CARBON-FREE EUROPE
AN INCLUSIVE CLIMATE INITIATIVE

Analysis of Net-Zero Pathways for the EU+UK

March 2022

Energy Systems Analysis Conducted by:

EVOLVED
ENERGY
RESEARCH

Land Use Analysis Conducted by:

Montara Mountain Energy

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Executive Summary

Project Overview

- Carbon-Free Europe has created a set of **five pathways** for the EU and UK to reach **net-zero climate emissions by 2050**, consistent with targets set by the European Climate Law

- We model Europe as an integrated system, and produce results for each country individually

EU Results	**National Results**
reveal areas where international coordination is needed to achieve net-zero	illustrate country-specific challenges and opportunities

- This technical report includes:
  - **Details on our modeling approach**
  - **Model inputs and assumptions**
  - **Scenario definitions**
  - **Presentation of EU-27 + UK results**
  - **Country-level takeaways**
  - **Policy implications**

Highlights of Analytical Approach

Optimization Modeling

This analysis uses the RIO model, an optimization model with high spatial and temporal resolution of Europe's entire energy supply system

Spatial Resolution
We produce country-level representations of all energy forms and decarbonization options, including all energy flow between countries (electric transmission, hydrogen pipelines, and other fuels)

Temporal resolution
Hourly optimization means our decarbonization scenarios represent systems that can operate reliably to meet European energy demand

All Energy Sectors
Modeling the full energy economy, and not just the electric sector, builds insight into how sector coupling can support high renewable electricity power systems

Natural Resource Constraints

Because the ability to site infrastructure is one of the most significant sources of divergence between model simulations and reality, our analysis highlights the resource limitations that have the potential to become binding in the EU on the path to net-zero

Renewable Electricity
We create our own wind and solar supply curves, including resource constraints, resource quality differentiation, and interconnection cost differentiation

Other Constraints
We leverage primary data research, including Joint Research Centre work, to model low-carbon biomass, geologic CO2 sequestration, H2 salt cavern storage, and new electricity interconnections

Scenario Analysis

We create scenarios to understand tradeoffs, risks and opportunities of different strategies

Core Scenario
Least constrained pathway to net-zero in 2050

Domestic Preference
Countries prioritize domestic energy supplies

Limited Renewable Siting
More restrictions on renewables development

Slow Demand Transformation
Adoption of demand-side decarbonization technologies is slower than anticipated

100% Renewable Primary Energy
Energy supply entirely from renewables by 2050, with no fossil or nuclear energy

Modeling Approach

About the Analysis Team

Carbon-Free Europe commissioned Evolved Energy Research (EER) to conduct this analysis. EER is an energy consulting firm focused on addressing key energy sector challenges posed by energy system transformation.

EER developed the two models used in this analysis to investigate pathways to deep decarbonization: EnergyPATHWAYS and RIO.

EER advises clients on issues of policy implementation and target-setting, infrastructure investments, R&D strategy, technology competitiveness, and asset valuation.

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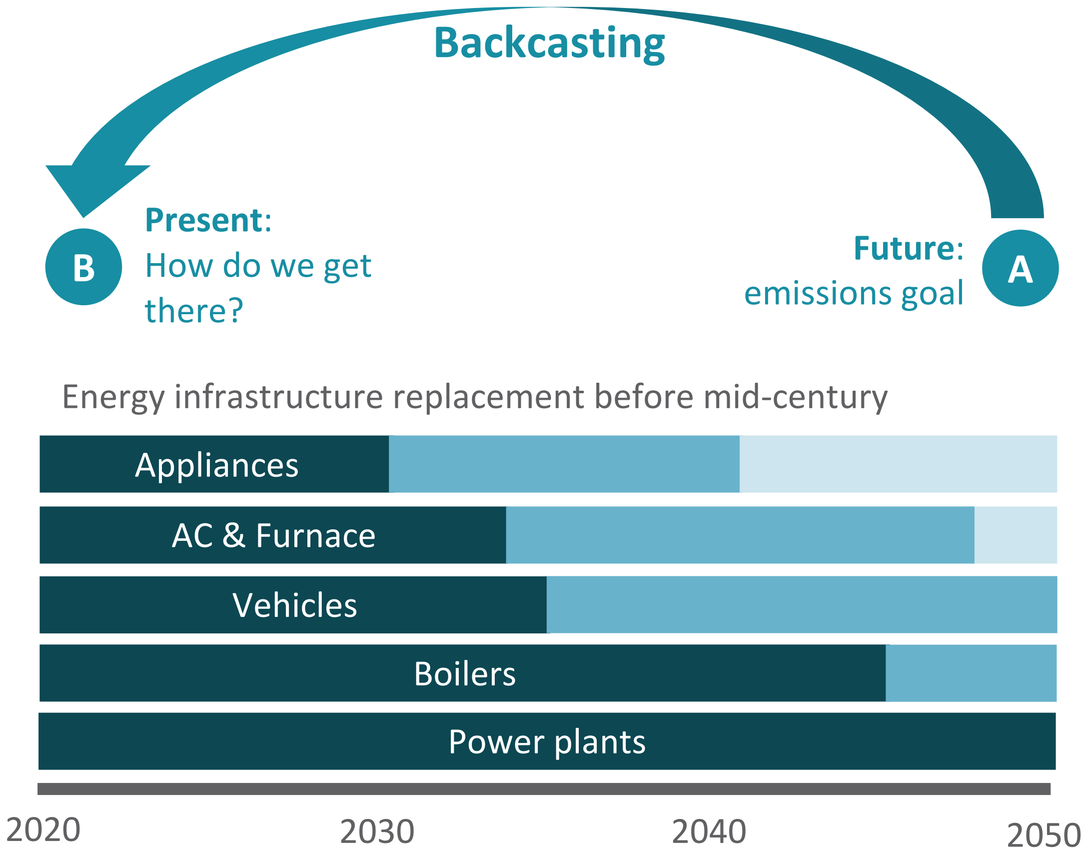
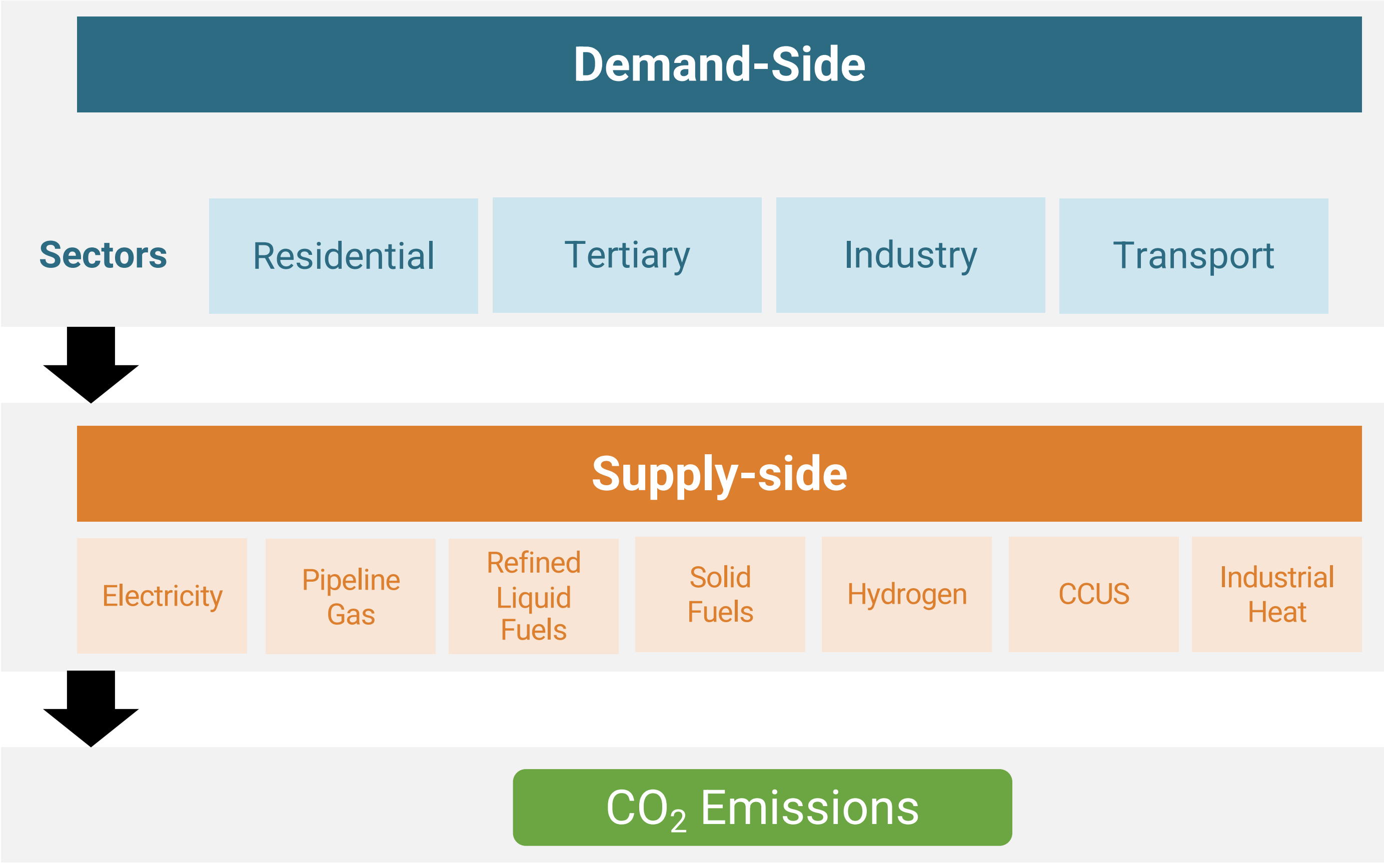
This analysis utilizes a backcasting approach to decarbonization modeling.

- **Backcasting** starts with an end-goal (a future emissions target) and works backwards to optimize **pathways** to that goal
- Transitioning to a low-carbon economy fundamentally relies on investment in long lead time, long-lived infrastructure assets
- Working backwards sheds light on the intermediate decisions and investments required to meet targets far in the future



We combine demand-side and supply-side models to represent the full spectrum of emissions sources and decarbonization strategies.



Demand-Side

Sectors

Residential

Tertiary

Industry

Transport

- **EnergyPATHWAYS** model used to develop demand-side scenarios
- Apply fuel switching and energy efficiency levers
- Strategies vary by end-use (residential space heating to heavy-duty trucks)

Supply-side

Electricity

Pipeline Gas

Refined Liquid Fuels

Solid Fuels

Hydrogen

CCUS

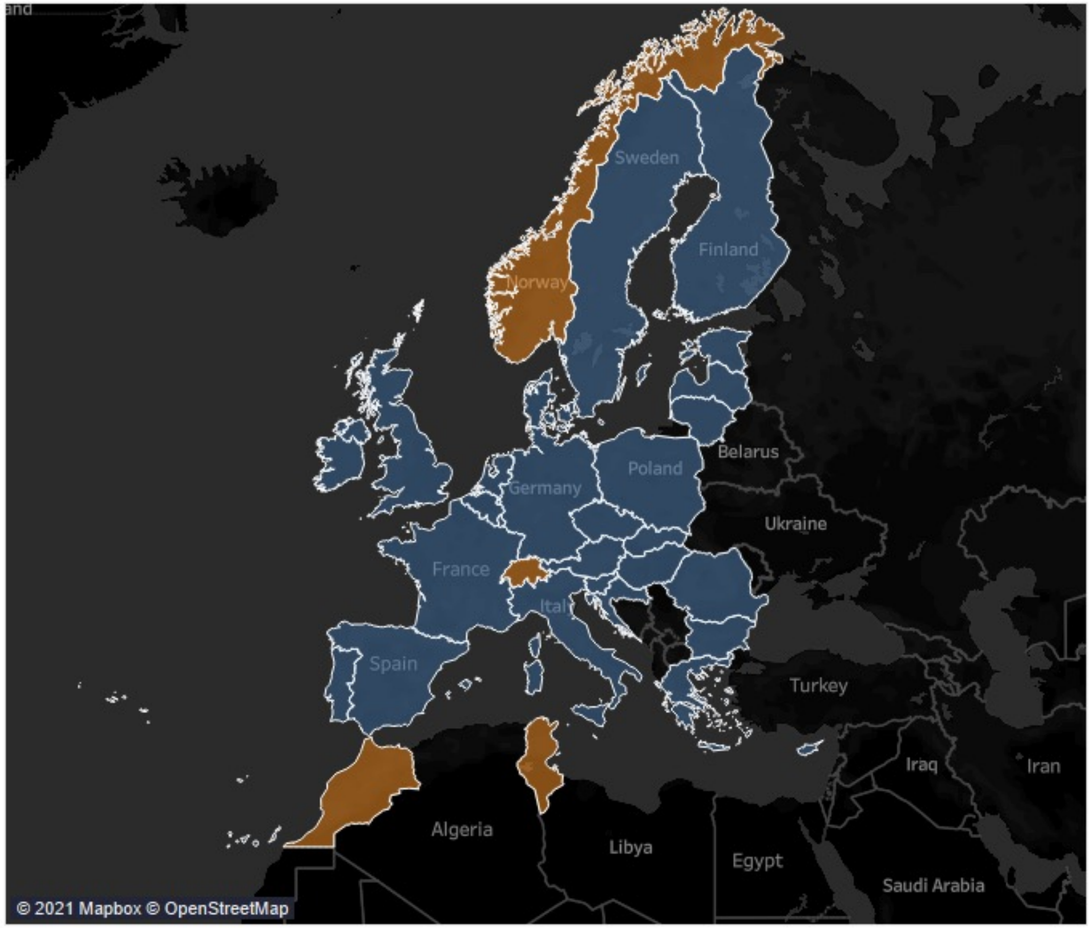
Industrial Heat

- **Regional Investment and Operations (RIO)** model provides cost-optimal energy supply combining a comprehensive supply-side capacity expansion framework with hourly system operations

CO_2 Emissions

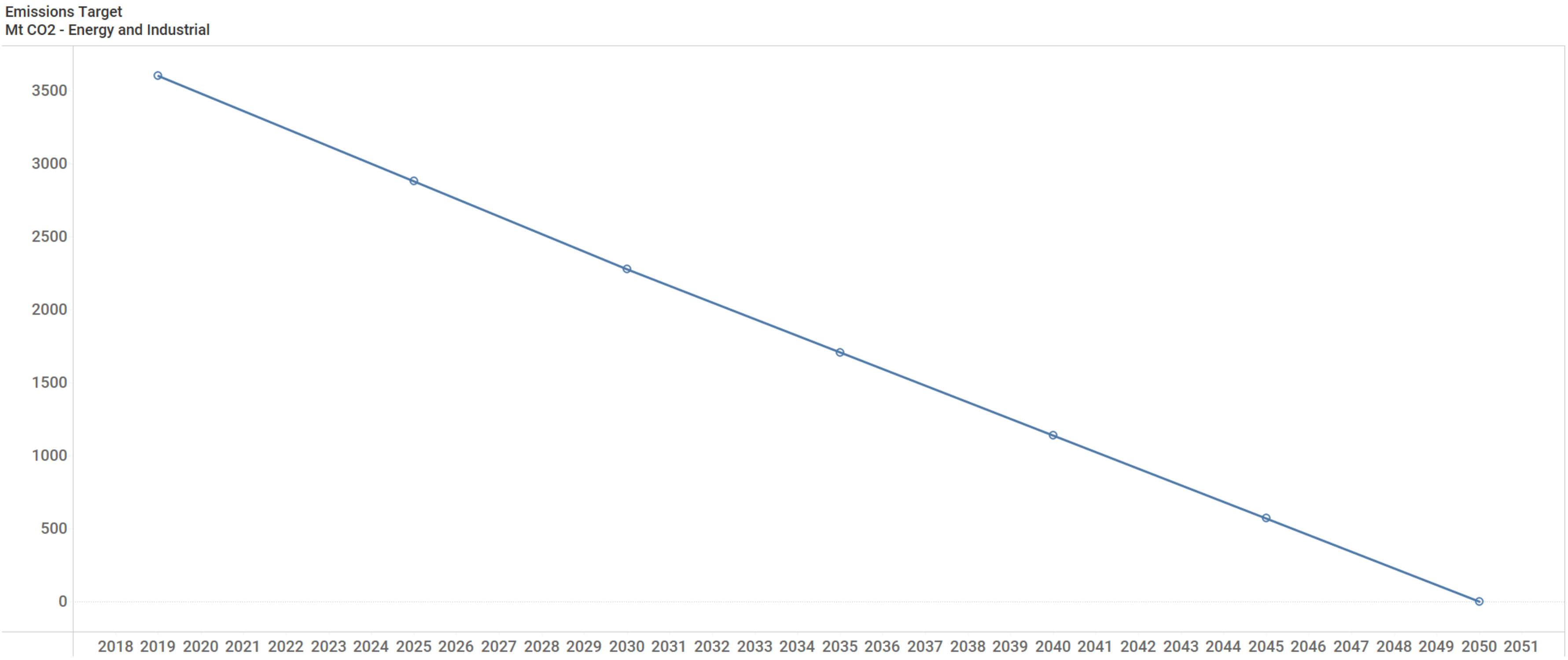
For more on the tools used in this analysis, view the Appendix or visit www.evolved.energy/about

We model energy supply and demand for each country in the EU, the UK, and additional countries important to the European energy system.



- Norway and Switzerland include full representation of electricity sector
- Morocco and Tunisia are represented as resource zones to provide renewable electricity via undersea transmission or hydrogen pipeline (to Spain, Italy, and UK)
- Aggregate results are shown for EU + UK. Where applicable, country-level results are shown for all modeled countries

All scenarios apply an economy-wide CO2 emissions constraint of 55% reduction relative to 1990 by 2030, and net-zero emissions by 2050.



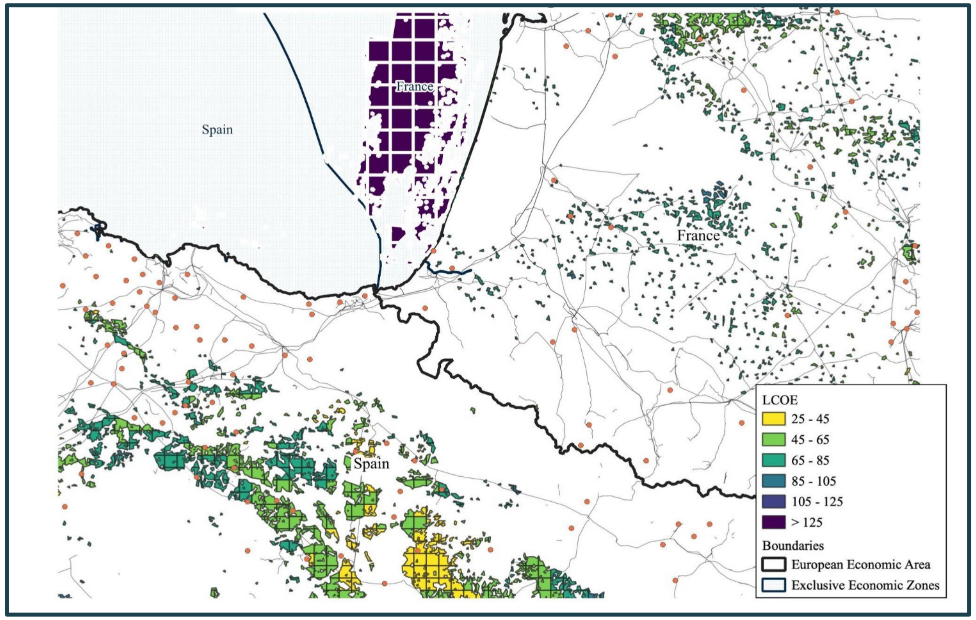
- Constraint applies to energy and non-energy (industrial) CO2 emissions in EU28 countries (EU + UK)
- Constraint is consistent with targets codified in the EU's European Climate Law
- We also implement a carbon price floor (rising to €108 by 2030) which causes some scenarios to exceed the targets in 2030

Inputs and Assumptions: Wind and Solar Resources

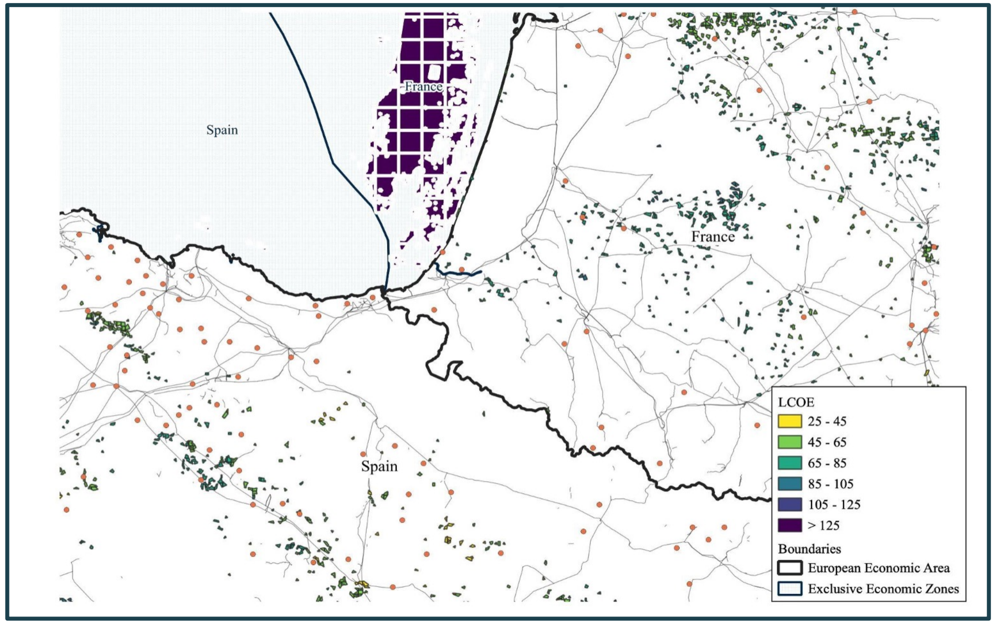
Renewable energy potential and cost is an important input to deriving achievable, economic decarbonization scenarios. We leverage GIS analysis to accurately represent wind and solar resources in our modeled geographies.

