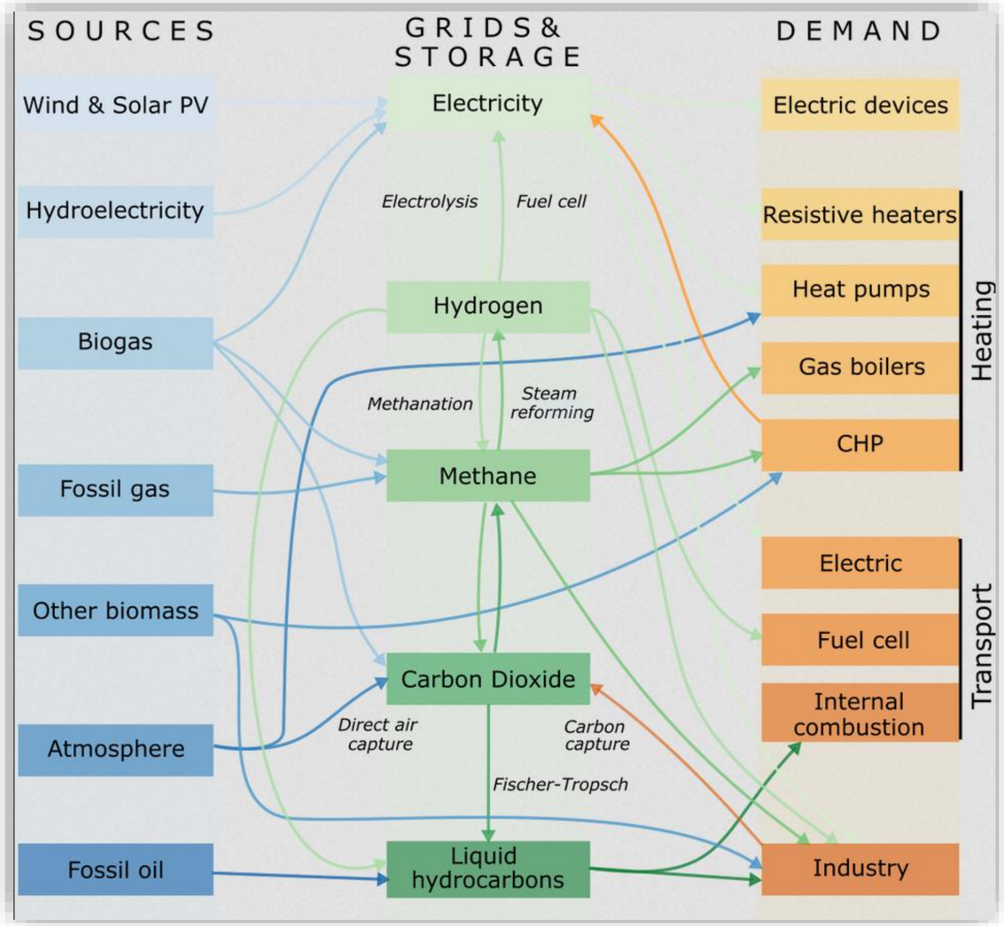
Generator constraints

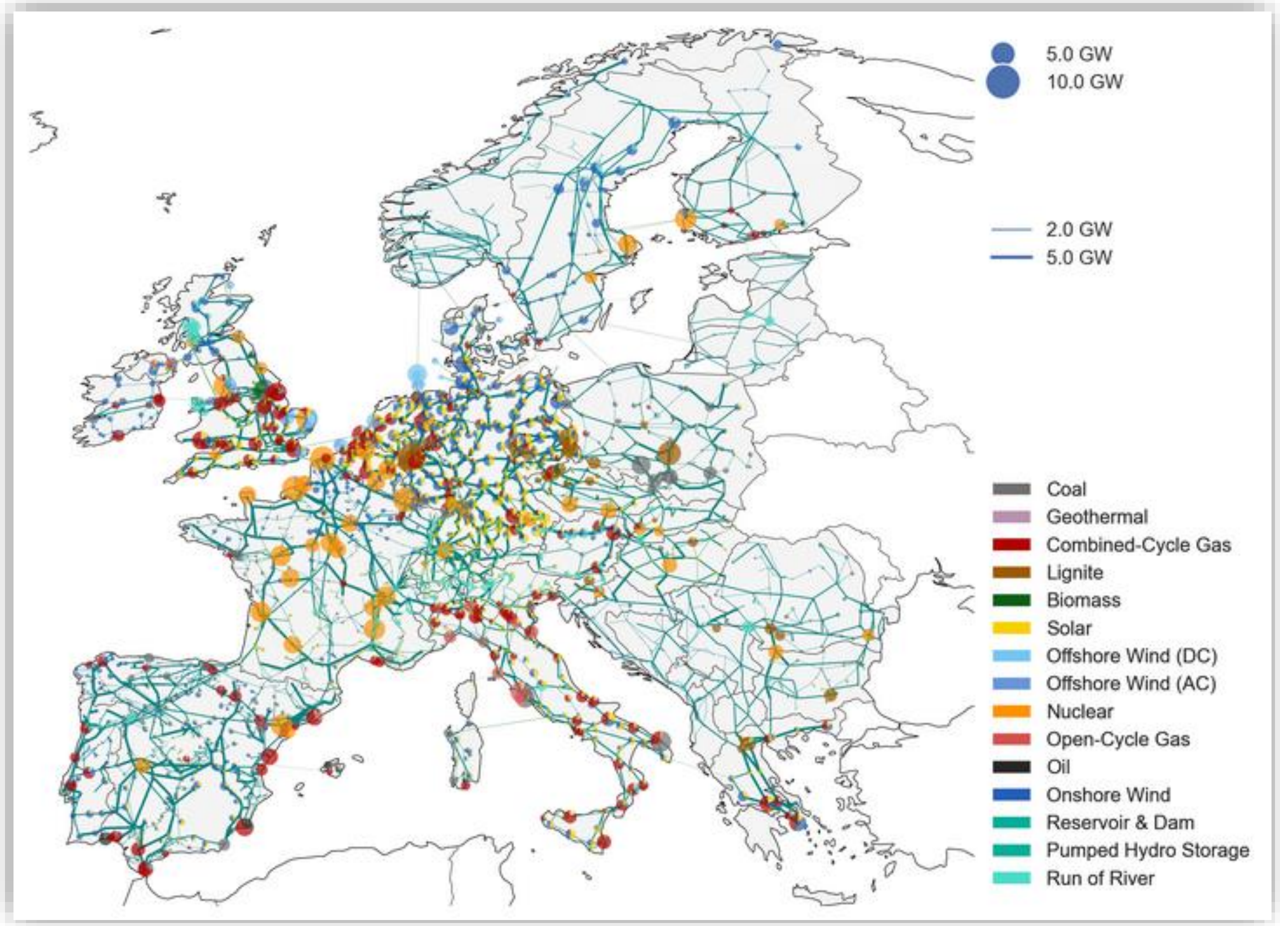
$$\sum_{n,s,t} \frac{1}{\eta_{n,s}} w_t \cdot g_{n,s.t} \cdot e_{n,s} \leq CAP_{CO_2}$$

Emission cap

Common modelling approach: Linear optimization

Example PyPSA-Eur





Assumptions and modelling decisions matter!

