

The logo consists of the letters 'TlW' in a white, elegant, cursive script font.

TerraWater
INSTITUTE

Germany Preliminary Results - Confidential

23rd of May

TerraWater Institute

Overview

01 Energiewende Assessment

02 TerraWater Scenario for Germany : Results

03 Conclusion

1. Energiewende Assessment

Germany's energy policy : 20 years of Energiewende and more

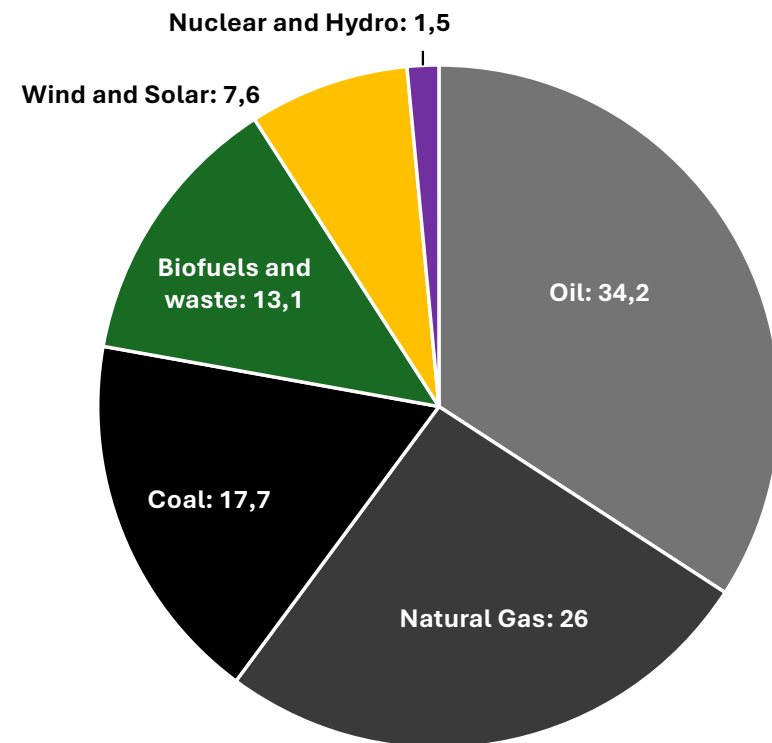
Energy Policy

Germany's Energiewende aims for **Net zero by 2045** and **KohlAustieg by 2038** at the latest, while ensuring a reliable electricity supply. Instead, **past policy choices have led to increased reliance on coal**

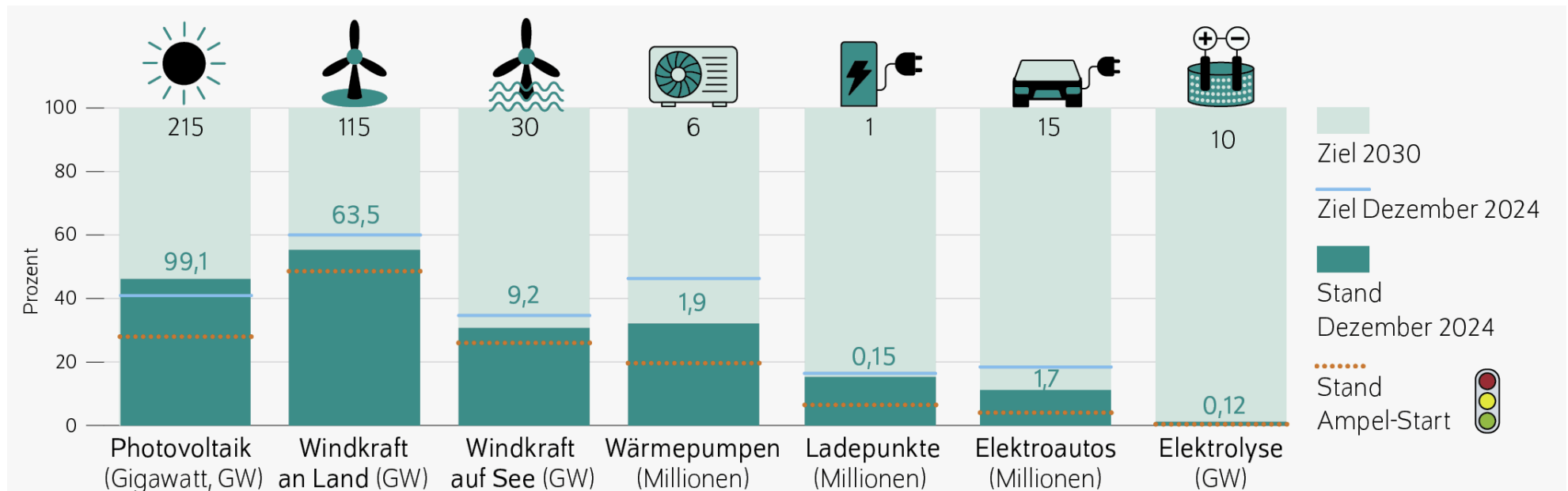
The TerraWater Institute: pragmatic pathways, reliable results

To succeed, the TerraWater Institute strongly believes that the transition must focus on **proven technologies, robust system**, and a balance between **environmental impact, economic viability**, and **energy sovereignty**

Germany's Primary Energy Consumption 2023



Energy transition targets set by the Ampel coalition for 2030 still require considerable further expansion



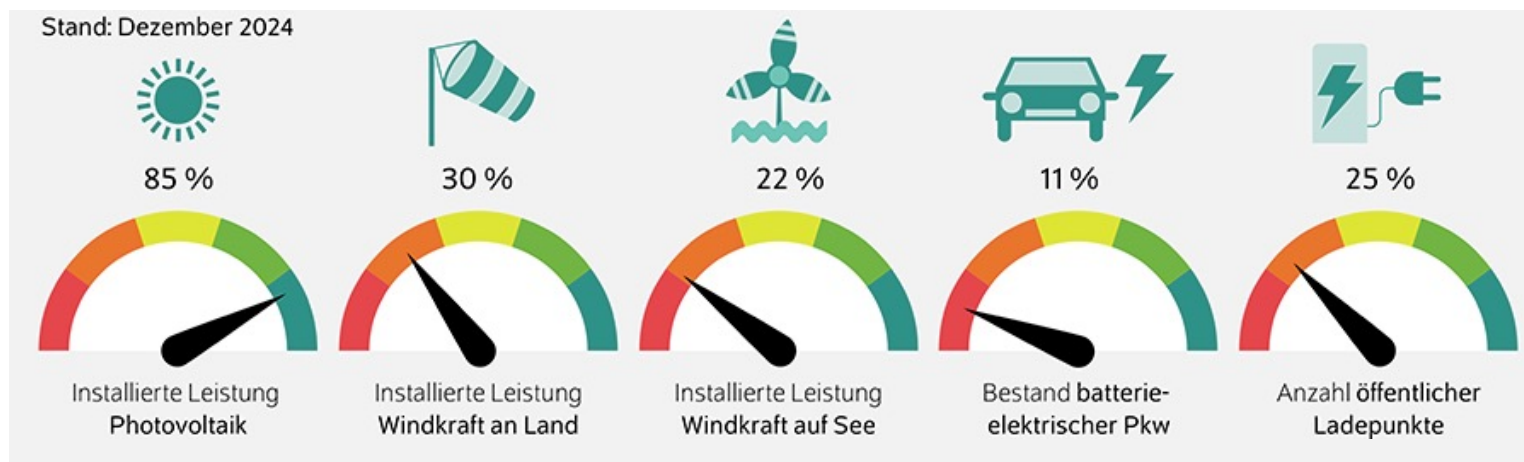
Anmerkung: Bei den Ladepunkten handelt es sich um öffentliche Schnell- und Langsamladepunkte. Bei ihnen ist der Datenstand Ende November 2024, sonst Ende Dezember 2024. Für die Elektrolyse lässt sich kein sinnvolles Zwischenziel für 2024 ableiten.

Quelle: Ampel-Monitor Energiewende.