- Montara Mountain Energy conducted a GIS analysis of resource and technical potential for onshore wind, offshore wind, and solar PV
- The GIS analysis uses two land use scenarios: a Base scenario and a Max Restrictive scenario, which more aggressively excludes specific renewables development sites based on environmental and economic criteria—more detail on those criteria is included in the appendix
- As an example, these maps show candidate project areas for onshore and offshore wind along the Spain/France border

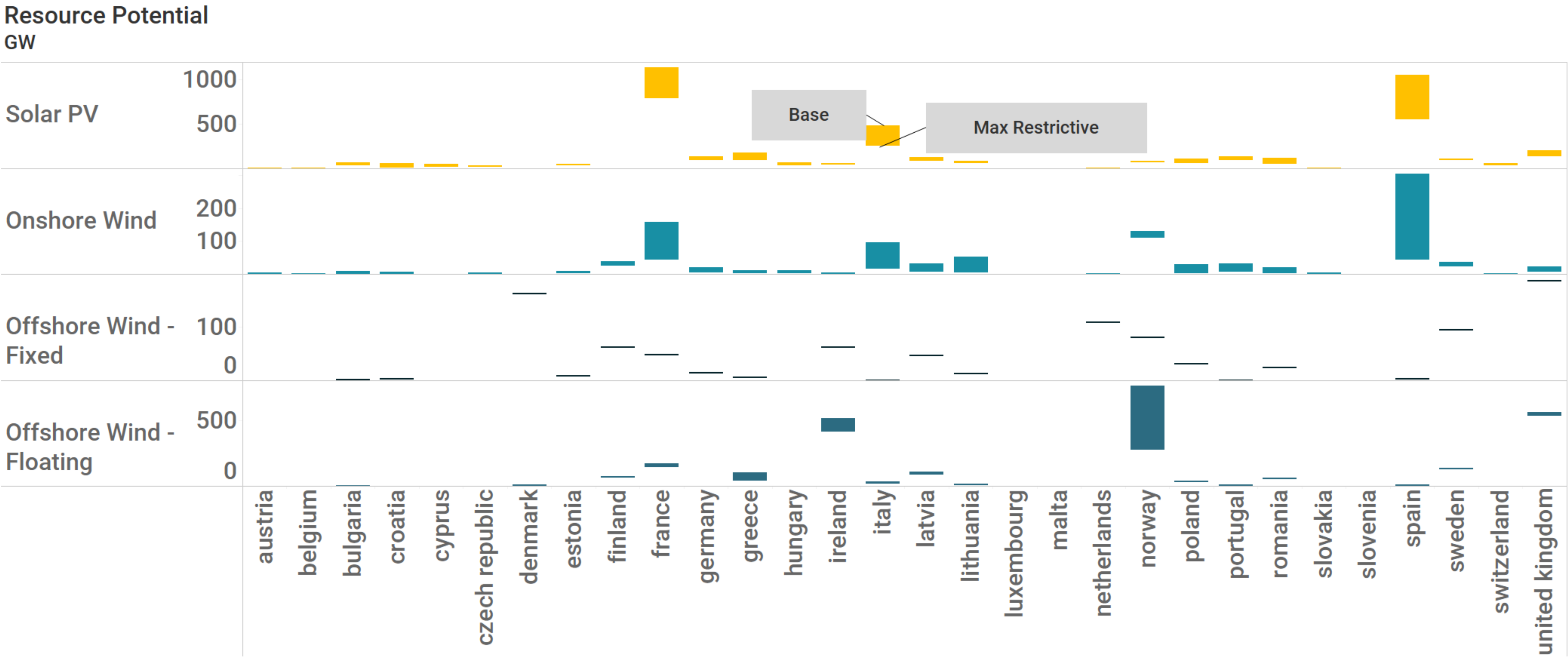
Base



Max Restrictive

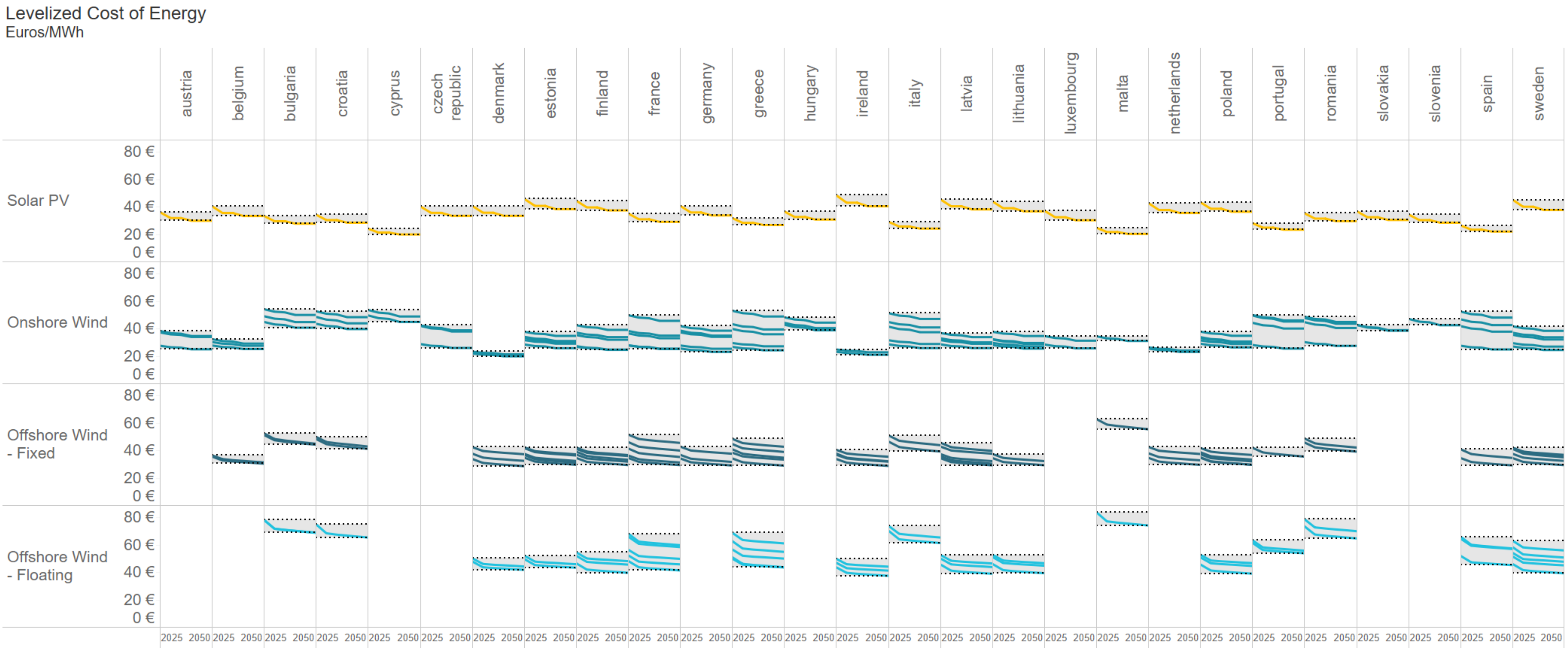


We then used candidate project areas (locations where wind and solar can likely be deployed) from the GIS analysis to determine total wind and solar resource potential for each country, under the Base and Max Restrictive land use scenarios.



To account for areas of higher- and lower-quality renewable resources, we group individual renewable energy candidate project areas into “bins” based on their levelized cost of energy (LCOE). For each bin, we forecast LCOE through 2050.

- We use 5 distinct bins to categorize each wind technology (offshore fixed, offshore floating, and onshore) and one bin for solar PV
- Lower-cost bins represent higher-quality renewable resources with better capacity factors and lower transmission costs
- Not all bins are available in every country, reflecting the variation in wind and solar resource quality
- Wind and solar cost assumptions from EUCO’s Reference 2020 scenarios.



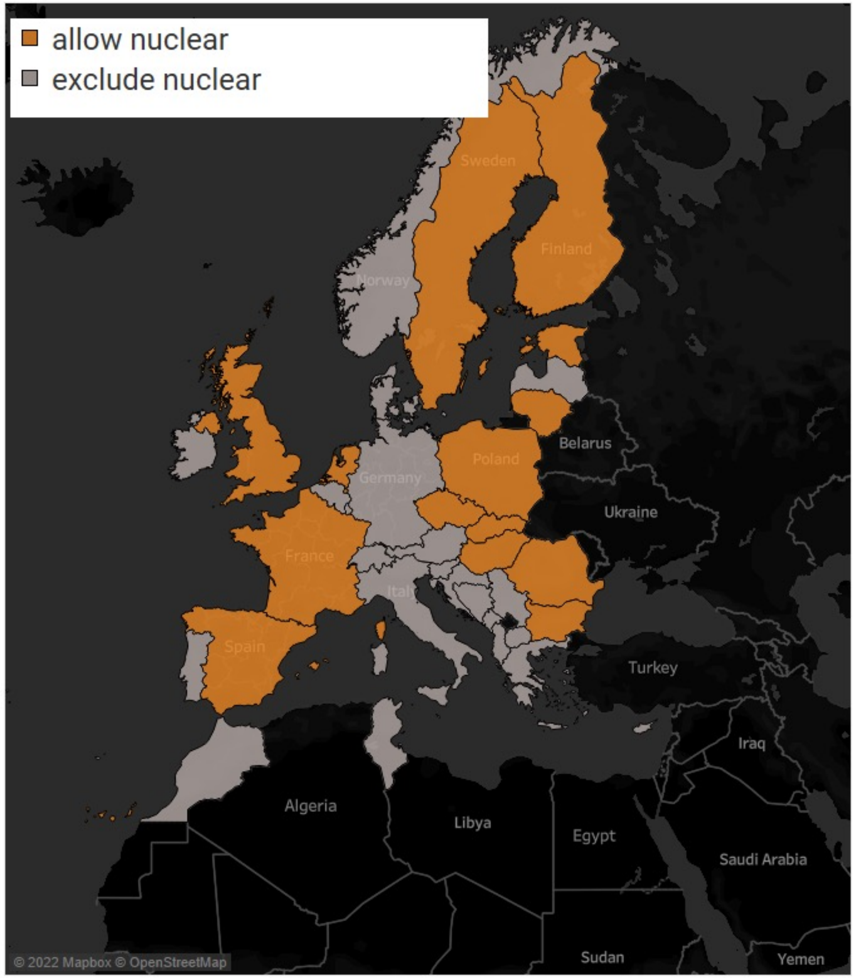
Inputs and Assumptions: Other Resource Constraints

In addition to wind and solar inputs, decarbonization pathways rely on input assumptions about cost and availability of other key technologies.

Geothermal	Availability sourced from GEO ELEC; Cost from POTENCIA
Rooftop PV	Availability and quality sourced from ENSPRESO. Cost sourced from IRENA.
Nuclear Biomass Geologic CO2 Sequestration Salt Cavern H2 Storage Electricity Interconnection Potential	Detailed in subsequent slides

GEO ELEC data available at http://www.geoelec.eu/wp-content/uploads/2011/09/D-2.5-GEOELEC-prospective-study.pdf
ENSPRESO data available at https://publications.jrc.ec.europa.eu/repository/handle/JRC116900

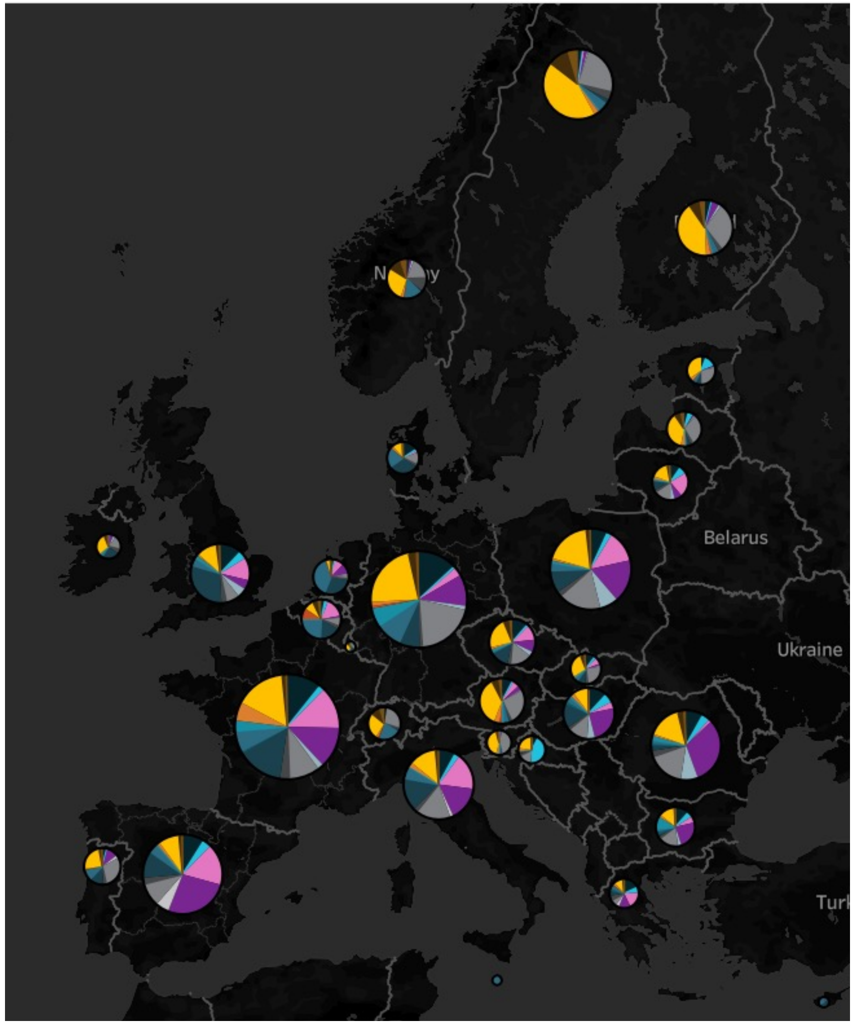
We allow nuclear resources only in select countries, based on existing national nuclear policies. Existing nuclear plants can be relicensed, and more sophisticated nuclear technologies become available over time.



- The life of existing nuclear can be extended in the model at a cost of €150/kW-year in ongoing O&M and capital
- New current-generation nuclear powerplants can be added starting in 2030
- Beginning in 2035, we model nuclear power as its modular components--an advanced nuclear reactor produces heat which is then paired with complementary technologies for different purposes:
  - **Electricity production** from either new steam turbine generators or from retrofitted existing coal plant generators
  - **Hydrogen production** from high-temperature electrolyzers (which are more efficient than low-temperature)
  - **Direct air capture** using nuclear heat
  - **High temperature thermal storage** of nuclear heat to time-shift electricity production, hydrogen production or direct air capture (DAC)
- The final economics and optimal deployment of each of these components is dynamically calculated in the model

Nuclear cost and performance assumptions are sourced from MIT – Future of Energy in a Carbon-Constrained World available at https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/
See appendix fore more detail on advanced nuclear operations in our model

Biomass resource availability constraints are based on resource categorization and costs from the ENSPRESO database's Medium Scenario.

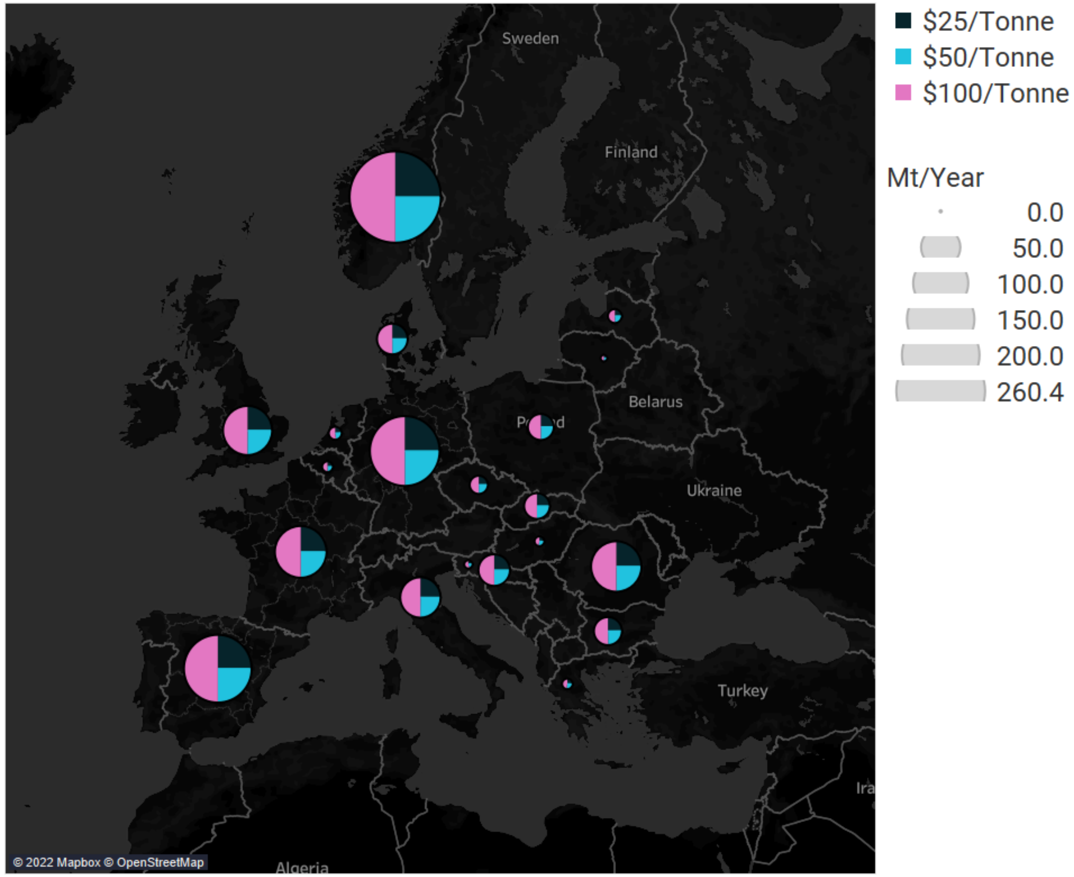


- The quantity and type of available biomass varies significantly by country
- Utilization of biomass resources is determined by their relative economics in the scenario analysis
- Given that Europe is not a closed system for biomass, the model also allows wood pellet imports at a high relative cost by 2050

ENSPRESO data available at https://publications.jrc.ec.europa.eu/repository/handle/JRC116900

Total geologic storage availability was derived from the EU GeoCapacity project, with the assumption that annual injection rates are equal to total available potential per 100 years.

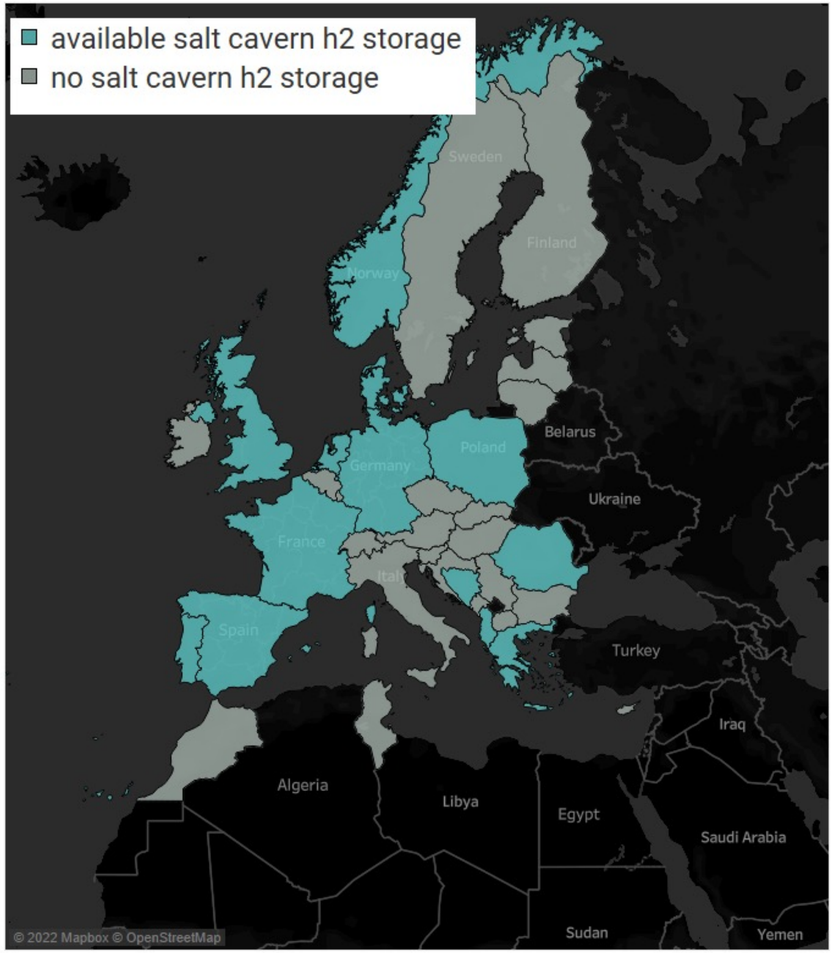
- This methodology results in a total available EU injection potential of 954 million tonnes of CO2 per year by 2050
- The GeoCapacity project does not include cost estimates; we assume that within each country, 25% of total annual injection potential is available at €50/tonne, 25% is available at €75/tonne, and the remaining 50% is available at €100/tonne. Our cost assumptions include inter-country transport and storage costs. We do not allow cross-border CO2 transport.



EU GeoCapacity data available at http://www.geology.cz/geocapacity

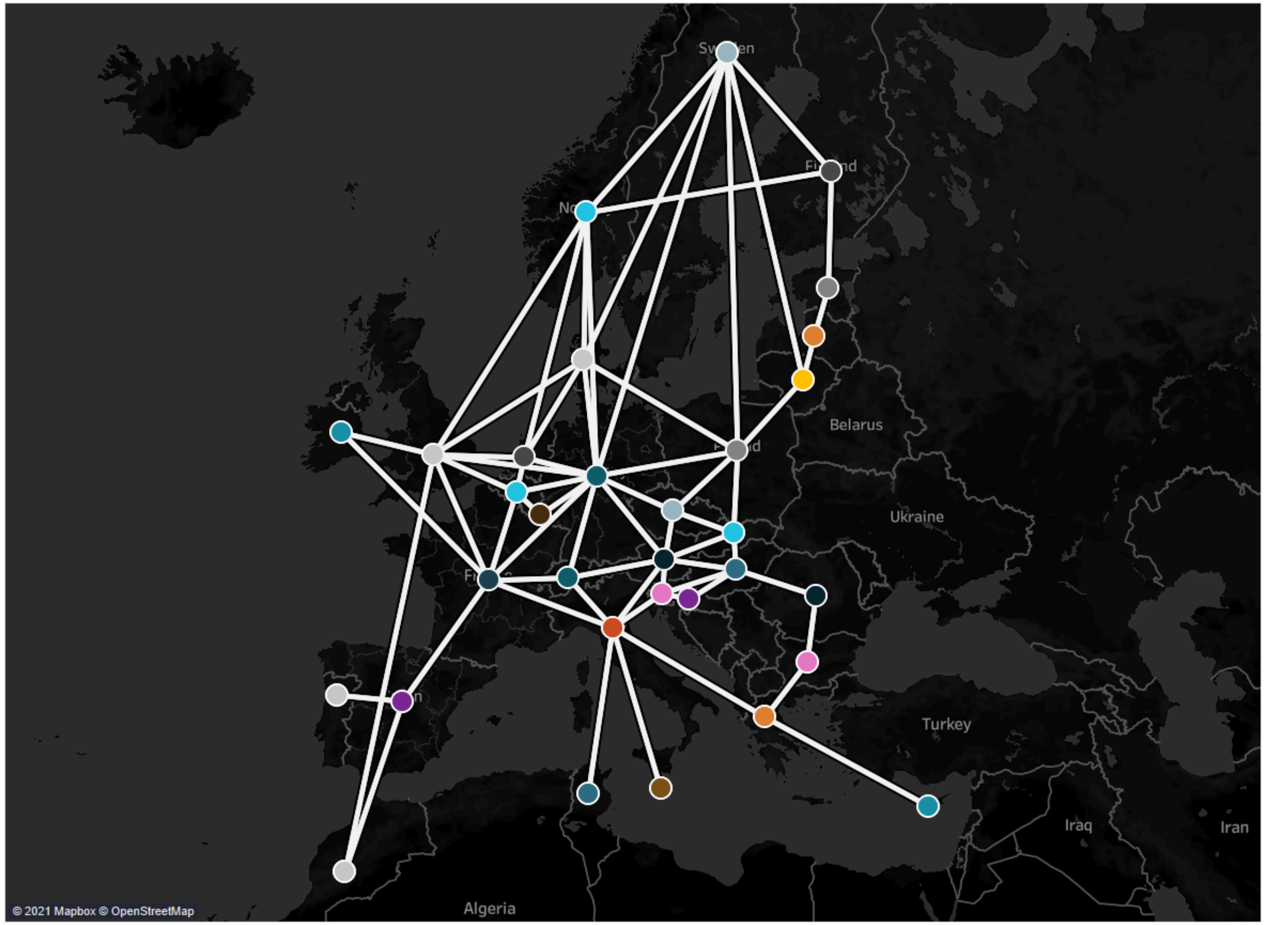
Salt cavern hydrogen storage is assumed to be available only in certain countries with appropriate geological conditions.

- Salt cavern H2 storage offers the potential for large-scale, low-cost seasonal balancing for energy systems that are dominated by renewable energy
- In countries with no salt cavern storage, underground H2 pipe storage provides seasonal balancing at higher cost
- Our model's supply-side optimization includes the option to build H2 pipelines to access these low-cost storage sites



Salt cavern annual injection potential and cost sourced from "Technical Potential of Salt Caverns for Hydrogen Storage in Europe", Caglayan et. al. International Journal of Hydrogen Energy 2020, available at https://www.preprints.org/manuscript/201910.0187/v1

The RIO optimization can build additional electricity transmission and hydrogen pipelines between countries, if economical based on input cost assumptions.



- Electric transmission cost assumptions are from ENTSO-E's 2020 Ten-Year Network Development Plan and include in-country upgrades to ensure power can be delivered from the transmission network to load
- Hydrogen pipeline costs are based on center-to-center distances between modeled zones and assumed costs of €263/MW-Mile

ENTSO-E data available at the following link: [Ten-Year Network Development Plan 2020](#)

Scenarios

This analysis creates 5 scenarios to explore possible paths to net-zero by 2050. The first scenario, called the "Core Scenario," is the least constrained and results in the lowest total costs.