Publications, open data and open modelling: Transparency and joint development

ELSEVIER

Energy

Volume 134, 1 September 2017, Pages 469-481

The benefits of cooperation in a highly renewable European electricity network

D.P. Schlachtberger [a], T. Brown [a], S. Schramm [a], M. Greiner [b]

CellPress Sneak Peek

A PREVIEW OF PAPERS UNDER REVIEW

Benefits of a Hydrogen Network in Europe

Joule

118 Pages • Posted: 26 Jul 2022 • Publication Status: **Review Complete**

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ELSEVIER

Applied Energy

Volume 341, 1 July 2023, 121096

PyPSA-Earth. A new global open energy system optimization model demonstrated in Africa

Maximilian Parzen [a], Hazem Abdel-Khalek [b], Ekaterina Fedotova [c], Matin Mahmood [a], Martha Maria Frysztacki [e], Johannes Hampp [d], Lukas Franken [a], Leon Schumm [h g], Fabian Neumann [g], Davide Poli [f], Aristides Kiprakis [a], Davide Fioriti [f]

nature communications

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Article | Open Access | Published: 04 December 2020

Early decarbonisation of the European energy system pays off

Marta Victoria, Kun Zhu, Tom Brown, Gorm B. Andresen & Martin Greiner

Nature Communications **11**, Article number: 6223 (2020) | Cite this article

13k Accesses | **69** Citations | **284** Altmetric | Metrics

Joule

CellPress

Volume 6, Issue 5, 18 May 2022, Pages 1066-1086

Article

Speed of technological transformations required in Europe to achieve different climate goals

Marta Victoria [1 2 5], Elisabeth Zeyen [3 4], Tom Brown [3 4]

Parameters and boundary conditions

Central boundary condition: emission cap (or carbon price)

- Objective function: usually cost minimization

$$\min z = \sum_{n,s} c_{n,s}\bar{g}_{n,s} + \sum_{n,s} c_{n,s}\bar{h}_{n,s} + \sum_{l} c_l F_l + \sum_{t} w_t \left[\sum_{n,s} o_{n,s,t}\, g_{n,s,t} + \sum_{n,s} o_{n,s,t}\, h_{n,s,t}\right] + \sum_{t}\left[suc_{n,s,t} + sdc_{n,s,t}\right]$$

Investment costs

(hourly) Operational costs

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Generator constraints

$$\sum_{n,s,t} \frac{1}{\eta_{n,s}} w_t \cdot g_{n,s.t} \cdot e_{n,s} \leq CAP_{CO_2}$$

Emission cap

National carbon budget
Per capita distribution of global budget

[ESYS 2023]

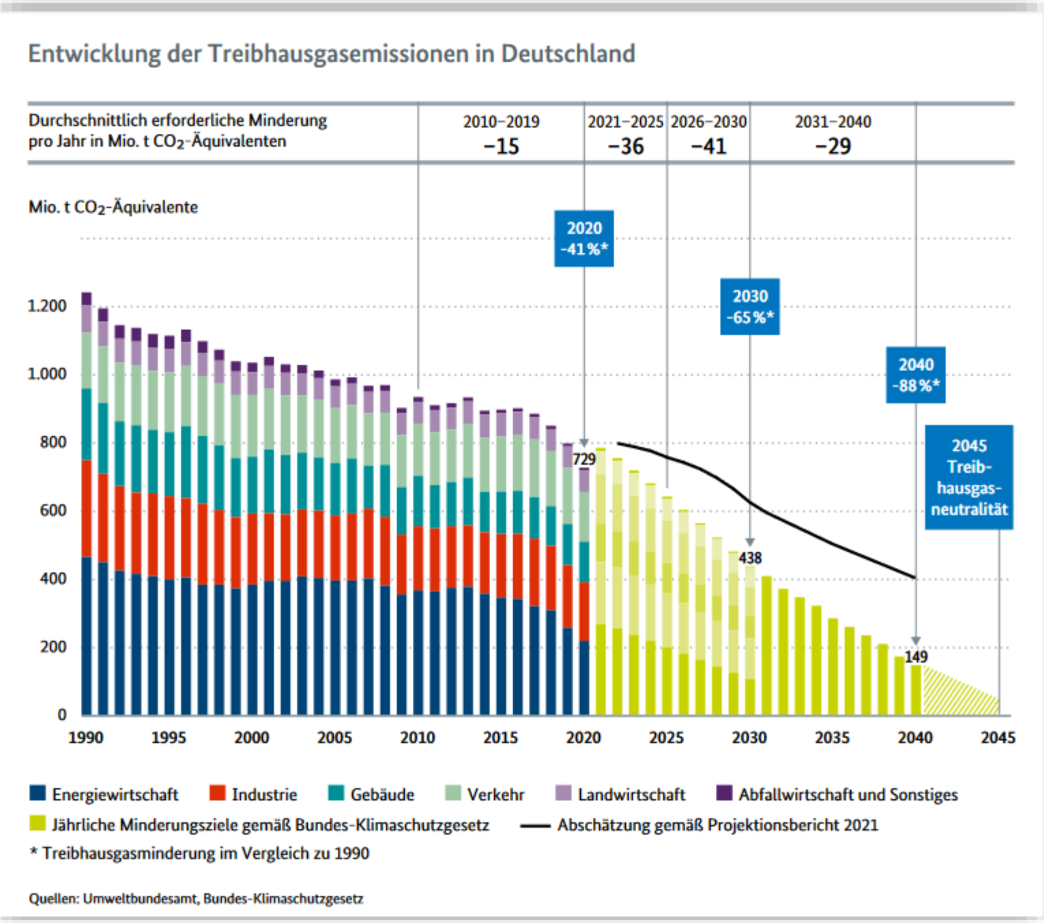
Globale Erderwärmung gegenüber vorindustriellem Zeitalter	Wahrscheinlichkeit der Begrenzung der Erderwärmung	Globales Emissionsbudget ab 2020	CO_2-Budget für Deutschland ab 2022
1,5 °C	50 %	500 $GtCO_2$	3,02 $GtCO_2$
1,5 °C	67 %	400 $GtCO_2$	1,92 $GtCO_2$
1,75 °C	50 %	925 $GtCO_2$	7,69 $GtCO_2$
1,75 °C	67 %	775 $GtCO_2$	6,04 $GtCO_2$
1,75 °C	83 %	600 $GtCO_2$	4,67 $GtCO_2$

Comparison with German climate policy
Emission reduction targets in the Climate Change Act

- Emission reduction pathways
- Climate neutrality in 2045
- After 2045 transition to net-negative emissions

