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Annual Decarbonization Perspective 2024

Prepared for: Carbon-Free Europe

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Agenda

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Role of the Annual Decarbonization Perspective

What is the purpose of the Annual Decarbonization Perspective?

- To investigate long-term strategies for achieving net zero emissions across Europe by developing deep decarbonization pathways.

What are pathways?

- Detailed technical plans, optimized using the RIO model, which chart the infrastructure shifts, technological advancements, and associated costs required to meet Europe's emissions reduction targets.

Don't we have enough modeling already?

Existing economy-wide European modeling tends to focus on the impact of policy design on the energy system as opposed to the more policy-agnostic techno-economic modeling conducted here. This is an independent perspective on European emissions goals with a focus on representing a broad suite of technologies and potential scenario conditions. Modeling is a practice, not a destination, and the ADP provides the opportunity to continually update our understanding.

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Annual Decarbonization Perspective

Provide an analytical venue for demonstrating the role of a comprehensive suite of technologies.

Produce a catalog of public data that can be leveraged for policy advocacy by NGOs, governments, and the private sector.

Analyze current policy discussions and highlight emerging topics that require attention.

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Research Methodology

About Evolved Energy Research

EVOLVED ENERGY RESEARCH

Energy consulting firm focused on addressing key energy sector challenges posed by energy system transformation

Developers of EnergyPATHWAYS and RIO, two models used to investigate pathways to deep decarbonization

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

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Energy systems modeling: high-level approach

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Energy PATHWAYS model used to develop demand-side cases

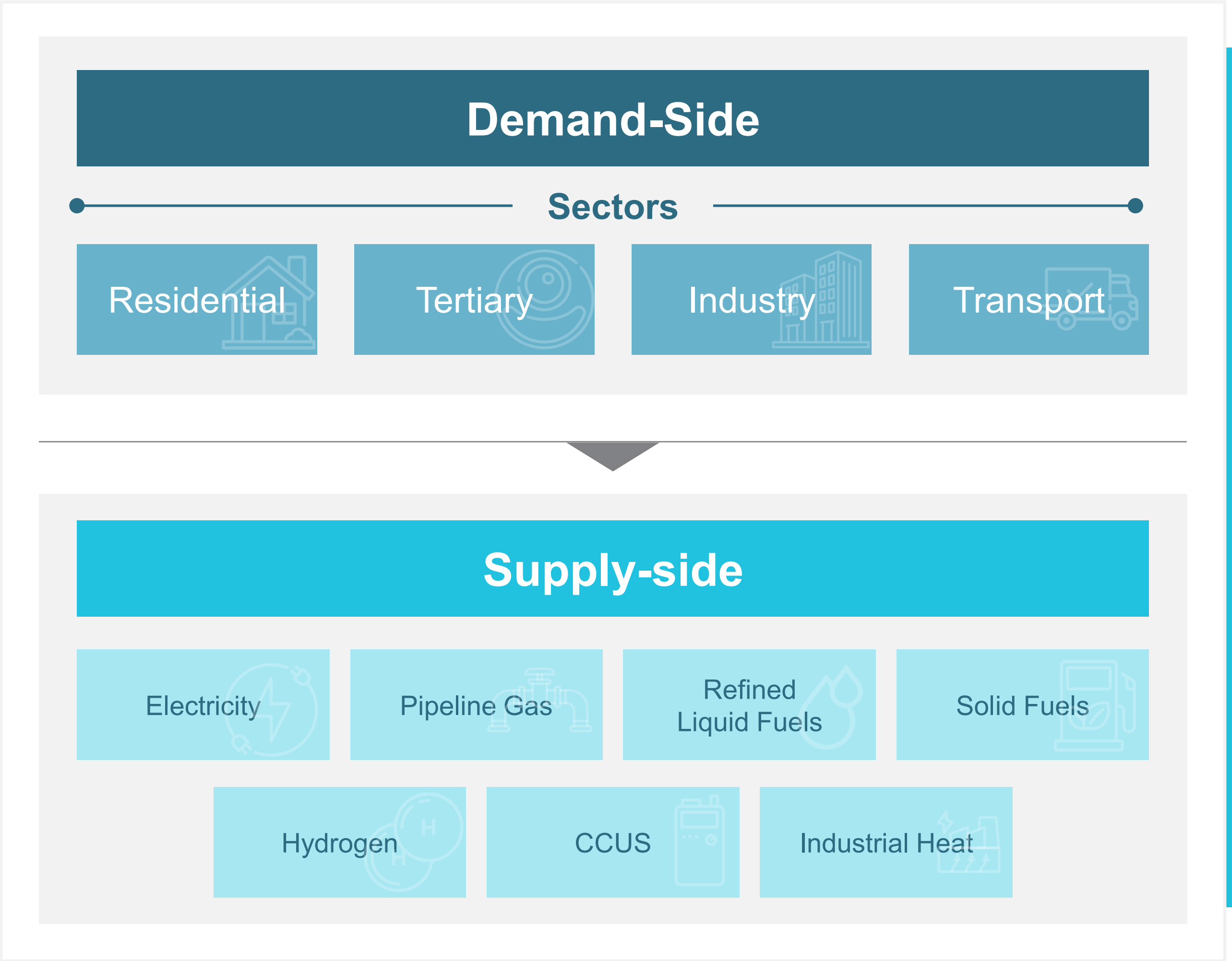
- Apply fuel switching and energy efficiency levers
- Strategies vary by end-use (residential space heating to heavy-duty trucks)

ENERGY PATHWAYS

Regional Investment and Operations (RIO

Model provides cost-optimal energy supply combining a comprehensive supply-side capacity expansion framework with hourly system operations

RIO



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Energy systems modeling: high-level approach

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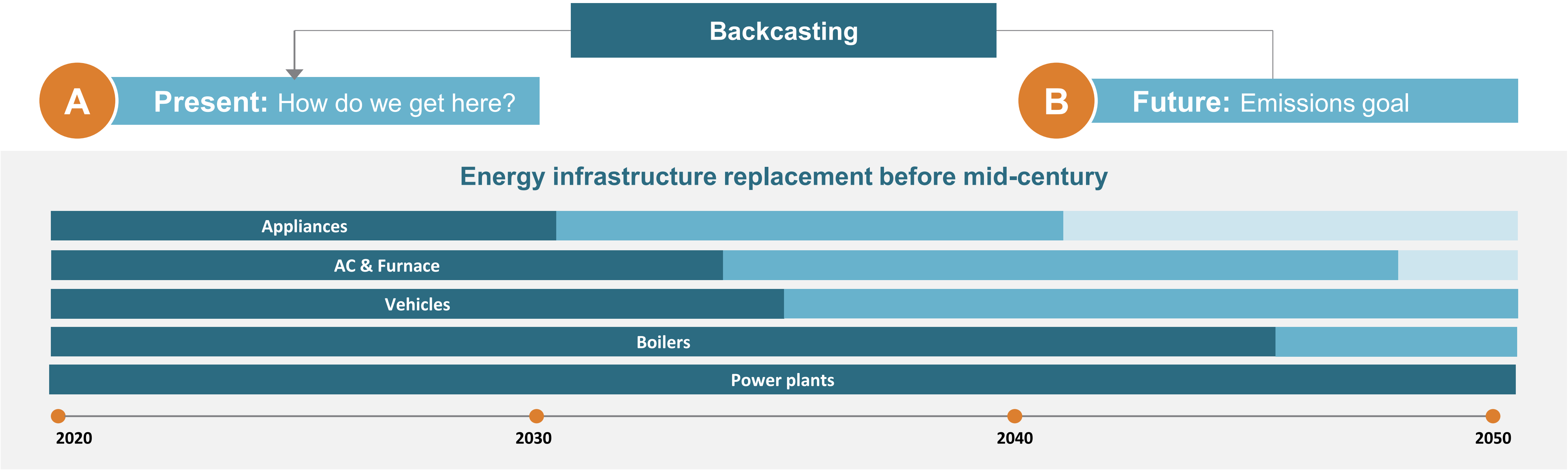
Backcasting: start with the end-goal and work backwards to understand implications

Shift to a low-carbon economy requires clarity on infrastructure needs

Large energy projects have long lead times and lifespans

Pathways demonstrate the long-term emissions and cost implications of energy infrastructure investments



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Energy systems modeling: demand-side