Core Scenario Definition

Reductions from 1990 levels in energy and industrial (E&I) CO_2 (for EU+28 countries) consistent with economy-wide 55% emissions reduction by 2030. Net-zero E&I CO2 by 2050.

Ambitious demand-side transformation including transport, building, and industrial electrification as well as decarbonized heavy industry (iron & steel via hydrogen-based DRI) and cement (carbon capture).

Supply side includes best-estimate assumptions for technology cost and availability (including renewable potential constraints).

Allows all clean energy technologies including nuclear power as well as some fossil generation.

Resulting Decarbonization Strategies

Aggressive electrification of end use technologies across all sectors.

Zero-carbon electricity generation from a mix of new renewables and nuclear.

Significant deployment of hydrogen electrolysis (both high- and low-temperature), advanced biofuels with carbon capture, and a limited amount of zero-carbon imports meet most remaining fuel demand.

BECCS and DAC offset modest residual emissions from fossil fuel use in industry and transportation.

The next 4 scenarios introduce constraints to explore key variables in public policy and consumer behavior.

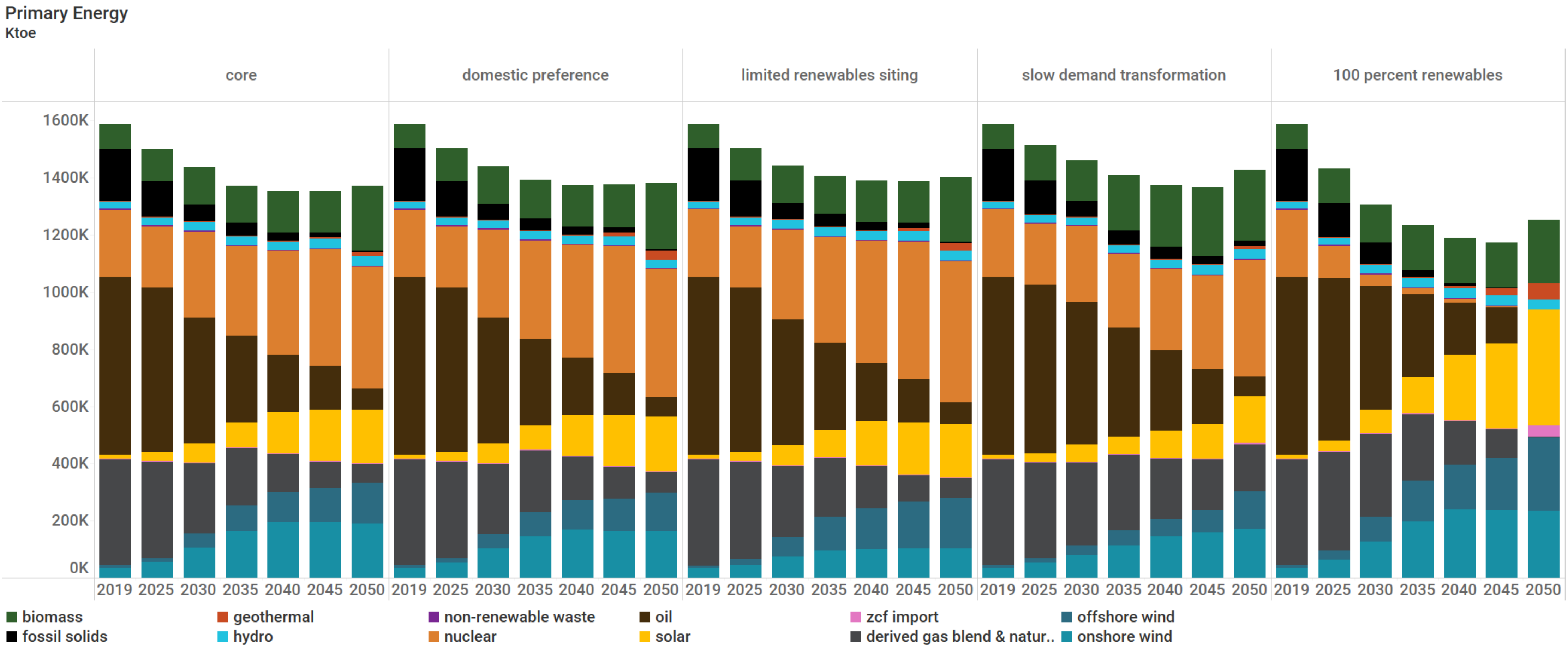
Scenario Definitions		Resulting Variation from Core Scenario
Domestic Preference	Simulates reduced appetite for international deployment of new electric transmission and hydrogen pipelines by applying a 5x cost multiplier on new infrastructure. No buildouts of large intercontinental infrastructure (i.e. H2 pipeline/transmission lines to Africa).	Limited energy transport infrastructure forces development of lower quality renewable resources, leading to higher overall energy costs. Increased share of generation comes from nuclear and geothermal. Some transport infrastructure is still required, revealing critical transmission needs for certain countries.
Limited Renewable Siting	Applies "Max Restrictive" land use scenario, resulting in reduced availability of grid-scale solar PV and onshore wind.	Land use restrictions cause overall decrease in onshore wind deployment, and generally shift solar development to lower-quality sites (i.e. lower solar capacity factors). Decrease in onshore wind and solar production is met with an increase in offshore wind and nuclear generation.
Slow Demand Transformation	Reduced rates of demand-side electrification in buildings and transport; slower industrial decarbonization.	Less electrification in buildings and transport leads to higher demand for decarbonized liquid and gaseous fuels, which is met with advanced liquid biofuels and expensive zero-carbon imports. Less electrification also reduces need for new electric capacity, but lower capacity investments do not fully offset cost increases from fuel demand.
100% Renewable Primary Energy	All primary energy must be sourced from renewables, excluding all fossil and nuclear energy from qualification by 2050. No geologic carbon sequestration is allowed.	Massive deployment of renewable energy is required to both offset lack of nuclear generation and produce zero-carbon fuels Highest overall cost scenario.

Note: Slow Demand Transformation scenario uses an alternate scenario in the EnergyPATHWAYS demand-side model. All other scenarios use the same "core" demand-side scenario while varying constraints in the RIO supply-side model.

EU + UK Results

Results: Energy System At a Glance

In all scenarios, primary energy shifts from fossil coal, oil, and natural gas towards renewables. Nuclear heat is a significant source of primary energy in all scenarios except 100% Renewables, which is also the only scenario with no fossil energy by 2050.



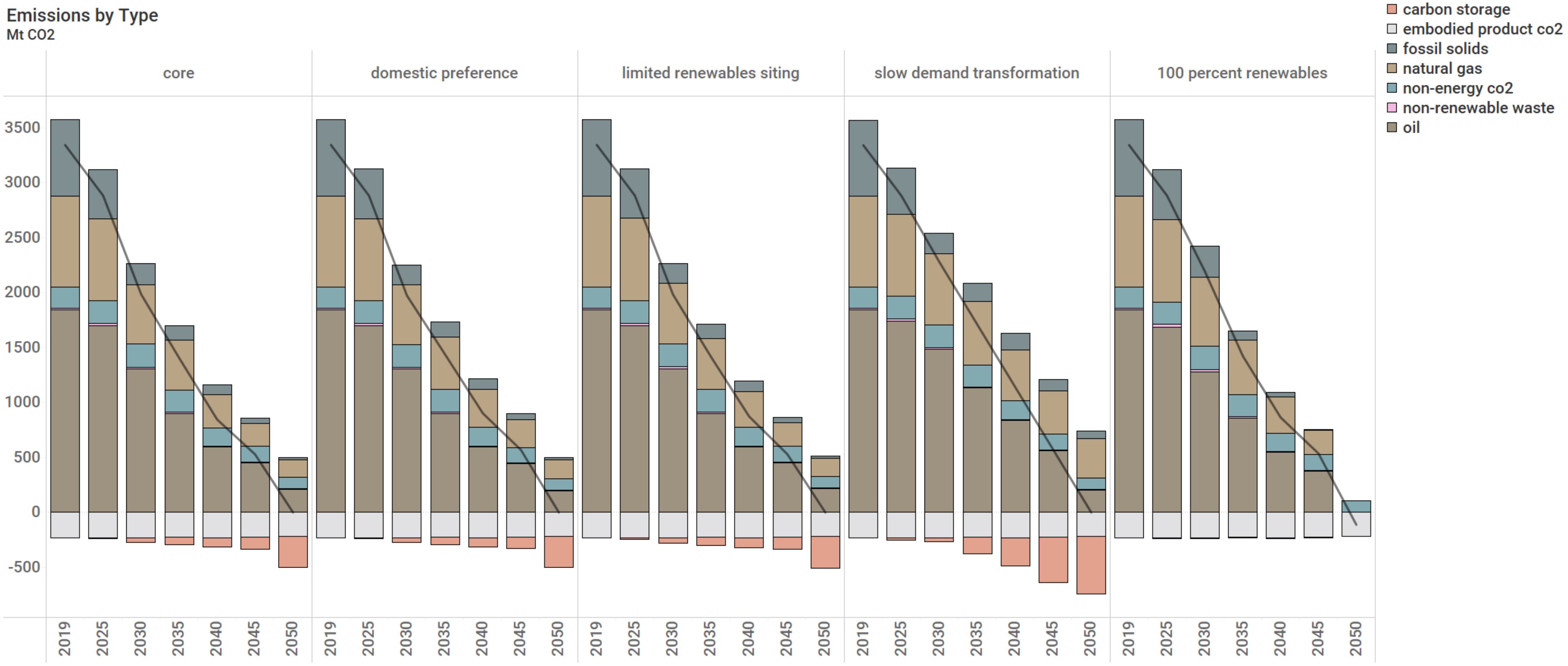
Our scenarios closely align with EU Fit for 55 scenarios through 2030.

Share of 2030 Primary Energy Supply by Type

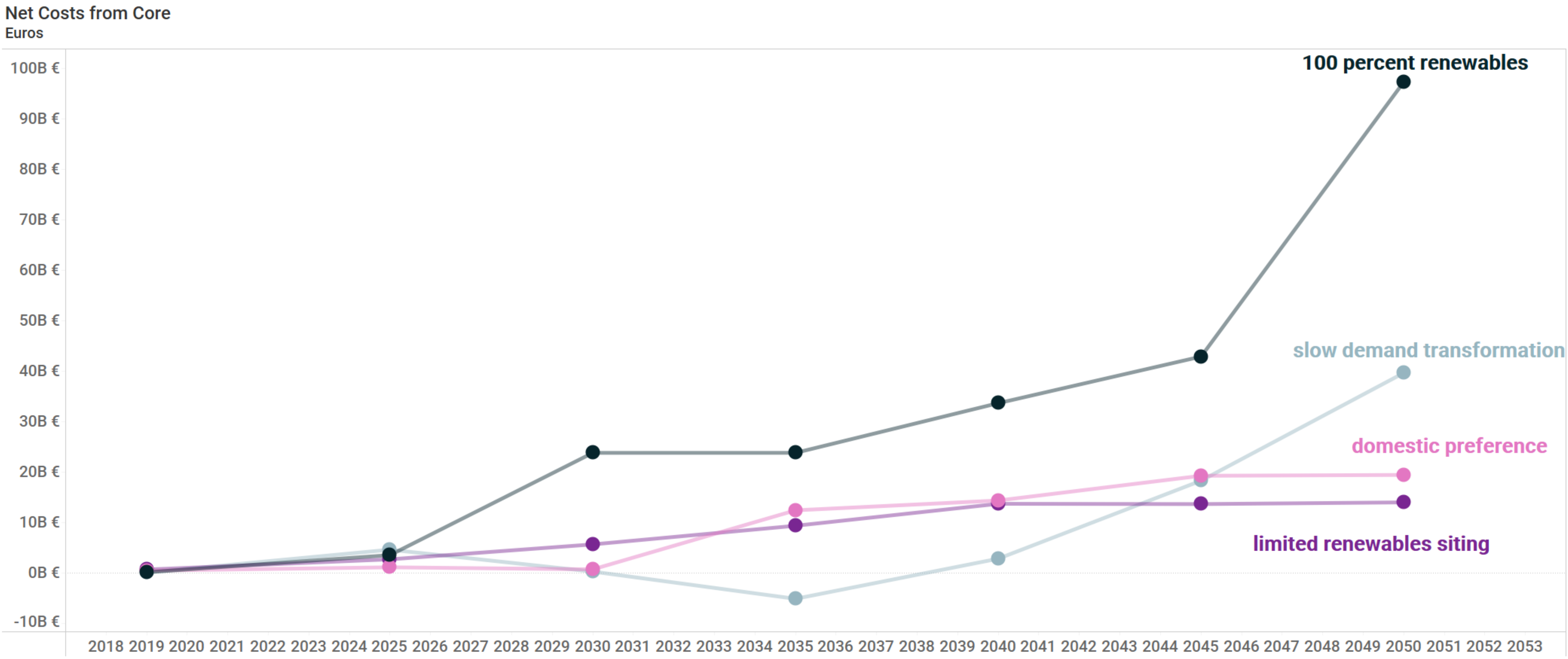
	EU Fit for 55 Scenarios			Carbon-Free Europe Scenarios				
Energy Type	EU 'Fit for 55' MIX-CP Scenario	EU 'Fit for 55' MIX Scenario	EU 'Fit for 55' REG Scenario	core	domestic preference	limited renewable siting	slow demand trans-formation	100 percent renewables
Solid fossil fuels	5.1%	5.6%	6.2%	4.3%	4%	4.2%	4.1%	6.2%
Crude oil and petroleum products	34.4%	34.5%	34.2%	30.3%	30.2%	30.2%	33.9%	32.5%
Natural and manufactured gases	21.9%	21.1%	20.4%	17.1%	17.2%	17.2%	19.6%	22.1%
Nuclear	11.5%	11.6%	11.7%	20.3%	20.8%	21.1%	17.9%	3.2%
Biomass & Waste	12.6%	12.8%	13.2%	9.8%	9.8%	9.8%	10.4%	10.7%
Hydro	2.7%	2.7%	2.7%	2.4%	2.3%	2.4%	2.1%	2.7%
Wind + Solar	11.7%	11.7%	11.7%	15.8%	15.5%	14.9%	11.8%	22.2%
ktoe	1,161,557	1,153,250	1,144,909	1,268,295	1,269,782	1,274,878	1,293,110	1,160,778

- Similarity of results through 2030 indicates that achieving the EU's interim targets is an important step in reaching net-zero by 2050
- Most significant variation comes from nuclear energy: Carbon-Free Europe scenarios include more electrification and electricity decarbonization by 2030
- The 100% Renewables scenario has the highest amount of natural gas remaining in the system by 2030
- Carbon-Free Europe scenarios provide additional insight into the significant transformation needed to progress from 2030 targets to net-zero

Coal emissions decline rapidly, while oil and gas emissions drop more gradually. In all scenarios except 100% Renewables, some fossil fuel emissions remain in 2050 and are offset by carbon sequestration, primarily as negative emissions from BECCS or DAC.

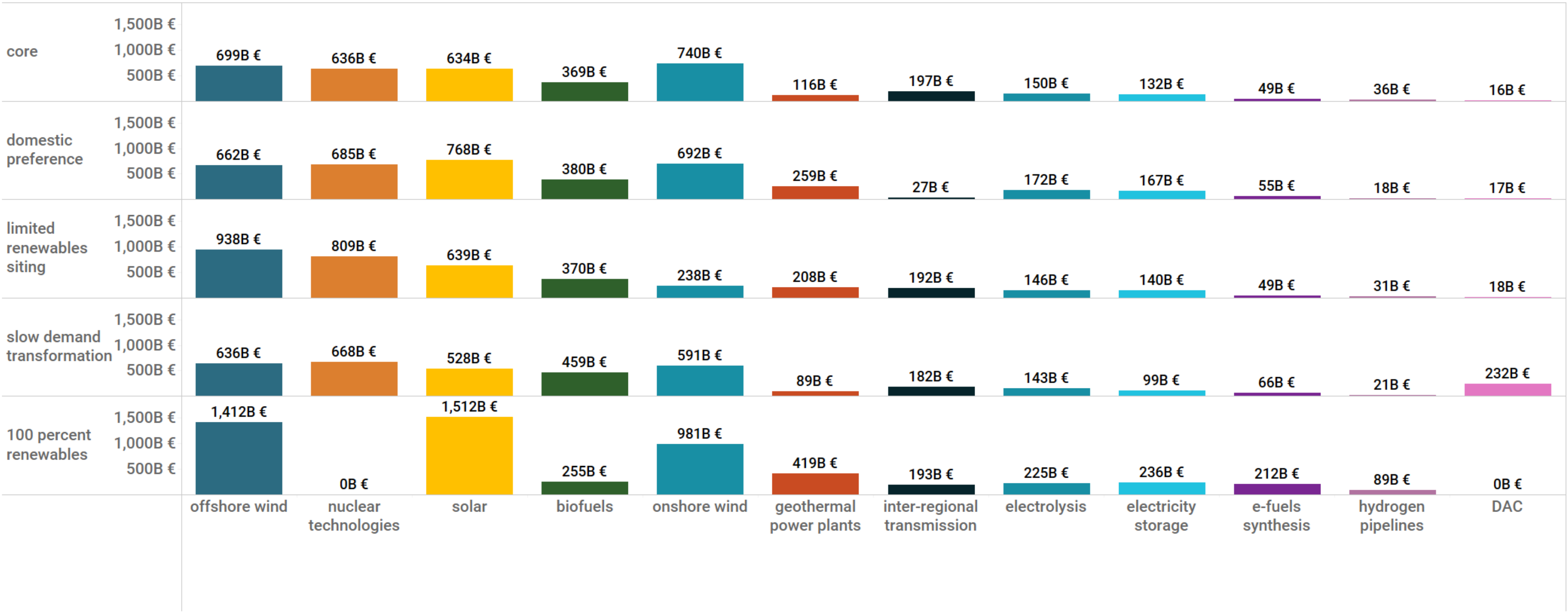


All scenarios increase costs above the **Core**, with the most significant cost increases seen in the **100 Percent Renewables** scenario.



*Costs include a cost of emissions at the floor price, to account for the impact of different emissions trajectories on costs.

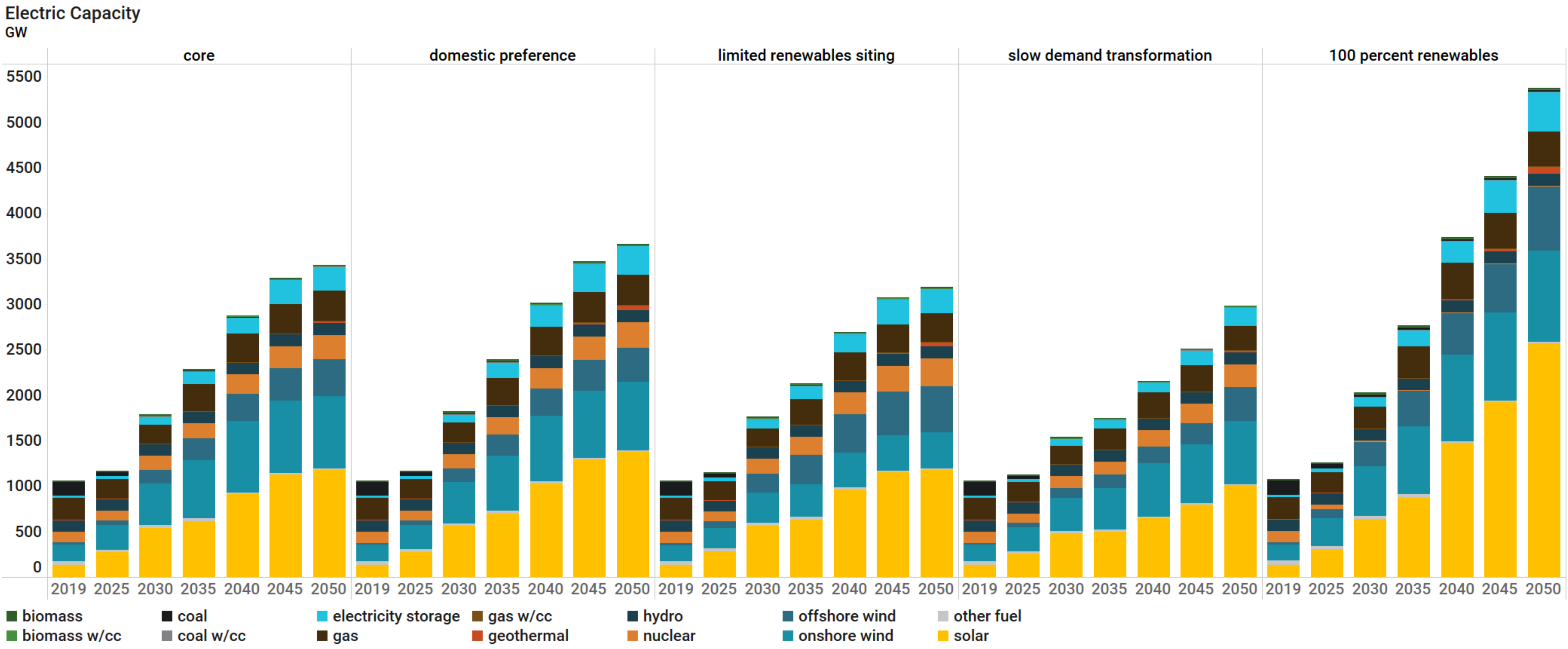
Investment needs over the next 30 years are substantial, with trillions of Euros of new investment going towards electricity generation, fuels technologies, and delivery infrastructure



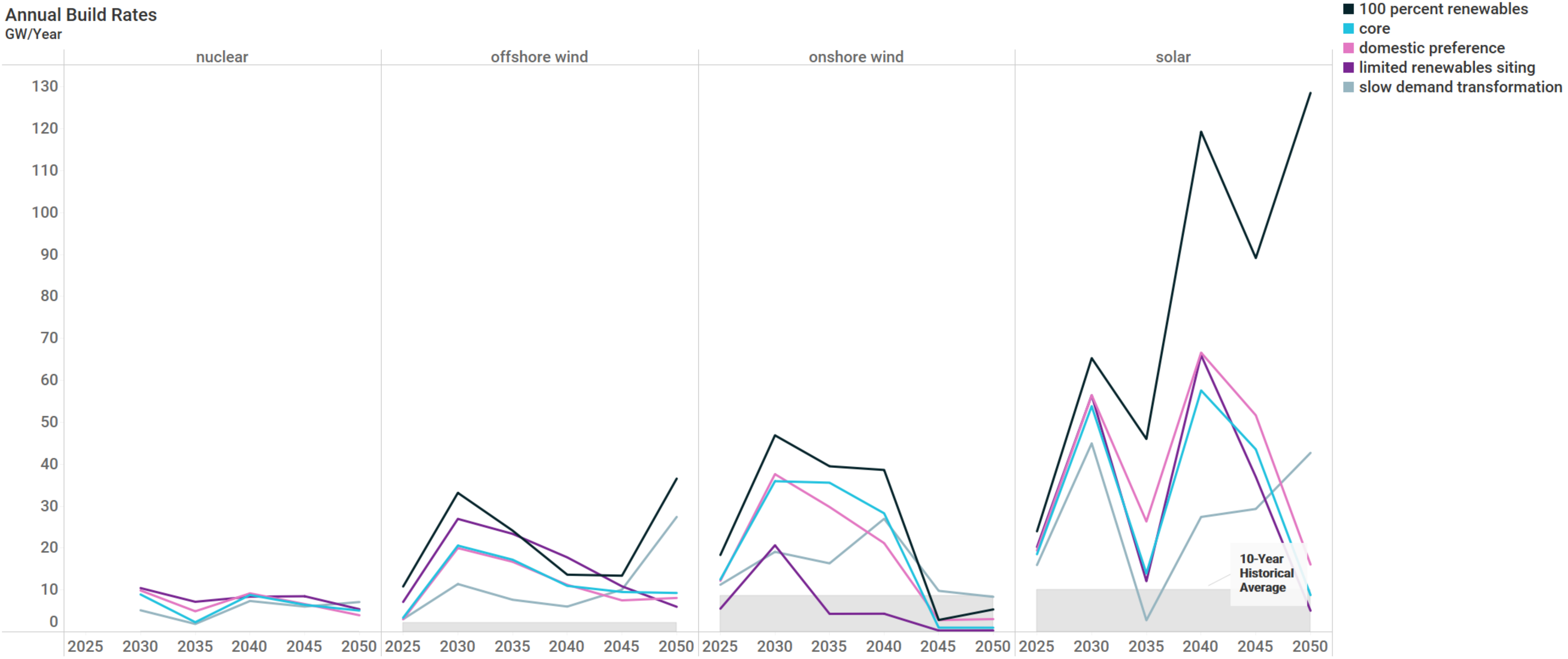
Investment Needs in Key Technologies
Euros (2020-2050)