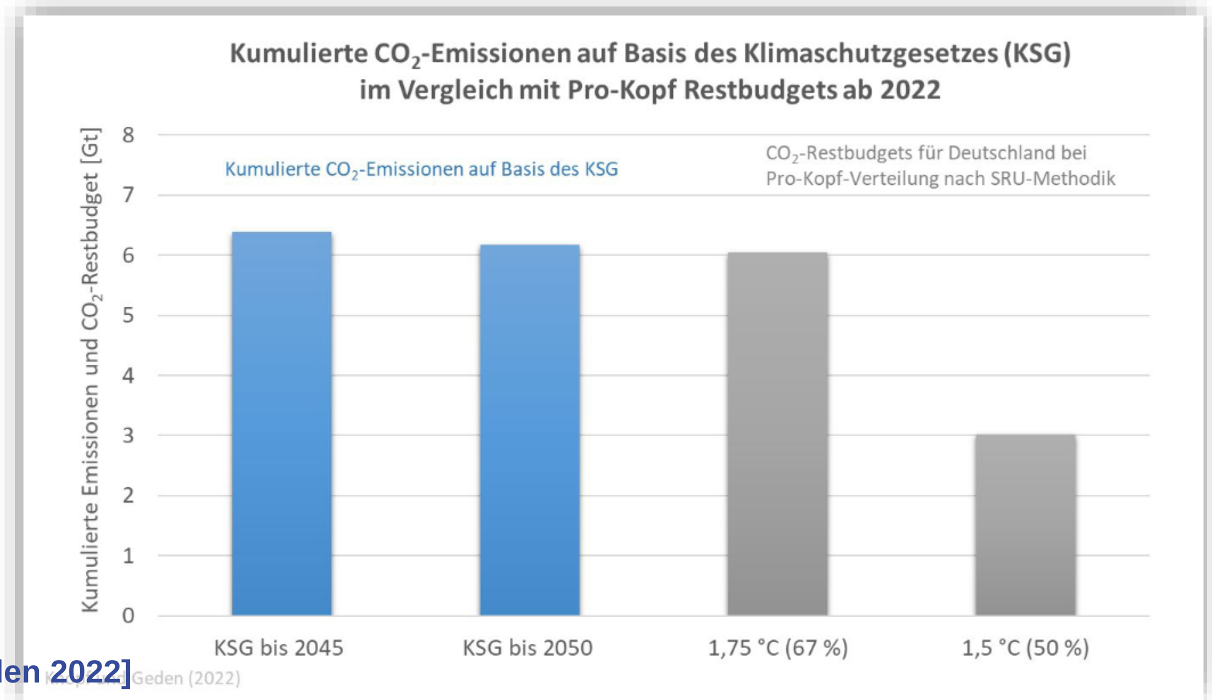
- Global carbon budget is expressed in CO_2, Climate Change Act refers to CO_2eq
- Climate Change Act does not contain an explicit carbon budget

[BMWK 2022]



Comparison with German climate policy
Emission reduction targets in the Climate Change Act

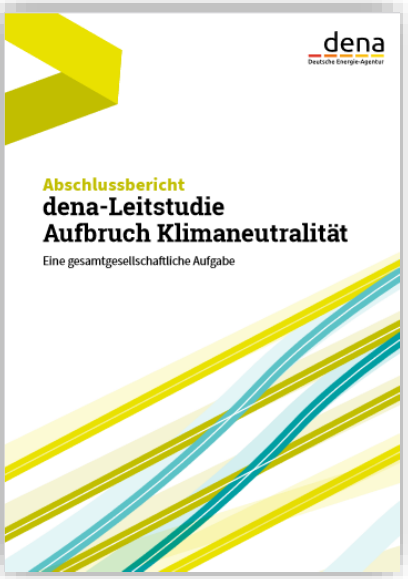
- Emission reduction pathway in the Climate Change Act approx. corresponds to cumulated emissions of 6.4 $GtCO_2$ between 2022 to 2045
- Budget compatible with the target in the Paris Agreement: „well below 2 °C“ (assuming a per capita distribution of the global budget)
- Pathway not compatible with a global 1.5 °C budget (per capita distribution)

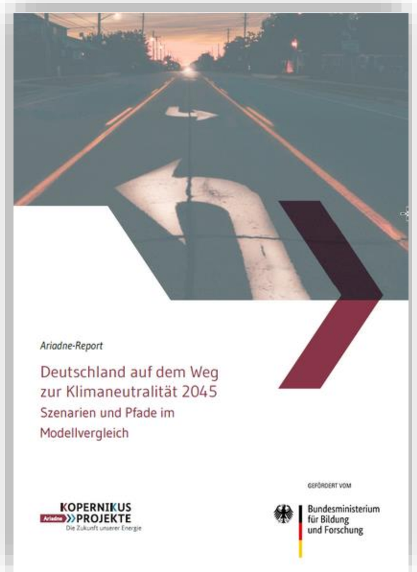


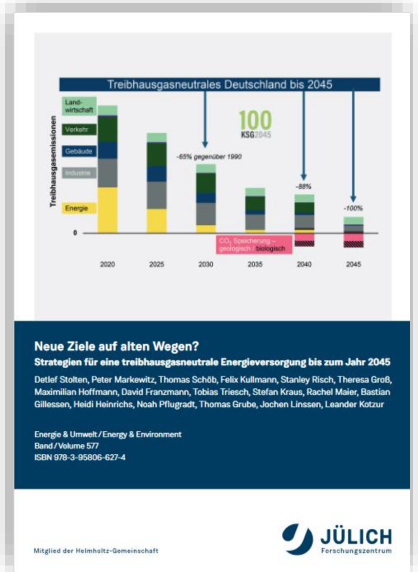
[Knopf & Geden 2022]

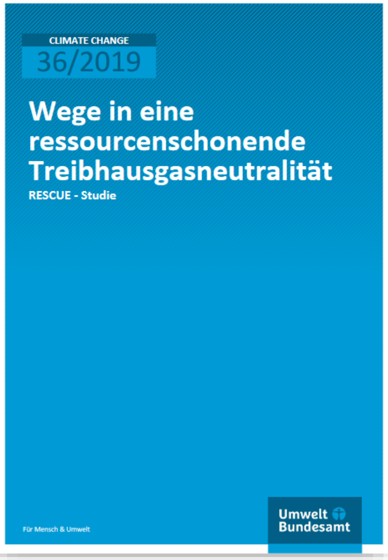
Scenario studies
Climate Neutrality 2045/50