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

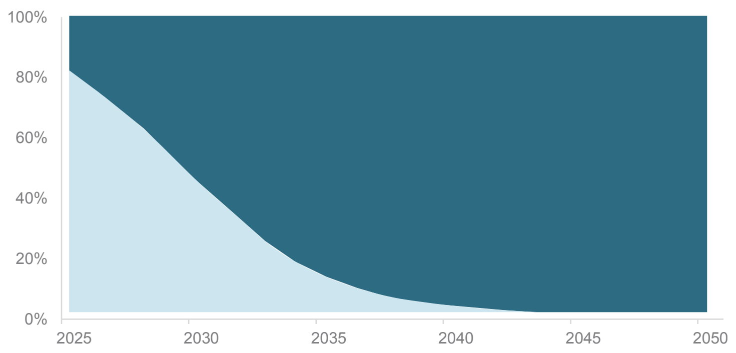
ENERGY PATHWAYS

Input: Consumer Adoption
EV sales are 100% of consumer adoption by 2045 and thereafter

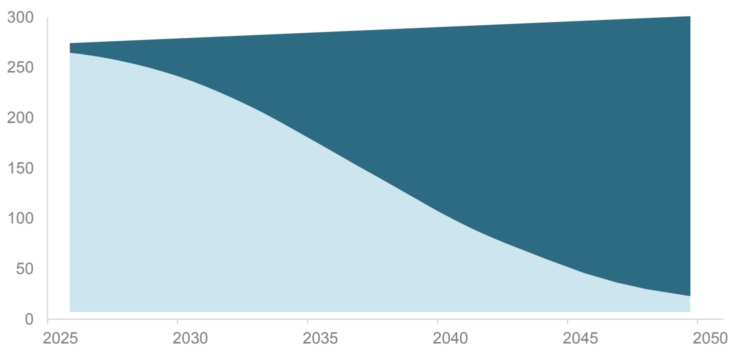
Output: Vehicle Stock
Stocks turn-over as vehicles age and retire

Output: Energy Demand
EV drive-train efficiency results in a drop in final-energy demand

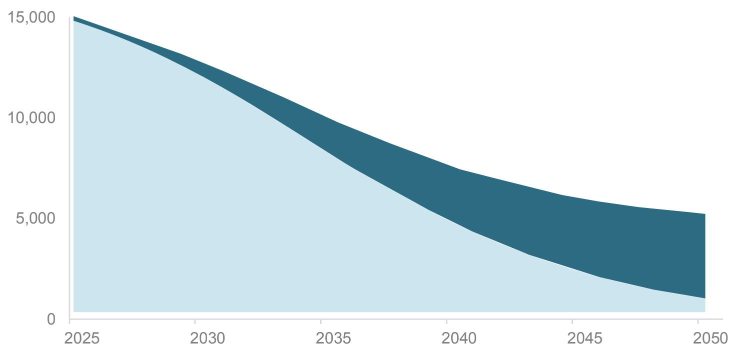
Sales Share
%



Stock
Vehicles on the road



Energy Demand
TBtu



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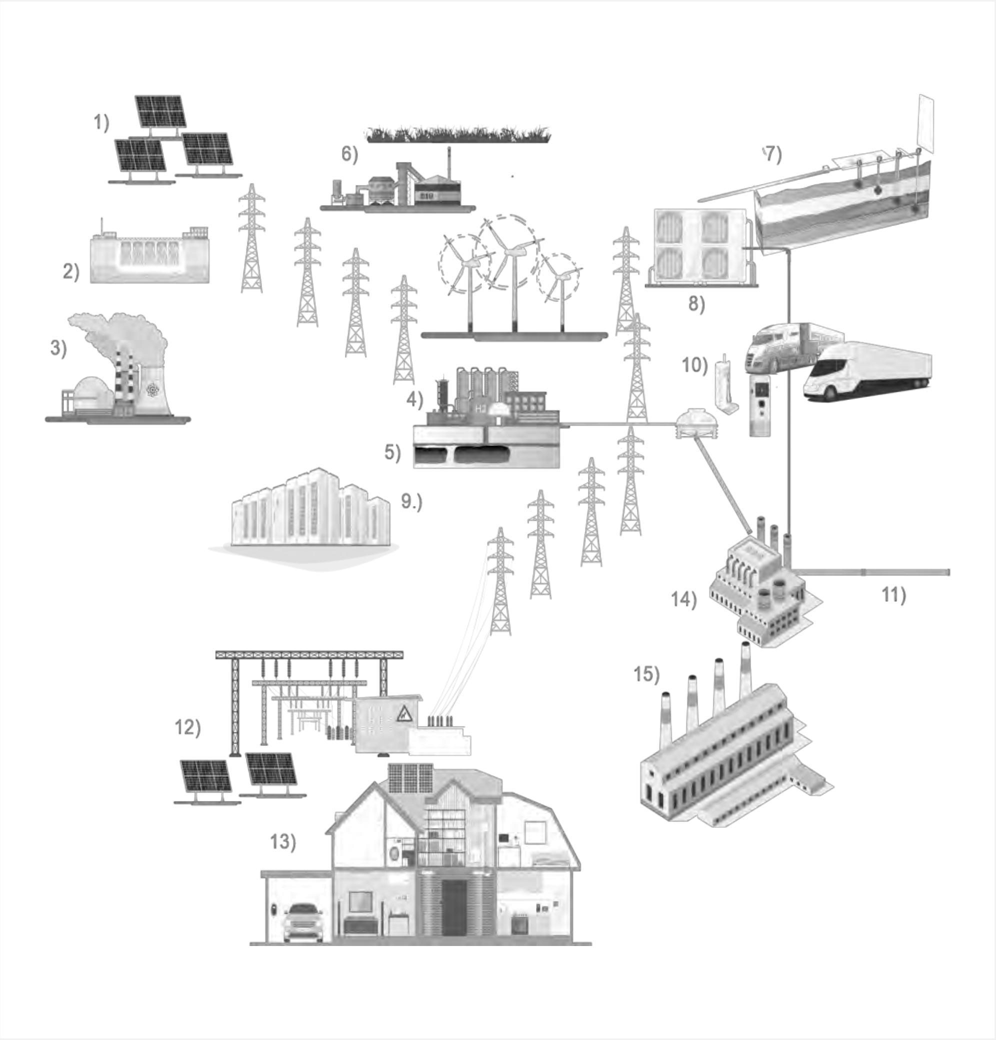
Energy systems modeling: RIO optimization scope



	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

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Energy systems modeling: supply-side

RIO

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

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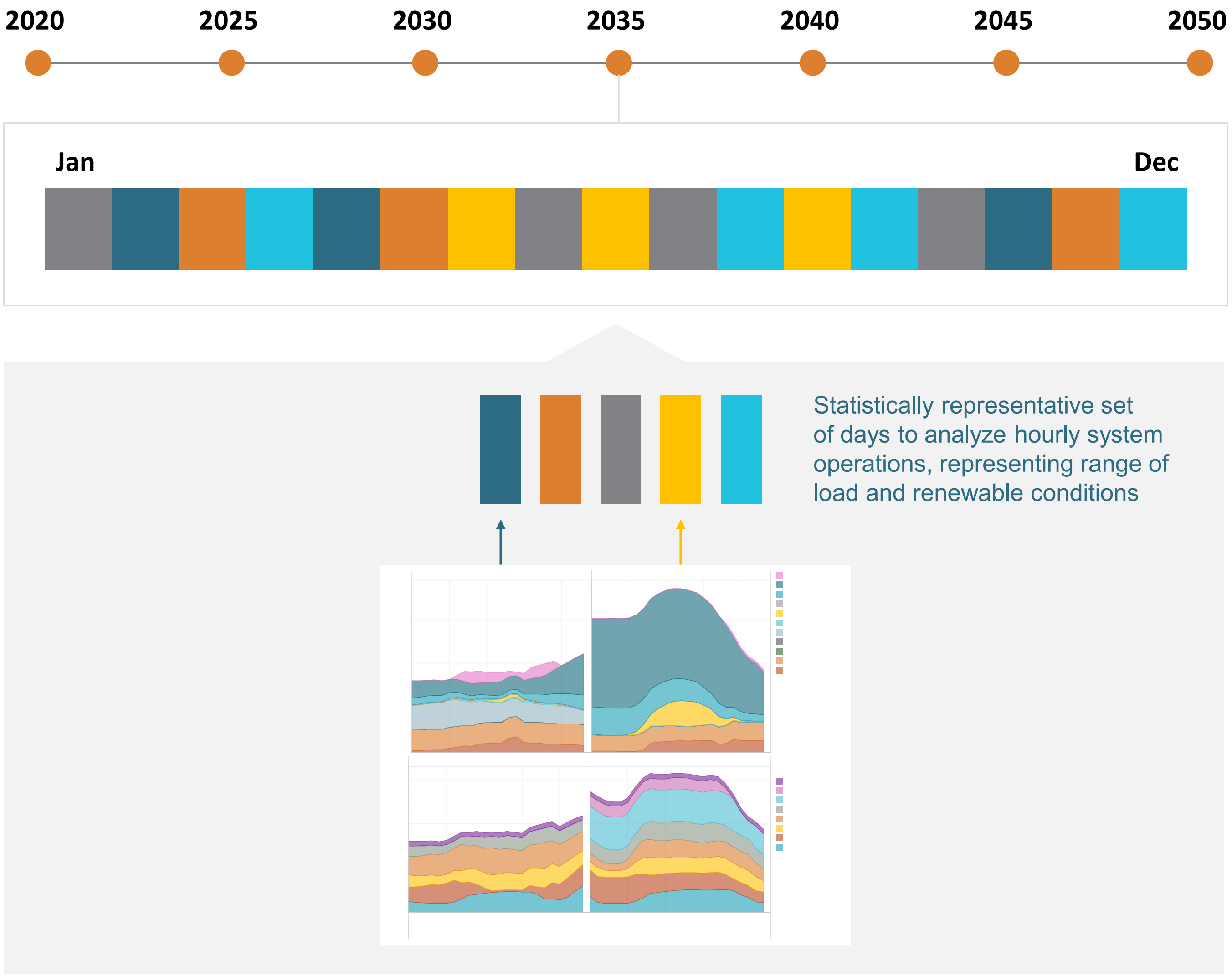