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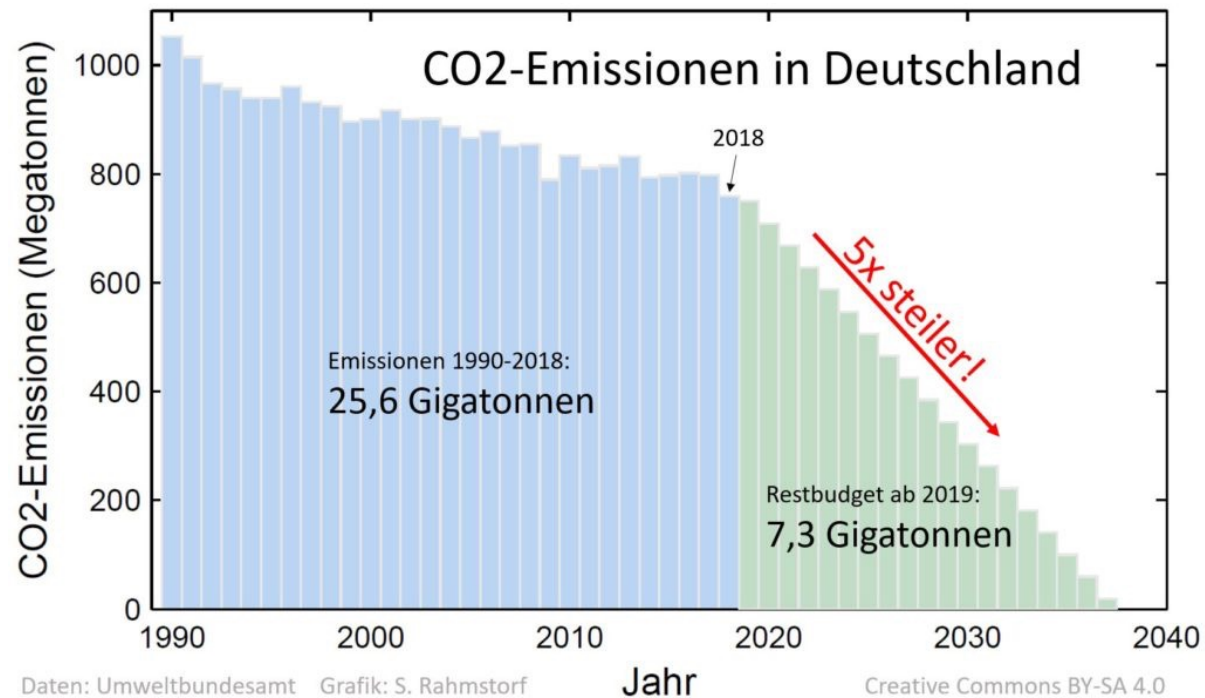
The current speed of the energy transition is too slow to achieve the 2030 targets

Comparison between the actual growth rate over the last 12 months and the average pace required to reach the 2030 targets.



The PV expansion rate is currently only 85% of the average rate needed to meet 2030 targets.

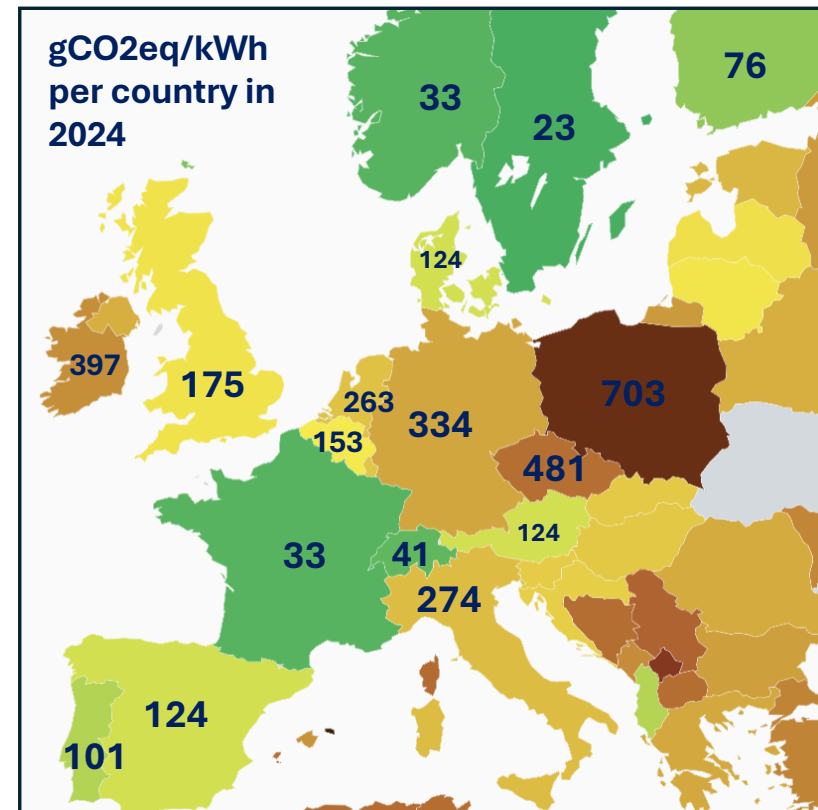
There's no time to waste: Germany must reduce its CO₂ emissions quickly



2000 – today

For the past 25 years, Germany’s decarbonization strategy has involved massive investments, yet the results remain disappointing

- A study by the Düsseldorf Institute (DICE), quoted by the Bundesrechnungshof, estimates that the cumulative costs of the energy transition for the electricity sector alone will amount to around **€520 billion** between 2000 and 2025.
- According to our estimates, the various support schemes for **renewable electricity generation** have cost a total of **€383 billion** over the past 25 years.
 - Between 2000 and 2021, the Renewable Energy Sources Act (EEG) cost an estimated **€315 billion**. Since 2021, it has alternatively added **€68 billion** to the federal budget.
 - In addition :
 - **network congestion** has cost **€10 billion**
 - and **grid development** another **€55 billion**.
 - This brings the **total to €448 billion**
- For a result that remains deeply disappointing when compared to the carbon intensity of the electricity mix in neighboring European countries.



Source : electricity maps

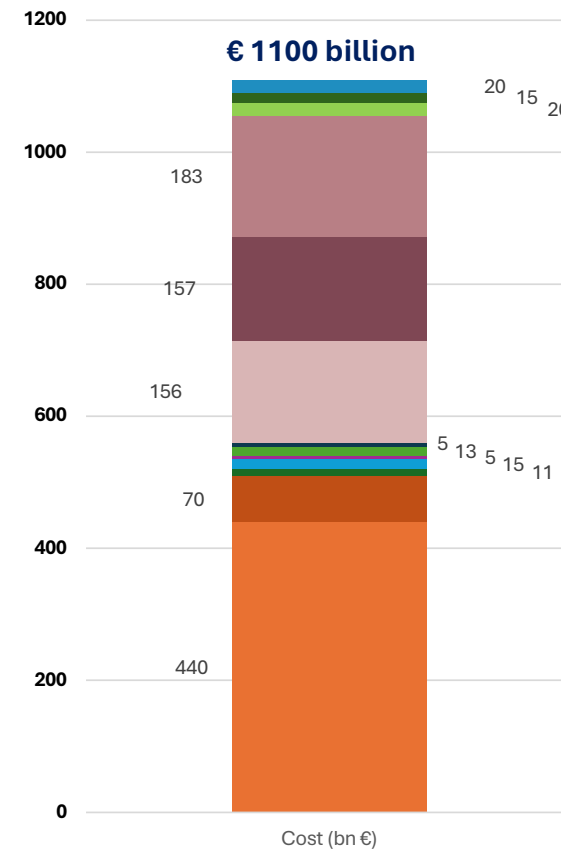
2025 – 2045

The restructuring of the energy system in Germany will require investments of more than one trillion euros in the coming years.

Germany needs 1.1 trillion euros to achieve the statutory goal of climate neutrality by 2045.

Category	Subcategory	Cost (bn €)
District Heating Network	District Heating Network	20
Hydrogen Grid	Distribution network	15
	Core network	20
Power Grid	Distribution grid	183
	Offshore transmission grid	157
	Onshore transmission grid	156
CO ₂ Infrastructure	CO ₂ transport	5
Energy Storage	Hydrogen storage	13
	CO ₂ storage (CCS)	5
	Home storage	15
Electricity Generation	Electrolysers	11
	Controllable power plants + flexibilities (incl. pumped & battery storage)	70
	Expansion of renewable energies	440

Handlesblatt - source: HRI, Bundesnetzagentur, EWI, Dena, FNB Gas, DVGW, BNEF, KfW, BVEG