- ESYS: Review of seven studies plus own scenario modelling



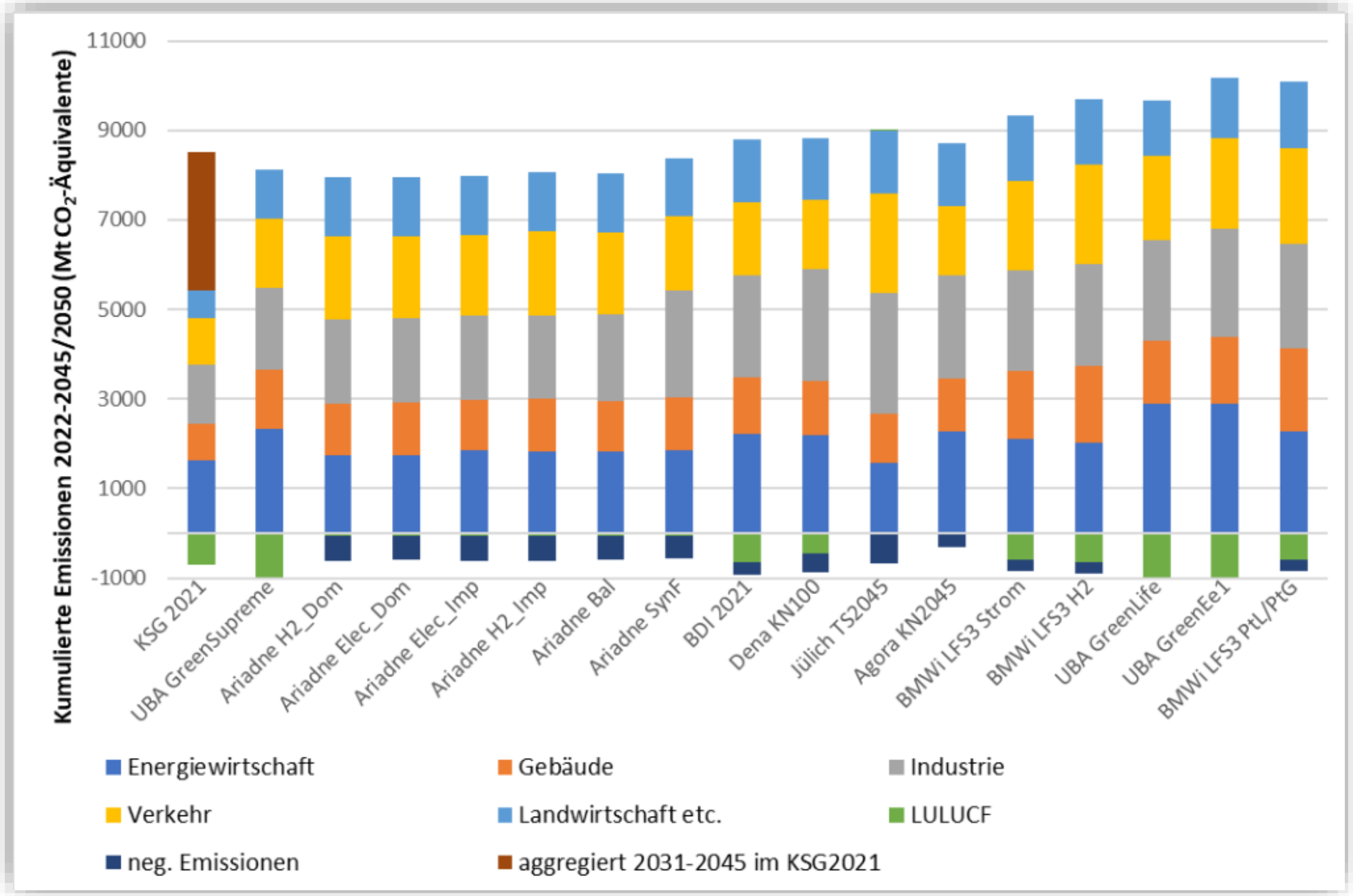




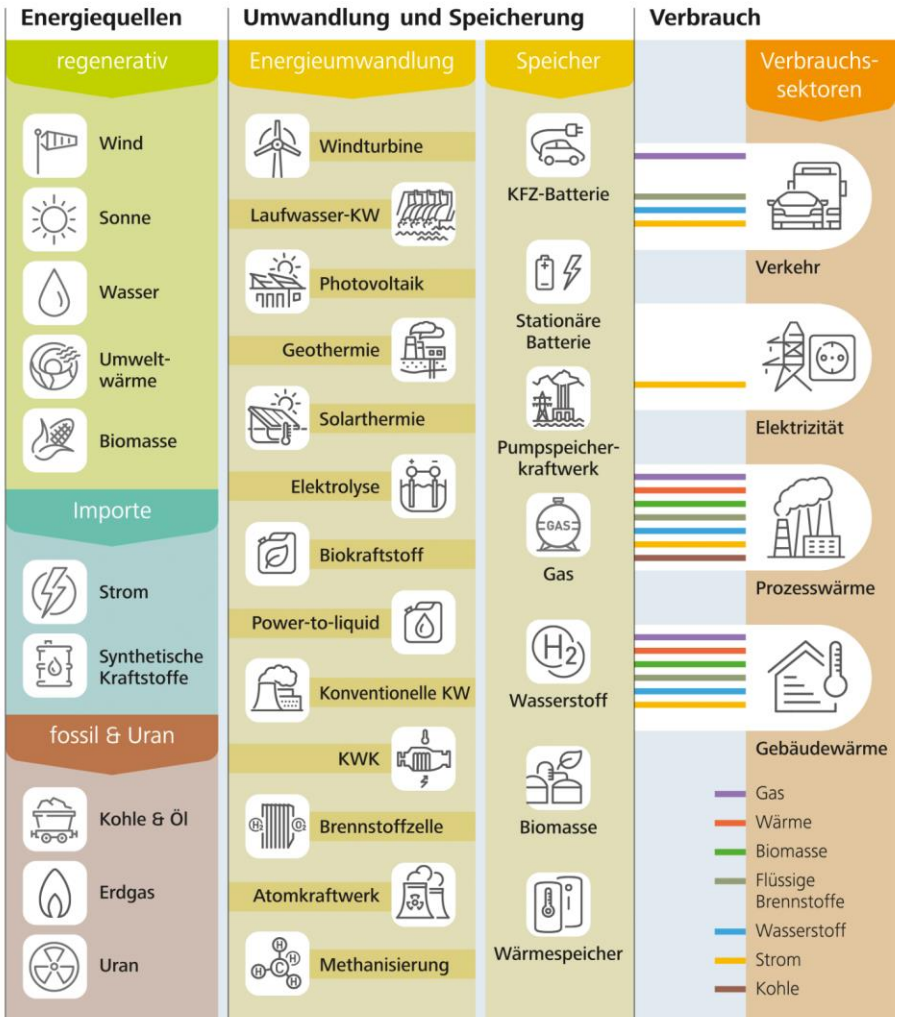


Scenario studies

Climate Neutrality 2045/50, cumulated emissions close to the emissions implied in the Climate Change Act



Own scenario modelling
ReMOD (Fraunhofer ISE)



[FhG ISE 2023]

Scenarios

Main and focus scenarios

Main scenario KN2045

- Ambitious technology rollout
- Moderate demand reduction (efficiency)

Focus „demand reduction“

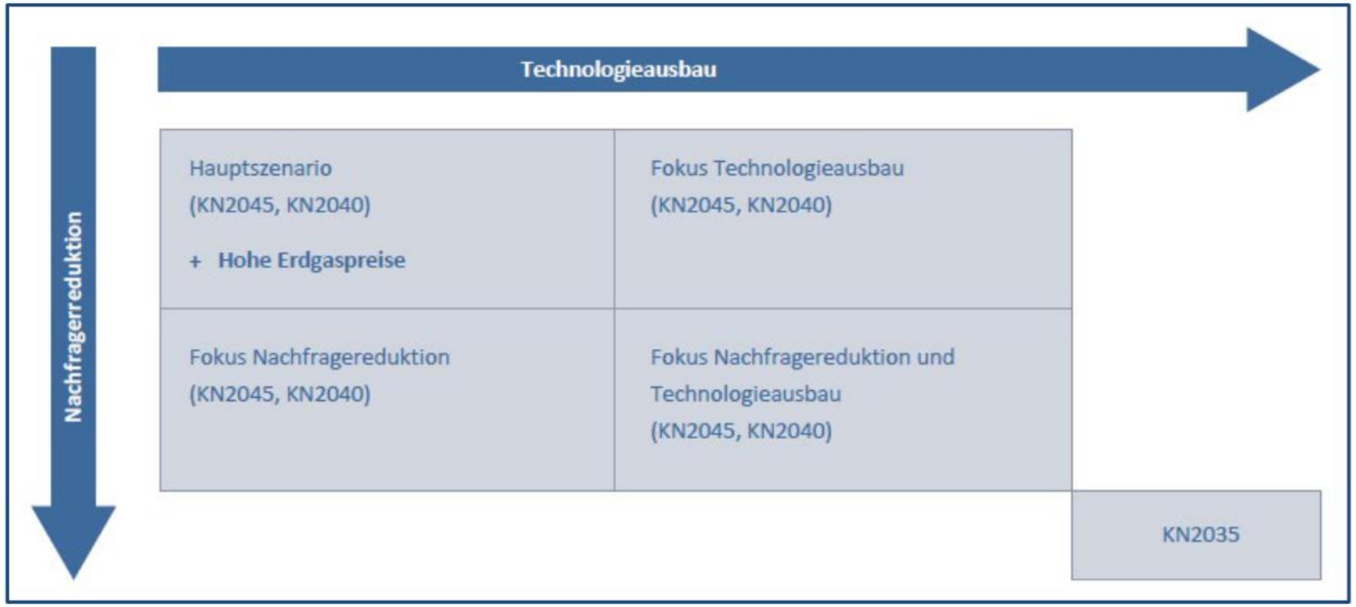
- Very ambitious demand reduction (efficiency, sufficiency)