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How is RIO used?

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

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2024 Analysis Updates

OPTION 2

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Analysis Updates

- Analysis now includes all greenhouse gas emissions (non-energy, non-co^2, land sink, and energy & industrial co^2).

- Includes cost projections for consuming, delivering, producing, converting, and storing infrastructure, allowing us to calculate total energy system cost impacts.

- Updated underlying demand-side data to the JRC-IDEES-2021 database, which provides end-use disaggregation for energy equipment and energy service demand.

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Analysis Updates
Downscaling

In an effort to improve our understanding of the impact of different energy system choices, **we are leveraging an approach called downscaling to visually illustrate the siting of the power sector portfolios developed in this analysis.**

Full downscaling results are available on carbon free europe modelling page

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Analysis Updates
Scenarios

- We've developed a new set of scenarios this year with the intent of illustrating diverse transformation pathways across countries.
- We've also included a Baseline scenario to assess net energy system costs (i.e. the cost of decarbonization above a no-emissions-policy baseline).

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Core	**Include Gas with Carbon Capture**
No Sequestration	**90% by 2040**
Limited Networks	**Slow Electrification**
Constrained Renewables	**Low Demand**
Unconstrained Renewables	**High Biomass**
No New Nuclear	**Baseline**

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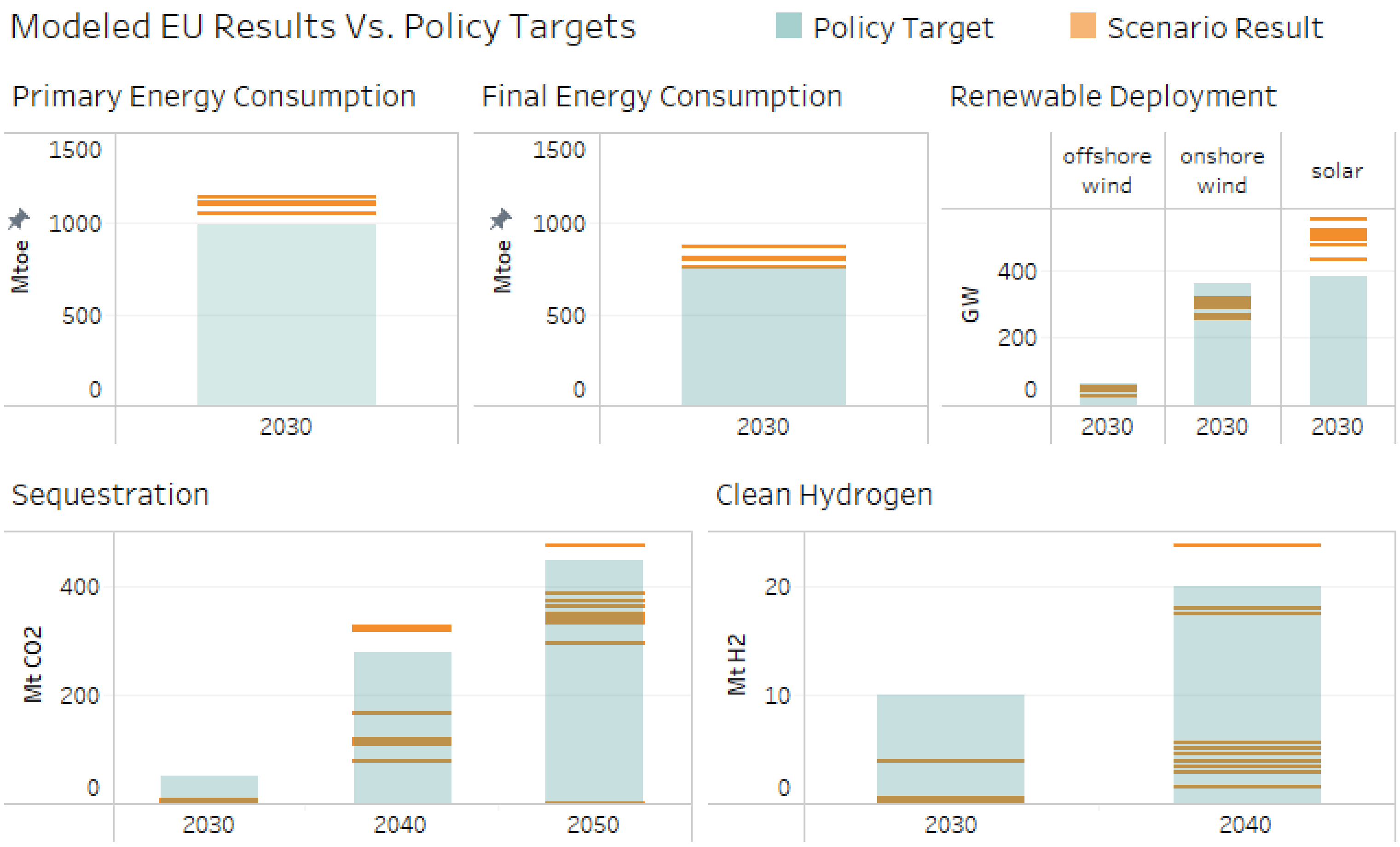
Result Highlights