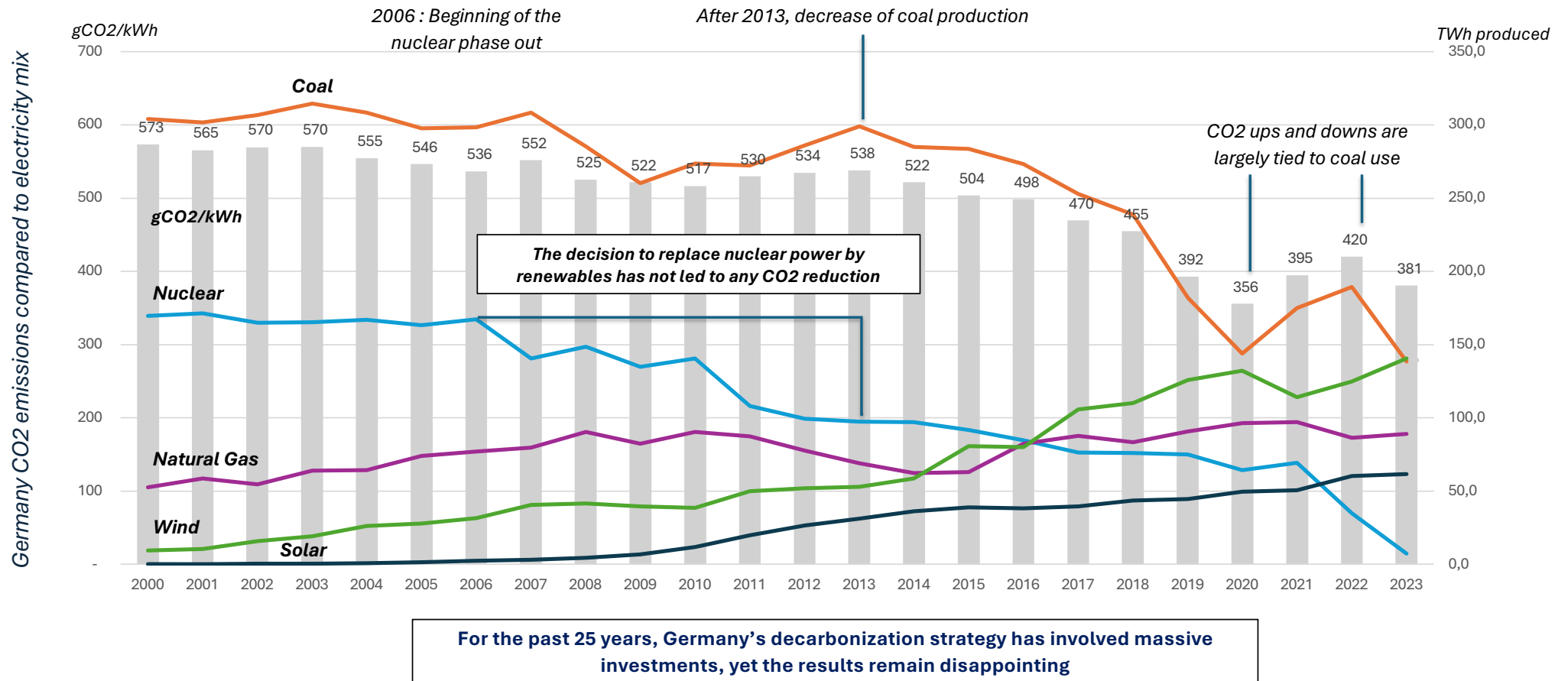


Former Coalition’s Experts expose major gaps in 2030 climate target

Dimension	Sub-dimension	Indicator	
• Energy Supply	Electricity	<ul style="list-style-type: none"> Evolution of absolute electricity generation from renewable energies (Chapter 2.3.1) Evolution of renewable electricity generation capacities (Chapter 2.2.1) Evolution of the share of renewables in gross electricity production (Chapter 3.2.1) 	Green
	Final Energy Carrier	<ul style="list-style-type: none"> Green hydrogen (Chapter 4.4) 	Yellow
	Overview of the Energy Sector	<ul style="list-style-type: none"> Evolution of the share of renewables in gross final energy consumption (Chapter 2.1) Evolution of final energy consumption (Chapter 2.1) 	Red
• Security of Supply	Grids	<ul style="list-style-type: none"> Development of the transmission network (Chapter 3.4.2) Digitization (Chapter 3.5.3) Implementation of congestion management measures (Chapter 3.4.3) 	Red
		<ul style="list-style-type: none"> SAIDI Electricity and SAIDI Gas (Chapters 6.1.4 and 6.2) 	Green
	Dispatchable Power Plants	<ul style="list-style-type: none"> Dispatchable power plants (Chapter 6.1) Battery storage capacity (Chapter 3.5.1) 	Yellow
• Energy Security	Diversification	<ul style="list-style-type: none"> Herfindahl index for natural gas (Chapter 6.2) 	Red
	Access to Resources	<ul style="list-style-type: none"> Non-energy resources relevant to supply (Chapter 6.3) 	Red
• Affordability / Cost-effectiveness	Energy Efficiency	<ul style="list-style-type: none"> Energy productivity (Chapter 2.1) Heat demand (Chapter 5.1) Energy efficiency in the residential sector (Chapter 5.1) 	Red
		<ul style="list-style-type: none"> Share of household electricity costs in GDP per capita (Chapter 7.1) 	Yellow
	Energy Costs	<ul style="list-style-type: none"> Energy costs for industry in Germany (Chapter 7.1) Average annual electricity expenditures of households (Chapter 7.1) Average electricity price for households (Chapter 7.1) 	Yellow
		<ul style="list-style-type: none"> Reduction of greenhouse gas emissions (Chapter 3.1) Phase-out of coal (Chapter 3.3) Deployment of heat pumps (Chapter 5.3) Share of electric vehicles (Chapter 3.1) 	Red
• Environmental Compatibility	Greenhouse Gas Emissions	<ul style="list-style-type: none"> Reduction of greenhouse gas emissions (Chapter 3.1) Phase-out of coal (Chapter 3.3) Deployment of heat pumps (Chapter 5.3) Share of electric vehicles (Chapter 3.1) 	Yellow
• Societal Aspects	Acceptance	<ul style="list-style-type: none"> General support for the energy transition goals (Chapter 8.2) Support for the implementation of the energy transition (Chapter 8.2) Perceived personal impact of the energy transition (Chapter 8.2) 	Green
		<ul style="list-style-type: none"> Energy equity (Chapter 8.1) 	Red
	Redistribution	<ul style="list-style-type: none"> Energy cost burden relative to household income (Chapter 8.1) 	Yellow
		<ul style="list-style-type: none"> Energy cost burden relative to total consumer spending (Chapter 8.1) 	Yellow

Source: Expert Commission on Energy Transition Monitoring (as at June 2024)

Energiewende has failed to reach a low carbon electricity mix : The hardest part is yet to come

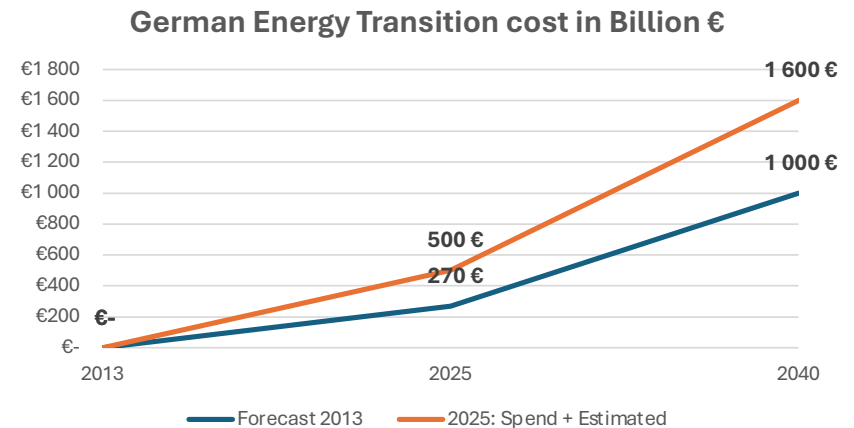


2.