Results: Electric Generation

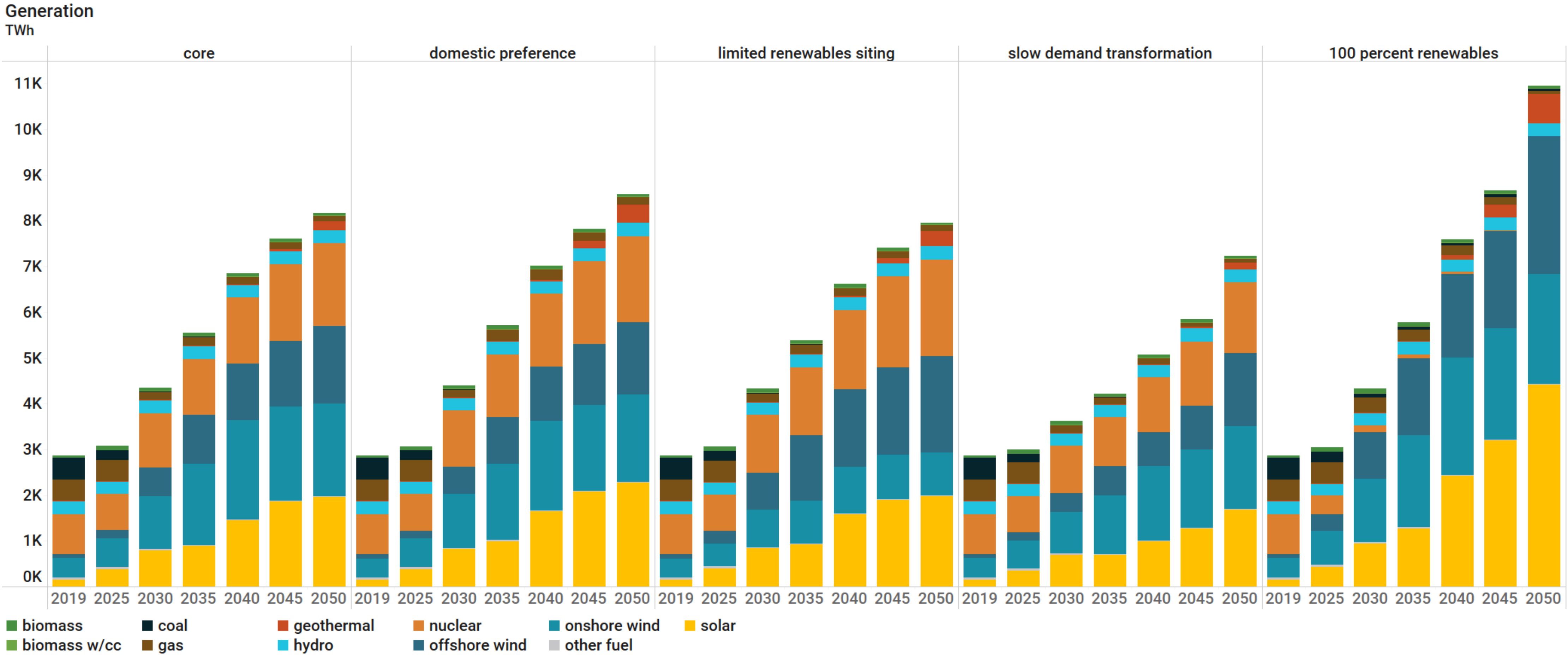
In all scenarios, electric generation capacity grows rapidly as the electric sector becomes the backbone of a decarbonized energy supply system, serving both direct electricity use and producing electrolytic hydrogen for fuels.



Annual build rates demonstrate the enormous scale of necessary clean energy deployment. All cases require unprecedented levels of electric capacity buildout.

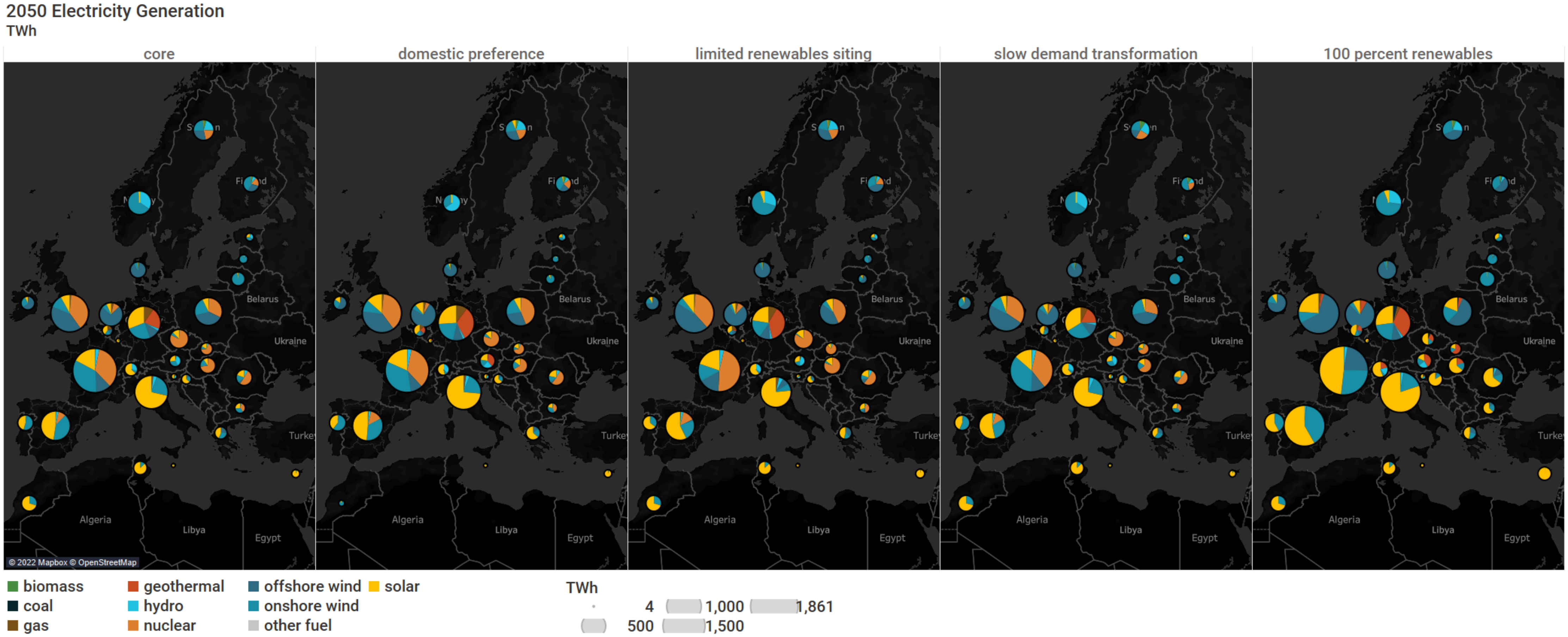


Decarbonization of the economy requires more than 3x the amount of generation as today, with the **100% Renewables** scenario require more than 4x due to large amounts of H2 production. In most cases, this is met with a balanced portfolio of solar, onshore wind, offshore wind, and nuclear.



Resource portfolios vary widely by country based on resource endowments for wind, solar and geothermal, and based on nuclear policy constraints.

- Country-level electric portfolios need not be monolithic—their complementarity can reduce costs and support feasibility of low-carbon electricity systems.

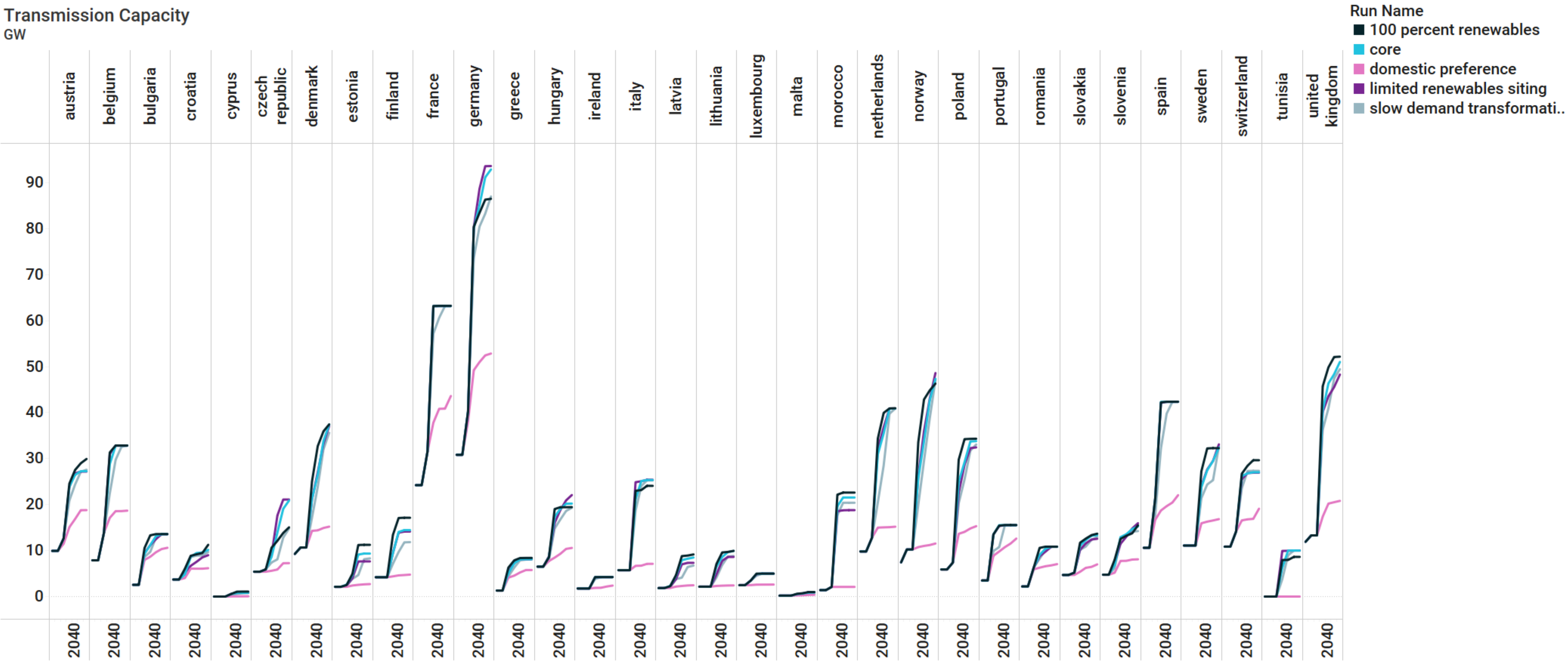


2050 Electricity Generation

TWh

Results: Electric Transmission

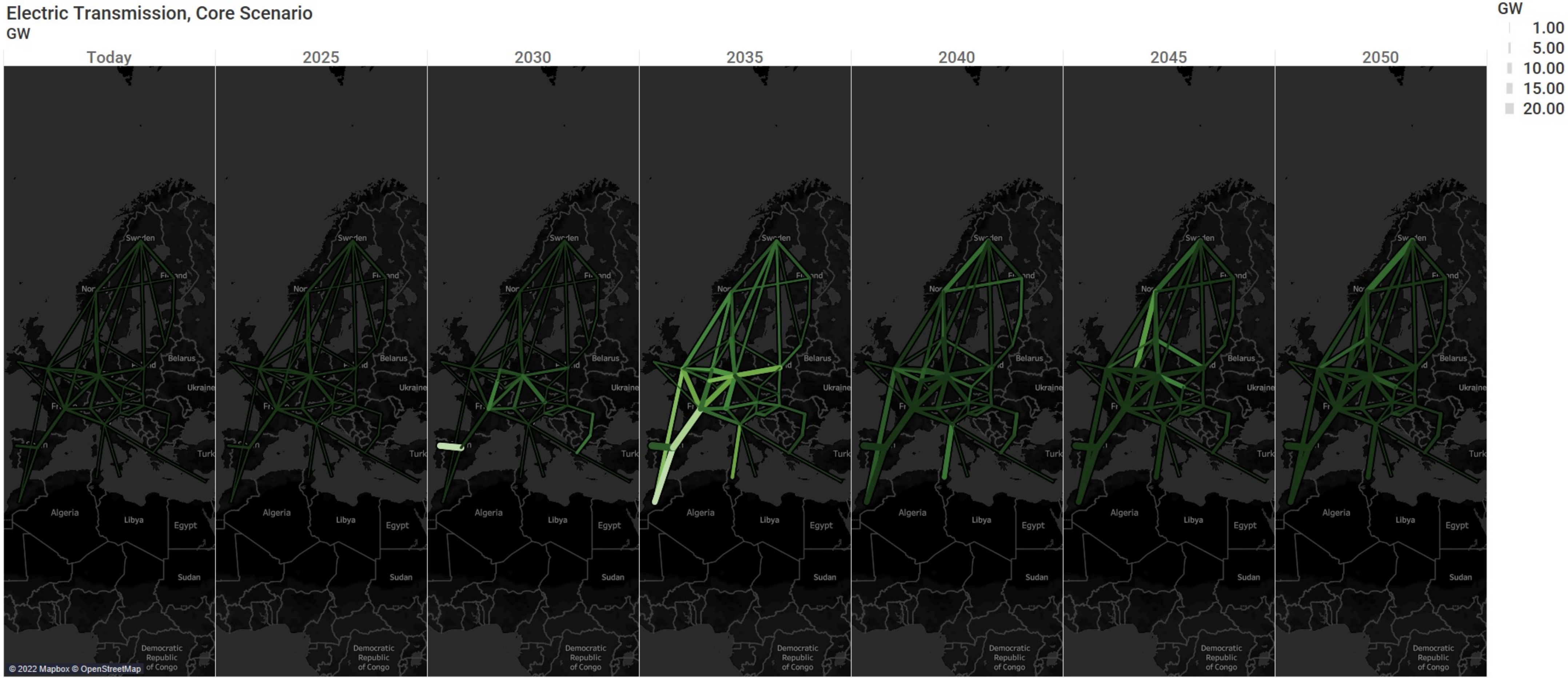
Even in the **Domestic Preference** scenario, which applies a cost penalty to international transmission expansion, significant new transmission capacity is deployed—highlighting the need for EU-wide coordination under any scenario.



Transmission buildout peaks in the 2035-2045 timeframe, coincident with the peak deployment rates for renewables and peak electrification rates. Electric sector decarbonization is mostly complete by 2045.

Electric Transmission, Core Scenario

GW



The width of the lines represents total transmission capacity in service between regions in each year. The brightness of the lines represents the scale of new transmission capacity placed in service in that year.

Results: Electric Operations

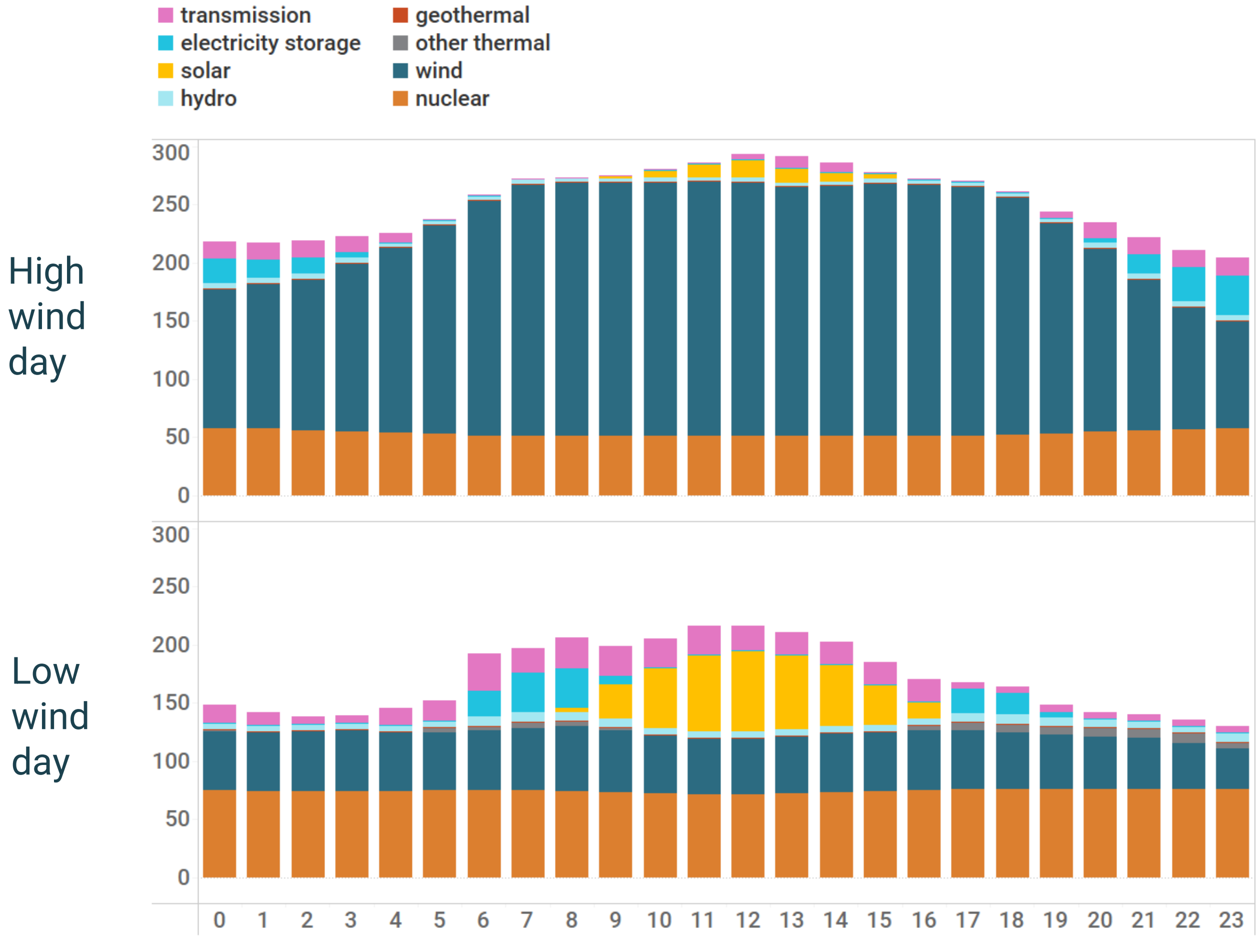
High levels of variable renewable generation require a suite of solutions to ensure reliable electric operations.

The model deploys a range of strategies to match supply and demand on an hourly, daily, and seasonal basis:

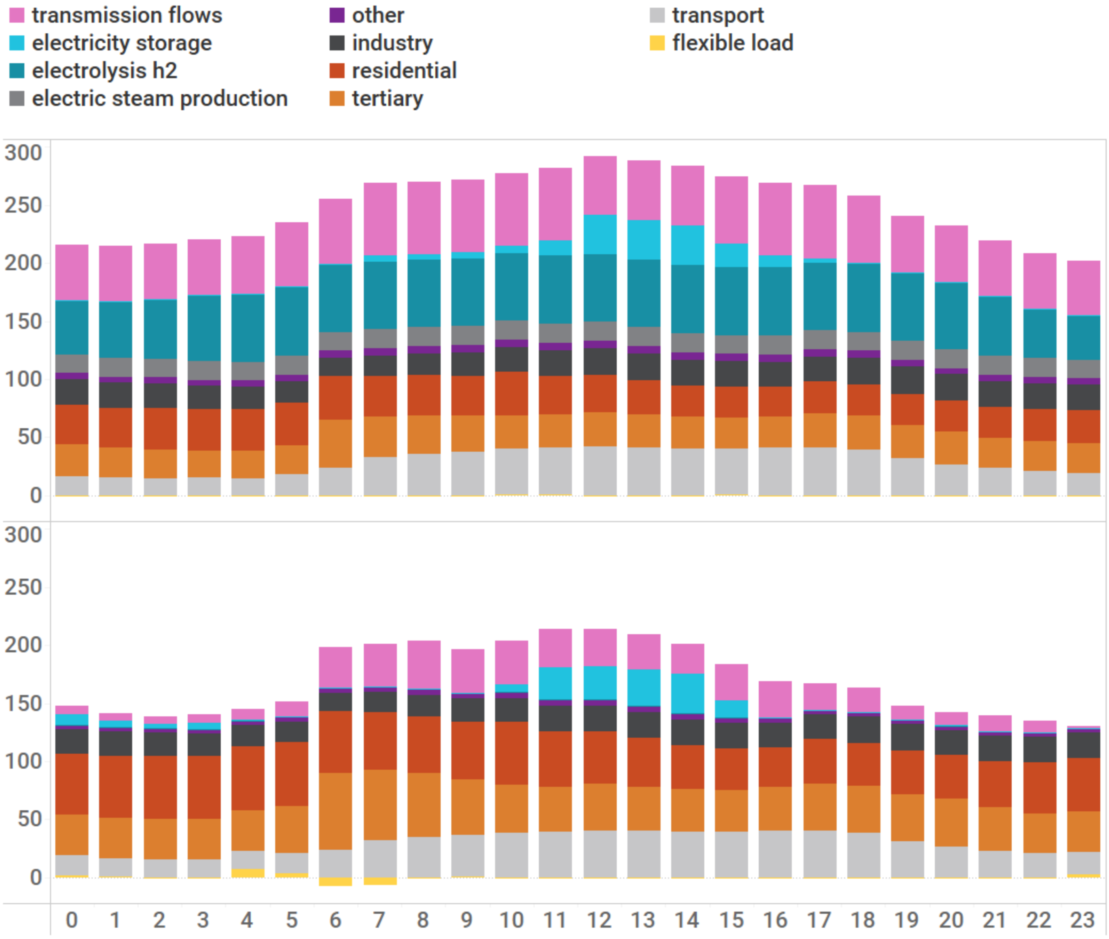
1. **Transmission** buildout allows imports and exports to balance supply and demand, reducing variability geographically
2. **Batteries** are used for diurnal balancing, typically charging mid-day during solar overgeneration conditions
3. **Electrolyzers and electric boilers** introduce hourly and seasonally flexible demand
4. **Flexible advanced nuclear reactors** can co-produce hydrogen and electricity, or can be deployed with thermal energy storage
5. **Flexible end-use loads** from vehicles and thermal end-uses in buildings reshape load on an hourly basis
6. **Thermal capacity** remains online as cheap backup power and runs sparingly during reliability periods

Two sample days show how the model balances hourly variation in renewable generation under different conditions.