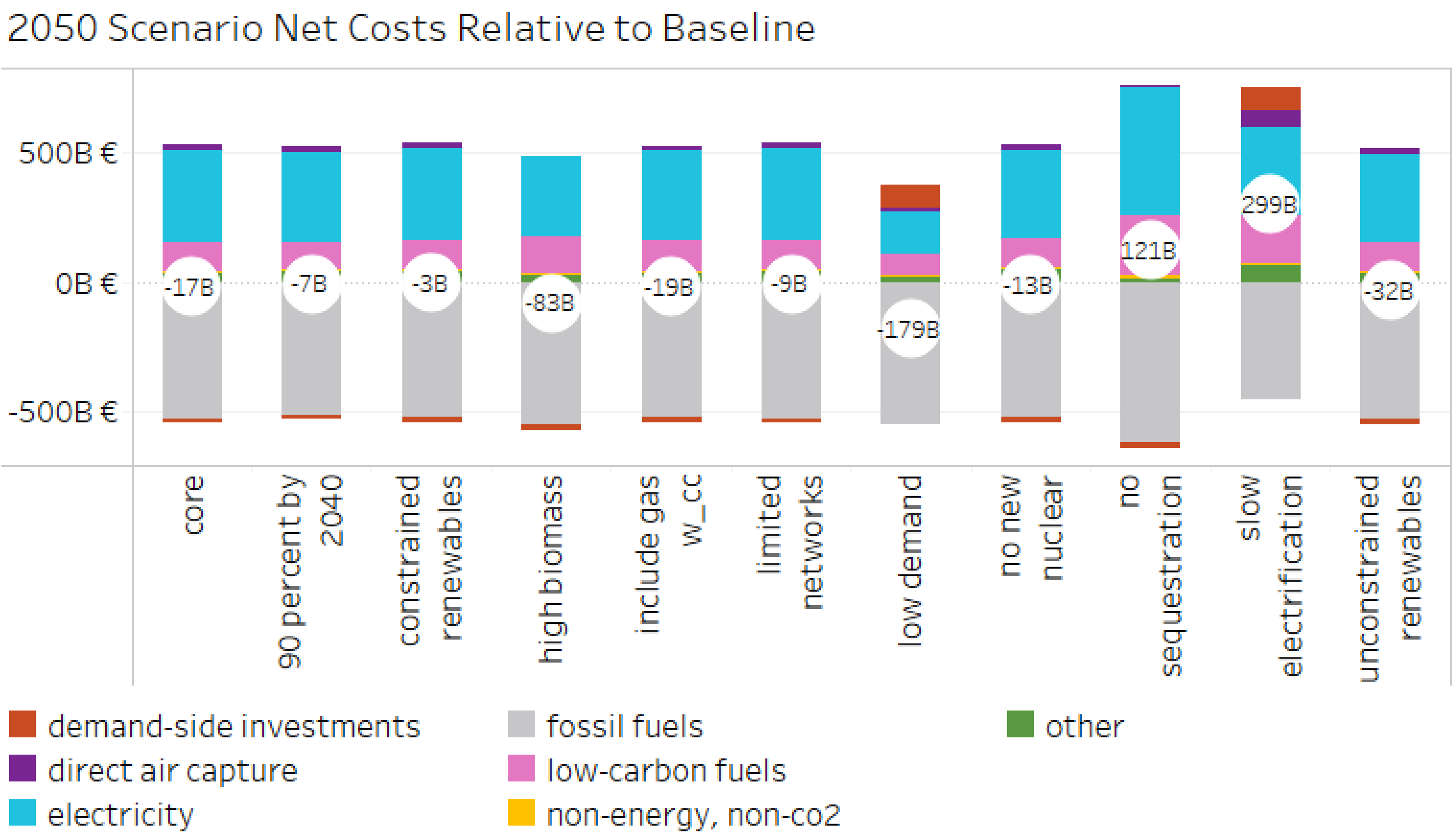
Prescriptive Policy

- 2030 EU emissions targets have been translated into overly-prescriptive member-state implementation plans and EU targets.
- Rigid sector-specific targets limit flexibility, making country-level decarbonization efforts more complicated and riskier, as countries are less able to adjust to changing technology costs, market dynamics, and consumer preferences
- Unrealistic targets may also create public pessimism about overall decarbonization efforts if they are not met



The Cost of Inaction

- This year's ADP assessed both net-zero scenarios and a baseline scenario, freezing consumer technologies (cost/efficiency/fuel choice) at 2021 levels without implementing carbon policy on the energy supply-side, to understand the full costs of decarbonization.
- If managed correctly, the transition could lead to a decarbonized economic system that saves Europe money in the long term.
- *But* the energy transition presents economic challenges: increasing capital available for financing; overcoming first-cost hurdles for vehicle and home heating systems; and managing cost allocation for new decarbonized investments



Winter is Coming

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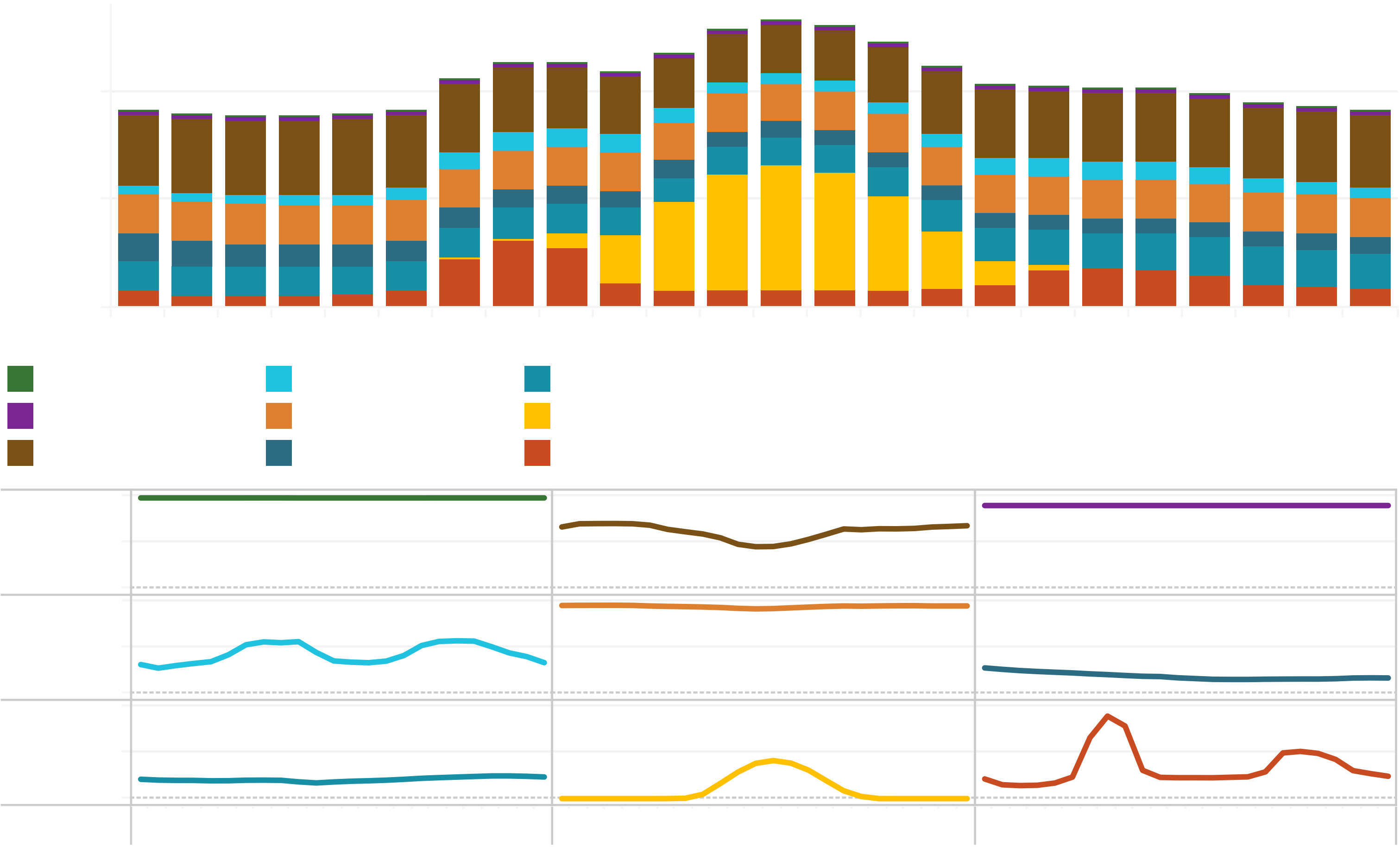
- Europe is likely to sustained periods of high net electricity load during winter in the future. Widespread electrification of heating systems increases winter electricity demand, which coincides with low renewable energy generation, particularly from solar.
- The challenge of sustained high net-load events during winter highlights the need for a diverse energy portfolio, beyond simplistic comparisons based on metrics like Levelized Cost of Energy (LCOE).
- Solutions include deploying hundreds of gigawatts of short-duration energy storage for daily fluctuations, multi-day energy storage (MDES) systems for periods of low renewable output, expanding the nuclear fleet for reliable low-carbon power and anticipating the need for up to 250 gigawatts of new fuel-flexible backup generators, capable of running on fossil gas, hydrogen, or biogas.