Preliminary results of the study

Germany's Energy Transition: Rising Costs, Higher Prices, and Growing Dependence

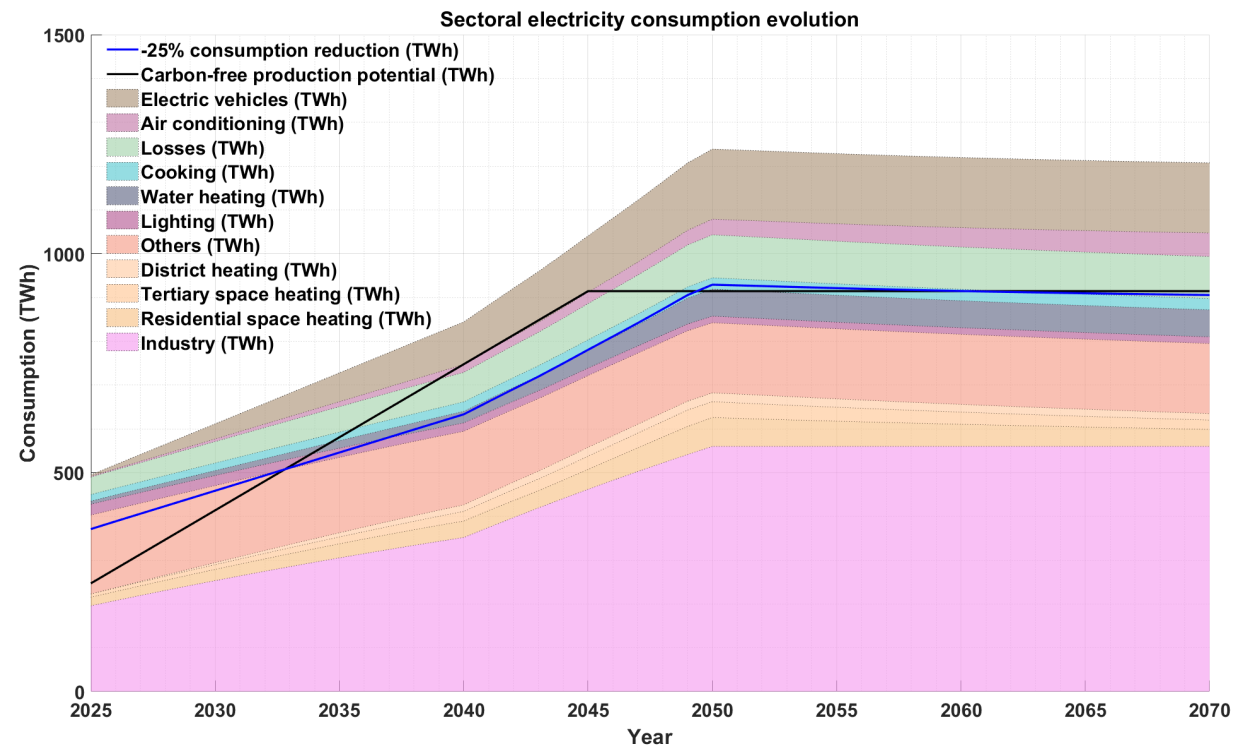
- **Germany's new government confirms that meeting the objectives of the Paris climate agreement is a priority.** The national goal of carbon neutrality by 2045 set by the Federal Climate Protection Act, which came into force in August 2021, will not be called into question.
- **+ 100€ Billions** of the special extra-budgetary infrastructure fund adopted in March 2025 will go to an existing special fund, which is supposed to **promote Germany's net zero emission targets by 2045.**
- **+ Incentivized construction of 20 GW of gas-fired power plants by 2030** to offset the production variability of renewable energies such as wind power and photovoltaics, the plan is to rapidly launch technologically open tenders for the **construction of the gas-fired power plants**
- **Nuclear power is not mentioned at all in the coalition agreement.** The new coalition does not envisage a return to the use of nuclear power until further notice. However, support for fusion research will be stepped up, with the aim of "building the world's first fusion reactor in Germany".



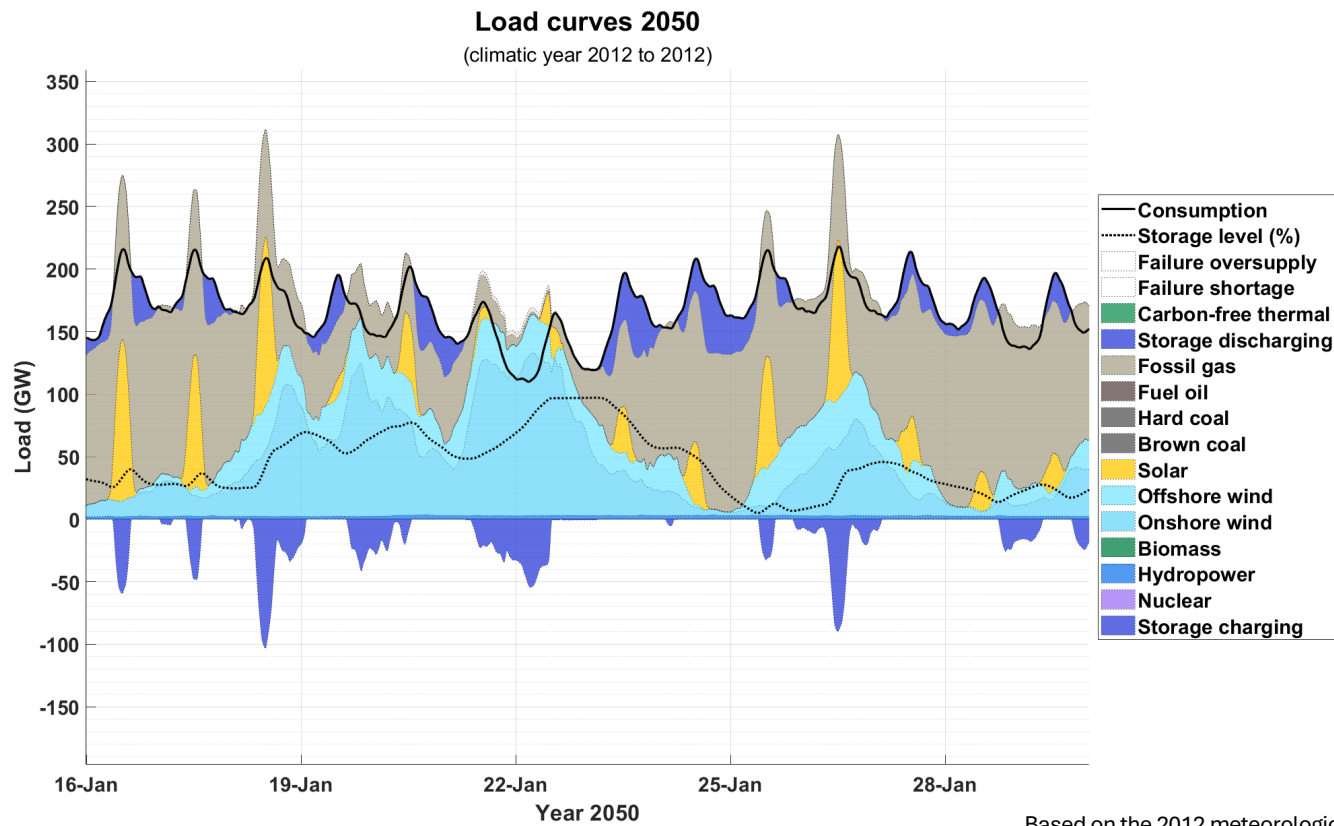
Back in 2013, the message was: "The energy transition will cost €1000 billion and be completed by 2040." Today, Germany is told to invest an additional €1000 billion to achieve CO₂ neutrality—while facing higher, non-competitive energy prices and increased import dependency.

Full electrification is the only way to reach net-zero To do so Germany needs 2.5 times more power than today

- To minimize environmental impact, electricity needs and climate change vulnerability, bioenergy use must be banned from **every** stationary energetic applications.
- Total electricity need, 1250 TWh/year.
- Peak load of 282 GW (residual: 242 GW)
- This already takes into account :
 - +1,7°C increase in average temperature over Germany
 - 20% improvement in heat-pumps efficiency.
 - 100% increase in district heating share (9% today) with 75% of combined heat-and-power.
 - A 1,5%/year reduction of space heating needs
 - 20% efficiency gains from industry electrification.
 - 100% electric car and truck fleet.
- It doesn't include the electricity needed for synthetic fuels for aviation (+100~150 TWh/year if biomass saved, ~250 TWh/year if biomass wasted)**
- If e-SAF are made from imported hydrogen -> It will require equivalent to current natural gas imports

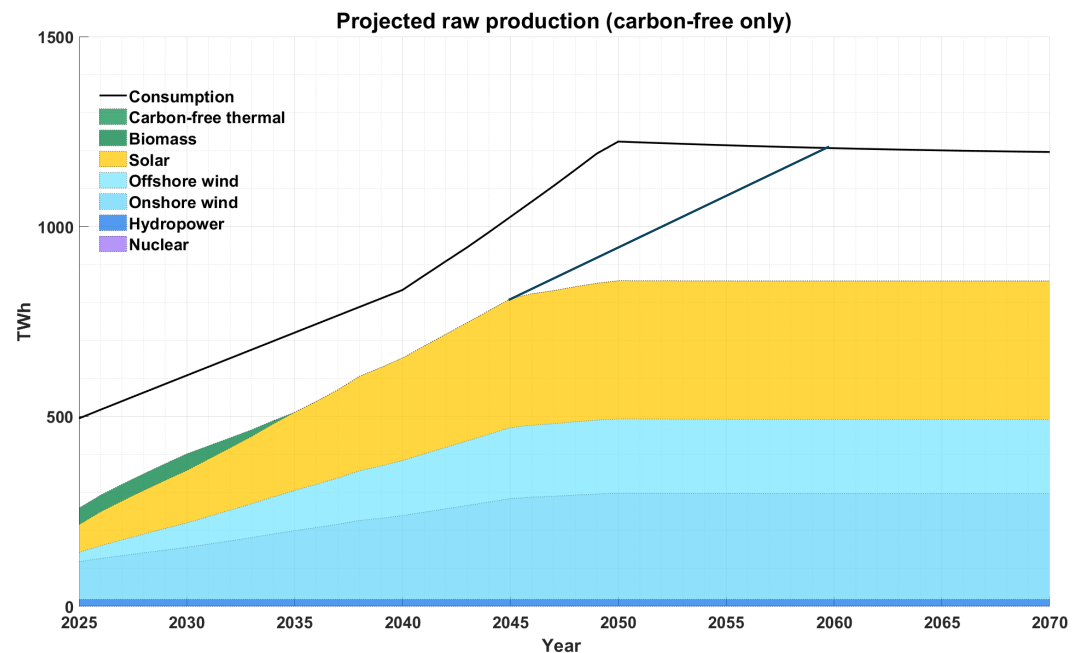


To meet demand, especially during winter months, Germany would need around 200 GW of gas-fired power plants.