Focus „technology rollout“

- Very ambitious technology rollout

KN2040, KN2035, Sensitivity to gas prices

Scenario	Energy-related CO_2 emissions
Climate neutrality 2045	Budget of 7.8 Gt_{CO2} with -65 percent in 2030 and -100 percent in 2045
Climate neutrality 2040	Budget of 6.2 Gt_{CO2} with -65 percent in 2030 and -100 percent in 2040
Climate neutrality 2035	Budget of 4 $Gt_{CO2,}$ -100 percent in 2035

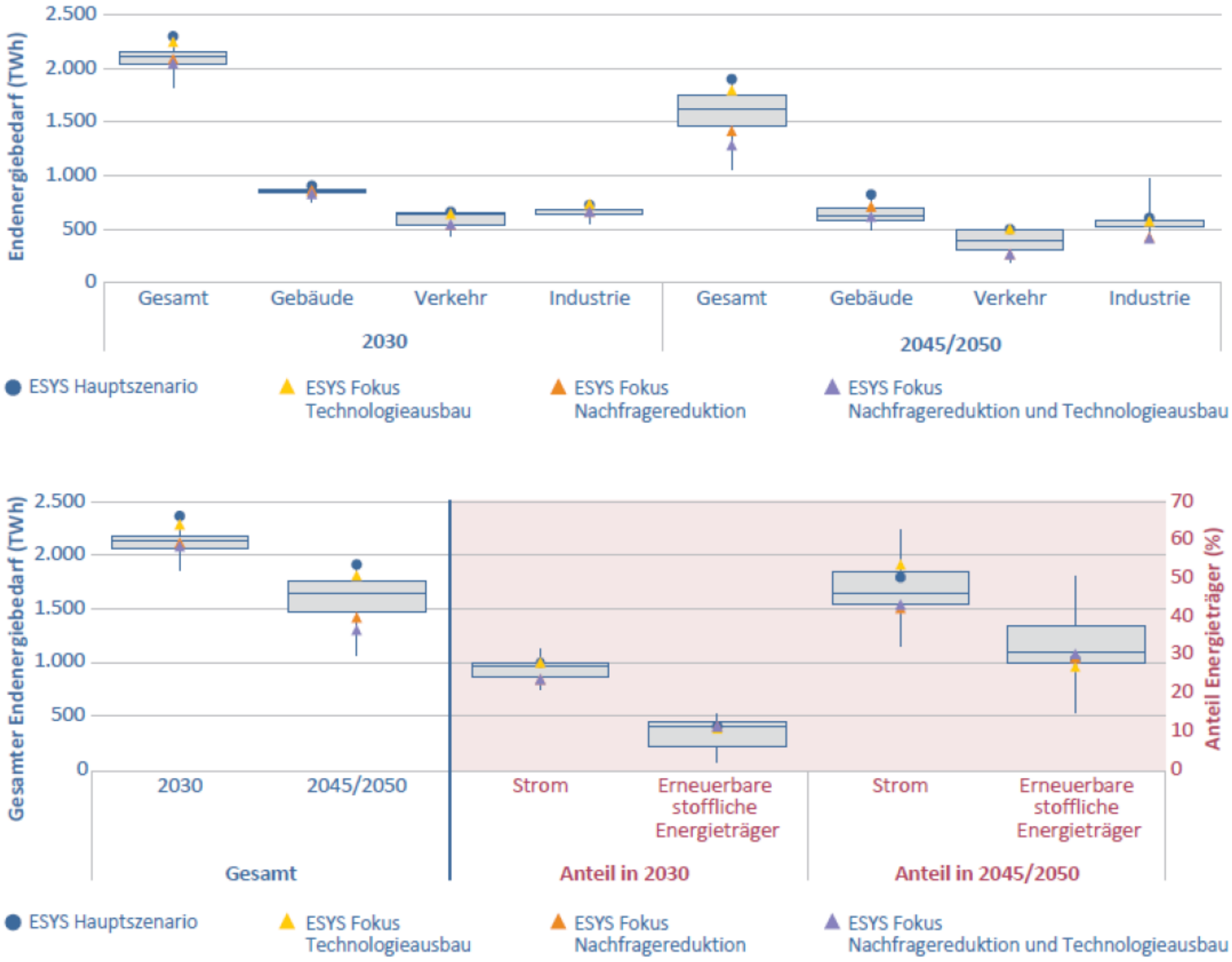


5 „Key messages“

1. Die Transformation zur Klimaneutralität erfordert eine umfassende gesellschaftliche und politische Neuausrichtung (*political and societal reorientation*)
2. Die Klimaziele sind ohne Nachfrageänderungen kaum erreichbar (*demand side options necessary*)
3. Der technologische Umbau muss erheblich beschleunigt werden (*accelerate technological transition*)
4. In der Industrie ist der Dreiklang aus klimaneutralen Prozessen, Kreislaufwirtschaft und Materialeffizienz nötig (*industry: climate neutral processes, circularity, material efficiency*)
5. CO_2-Entnahmen sind erforderlich, ersetzen jedoch nicht die CO_2-Vermeidung (*negative emissions necessary, but do not replace mitigation efforts*)