Hourly electric generation, France, 2050
Core Scenario



Hourly electric demand, France, 2050
Core Scenario



Date on Y-Axis refers to the historical weather that was modelede

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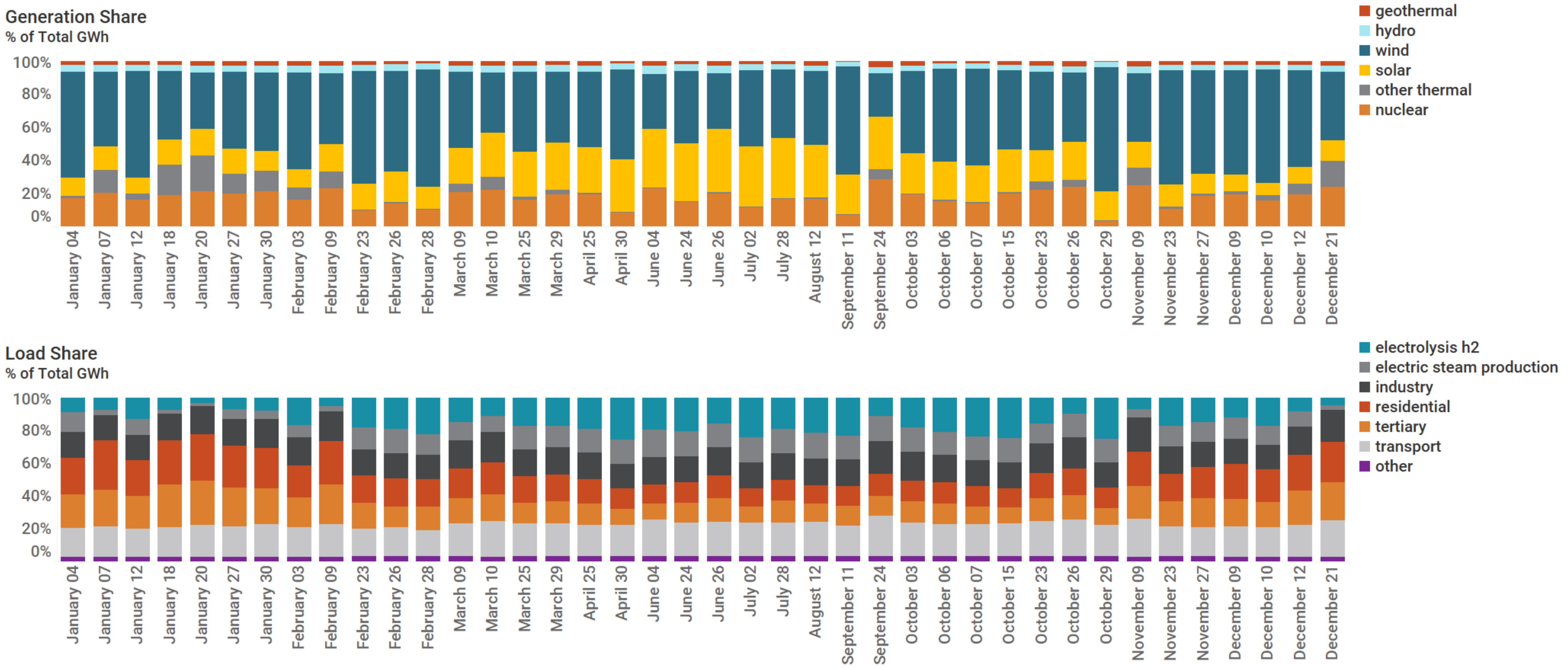
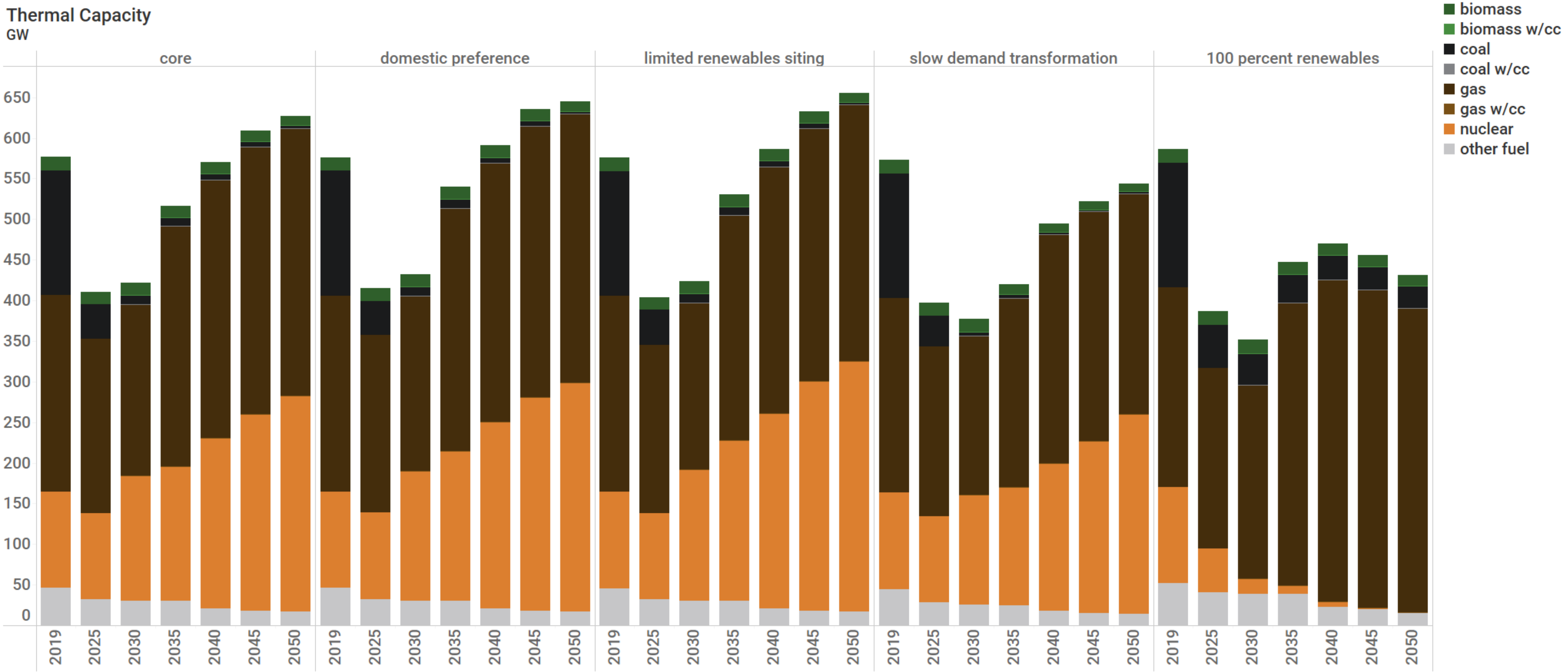
Comparing sample days over the course of a year shows how seasonal variation in wind and solar generation in the EU is balanced with ramping up and down nuclear generation, hydrogen production, and electric boiler use.



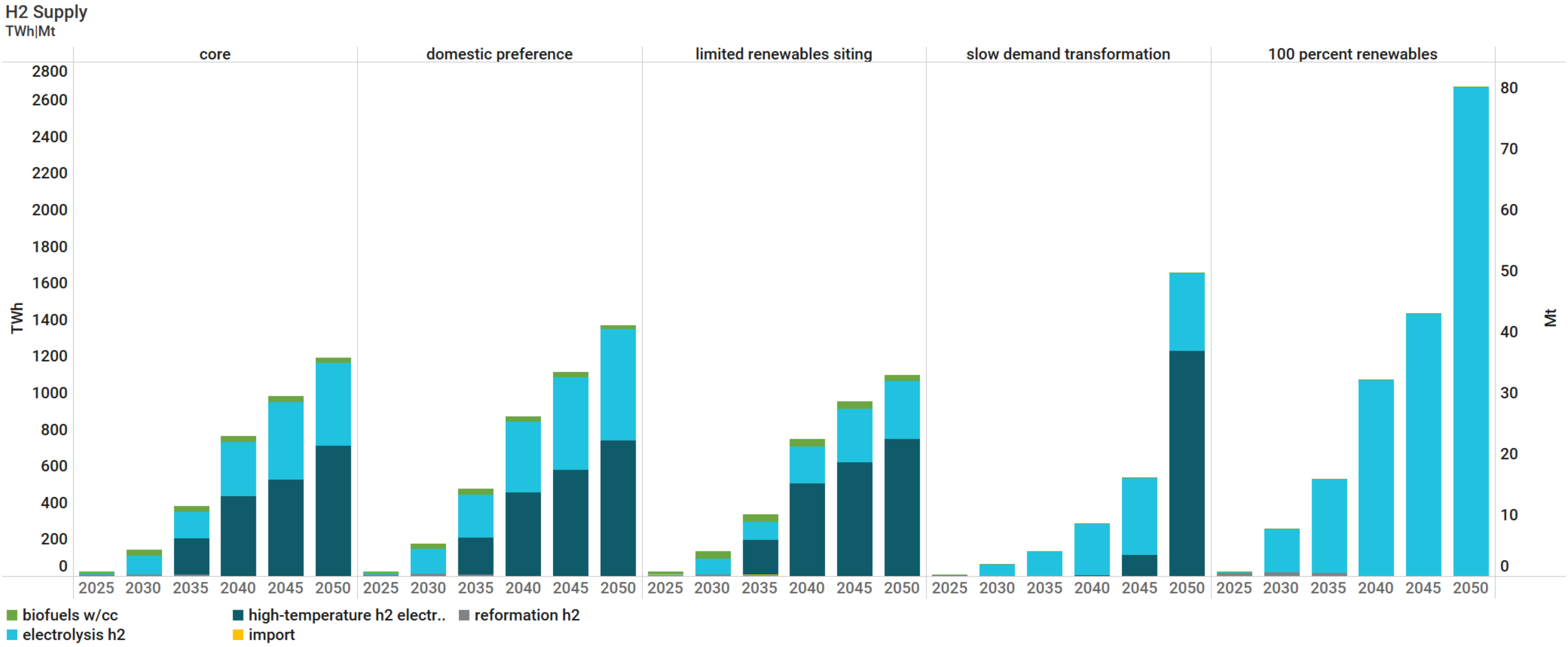
Under all scenarios, some thermal capacity is still needed in 2050 to support reliability in a small number of hours. This thermal electric generation can use fossil fuels, or alternatives like hydrogen, e-fuels, or biofuels.



Results: Hydrogen Supply, Demand, and Infrastructure

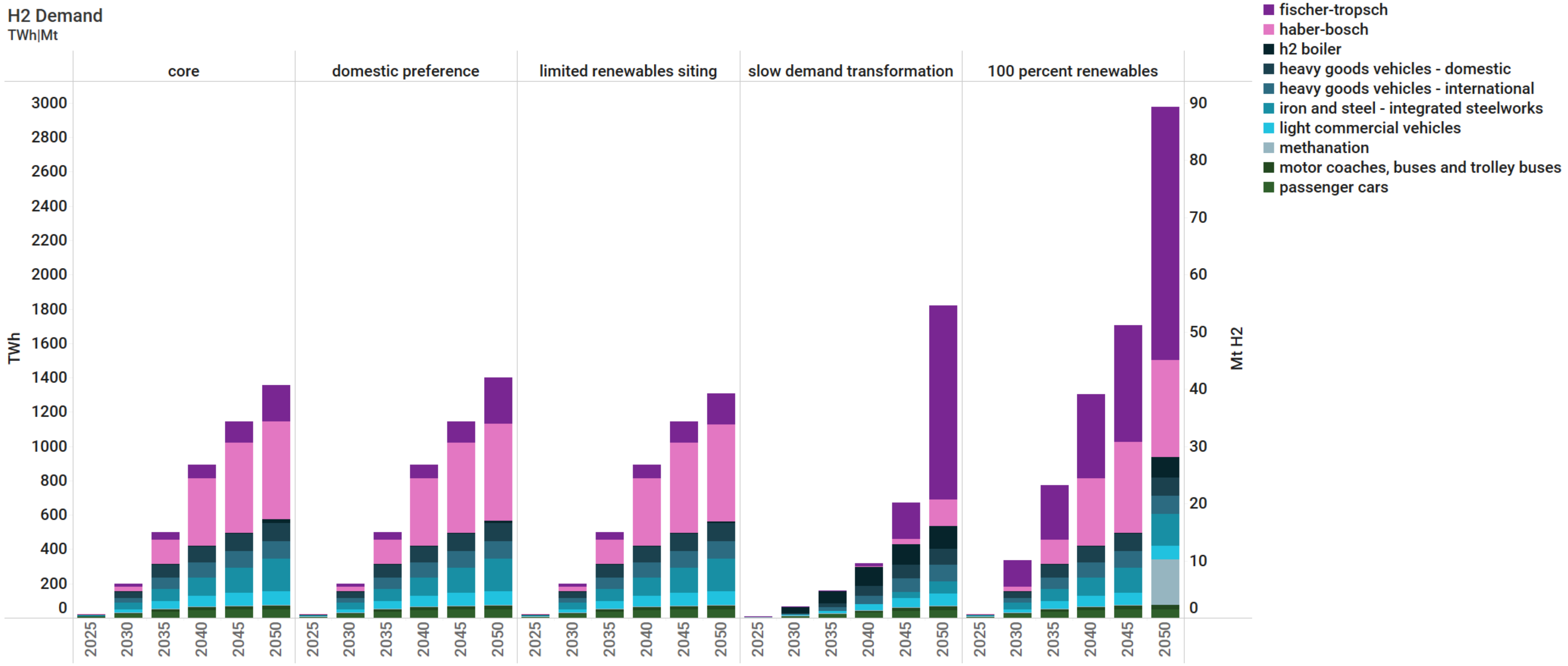
All scenarios deploy significant hydrogen production to meet zero-carbon fuel demand in applications that cannot easily be electrified.

- Hydrogen is particularly important in these scenarios because of the limited availability of biomass in the EU
- Clean hydrogen supply comes from biofuels with carbon capture and/or low- or high-temperature electrolysis
- High-temperature electrolysis is more efficient than low-temperature, meaning it requires less renewable electricity as an input—an important consideration given likely renewable resource buildout constraints in the EU

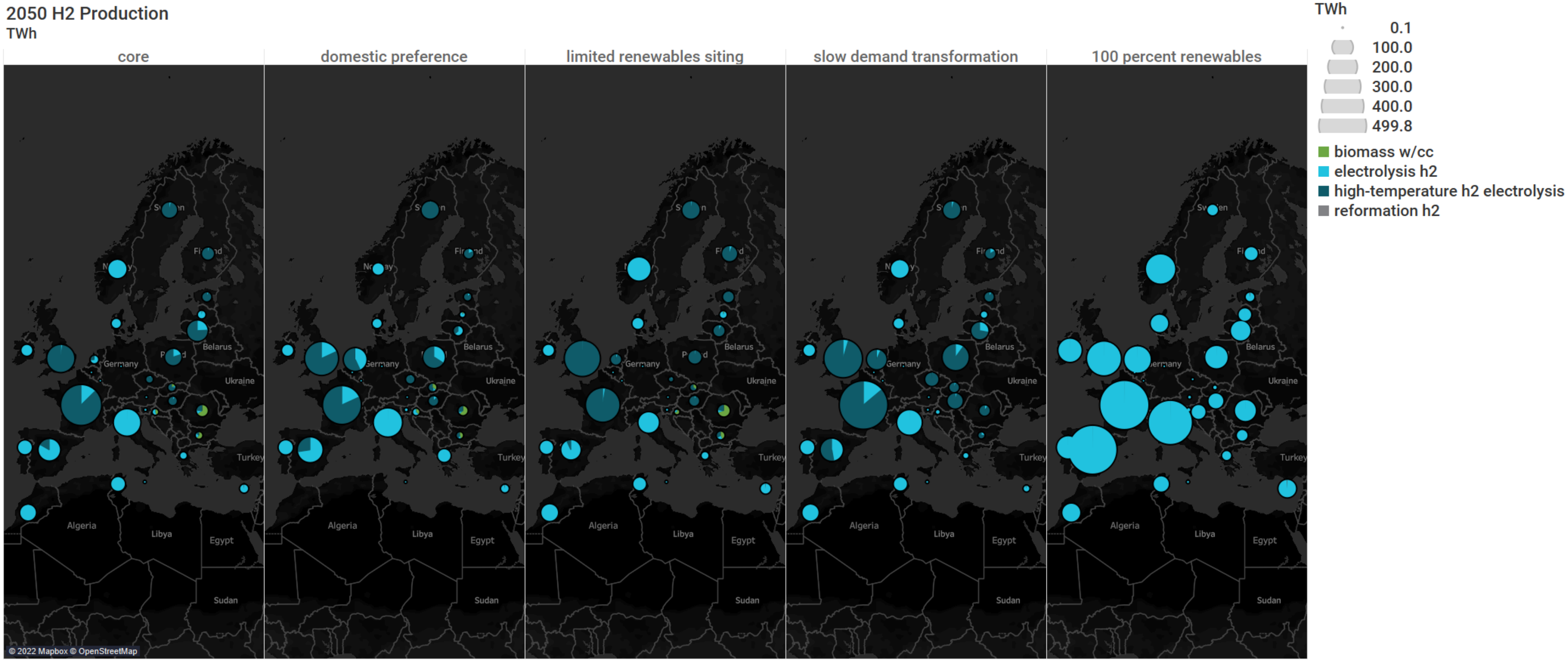


Note: we model high-temperature heat from nuclear facilities but it could also potentially come from exothermal processes like methanation or industrial waste heat, though required temperatures to achieve the modeled efficiency are very high.

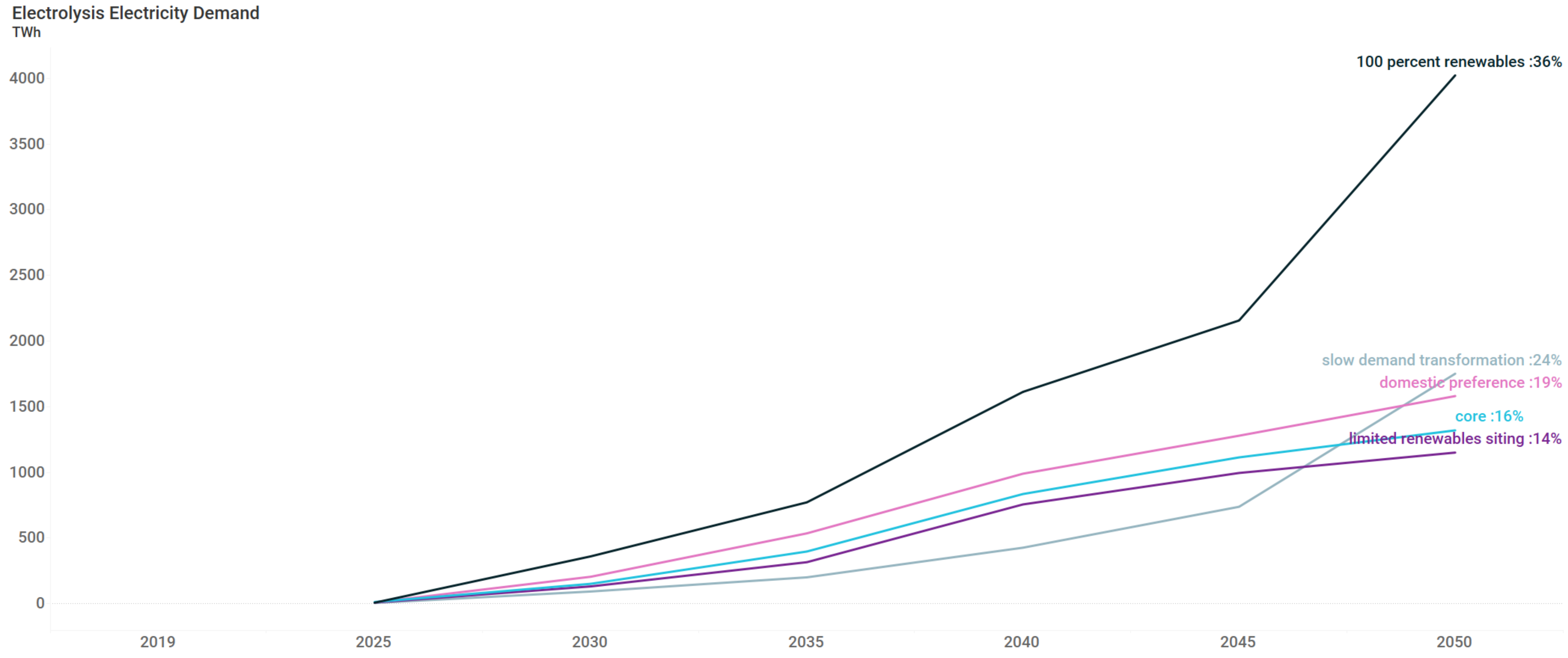
Hydrogen is used directly in applications like heavy-duty trucking and green steel production, but it is also important as a feedstock for other fuel synthesis processes (fischer-tropsch to produce refined liquids, methanation to produce pipeline gas, and haber-bosch to produce ammonia)



Hydrogen production is concentrated in areas with high-quality renewables and/or areas that have access to high-temperature nuclear heat (for high-temperature electrolysis)

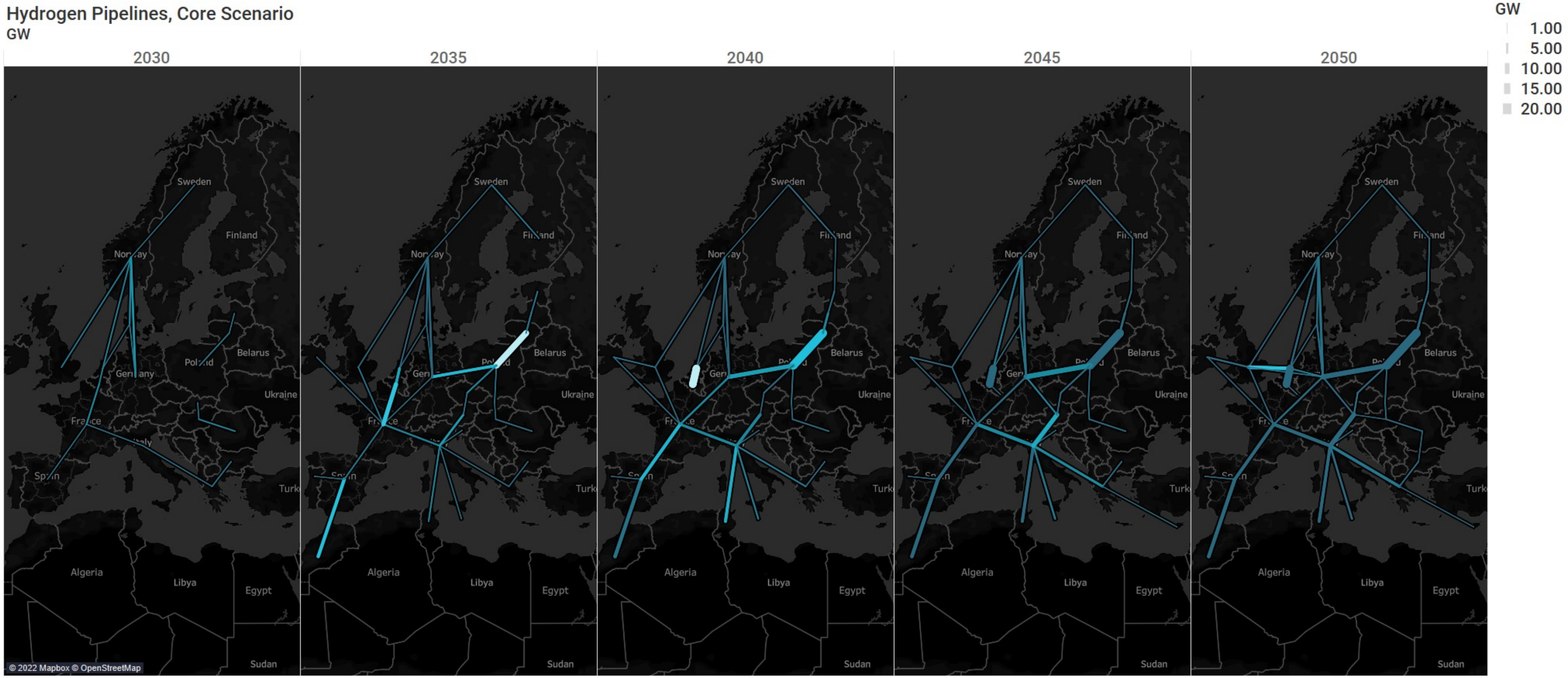


Hydrogen electrolyzers become the largest consumer of electricity in all scenarios, representing 14-24% of electricity demand in all scenarios except **100% Renewables**, where 36% of electricity generated goes to hydrogen production



Hydrogen transport is needed to connect hydrogen demand with low-cost supply resources.