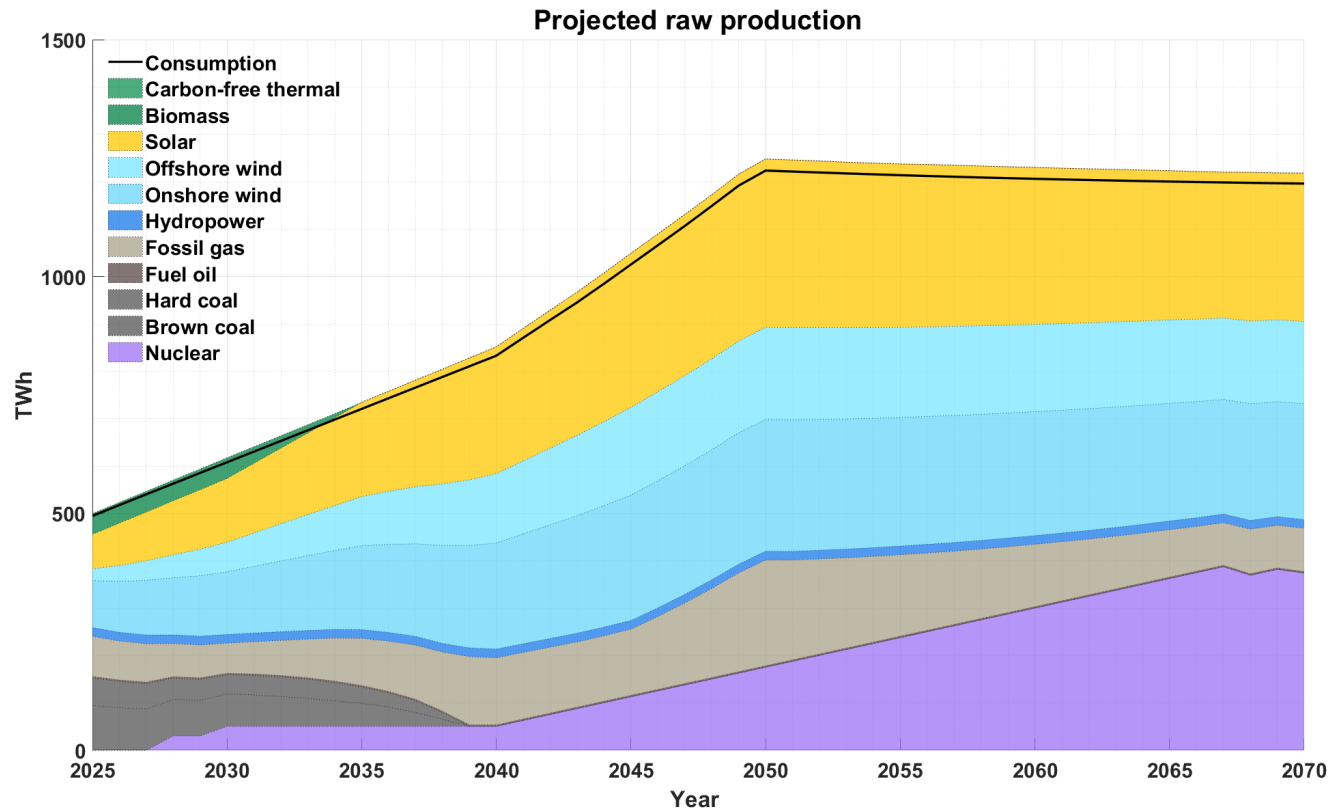
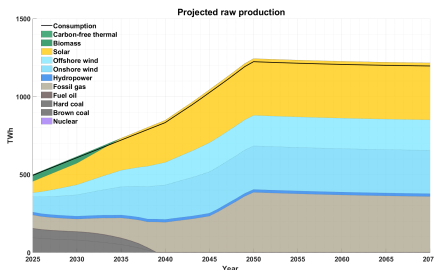


Even assuming renewable expansion post-2045 at the same rate, the required power wouldn't be reached before 2060

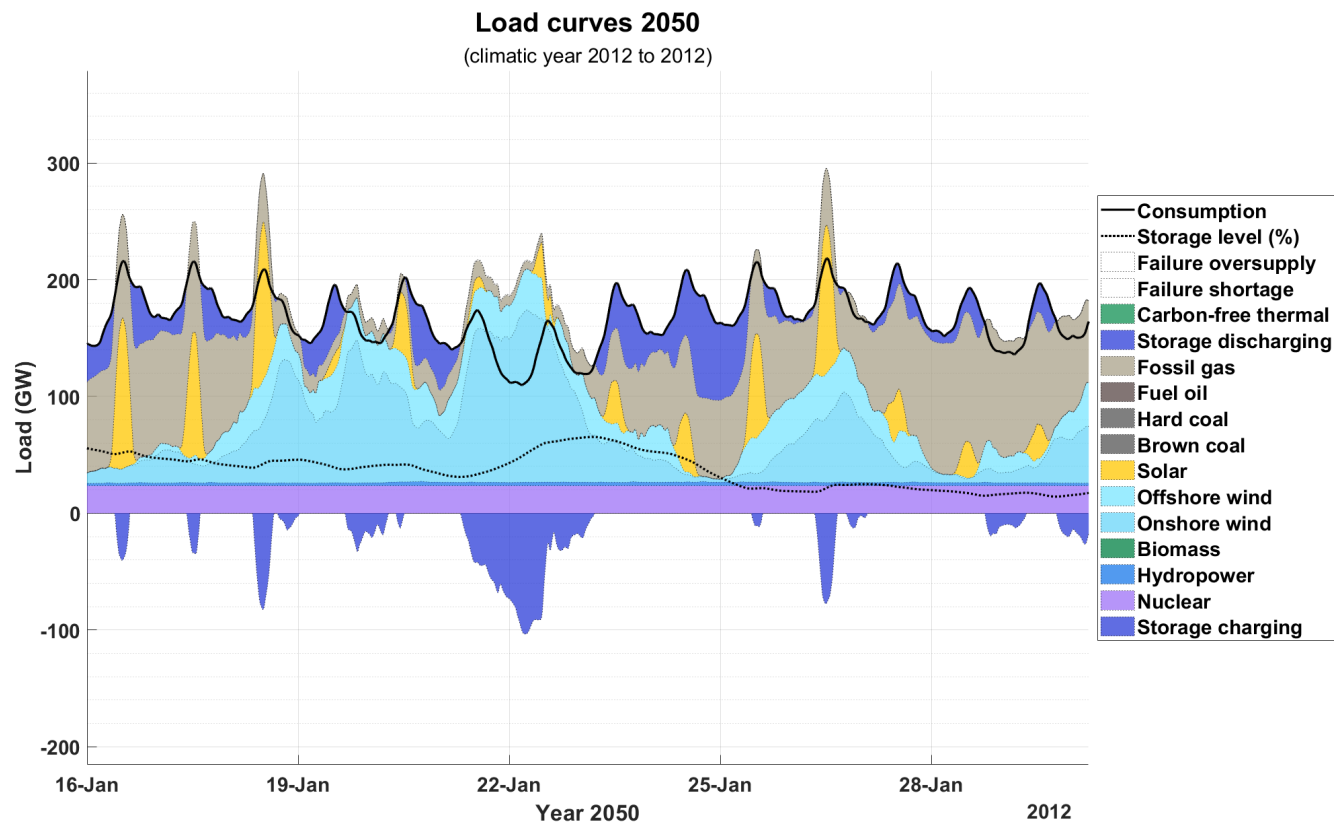
- Government announced renewable capacities can only provide around 2/3 of the required power :
 - +17 GW of solar PV per year for 20 years non-stop (from 105 GW today to 440 GW)
 - +5.6 GW of onshore wind per year for 20 years non-stop (from 65 GW today to 176 GW)
 - +3 GW of offshore wind per year for 20 years non-stop (from 9 GW today to 70 GW and saturating the available resource)
 - 180 GW of battery storage (assuming 8 hours of duration while government plans only assume 2 hours) (from 14 GW/20 GWh today),



A return of nuclear can significantly lighten the burden on the complementary production (i.e. fossil fuel)



Reinstating nuclear would allow to decrease that amount by 20 GW in 2050, and 50 GW in 2070.