From Storage to Balancing

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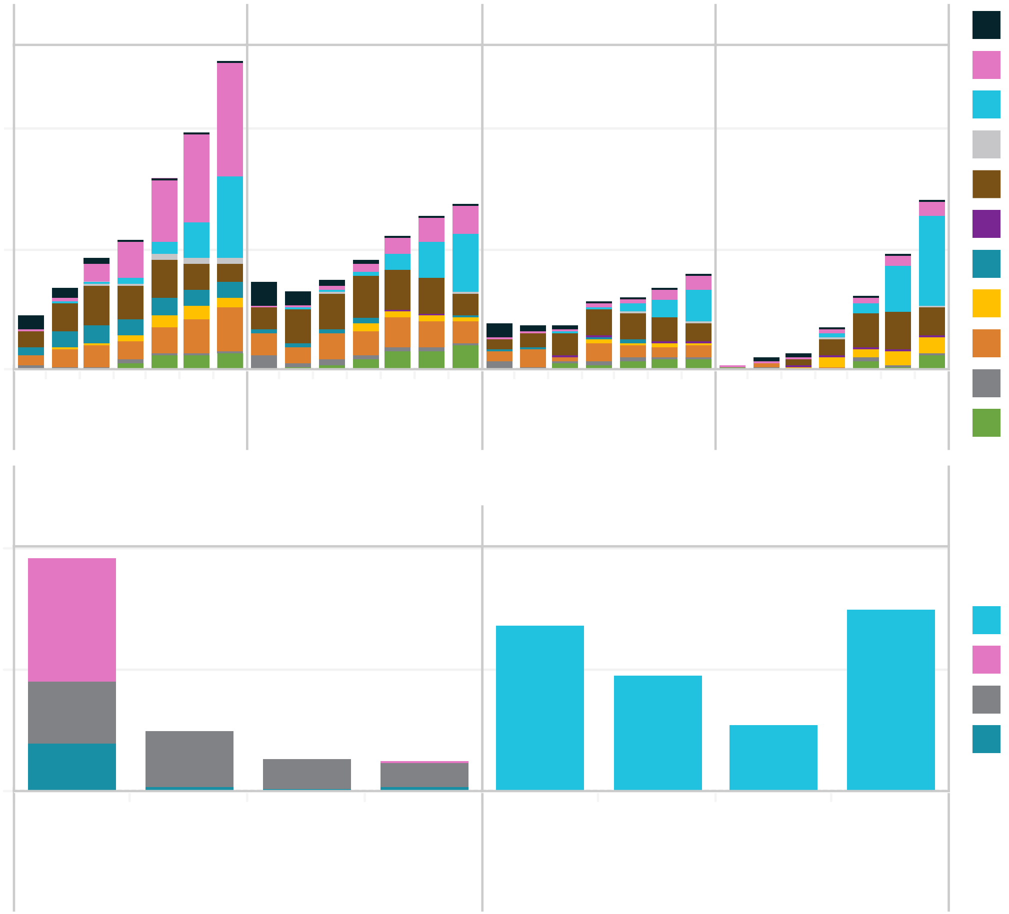
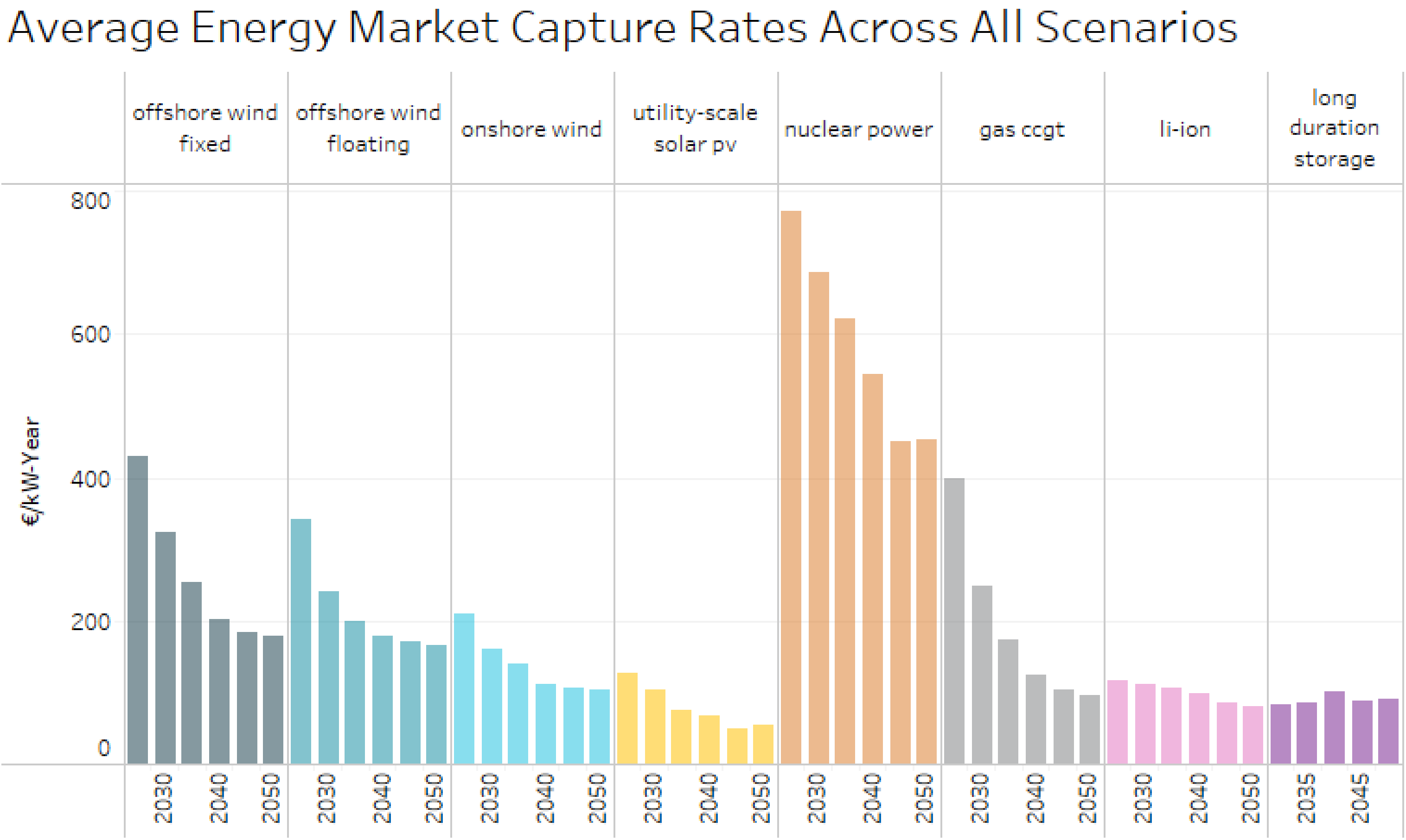
- Figure Explainer
  - This chart shows balancing (the reduction in net load deviations accomplished at each timescale) by generation, storage, flexible load, and transmission
- As renewable electricity surpluses and deficits, i.e. *Dunkelflaute*, begin to persist, the system requires sustained dispatchable resources. A portfolio approach is the most economic, employing industrial-scale load shifting (electrolysis and industrial steam), multi-day energy storage, and flexible thermal operations to help balance over- and under-generation periods.
- Balancing challenges at different timescales are addressable by very different resource types. “More batteries” won’t be the answer to seasonal balancing challenges.