- Because curtailed electricity alone isn't sufficient to produce H2 at high volumes, dedicated inter-regional pipeline and storage infrastructure is developed to manage the supply/demand imbalances across the EU
- H2 is also imported to the EU from North Africa up through the Iberian peninsula and down from the Nordic countries, leveraging the high-quality renewables in those regions

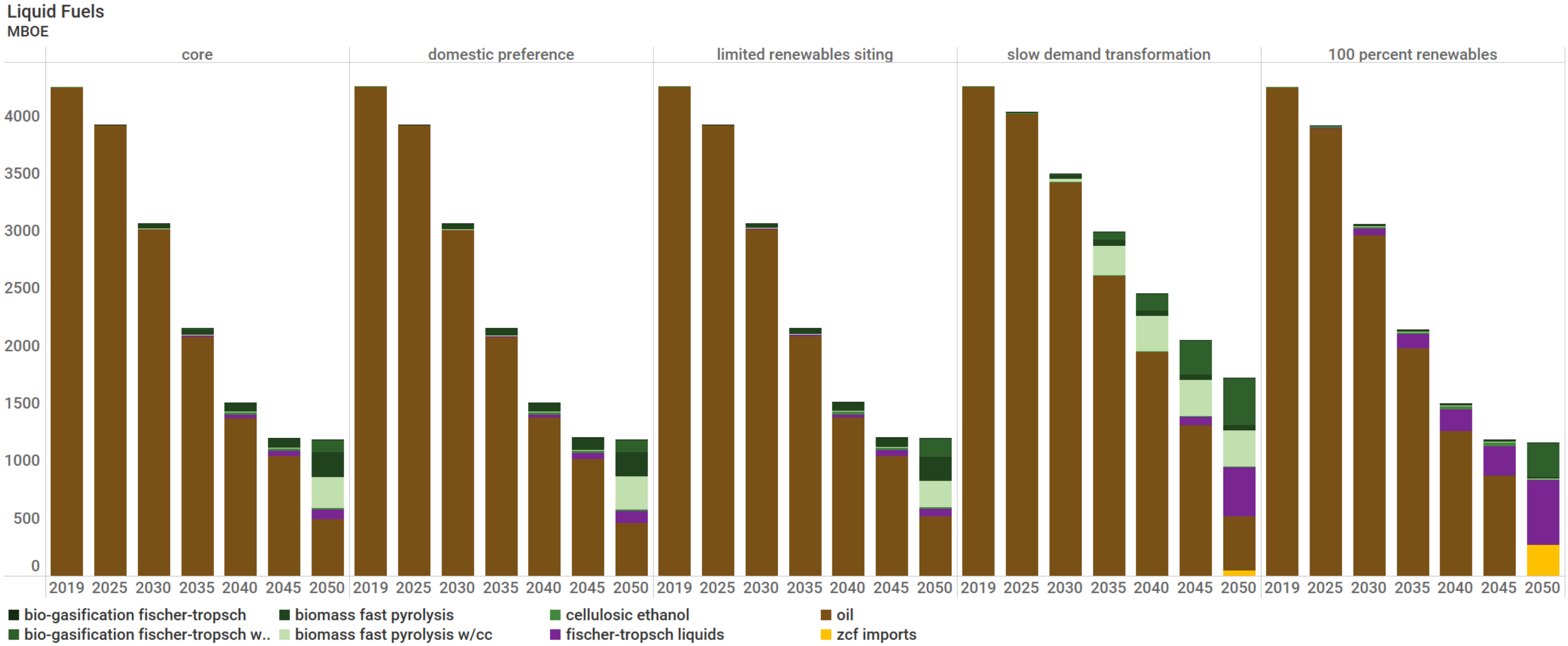


The width of the lines represents total transmission capacity in service between regions in each year. The brightness of the lines represents the scale of new transmission capacity placed in service in that year.

Results: Other Fuels and Carbon Management

Demand-side transformation dramatically reduces overall need for liquid fuels by 2050. Residual demand is met with a mix of fossil, biofuels, and electric fuels.

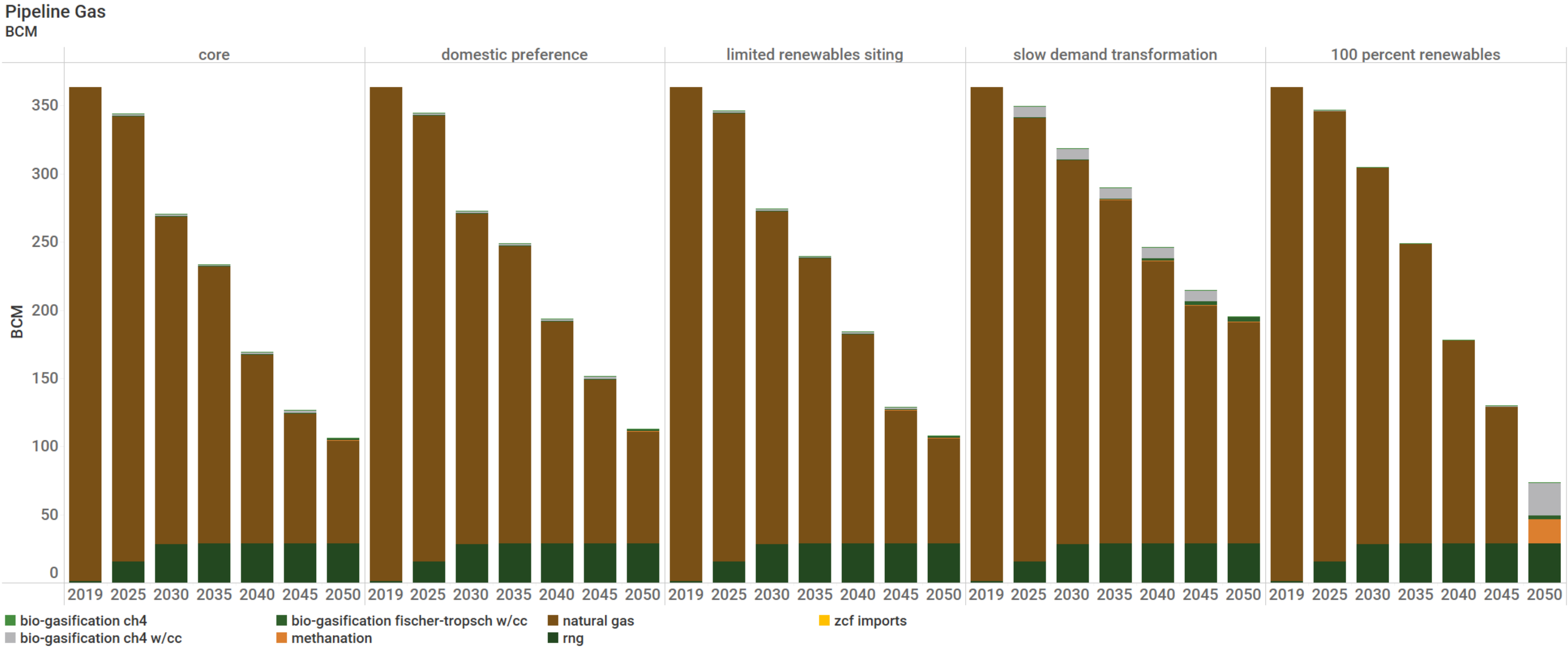
- In less-constrained scenarios, the model preserves a small amount of continued fossil fuel usage, offset by negative emissions from DAC or BECCS[1]
- Aviation and bulk chemicals (with the fuel used as a feedstock) are the only end uses still requiring large volumes of liquid fuels in 2050
- In **100% Renewables** and **Slow Demand Transformation**, the model still imports some zero-carbon fuels at a high price (200€/BOE)



1. This assumption is sensitive to assumed fossil prices, biomass prices, and renewables availability

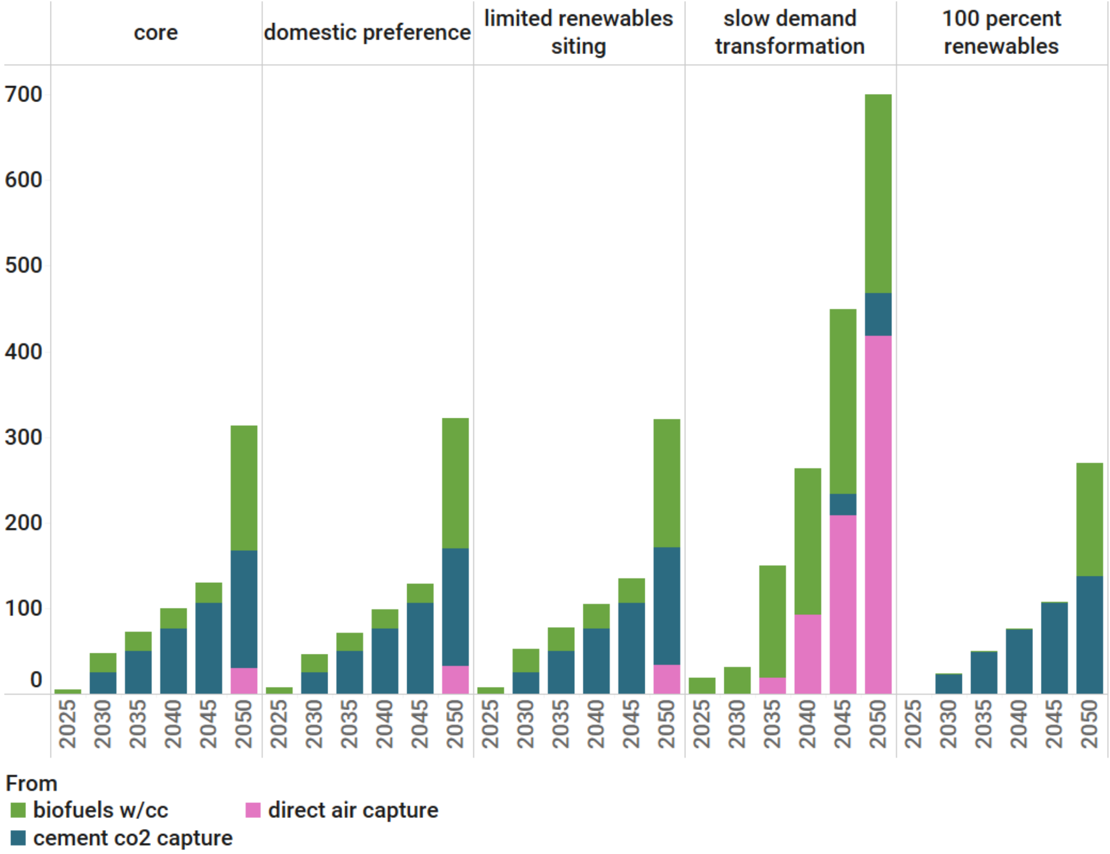
Electrification of heat and decarbonization of electricity reduces gas demand in the short term. Biogas production is also ramped up through 2030 to reduce natural gas usage.

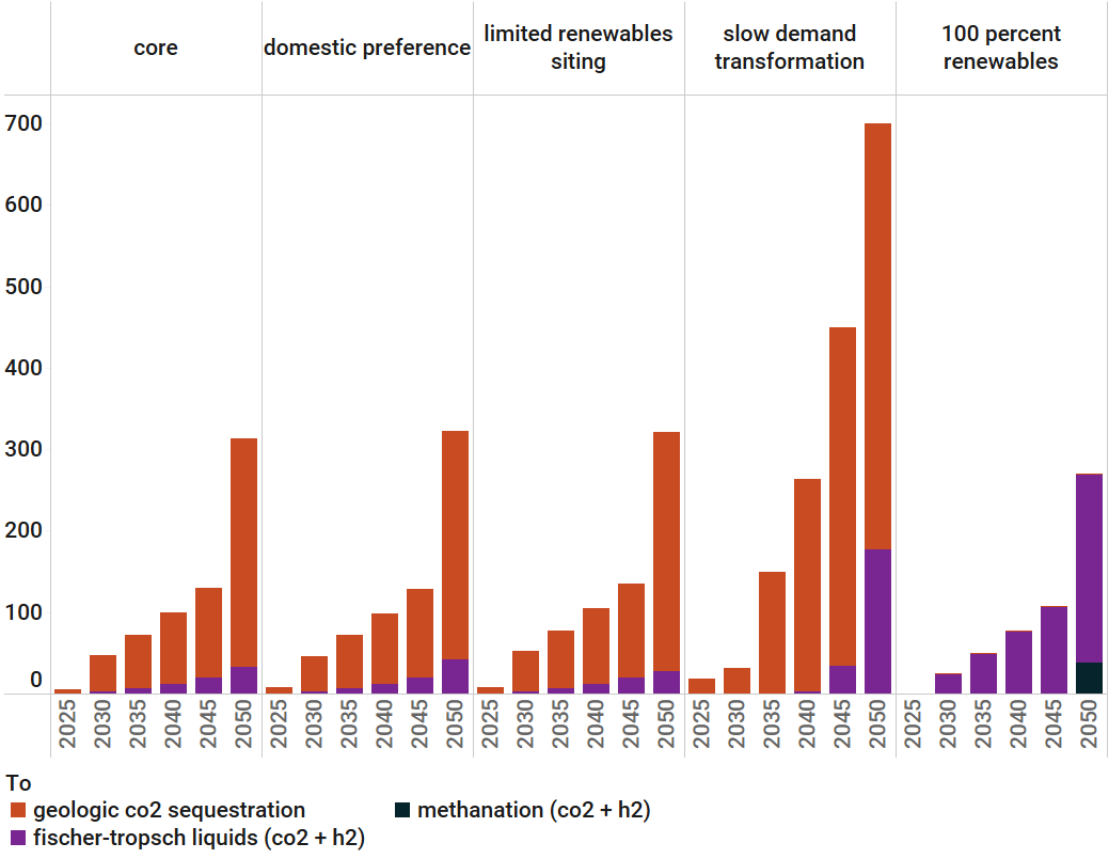
- By 2050, gas pipelines operate at 30% of peak throughput, and a significant portion of pipeline flow is renewable natural gas from biomass.
- Biogas production is often paired with carbon capture to yield negative emissions
- In the **Slow Demand Transformation** scenario, less electrification results in more overall demand for pipeline gas, and less biogas is available due to competition from the liquid fuels sector
- In the **100% Renewables** scenario, imports and power-to-gas (methanation) replace continued use of fossil gas



All scenarios utilize carbon capture with underground sequestration or for fuels synthesis.

- Carbon capture is not deployed with fossil electricity generation in the model. Instead, carbon capture is principally deployed to capture CO2 emissions from cement production and biofuel production.
- The **Slow Demand Transformation** scenario requires significantly greater quantities of capture to offset more residual fossil fuel usage and sees the largest deployment of DAC.
- Where allowed by scenario constraints, captured carbon is mostly geologically sequestered; in the **100% Renewables** scenario, sequestration is not permitted, so the carbon is entirely devoted to fuels synthesis


CO2 Captured
Mt CO2


CO2 Demand
Mt CO2

Conclusions and Next Steps

Project Conclusions

A variety of potential energy mixes could allow the EU to achieve net-zero emissions in 2050

- All of our scenarios require some **thermal capacity** to support system reliability during periods of high load and load renewable energy production—in the form of natural gas, nuclear, or alternatives like hydrogen, e-fuels or biofuels
- All modeled scenarios also require some carbon capture, but not in the power-sector—instead, carbon capture is deployed in biofuels and industrial cement production, and direct air capture is selected in some scenarios

Each of our scenarios requires rapid expansion of renewable electricity generation compared to historical build rates, with electricity generation more than tripling over the next 30 years as electrification of transport, heat, and hydrogen drives new demands for clean electricity

- At this level of electricity demand, many countries are likely to face **resource constraints**
- Renewable energy siting and permitting, and social acceptance of **infrastructure expansion**, are likely to be key to successful decarbonization

Domestic resource endowment and existing energy infrastructure dictate each country's future supply portfolio, and optimal portfolios vary widely across countries

- Large new inter-regional electric transmission and hydrogen pipelines can balance geographic variation in resource availability, indicating that **EU-level coordination** can make decarbonization more cost-effective and feasible
- Domestic energy policies are likely to have significant **cascading effects** on other countries, further suggesting the value of coordination

Next Steps

- Run additional sensitivity analyses on cost and availability of nuclear technology (coming soon)
- Investigate other scenarios of technology cost and availability and higher levels of efficiency and service demand reductions to reduce scale of necessary infrastructure
- Integrate additional EU policy designs into scenarios (member-state emissions allocations, more stringent electricity and industry targets, etc.)
- Explore member-state level policy and planning questions

For More Information

Visit carbonfreeeurope.org to view complementary interactive maps and country-specific interactive Tableau Workbooks detailing:

- Electric capacity
- Transmission capacity
- Hydrogen production, consumption, and pipeline capacity
- Low carbon fuels production, imports and demand
- Carbon capture, utilization and storage
- Energy demand by sector, end-use, and type

Appendix

Modeling Approach
Renewable Resource Constraints GIS Analysis
Nuclear Power Operations and Costs
Demand-Side Scenarios

Modeling Approach

Key Sources

Source	Link	License Link
ENSPRESO	http://data.jrc.ec.europa.eu/collection/id-00138	http://creativecommons.org/licenses/by/4.0/
NREL Annual Technology Baseline 2021	https://atb.nrel.gov/electricity/2021/data	
IRENA Renewable Capacity Statistics	https://www.irena.org/publications/2021/March/Renewable-Capacity-Statistics-2021	
IRENA Renewable Power Costs in 2020	https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020	
JRC Open Power Plants Database	https://data.europa.eu/data/datasets/9810feeb-f062-49cd-8e76-8d8cfd488a05?locale=en	https://creativecommons.org/licenses/by/4.0/legalcode
Mantzos, Leonidas; Wiesenthal, Tobias; Neuwahl, Frederik; Rózsai, Máté (2019): POTEnCIA Central-2018 scenario. European Commission, Joint Research Centre (JRC) [Dataset] PID	http://data.europa.eu/89h/3182c195-a1fc-46cf-8e7d-44063d9483d8	
GeoCapacity	http://www.geology.cz/geocapacity/project	
GeoElec	http://www.geoelec.eu/	
ENTSOE-E TYNDP	https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2020/FINAL/entso-e_TYNDP2020_IoSN_Main-Report_2108.pdf	

Demand-Side Model (EnergyPATHWAYS) Overview

- Scenario-based, bottom-up energy model (not optimization-based)
- Characterizes rollover of stock over time
- Simulates the change in total energy demand and load shape for every end-use
- Illustration of model inputs and outputs for light-duty vehicles

ENERGY PATHWAYS

Input: Consumer Adoption

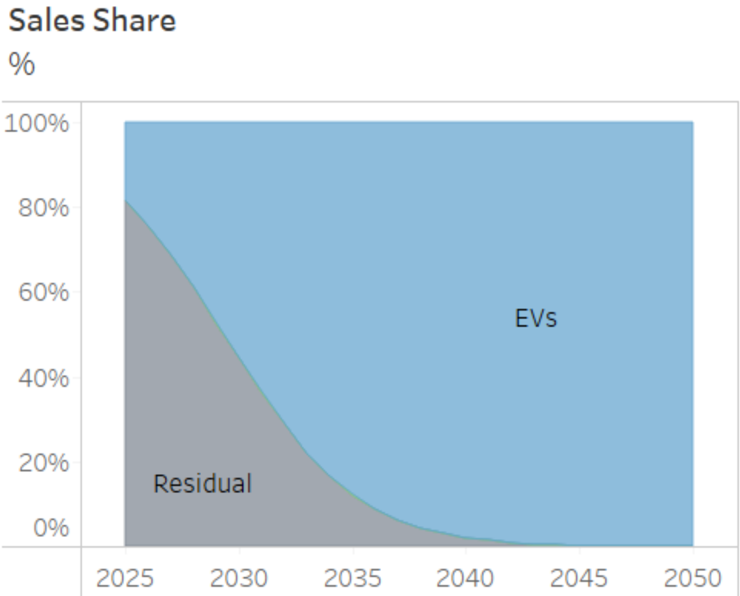
EV sales are 100% of consumer adoption by 2045 and thereafter

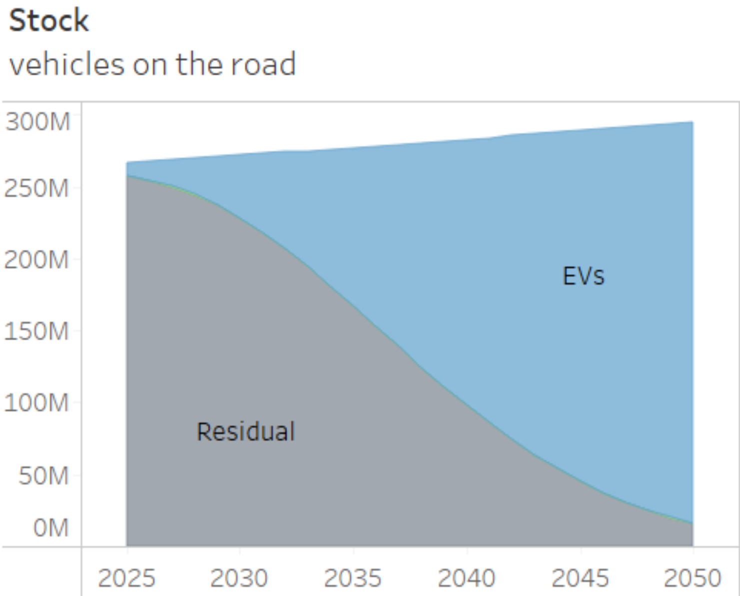
Output: Vehicle Stock

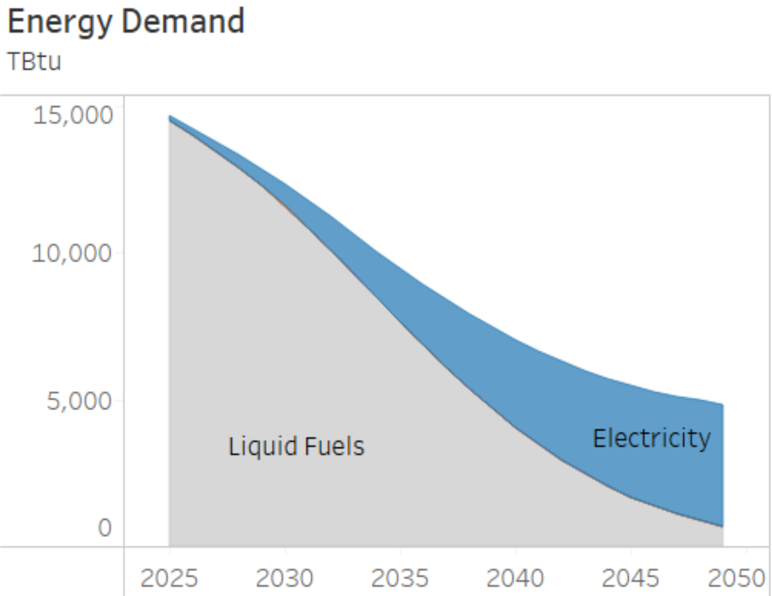
Stocks turn-over as vehicles age and retire

Output: Energy Demand

EV drive-train efficiency results in a drop in final-energy demand


Sales Share
%

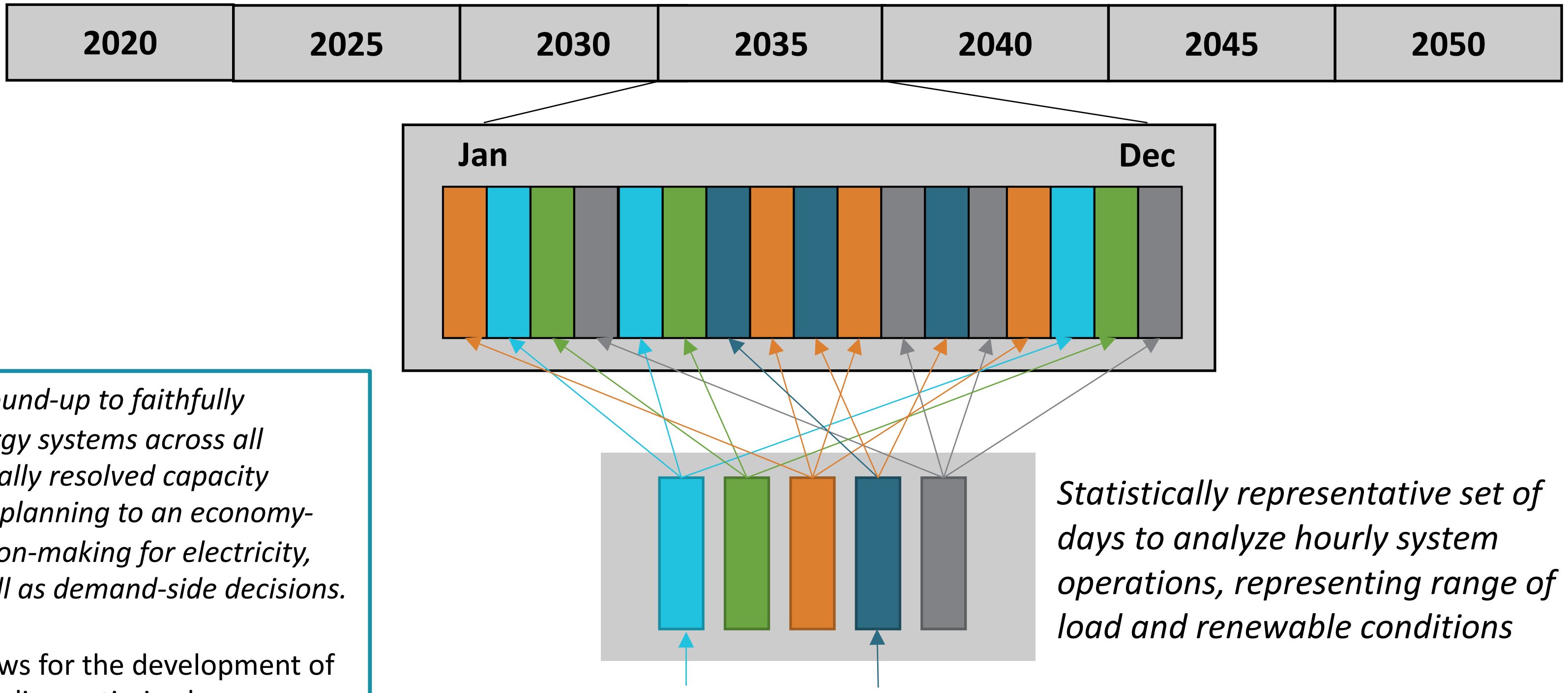

Stock
vehicles on the road


Energy Demand
TBtu

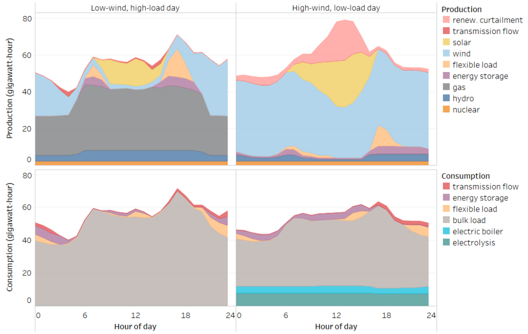
Supply-Side Model (RIO) Overview

RIO is an energy system model designed from the ground-up to faithfully represent the economics of deeply decarbonized energy systems across all sectors. It extends the framework of a highly temporally resolved capacity expansion model past its traditional use in electricity planning to an economy-wide representation. This allows for integrated decision-making for electricity, gas, hydrogen, carbon management, and fuels as well as demand-side decisions.