Final energy demand
By sector and by energy carrier

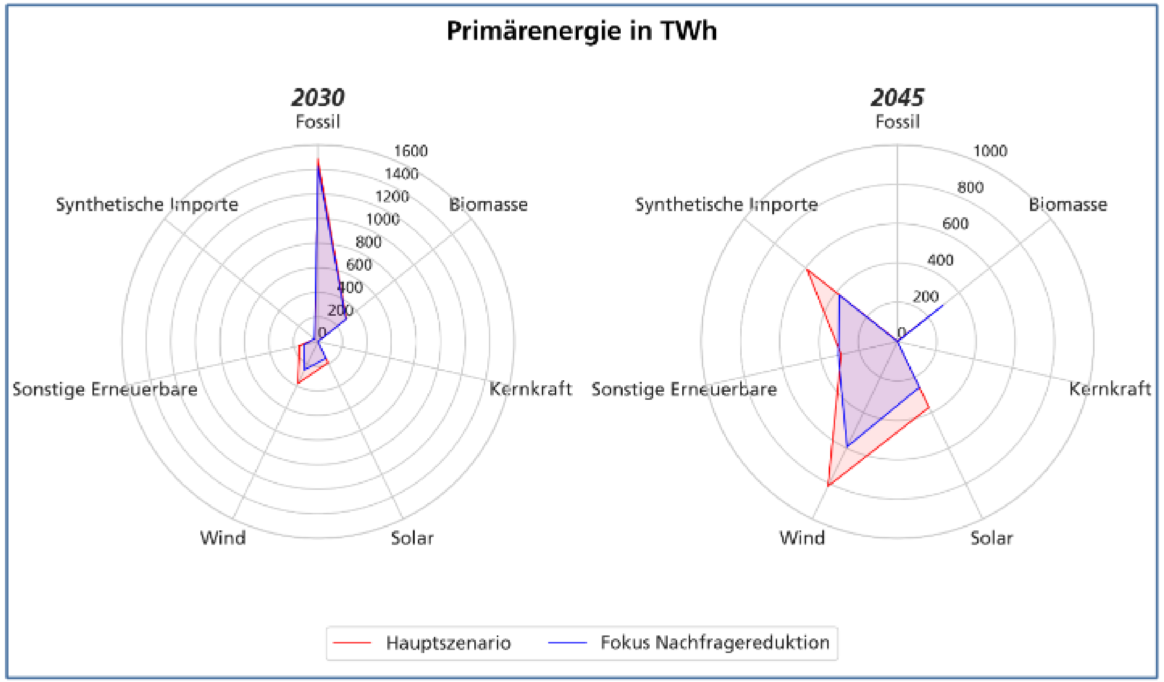
- Reduction of final energy demand in all studies
- Increasing electricity demand

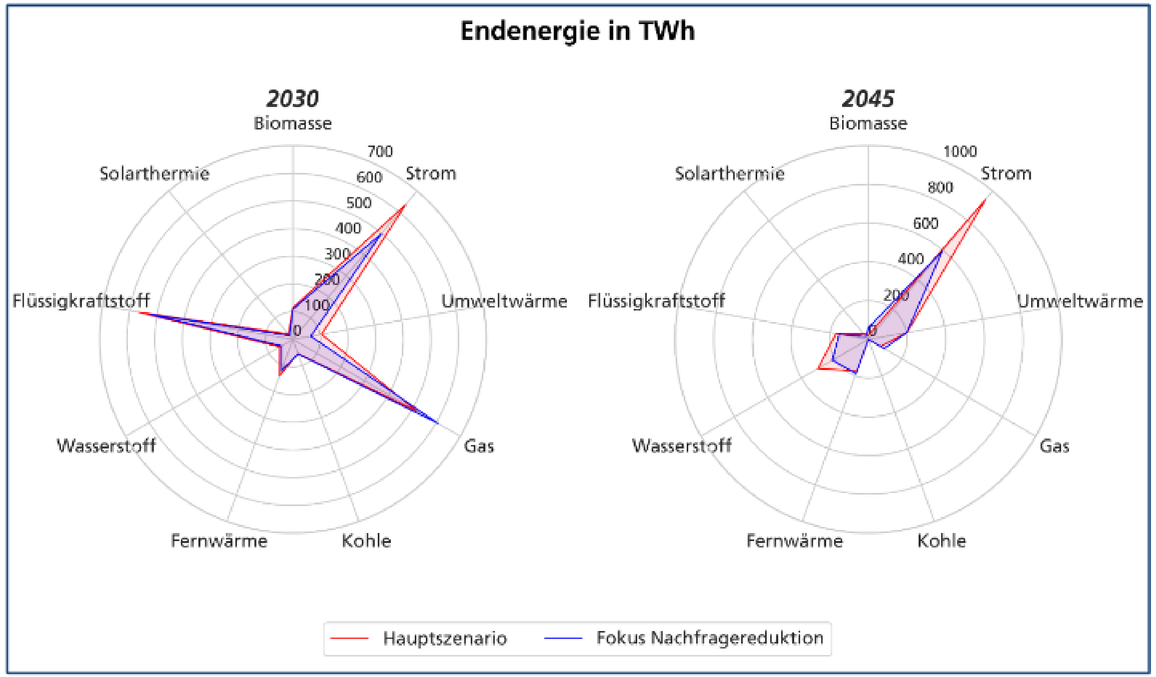


[ESYS 2023]

Focus „demand reduction“

Reduces „pressure“ and provides flexibility, but ambitious technological rollout still needed





[ESYS 2023]

Demand side options

Mobility, buildings, industry, consumption

- „Avoid, Shift, Improve“ categorization

- Further research needed on quantification of potentials and limits, impact chains, representation in energy system models,…

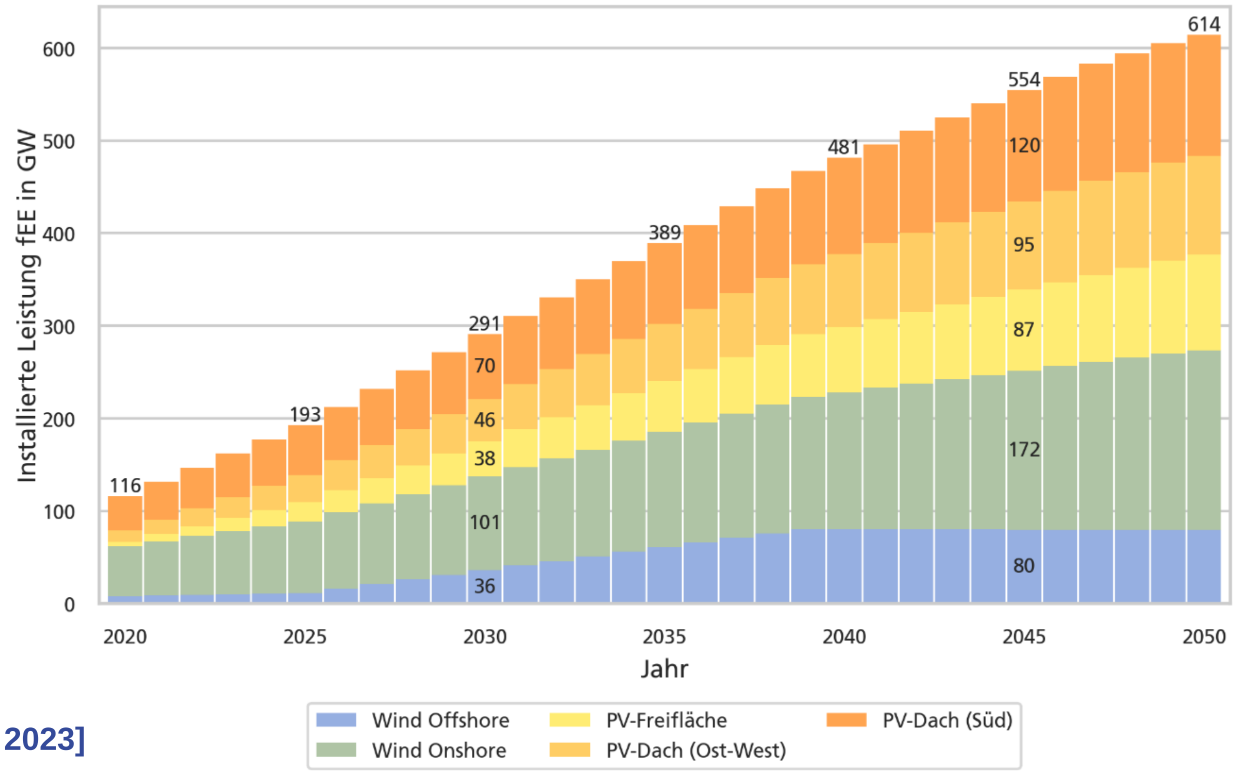
Sector	Short-term impact (1–3 years)	Medium-term impact (2030 climate targets)	Long-term impact (2045 climate targets)
Transport (passenger)		Travel shorter distances to access amenities (urban and rural areas)	
	Enable "digital mobility" (home working, digital business trips, e-government)		
	Short-term increase in local public transport capacity	Develop local public transport system offering good geographical and timetable coverage, including sharing and on-demand solutions	
	Incentives to increase local public transport use, e.g. cheap tickets and user-friendly booking		
	Pop-up cycle lanes and footpaths	Reorganise traffic space to promote cycling and walking	
	Temporary long-distance bus services	Expand national and international long-distance train services	
	Financial incentives to switch away from cars, removal of passenger car subsidies		
		Incentives for higher vehicle occupancy, e.g. promotion of ridesharing and smaller vehicle sizes	
		Improve drive system efficiency (conventional and electric)	
		Incentives to switch to EVs, e.g. expand charging infrastructure	
	Speed limits		
Transport (freight)		Avoid, e.g. through policy measures to reduce demand and regionalisation	
		Incentives to shift to (hybrid) catenary trucks, rail and shipping (e.g. infrastructure development, financial incentives)	
		Improve efficiency of aircraft, ships and HGVs	
	Increase percentage of electric trucks, e.g. through emission-based HGV toll		