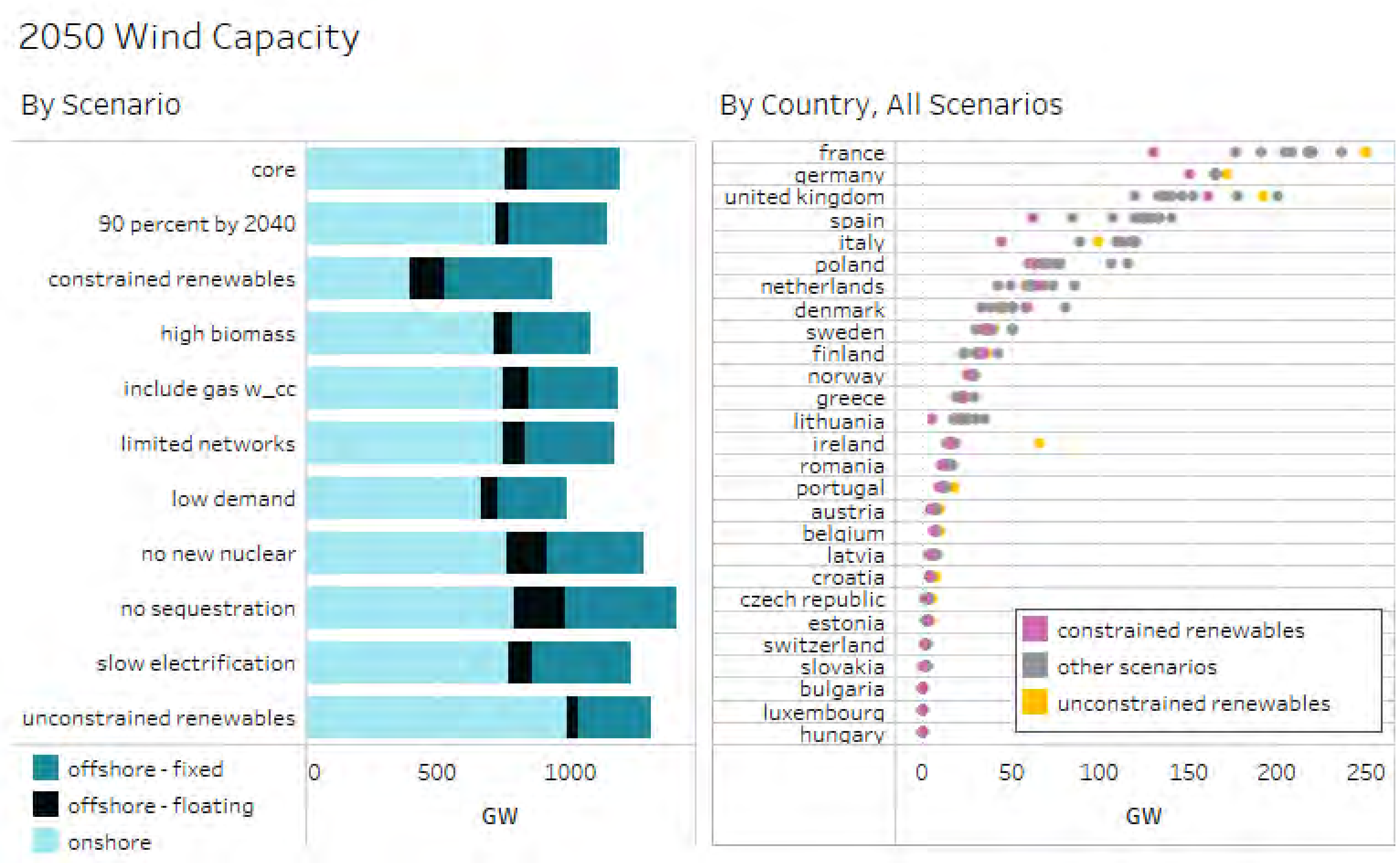
Electricity Market Evolution

- The growth of low variable cost renewables, like wind and solar, has significantly impacted these markets by driving down prices.
- Despite lower market prices from renewable energy, capacity resources lil batteries, gas plants, and dispatchable power sources are still needed to mainta grid stability during periods of low renewable output.
- Current market structures often undercompensate these capacity resources, as they are paid primarily for energy they provide. Without market reform, the retirement of crucial resourc such as nuclear power could undermine long-term electrification and decarbonization goals.



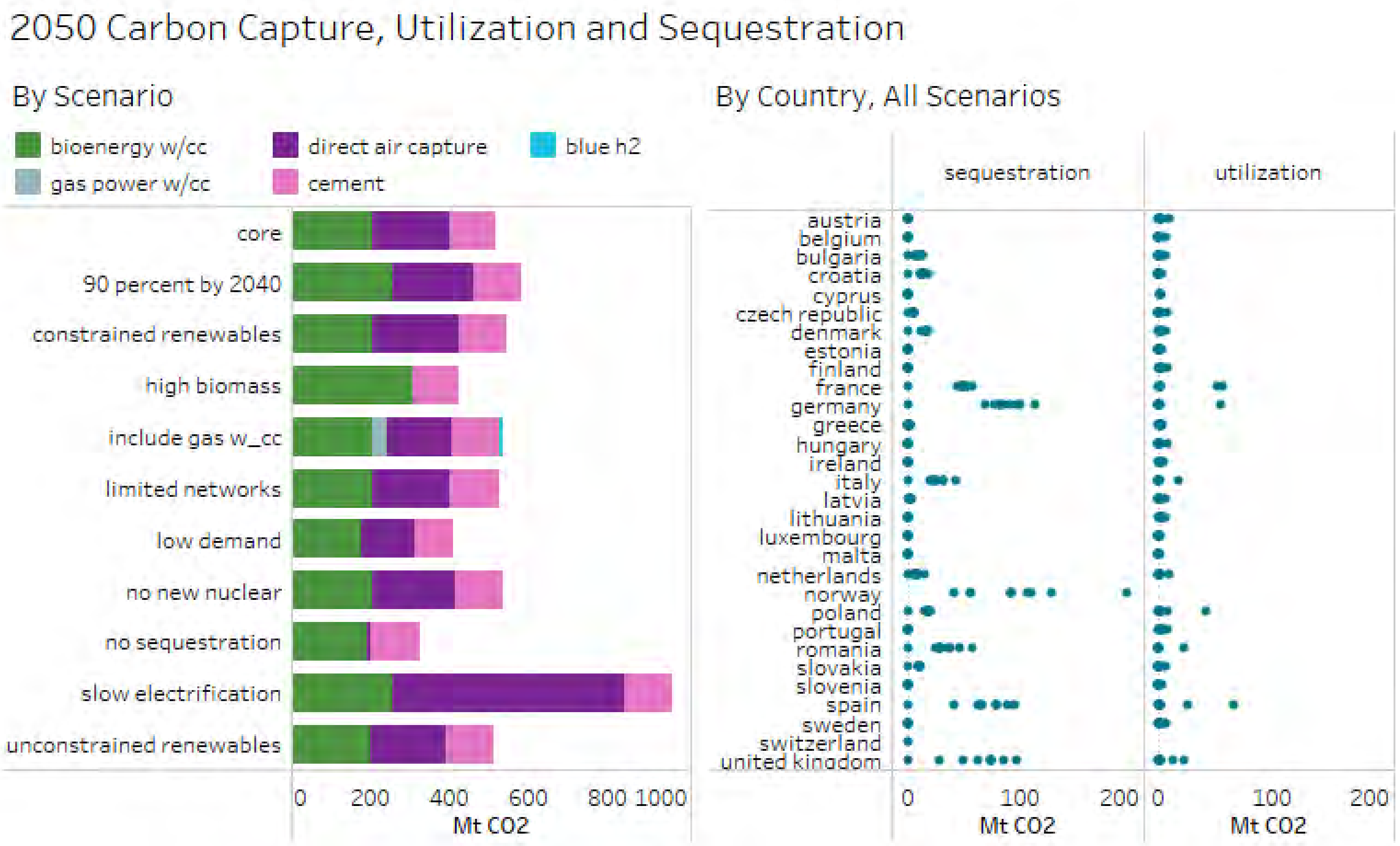
Where the Wind Blows

- Our analysis selects over 900 GWs of total wind in Europe by 2050 across all scenarios, with the type of wind and location varying substantially by scenario.
- New wind development in Europe has been delayed by supply chain issues, public pushback, and project costs.
- Solar and wind are poor substitutes for each other, so recent headwinds faced by European wind won't necessarily be ameliorated by the booming solar market. Countries will need another zero-carbon generation source (nuclear, geothermal, gas w/cc) where wind isn't able to be deployed



What to do with the CO_2

- Achieving net-zero emissions requires a major expansion of carbon capture technologies, with industry, biofuels, and direct air capture as key opportunities.
- The fate of captured carbon depends on factors like technological advancements, policy, and public acceptance, with options including sequestration in geological formations or utilization to produce fossil fuel substitutes.
- Sequestration feasibility is influenced by geological conditions and proximity to carbon capture sources, while utilization potential is driven by the availability of surplus renewable energy for producing carbon-based fuels.