3. Conclusion

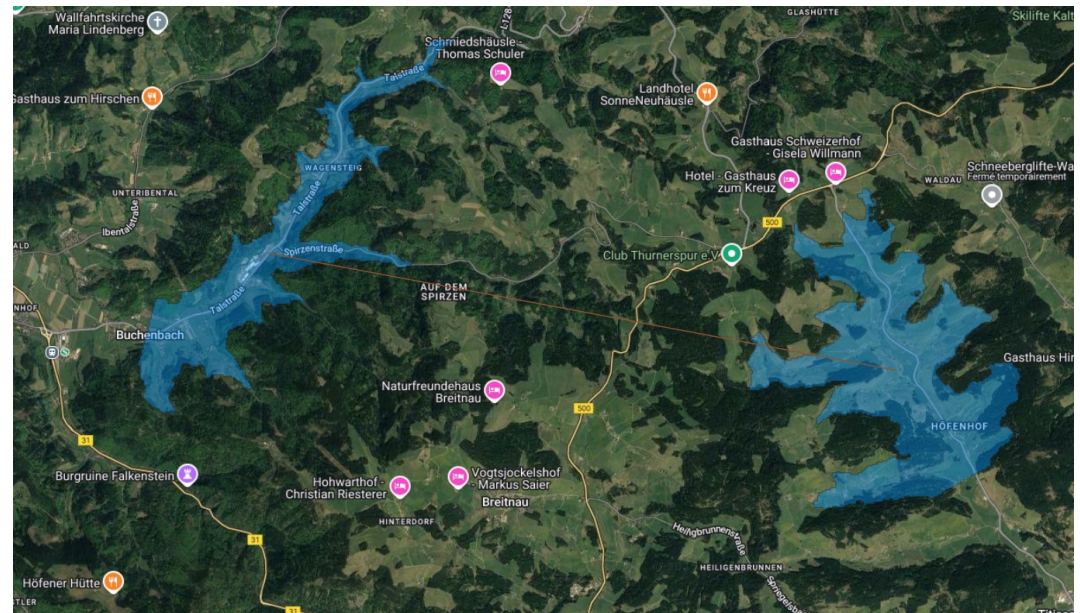
Aligning rising electricity demand with decarbonization pathways necessitates reintegrating nuclear into the energy mix, and eventually adding PSP capacities to bring additional grid support

- Based on a demand scenario reduced (-10%) as compared to government prediction (cogen gaz)
- There is still a **300 TWh/year gap** to fill
 - **75 TWh/year in electricity imports** is manageable though tough on neighbours
150 TWh/year of electricity imports from neighbouring countries is a huge bet. Theoretically feasible, but very uncertain (record exporter (France) average export is 50 TWh/year, up to 90 TWh/year punctually (2024)).
 - **75 TWh/year in demand reduction** must be found
For instance, such amount can be saved though a 10% reduction in both industrial production and road traffic.
 - **Nuclear can bring 150 TWh/year by 2050.**

Pumped Storage Plant development in Germany is possible and should be encouraged



PSP characteristics		
Power (MW)		643
Storage Capacity GWh (400h)		257
Altitude of reservoir (meter)	Upper	990
	Lower	596
Volume of reservoir (hm ³)	Upper	383
	Lower	294



- This PSP would be located next to Freiburg, less than 400 houses are located on this site
- In comparison, the Hambach mine relocated over 3,000 people and wiped 6 villages.

The TerraWater scenario adopted a rigorous methodology that simulates real-world energy dynamics to guide credible and actionable transition strategies

Objective and Approach

- Develop a **data-driven**, dynamic model to assess Germany's future power system.
- Focus on **realistic system operation**, not just theoretical deployment.
- Evaluate energy transition scenarios over time, **from 2025 to 2070**

Key Modeling Principles

- **Hourly resolution** captures demand fluctuations and variable renewable generation.
- Uses a **brownfield approach**, building on the existing energy system.
- Avoids rigid optimization focuses on **technical feasibility** over theoretical cost-optimality.
- **Multiple weather years** (2012–2024) ensure robustness against meteorological variability.
- Applies a **copper plate assumption** (no grid bottlenecks), while flagging transmission as a separate research topic.

Input Data Strategy

- **Demand profiles** separated by sector (residential, commercial, industrial, transport).
- Uses **normalized capacity factors** based on actual hourly generation and installed capacity.
- Includes **EV charging assumptions** using IEA data, scaled to maximum fleet size for stress testing.

Algorithm Mechanics

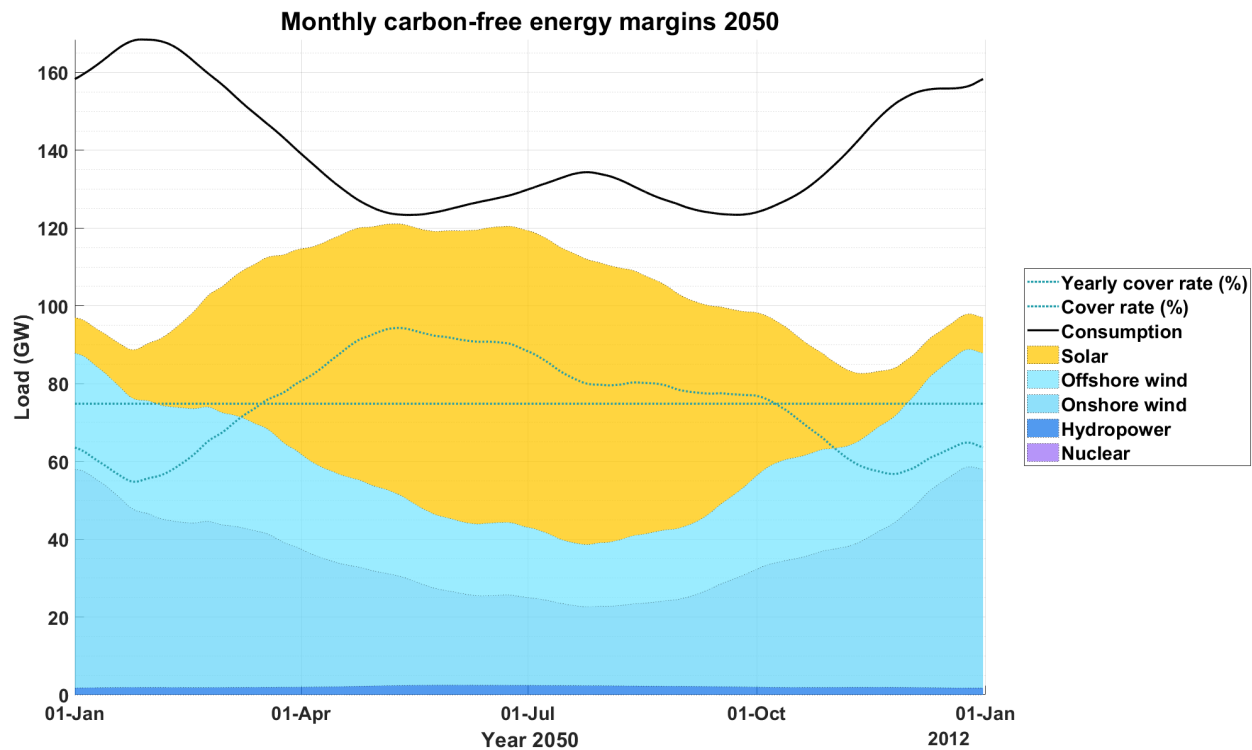
- Balances generation, demand, and storage using an **iterative loop**.
- Tracks hourly **energy difference** (supply vs. demand) across the year.
- Dynamically adjusts **generation dispatch and storage operations** to minimize mismatch.
- Uses **load duration curves** and flexible storage behavior to align system needs and capabilities.
- Repeats until **yearly energy balance converges to near-zero** ensuring operational realism.