- Multi-year optimization in a single objective allows for the development of coherent multi-decadal infrastructure plans including optimized resource retirements, repowers, retrofits, as well as deployment of new infrastructure
- Automated day sampling approach allows for a representation of *reliable* and *economic* low-carbon energy systems
- Technology build and usage is decoupled and, allowing for dynamic utilization of all energy producing, transporting, consuming, and converting infrastructure across all timescales



Statistically representative set of days to analyze hourly system operations, representing range of load and renewable conditions

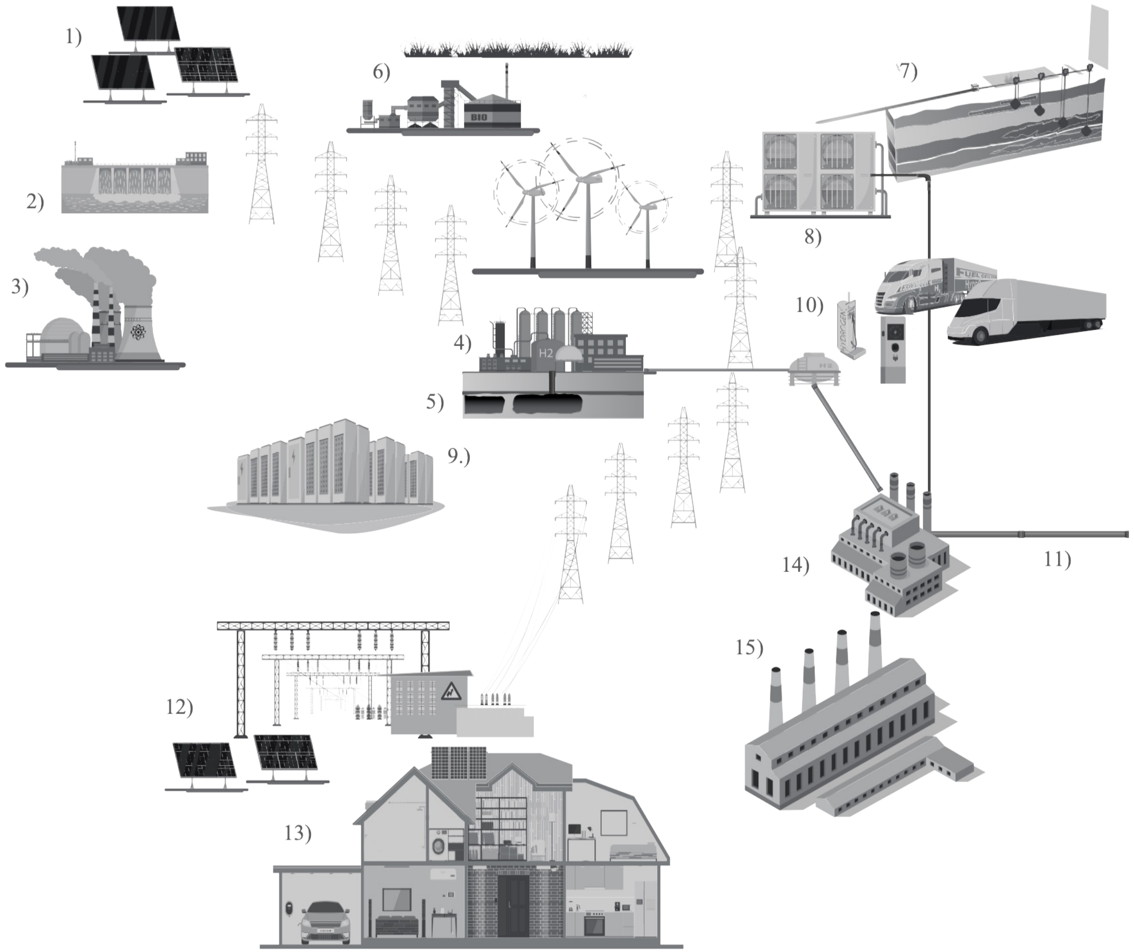


Supply-Side Technologies Modeled

autothermal reforming w/cc	electrolysis h2
bio-gasification ch4	gas power w/cc
bio-gasification ch4 w/cc	gas combined cycle
bio-gasification fischer-tropsch	gas turbine
bio-gasification fischer-tropsch w/cc	h2 boiler
bio-gasification h2 w/cc	h2 storage salt cavern
biomass fast pyrolysis	h2 storage underground pipes
biomass fast pyrolysis w/cc	haber-bosch
blast furnace	li-ion
cellulosic ethanol	methanation
coal power w/cc	petroleum refinery
coke oven	pipeline gas boiler
direct air capture	rooftop solar
steam reforming	steam reforming w/cc
electric boiler	utility-scale solar
offshore wind	onshore wind
advanced nuclear reactor	advanced nuclear – STG - new
high-temperature SOEC	advanced nuclear – STG – retrofit
thermal storage	geothermal
advanced nuclear – direct air capture	

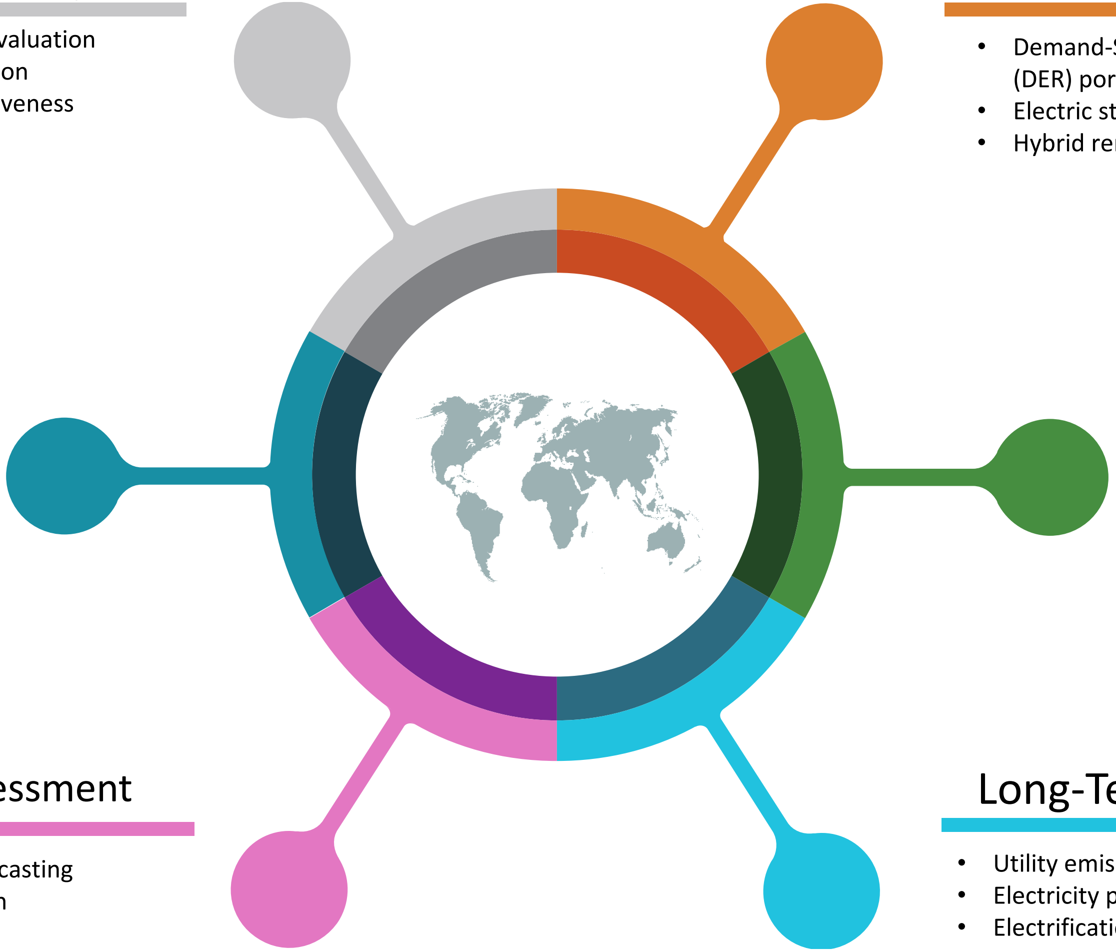
Supply-Side Energy Resource Categories

The supply-side model (RIO) includes 15 resource categories as potential supply for the analysis



	Resource Categories	Examples
1.	Utility-Scale Renewables	Solar PV, Onshore Wind, Offshore Wind, Geothermal,
2.	Dispatchable Hydroelectric	Reservoir hydro, On-Stream Pumped Hydro
3.	Thermal Power Plants	Gas CT, Gas CCGT, Coal, Coal w/CC, Gas w/;CC, Gas w/CC (Allam), SMR, Gen IV nuclear, Biomass, Biomass w/CC, Biomass w/CC (Allam), Gas and Coal CC retrofits
4.	Hydrogen Production	Electrolysis, BECCS H2, SMR, SMR w/CC, High-Temp Electrolysis, ATR w/CC
5.	Hydrogen Storage	Aboveground tanks, underground pipes, salt cavern storage
6.	Biomass/Biomass Conversion	Biomass supply curves including existing woody and waste resources, new woody/herbaceous/waste resources, corn ethanol land displacement, anaerobic digestion feedstocks (LFG, water resource recovery facilities, food waste, animal manure). Conversion technologies including Fischer-Tropsch, pyrolysis, BECCS H2, cellulosic ethanol, corn ethanol, and biochar.
7.	Geologic Sequestration	EOR, onshore saline, offshore saline
8.	Direct Air Capture	DAC for synthetic hydrocarbon production (e-fuels), DAC for geologic sequestration
9.	Electricity Storage	Li-Ion, Flow batteries, long duration energy storage (LDES), pumped hydro, thermal storage
10.	Zero Emission Vehicles	Light-duty, medium-duty, heavy-duty, and bus vehicle types
11.	Pipelines	Ammonia, hydrogen, CO2
12.	Electric T&D Infrastructure	Distribution upgrades, generator interties, existing corridor upgrades, new AC and DC corridors
13.	Distributed Energy Resources	Flexible end-use loads (EVS, water heating, space heating, air conditioning, appliance loads)
14.	Zero-Carbon Fuel Synthesis	Ammonia, synthetic hydrocarbons (refined and unrefined), methanol
15.	Industrial Decarbonization solutions	Industrial carbon capture, solar thermal heat, dual-fuel boilers, hydrogen

RIO Model Applications



Technology Development

- Technology feature evaluation
- Innovation prioritization
- Technology competitiveness assessments

Asset Valuation

- Demand-Side Energy Resource (DER) portfolio
- Electric storage facilities
- Hybrid renewable-storage systems

Target Setting

- Near and long-term Federal emissions targets
- State emissions targets
- Vehicle and building electrification targets

Policy Development

- Clean electricity policy design including target share, resource qualification, and incentive structures
- Zero-emission vehicle policy design
- Clean fuels policy design

Market Assessment

- Price and value forecasting
- Market prioritization
- Market-sizing

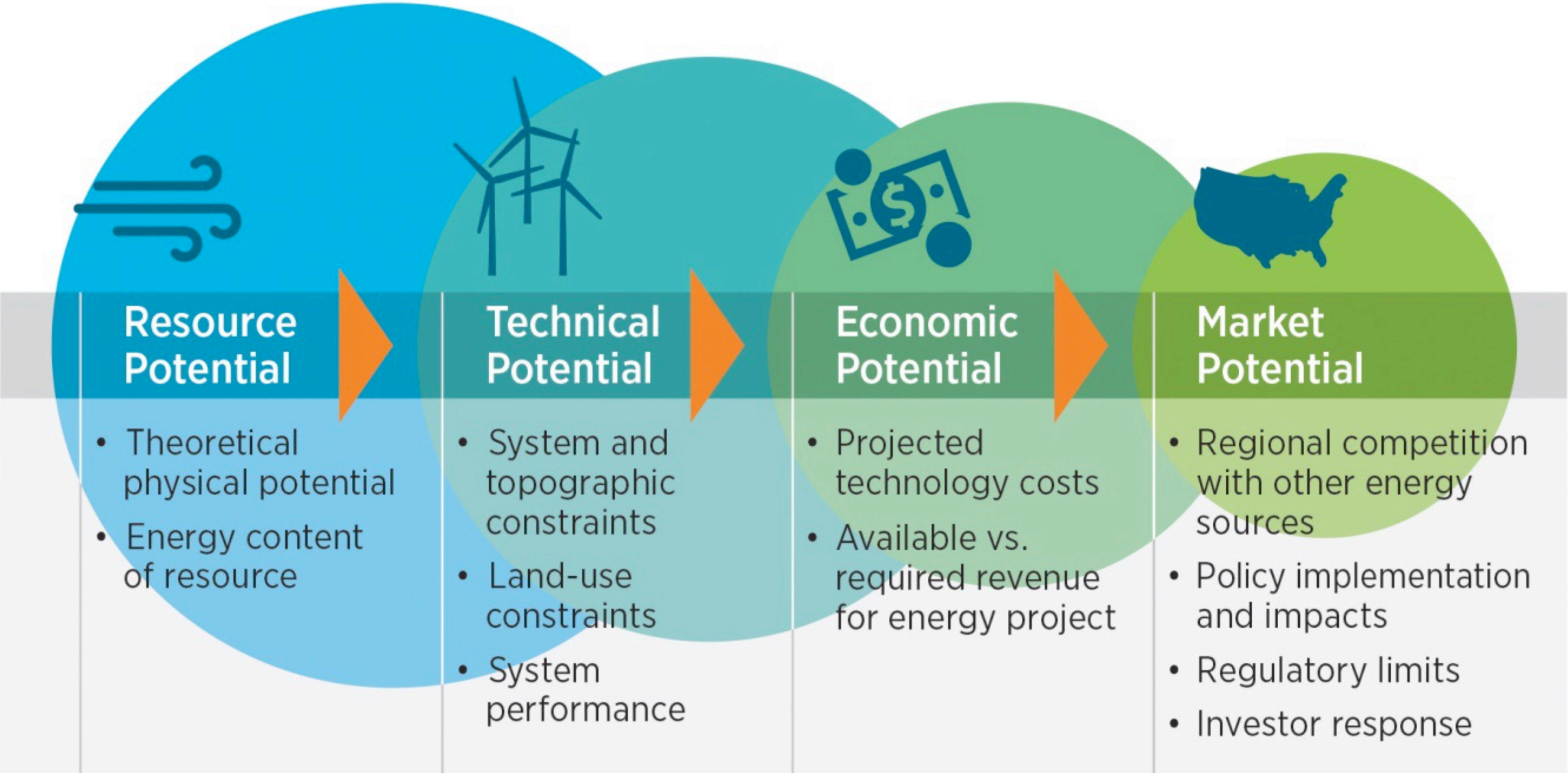
Long-Term Planning

- Utility emissions goals
- Electricity portfolio development
- Electrification planning

Renewable Resource Constraints GIS Analysis

Renewable resource supply curves are derived from an overlay of GIS analysis with economic analysis in the RIO model.

- Montara Mountain Energy conducted the GIS analysis of constraints on the resource and technical potential for onshore wind, offshore wind, and solar resources
- Evolved Energy Research then combined the GIS analysis with supply-side (RIO) modeling assumptions of economic and market potential (projected technology costs and competition with other energy sources) to estimate renewable energy deployment potential



Resource Potential
- Theoretical physical potential
- Energy content of resource

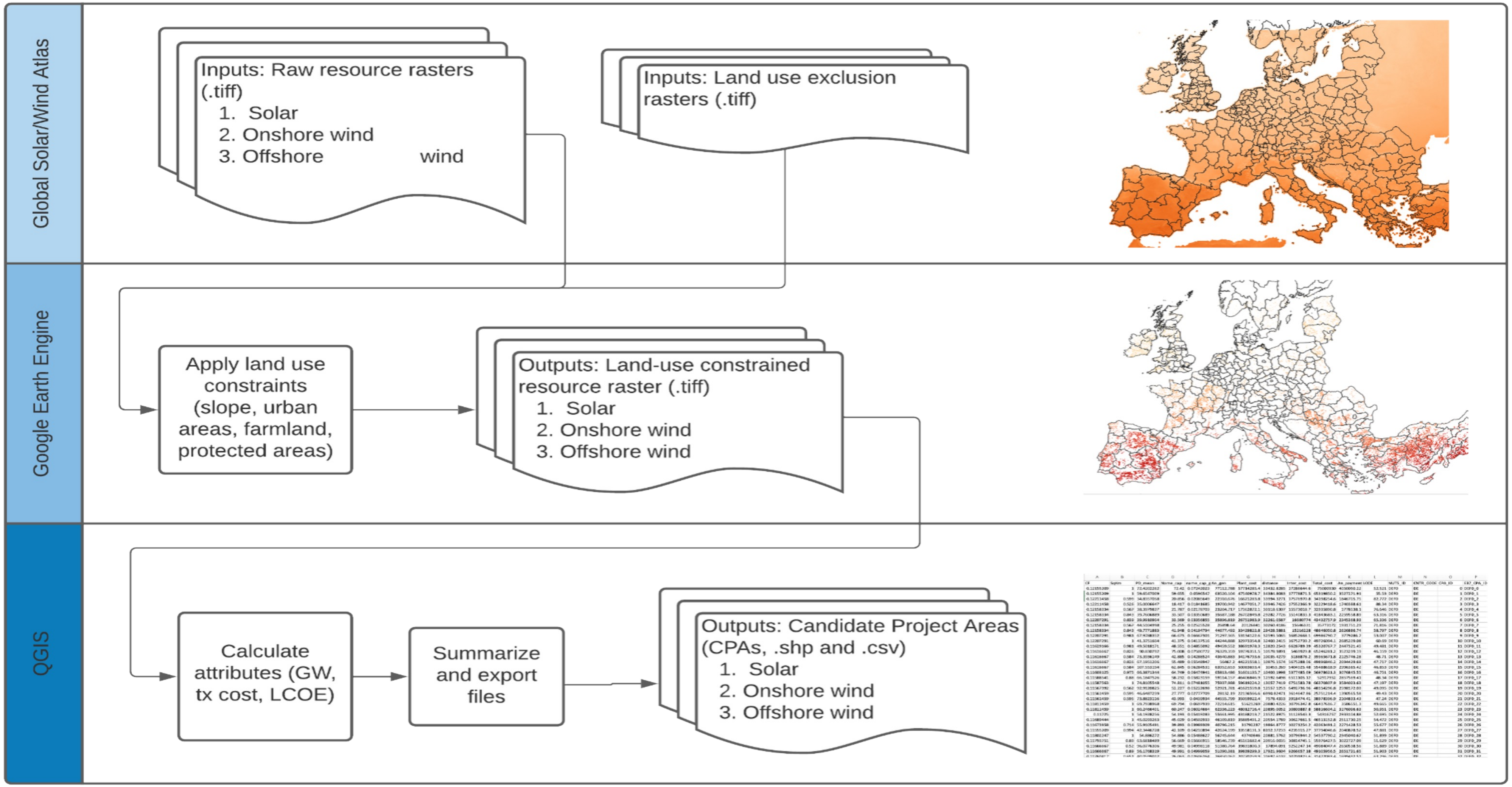
Technical Potential
- System and topographic constraints
- Land-use constraints
- System performance

Economic Potential
- Projected technology costs
- Available vs. required revenue for energy project

Market Potential
- Regional competition with other energy sources
- Policy implementation and impacts
- Regulatory limits
- Investor response

[National Renewable Energy Laboratory: Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results]

Renewable Resource Constraints: GIS Methodology



Global Solar/Wind Atlas

Inputs: Raw resource rasters (.tiff)
1. Solar
2. Onshore wind
3. Offshore wind

Inputs: Land use exclusion rasters (.tiff)

Google Earth Engine

Apply land use constraints (slope, urban areas, farmland, protected areas)

Outputs: Land-use constrained resource raster (.tiff)
1. Solar
2. Onshore wind
3. Offshore wind

QGIS

Calculate attributes (GW, tx cost, LCOE)

Summarize and export files

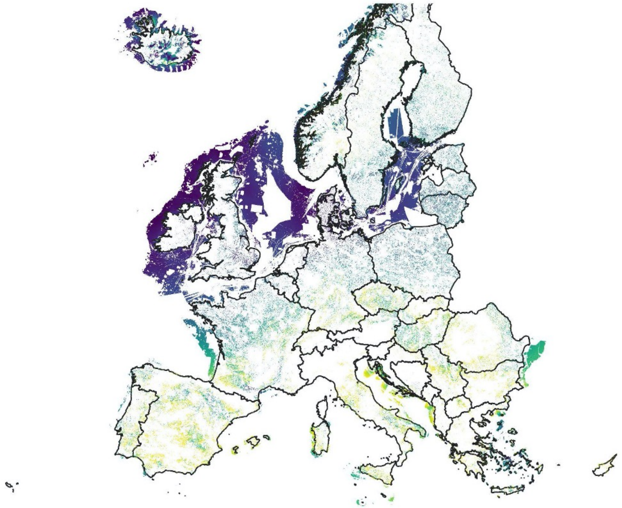
Outputs: Candidate Project Areas (CPAs, .shp and .csv)
1. Solar
2. Onshore wind
3. Offshore wind

Renewable Resource Candidate Project Areas

Economically Viable Resource Potential

Attribute:

- Capacity Factor



GIS Project Model

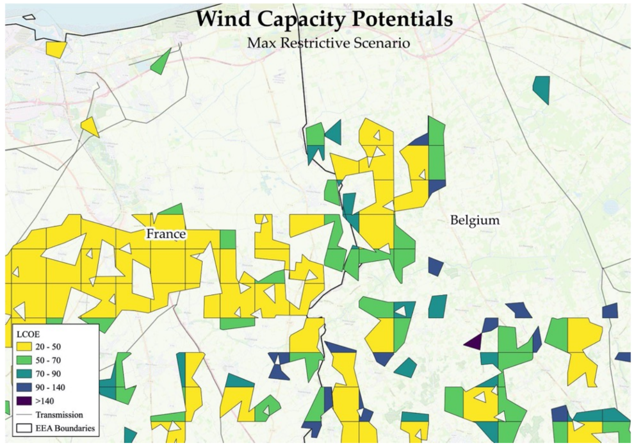
Parameters from Literature:

- Power density
- Project size
- Capital expenditure
- Interconnection cost
- Cost of capital

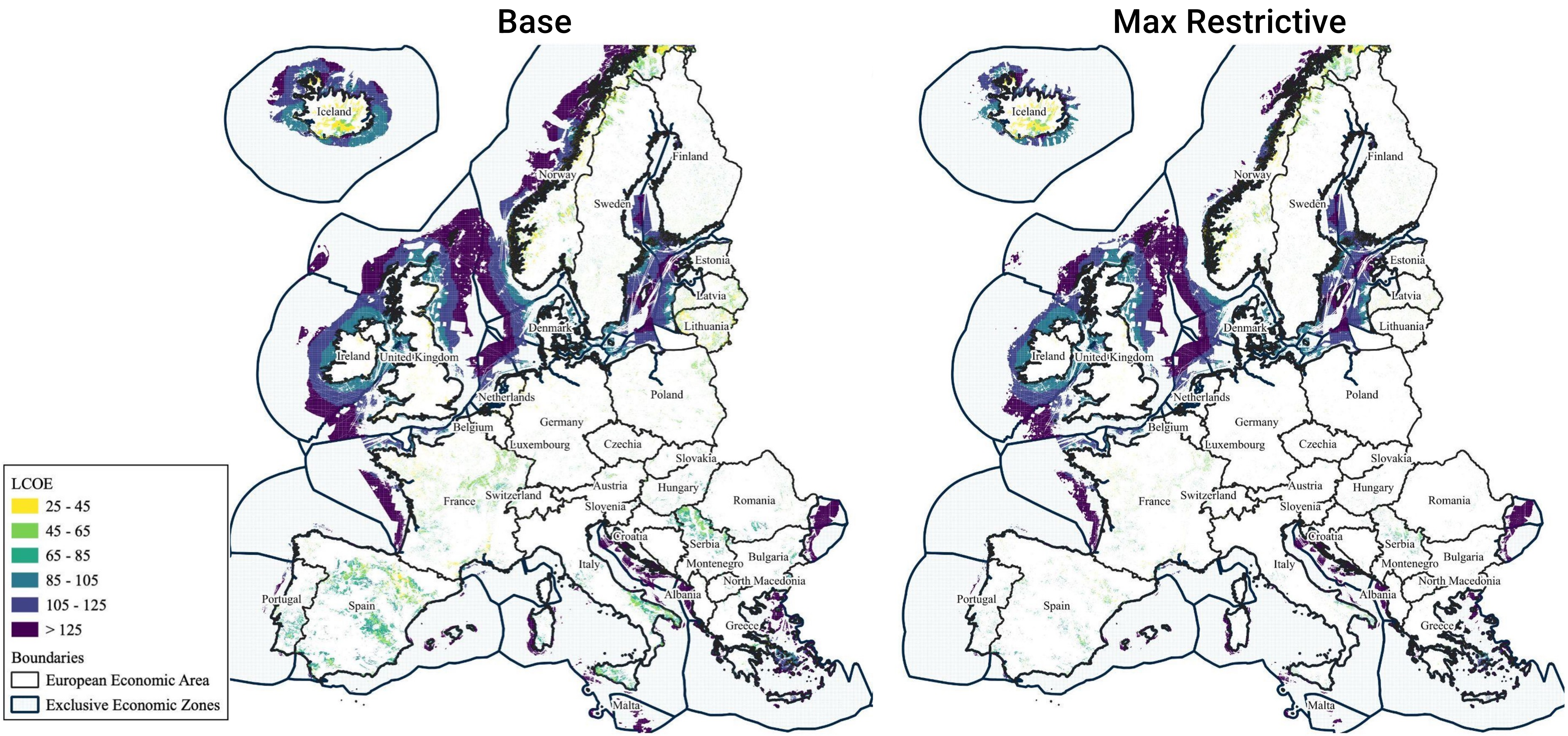
Candidate Project Areas

Attributes:

- Size
- Levelized cost of energy
- Capacity and annual generation (GW and GWh)



Renewable Resource Candidate Project Areas: Wind



Base

Max Restrictive

Renewable Resource Constraint Examples: Exclusions for Supply Curves

	Techno-Economic	Environmental	Existing Energy Infrastructure
Fixed Parameters	• Military • Urban • Water bodies, rivers, & flood zones • Infrastructure	• Nationally protected • Protection of habitat and biodiversity • Sensitive ecosystems	• Solar • Wind • Offshore wind
Input Variables	**• Farmland soil productivity** **• Ship density** **• Technical limitations (slope, wind capacity factor, sea depth, sea ice)** **• Population density**	**• Farmland with high biodiversity** **• Level of human modification (untouched lands)** **• Sequestered carbon stocks** **• Intact forest**	

Land-Use Scenario Attributes

Scenario 1: Base Restrictive Across All				
Exclusion Variable Names	**Model Variables**	**Solar**	**Onshore Wind**	**Offshore Wind**
All farmland	Binary (0/1)	0	0	NA
Highly productive farmland	Percentile: Top x%	95	85	NA
Farmland with high natural/biodiversity value	Binary (0/1)	1	1	NA
Land with high population density	Threshold: Ppl per square km	65	45	NA
Land with technologically unsuitable slope	Threshold: Degrees	8	15	NA
Forested land that remains intact	Binary (0/1)	1	1	NA
Low levels of human modification	Percentile: Bottom x%	30	20	NA
Irrecoverable Carbon	Percentile: Top x%	100	100	NA
Low output for onshore wind	Threshold: Capacity Factor	NA	20	NA
Low output for offshore wind	Threshold: Capacity Factor	NA	NA	26
Marine areas with high ship density	Percentile: Top x%	NA	NA	50
Trawler Fishing Vessel Density	Percentile: Top x%	NA	NA	50
Sea Depth	Threshold: Depth (meters)	NA	NA	300
Sea Ice	Threshold: Avg days/year with ice cover	NA	NA	50
Distance from shore (min)	Threshold: Distance from shore (meters)	NA	NA	22,000

Scenario 2: Max Restrictive Across All				
Exclusion Variable Names	**Model Variables**	**Solar**	**Onshore Wind**	**Offshore Wind**
All farmland	Binary (0/1)	1	1	NA
Highly productive farmland	Percentile: Top x%	NA	NA	NA
Farmland with high natural/biodiversity value	Binary (0/1)	1	1	NA
Land with high population density	Threshold: Ppl per square km	50	25	NA
Land with technologically unsuitable slope	Threshold: Degrees	8	15	NA
Forested land that remains intact	Binary (0/1)	1	1	NA
Low levels of human modification	Percentile: Bottom x%	75	75	NA
Irrecoverable Carbon	Percentile: Top x%	100	100	NA
Low output for onshore wind	Threshold: Capacity Factor	NA	20	NA
Low output for offshore wind	Threshold: Capacity Factor	NA	NA	26
Marine areas with high ship density	Percentile: Top x%	NA	NA	75
Trawler Fishing Vessel Density	Percentile: Top x%	NA	NA	75
Sea Depth	Threshold: Depth (meters)	NA	NA	150
Sea Ice	Threshold: Avg days/year with ice cover	NA	NA	50
Distance from shore (min)	Threshold: Distance from shore (meters)	NA	NA	22,000

Nuclear Power Operations and Costs

Nuclear Power Costs: Example Advanced Nuclear Application Costs

- Tables below show the levelized cost of different energy products produced with advanced reactor heat (running at maximum capacity factors)
- The final economics of these products ends up being dynamically calculated in the model, with different technology components added as individual decisions and operated separately. When we include thermal energy storage, we're able to optimize deployment and operations to maximize the value of the energy during different time periods (next slide)

Heat - €/MWh_{th}		
Thermal Reactor Capital + Fixed OM	€	12.00
Fuel Costs	€	6.14
Variable O&M	€	3.23
LCOH	**€**	**21.37**

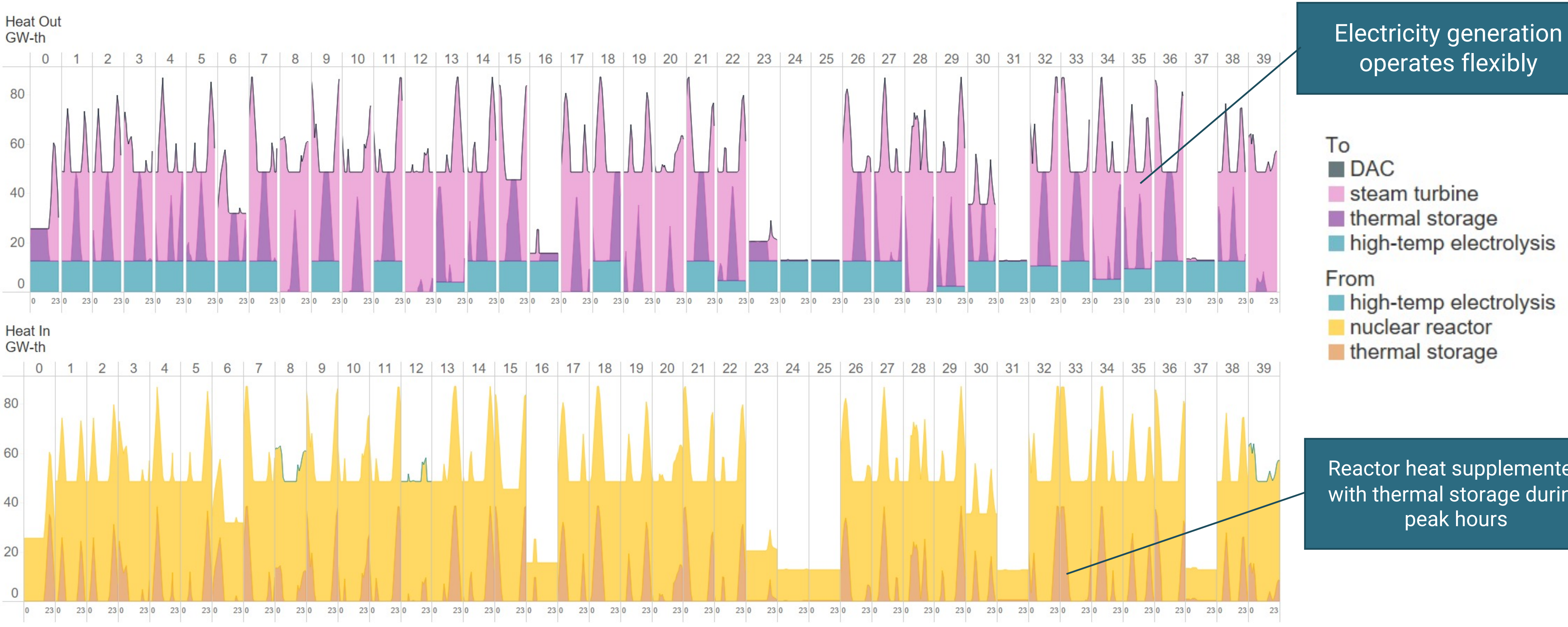
Electricity - €/ MWh_e		
Heat (LCOH/Efficiency)	€	49.54
Steam Turbine Generator + Fixed OM	€	7.20
Variable O&M	€	3.48
LCOE	**€**	**60.22**

Hydrogen - €/ tonne		
Heat (LCOH/Capture Efficiency)	€	0.21
Electricity	€	1.90
SOEC Capital + Fixed OM	€	0.48
LCOH	**€**	**2.59**

CO2 - €/Tonne CO_2		
Heat (LCOH/Capture Efficiency)	€	35.07
Electricity	€	5.29
DAC Capital + Fixed OM	€	42.85
LCOC	**€**	**83.22**

Nuclear Power Costs: Advanced Nuclear Operations

Nuclear power can generate electricity during off-peak hours for renewables and at other times provide energy for other sources (DAC, thermal storage, and high temp electrolysis), see top chart



Electricity generation operates flexibly

Reactor heat supplemented with thermal storage during peak hours

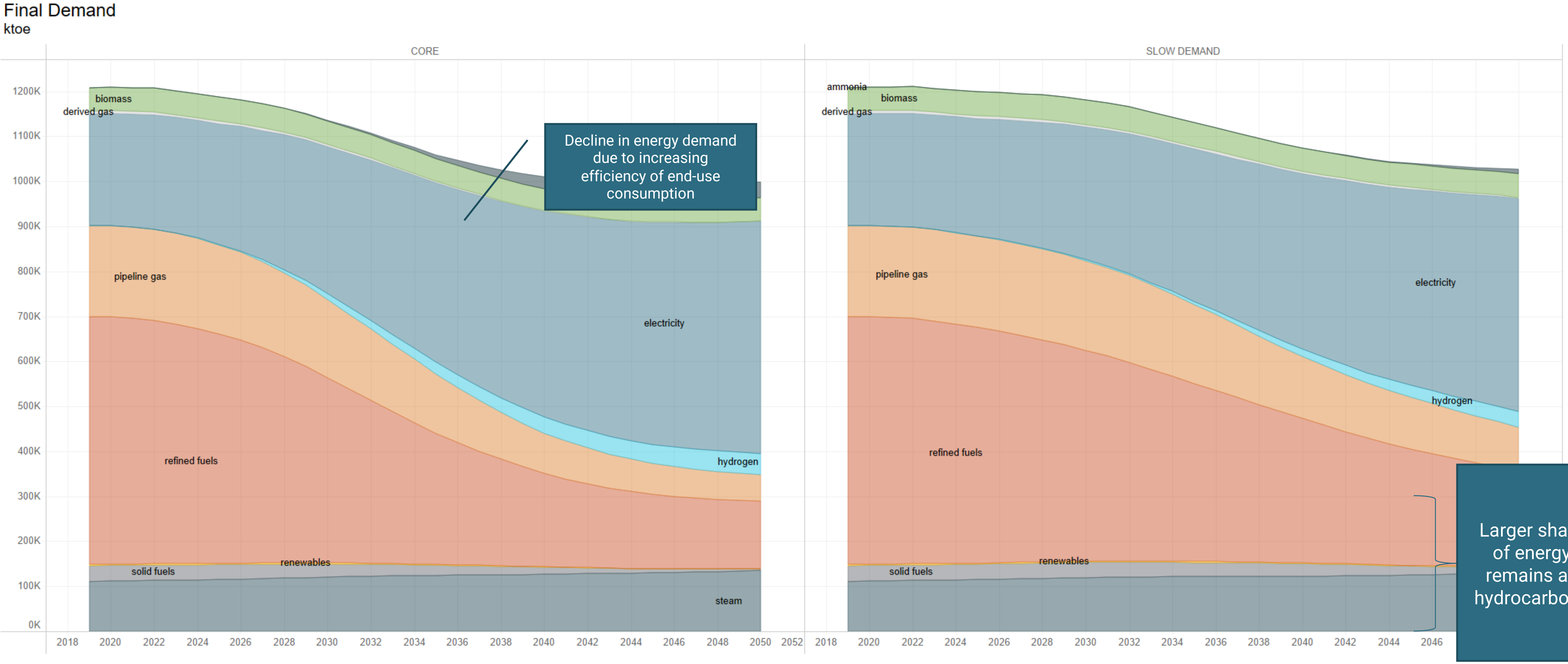
Demand-Side Scenarios

Demand-Side Scenarios Summary

- Final energy demand represents energy consumed to provide the services of modern life (heating, transport, etc.) We modeled two demand-side scenarios – Core and Slow Demand Transformation – to demonstrate the impact on the energy supply system of failing to achieve transformation of the way in which Europe consumes energy.
- Certain forms of energy are easier to directly decarbonize – electricity, hydrogen, ammonia, etc. – than others like refined fuels and so the demand-side equipment is rolled over to these other forms of energy. Slow Demand Transformation delays this transition for twenty years (other than maintaining the target of no internal combustion engine sales in passenger vehicles by 2035). Key areas of delay are in space heating, water heating, and the switching of industrial energy to electricity or hydrogen.
- Both cases show an overall decline in final energy (despite increasing demand for energy services) due to the efficiency benefit of new technologies like heat pumps and electric vehicles
- The largest transformation occurs in the buildings and transport sectors, with a smaller share of industrial energy being directly electrifiable

Final Energy Demand

Both scenarios show an overall decline in final energy demand through efficiency and electrification and a transition away from refined liquids and gaseous fuels. SLOW DEMAND is delayed in that transformation, leaving more of these fuel types in 2050.

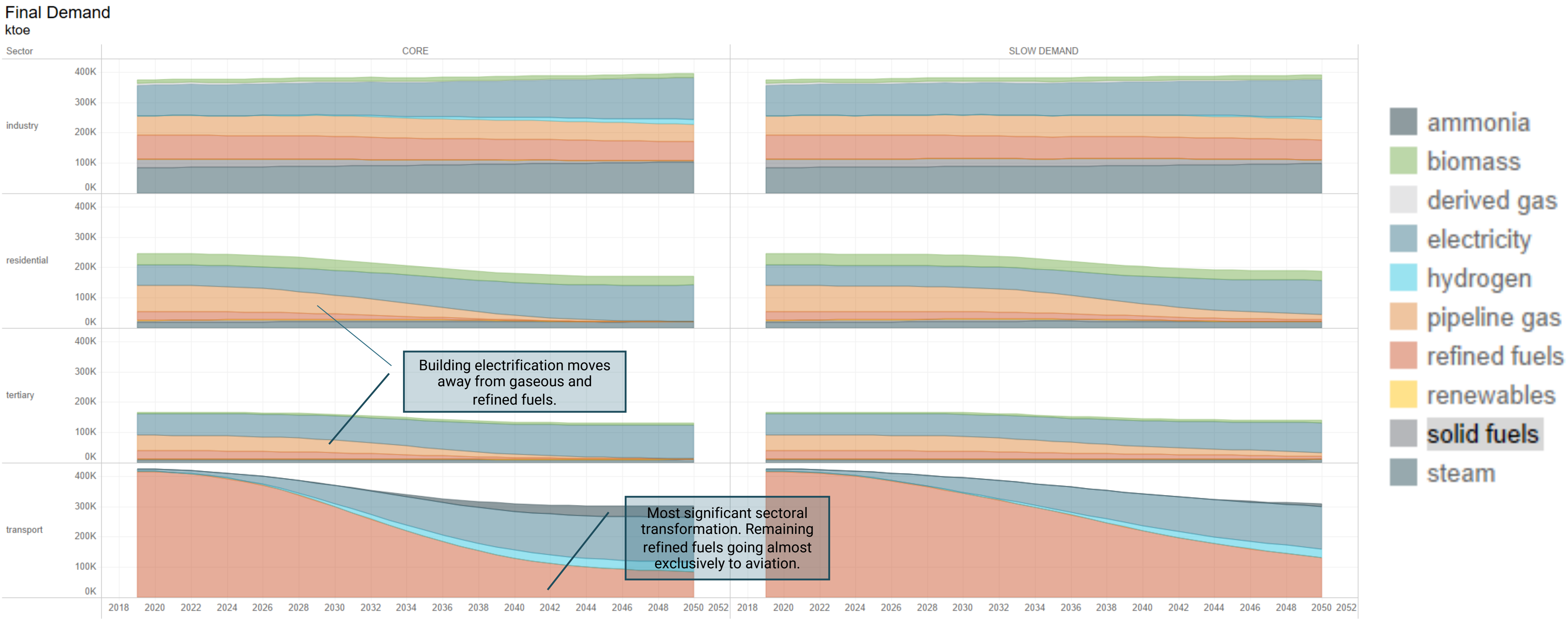


Decline in energy demand due to increasing efficiency of end-use consumption

Larger share of energy remains as hydrocarbons

Final Energy Demand by Sector

Energy demand changes significantly in all sectors. Industry sees an increase in direct electricity and hydrogen for process heating and other uses; Buildings electrify space heating, water heating, and cooking, resulting in a large decline in fuel demand and an increase in electricity. Transportation moves towards direct electricity or zero-carbon fuels (hydrogen/ammonia).

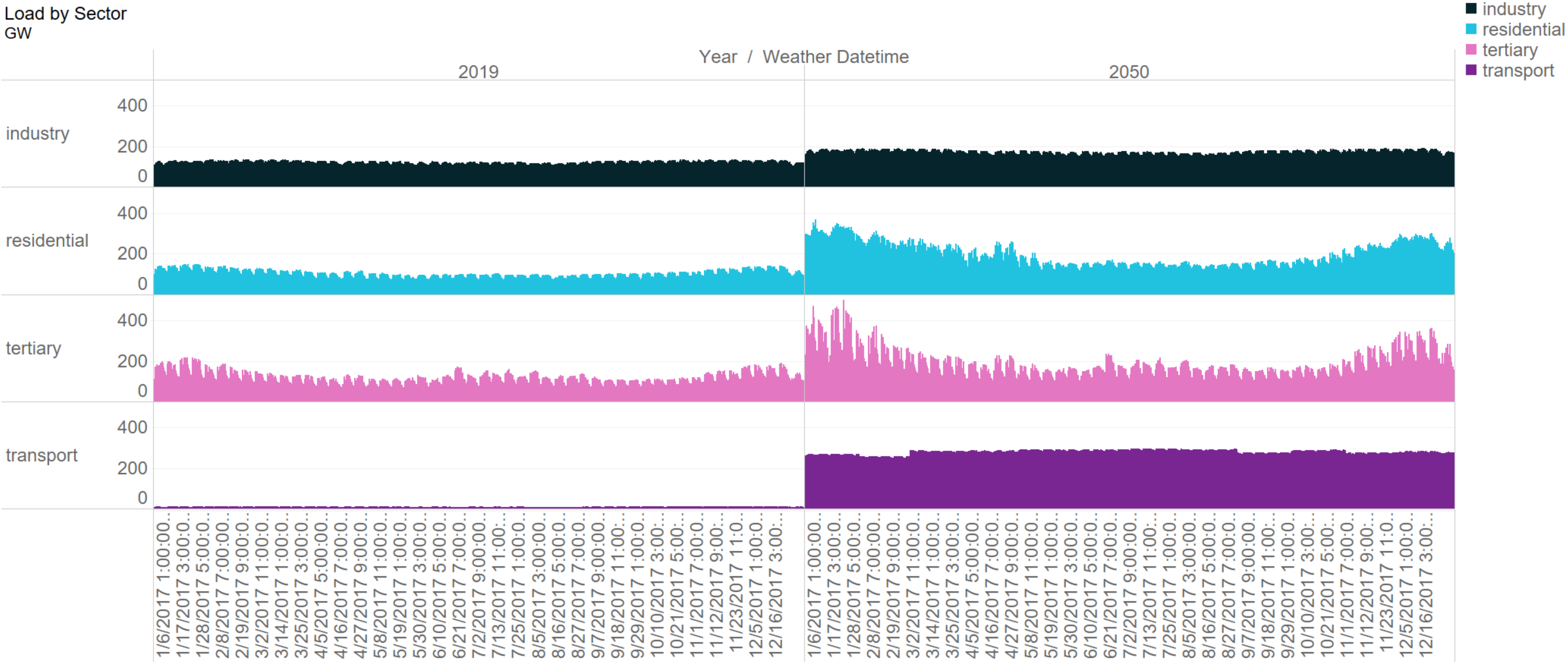


Building electrification moves away from gaseous and refined fuels.

Most significant sectoral transformation. Remaining refined fuels going almost exclusively to aviation.

Electricity Hourly Final Demand – Core Scenario

Increases in electric load vary significantly by sector and end-use. Transportation is the largest area of growth, going from almost no electricity demand in 2019 to a significant share of electricity load by 2050. Building loads increase, specifically in the winter with the addition of heating load.



Electricity Hourly Final Demand – Country-Level

These load transitions play out very differently by country, with colder countries seeing larger increases in their winter peak loads. All of these dynamics become increasingly important for electric sector planning.