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Detailed Results

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Scenarios

Core Scenario Summary

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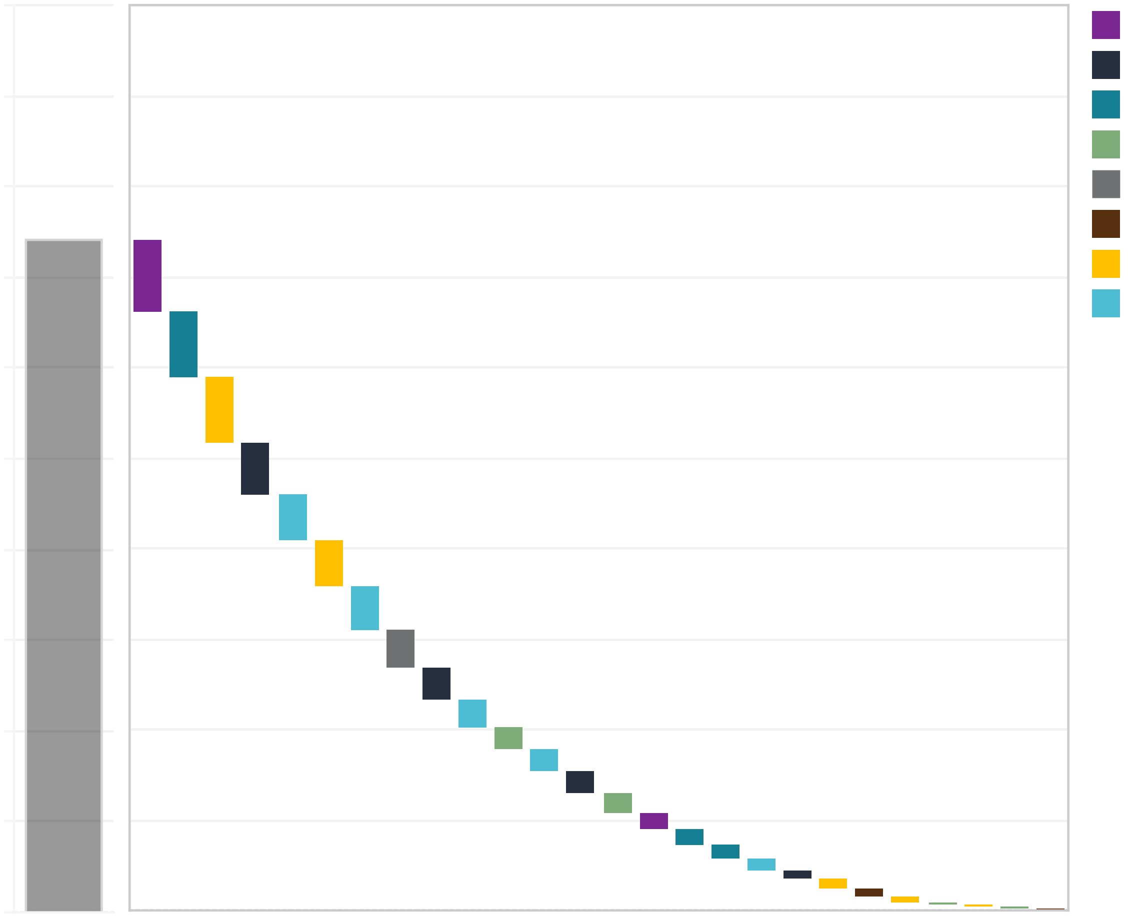
- **High-Renewables and Electrification Future**
  - Focus on electrifying transport, heating, and industrial processes, while substituting zero-carbon fuels in hard-to-electrify sectors.
- **Infrastructure Expansion:**
  - Requires large-scale deployment of renewables, clean hydrogen, and energy storage to accommodate increased electrification.
- **No Such Thing as *Hard to Decarbonize***
  - Rapid decreases in energy use and emissions across all sectors, with carbon capture in industry and biomass applications.
- **Economic Efficiency**
  - Despite significant infrastructure investment, promises lower overall costs compared to a fossil-fuel-dependent Baseline scenario.

Core Scenario Emissions Reductions

- Emissions reductions strategies are reflected in the waterfall chart
- Electrification of buildings, passenger cars, and steam are three of the four biggest emissions reductions opportunities
- Other large opportunities include biofuels, direct air capture, and renewable deployment

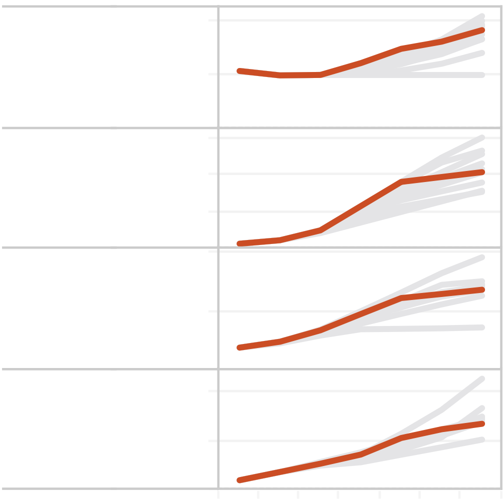


Core Scenario Key Numbers

Scenario Impacts 1-3

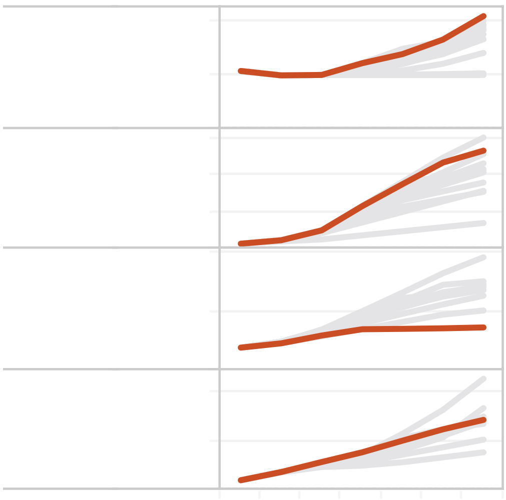
90% by 2040

Unsurprisingly, an accelerated target means accelerated deployment specifically of renewables, biofuels production, and direct air capture to achieve the level of emissions reductions necessitated by a 90% target without the scale of electrification we find by 2050.



Constrained Renewables

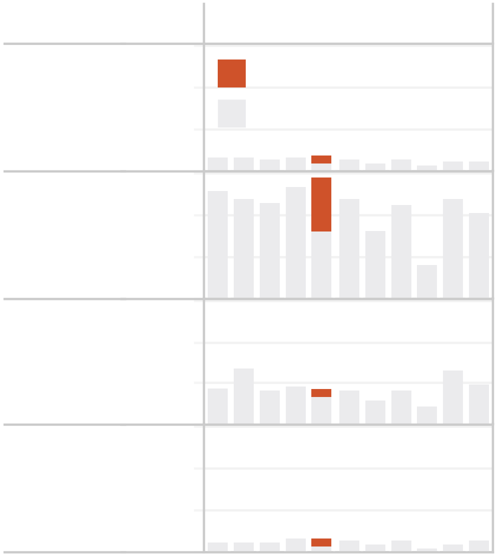
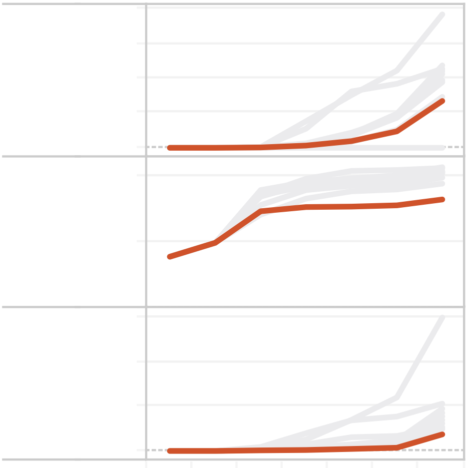
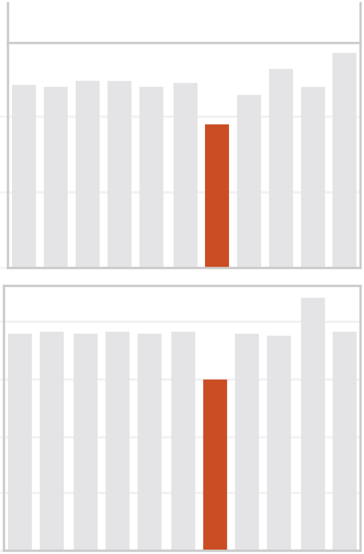
Constraining renewables, specifically onshore wind, requires the substitution of offshore wind (this scenario has the second highest deployment of offshore wind) and nuclear power (highest deployment).