ANNEXE

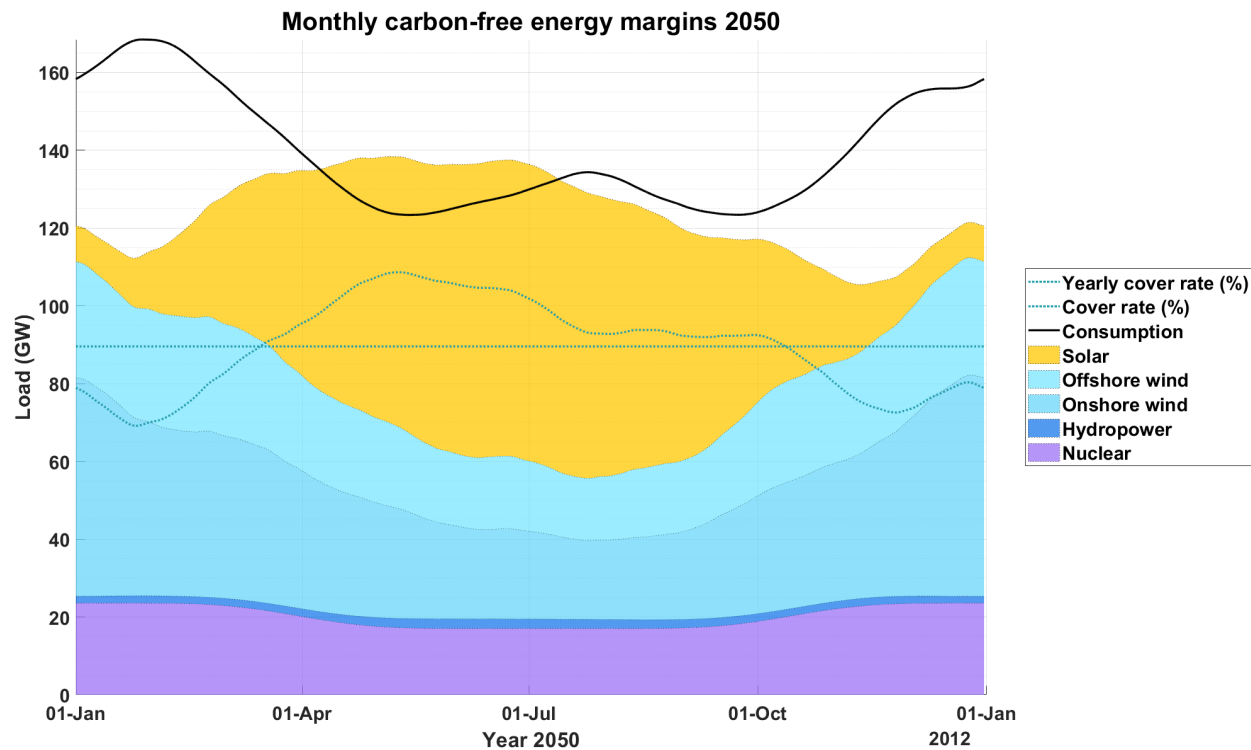
The key challenge is that decarbonization relies almost entirely on electricity, so no source of demand should be underestimated

- Rebuilding nuclear capacity is no longer optional, it is a necessity for energy sovereignty, decarbonization and secure supply.
 - **Sovereignty:** Without nuclear, countries depend on imports or fossil fuels, losing control over their energy future and exposing themselves to geopolitical risks.
 - **Decarbonization:** Nuclear is essential to achieving net-zero, providing stable, low-carbon electricity that complements variable renewables.
 - **Security of supply:** Electrification will massively increase demand; decommissioning delays the build-up of firm capacity we urgently need to avoid future shortages.
- But even with nuclear back in the mix, **reaching net-zero by 2050 remains extremely tight.**
- The path ahead demands **unprecedented coordination, massive infrastructure upgrades**, and realistic planning that goes beyond slogans.
- **Time is the most critical resource:** every year spent decommissioning is three years lost in reconstruction we cannot afford delay.

Current German plans lead to considerable seasonal discrepancy in the energy supply/demand equilibrium

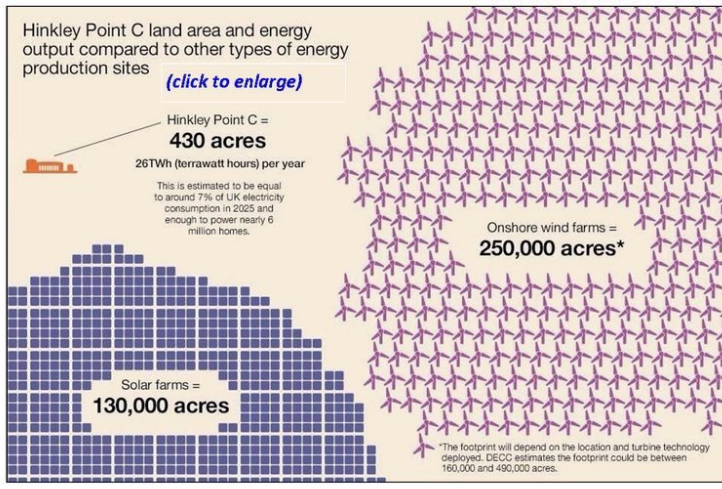


Adding nuclear isn't enough to correct the seasonal discrepancy in the energy supply/demand equilibrium, even in 2070

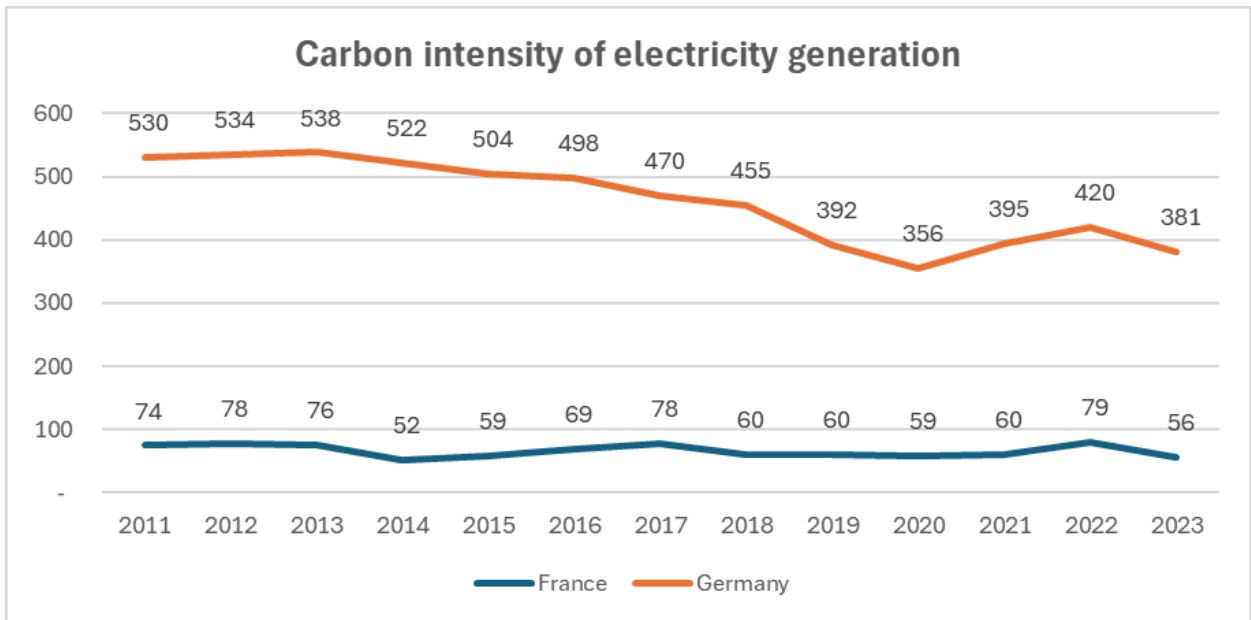


Issues with Germany's path to net Zero

How Much Land Is Needed For Wind & Solar Energy Production vs Nuclear Energy?