Example: Mobility sector

Technological rollout
Ambitious expansion of wind and solar power capacities

- 2030: approx. 144 GW PV, 100 GW Onshore-Wind, 36 GW Offshore-Wind
- 2045: 554 GW wind plus solar

Wind and solar expansion until 2045 in Germany (ESYS main scenario)

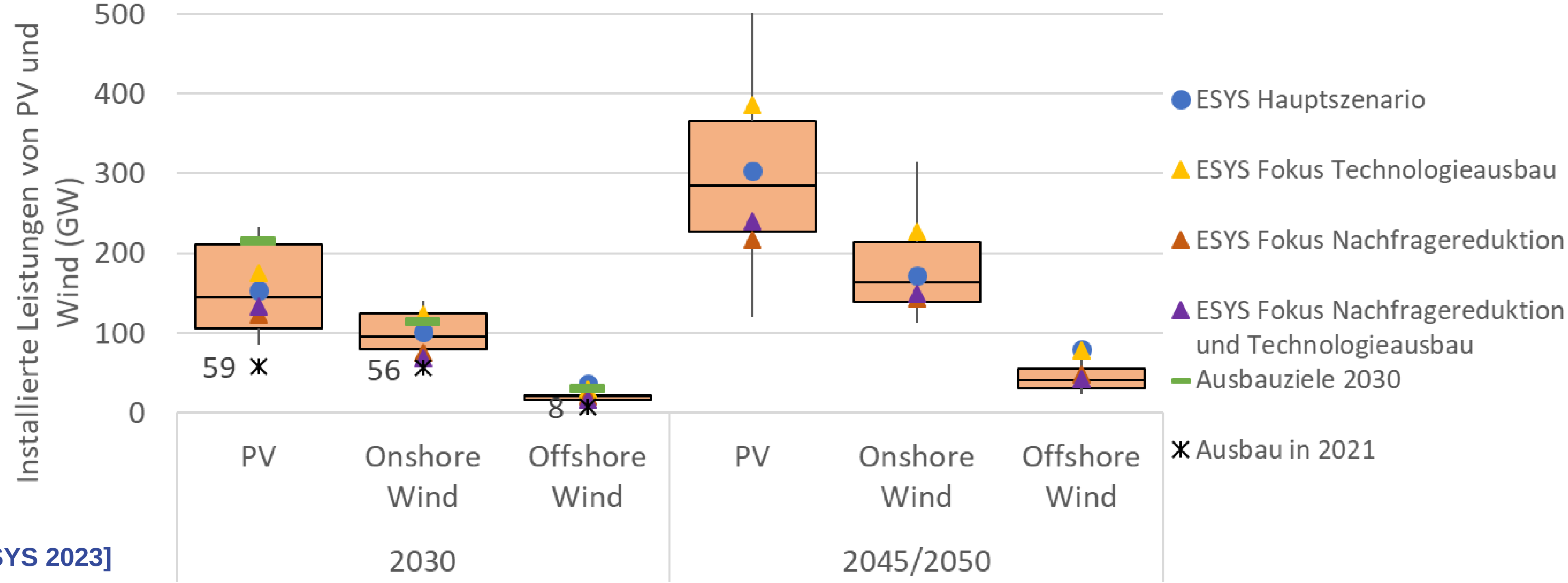


[ESYS 2023]

Technological rollout

PV and wind expansion similar to Government targets

- Scenario comparison: High differences between some scenarios
- Signicant difference between the focus scenarios „demand reduction“ and „technology rollout“



[ESYS 2023]

Technological rollout
Electricity vs. molecules

- Only limited quantities of hydrogen and hydrogen derivatives likely to be available in the medium term
- Ambitious expansion of electrolyser capacities needed
- Significant share of hydrogen and synfuels imported
- Priorisation in sectors in which realistic alternatives are missing (industry, long-distance travel and transport)

	Industry	Transport	Buildings[23]
Fuels (incl. biomass)	Feedstocks in steel and chemical industries	Intercontinental aviation and shipping	Buildings that are partly difficult to modernise
Mix of technologies probably best	High-temperature process heat	Long-distance heavy goods transport Aviation and shipping within Europe	District heat generation (large heat pumps: electricity, combined heat and power plants: fuels)
Electricity probably best	Medium-temperature process heat	Public road transport Light commercial vehicles Short and medium distance heavy goods transport	Buildings that can be modernised
Electricity definitely best	Low-temperature process heat	Private cars, passenger rail	New buildings

[ESYS 2023]

Scenarios
Main and focus scenarios

Main scenario KN2045
Focus „demand reduction“
Focus „technology rollout“

KN2040:

- Not feasible with the assumptions from the main scenario (demand reduction or more ambitious technological rollout needed)

KN2035:

- Only feasible for implausible assumptions for demand reduction and technology rollout