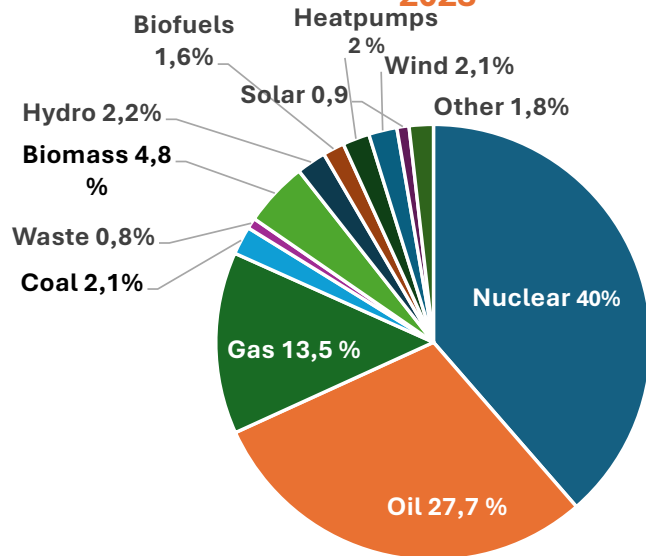


Carbon intensity of electricity generation



Two countries, diverging paths: France decarbonizes, Germany de-nuclearizes

France's primary energy consumption
2023



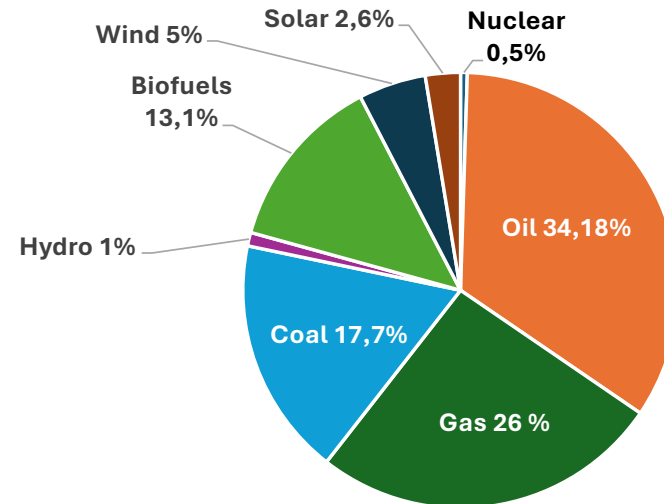
32 g CO₂/kWh

13,5%

€ 0.19/kWh

€ 0.12/kWh

Germany's primary energy consumption
2023



353 g CO₂/kWh

26%

€ 0.32/kWh

€ 0.22/kWh

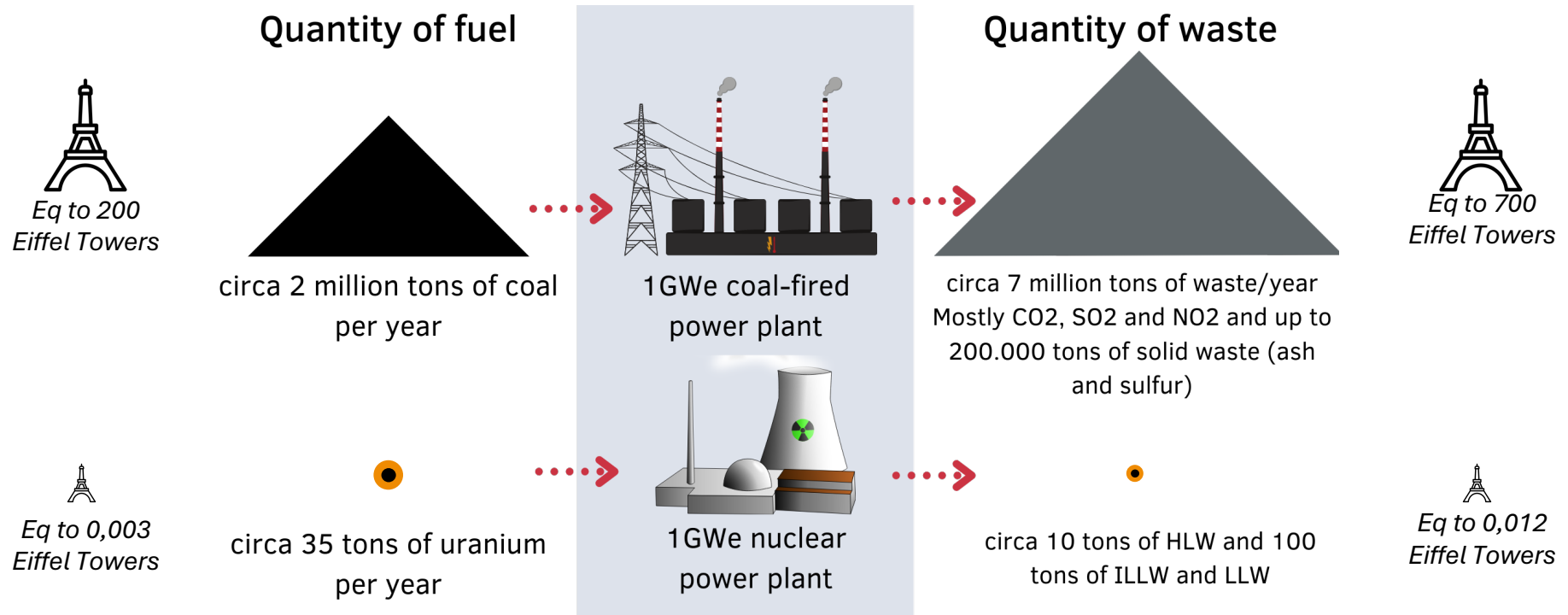
Carbon intensity of the mix (2023)

Part of gas in energy mix

Household electricity prices

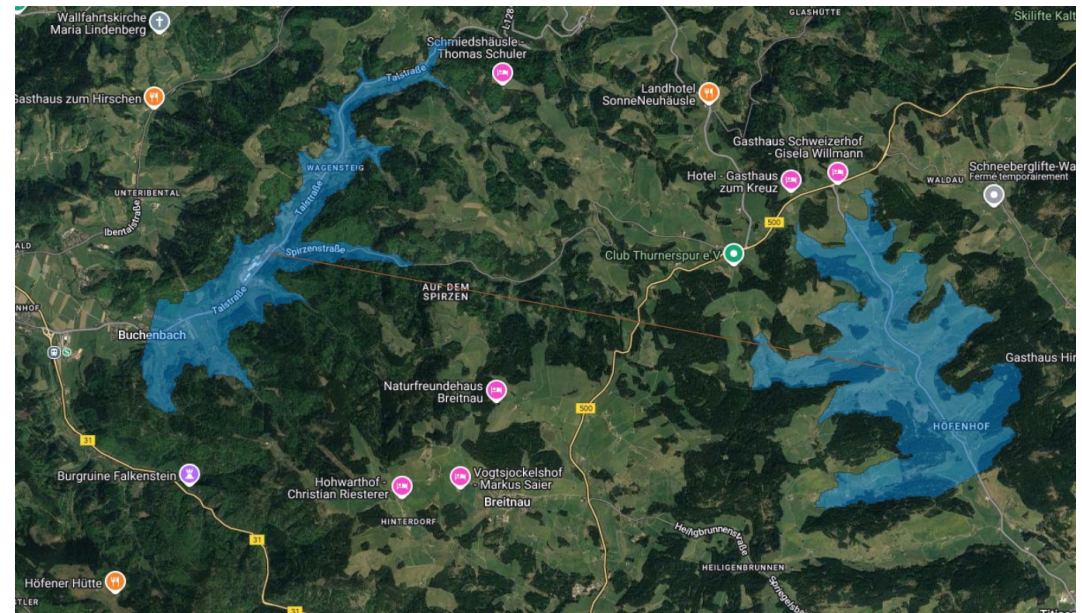
Non-household electricity prices

For the same capacity coal produces 60 000 more waste than nuclear



Pumped Storage Plant

Pumped Storage Plant development in Germany is possible and should be encouraged



PSP characteristics		
Power (MW)		643
Storage Capacity GWh (400h)		257
Altitude of reservoir (meter)	Upper	990
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- This PSP would be located next to Freiburg, less than 400 houses are located on this site
- In comparison, the Hambach mine relocated over 3,000 people and wiped 6 villages.

Compared to li-ion batteries, PSP offers a far more sustainable, durable, and resource-efficient solution for large-scale, long-duration energy storage

- Li-ion batteries require **large amounts of critical minerals** like lithium, copper, and graphite creating supply chain risks and environmental pressure.
- With typical service life of **10–15 years**, Li-ion batteries require frequent replacement compared to technologies like PSP.
- Li-ion systems are optimized for **short discharge times** (2–6 hours), making them inefficient and costly for storing energy over several days or weeks.

Criteria	Pumped Hydro (STEP) 257 GWh	Lithium-Ion Batteries 257 GWh
Use of critical materials	None	Lithium, graphite, copper, etc.
Estimated lithium use	0	35,000 to 46,000 tons
Estimated copper use	Low (1,000–2,000 tons)	50,000 tons
Other key materials	Concrete, steel, copper (non-critical)	Cobalt*, nickel*, aluminium, graphite, steel
Recyclability	Very high (>90%)	Partial (<50%, especially for lithium/graphite)
Typical lifespan	60–80 years +	10–15 years
Supply chain exposure	Low (local, abundant materials)	High (dependent on China, DRC, global markets)



This 257 GWh PSP may seem massive but

- It is small compared to Constance Lake
- It is even **smaller than a li-ion storage** site with the same capacity

Pumped Storage Plant development in Germany is possible and should be encouraged

- The extremely high intermittency of wind and solar is too high to be significantly managed by the meagre German pumped-storage potential and will still require considerable amounts of fossil gas.

How Much Space Will 100% Renewables Require? Hidden Footprint of the Energiewende

By 2045, Germany aims to install 160 GW of onshore wind, 75 GW of offshore wind, and 400 GW of solar capacity. Based on typical land use assumptions, this would require an estimated **35,000 km²** of space — including land and sea areas.

Technology	Target Capacity (2045)	Land Use Assumption	Total Estimated Land Use
Onshore Wind	160 GW	10 MW per km ² (i.e. 0.1 km ² /MW)	16,000 km ²
Offshore Wind	75 GW	5 MW per km ² (i.e. 0.2 km ² /MW)	15,000 km ² (at sea)
Solar PV	400 GW	1 hectare per MW (i.e. 0.01 km ² /MW)	4,000 km ²
Total (land + sea)	—	—	35,000 km ²

To put this in perspective, that's **more than the entire surface area of Belgium** (~30,500 km²), and nearly **eight times the size of the Ruhr region**, Germany's largest industrial area.