Scenario	Energy-related CO_2 emissions
Climate neutrality 2045	Budget of 7.8 Gt_{CO2} with -65 percent in 2030 and -100 percent in 2045
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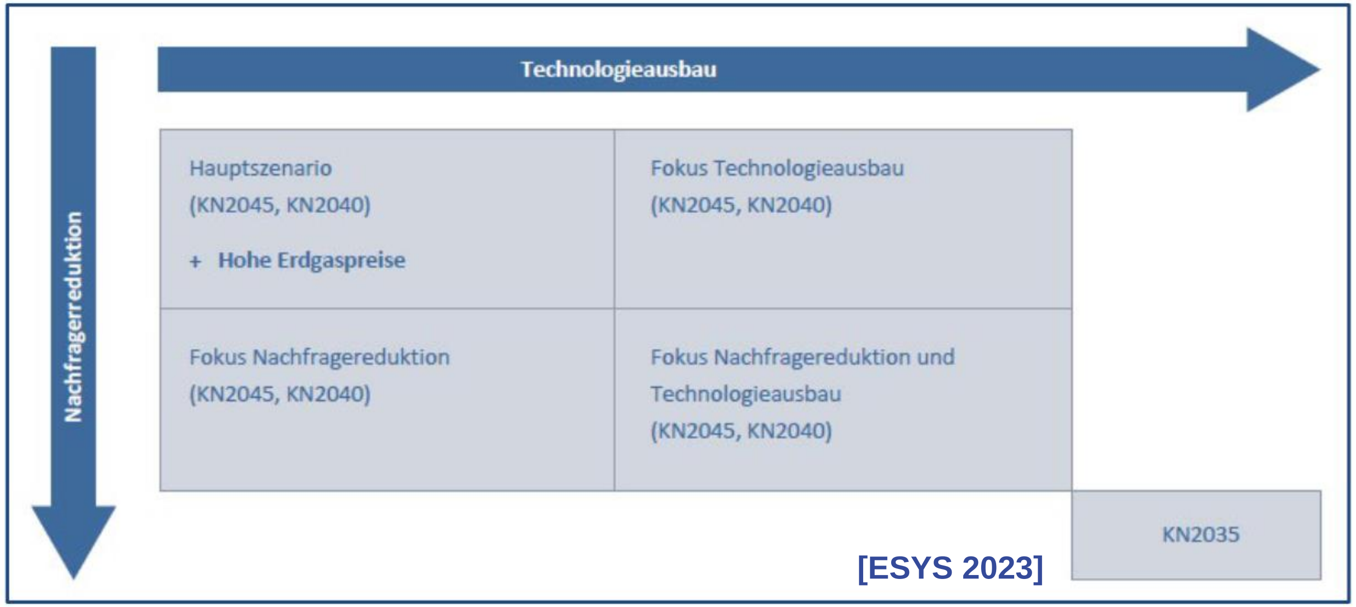


[ESYS 2023]

Limited scope of the models

Some perspectives mostly missing

- Life cycle perspective
- Consideration of (critical) materials
- International perspective
- Consideration of all energy demand for Carbon Dioxide Removal

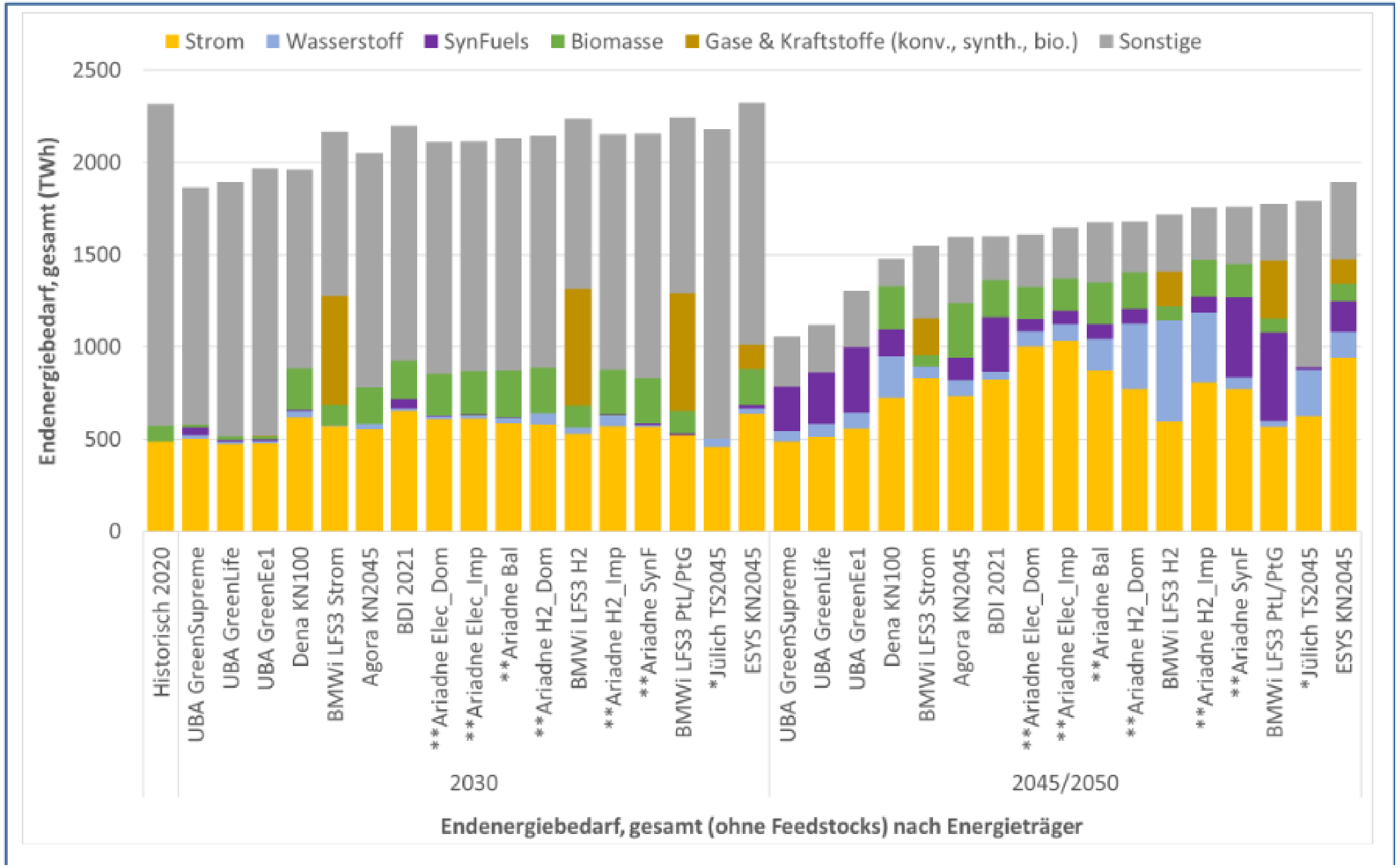
Further aspects:

- Conflicts of use for biomass
- Sustainability criteria for hydrogen

[https://www.se-trends.de/kreislaufwirtschaft]

Scenario analysis
Challenge: data availability and comparison

[ESYS 2023]



nfdi4energy

National Research Data Infrastructure for the Interdisciplinary Energy System Research

- Use Case (1/3):
  Long term energy system scenarios
  (transparent, open information; visualization features)

- Task Area 2:
  Integrating Society and Policy in Energy Research
  (communication and model representation)

[NFDI 2022]

Conclusions

- Enormous challenges to reach climate neutrality by 2045
- Various measures simultaneously needed in different sectors and dimensions
- Demand reduction necessary, but does not replace other efforts
- Wind and solar power as the basis, already show considerable growth rates
- Further technologies need development and upscaling
- Important task: system integration

- Scenario studies need to increase their scope (societal, political factors, material demands,…) and transparency/accessibility of results, assumptions, data

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Quellen

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