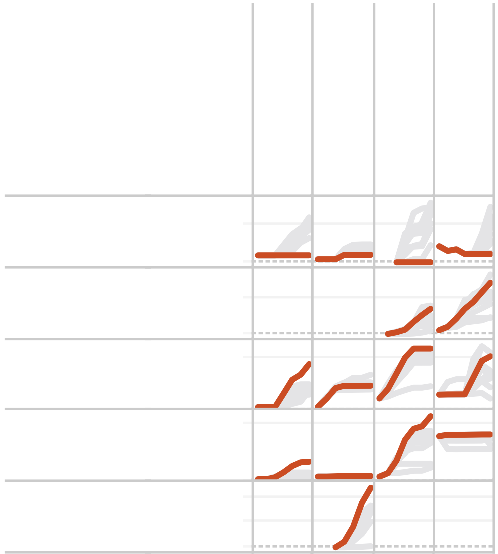
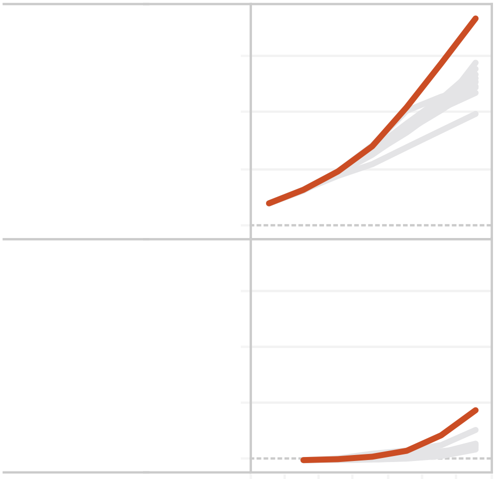
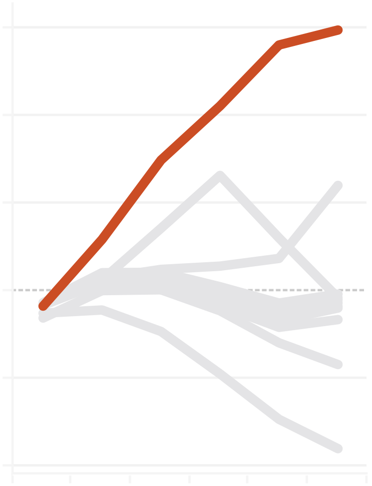
High Biomass

Low-carbon biomass is a valuable resource in a net-zero economy, as both a fuel feedstock and a source of CO2 for sequestration. If more biomass is available in the model, it is utilized and reduces the need for technical carbon capture (DAC). In reality, biomass production must be balanced with competing land-use requirements.

Scenario Impacts 4-6

Include Gas with Carbon Capture	Limited Networks	Low Demand
For certain countries, specifically those countries with limited renewables and an aversion to new nuclear facilities, gas with carbon capture is economic in both power and hydrogen production. 	*Increasing the costs of interconnection for new electricity, hydrogen, and CO2 pipeline reduces overall build of all three, forcing the model to rely on lower quality renewable resources, increase the share of nuclear capacity, and increase the amount of electricity storage for balancing but in general this infrastructure is not cost sensitive; the economics of building it is robust against significant cost increases.* 	*Reducing overall demand is helpful for achieving near-term emissions goals and reducing the overall scale of infrastructure build, but it is a linear solution to a non-linear problem and does not change the nature of the transformation imperative.* 

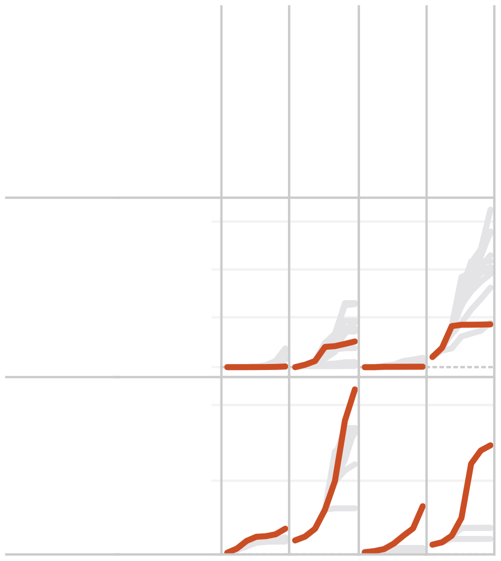
Scenario Impacts 7-9

No New Nuclear	No Sequestration	Slow Electrification
Foregoing new nuclear as a resource necessitates the build of more gas generation (for capacity) and floating offshore wind (for energy) where available. Otherwise, it necessitates the substitution of more expensive solar or geothermal resources. 	*Disallowing sequestration necessitates significant volumes of zero-carbon fuels and the use of large quantities of hydrogen as a feedstock. Increased hydrogen production puts a strain on Europe's available renewable resources and may necessitate more imported fuels.* 	*The delay of electrification means that the most cost-effective demand-side strategies of vehicle and heating electrification contribute less than they do in the* ***Core*** *scenario. This contribution is instead taken up by more low-carbon fuels at a higher price, making this one of the more expensive scenarios analyzed.* 

Scenario Impacts 10

Unconstrained Renewables

The renewable build constraints primarily operate to reduce the contribution from low-cost onshore wind resources. This moves wind builds offshore to onshore.



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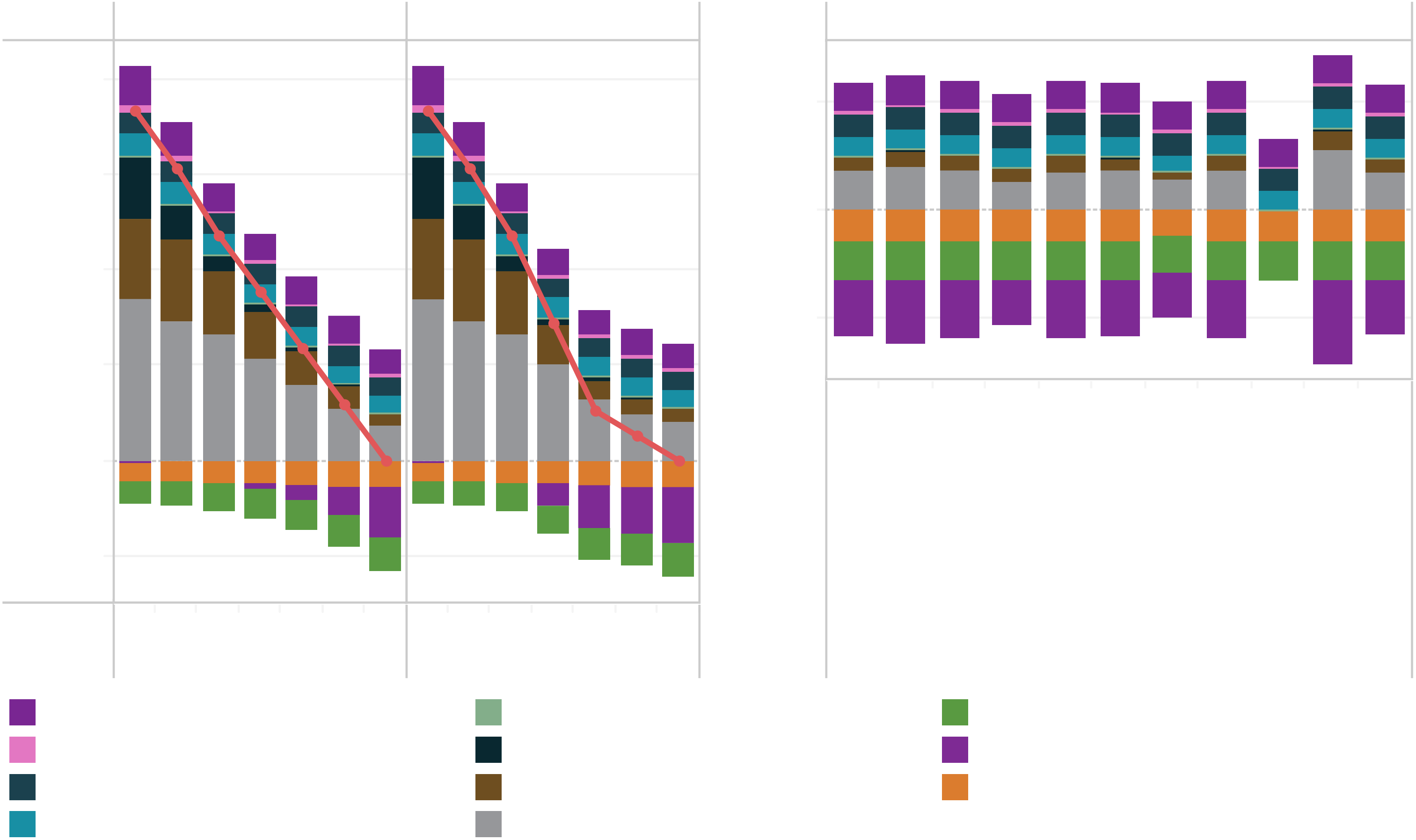
Emissions

Emissions by Source Category

- **Emissions Trajectories (Left)**
  - Two trajectories modeled: a net-zero from 2030 to 2050 path (Core), and a 90% reduction by 2040 path. Both are relative to 1990 levels.
- **2050 Emissions Balances (Right)**
  - Residual fossil fuel use and non-CO_2 emissions are offset by uncombusted fuels, geologic sequestration, and land sink contributions across scenarios.
- **Key Scenario Differences**
  - *No Sequestration* eliminates fossil fuels through low-carbon substitution, while *Slow Electrification* has higher residual fossil use and greater reliance on geologic sequestration.



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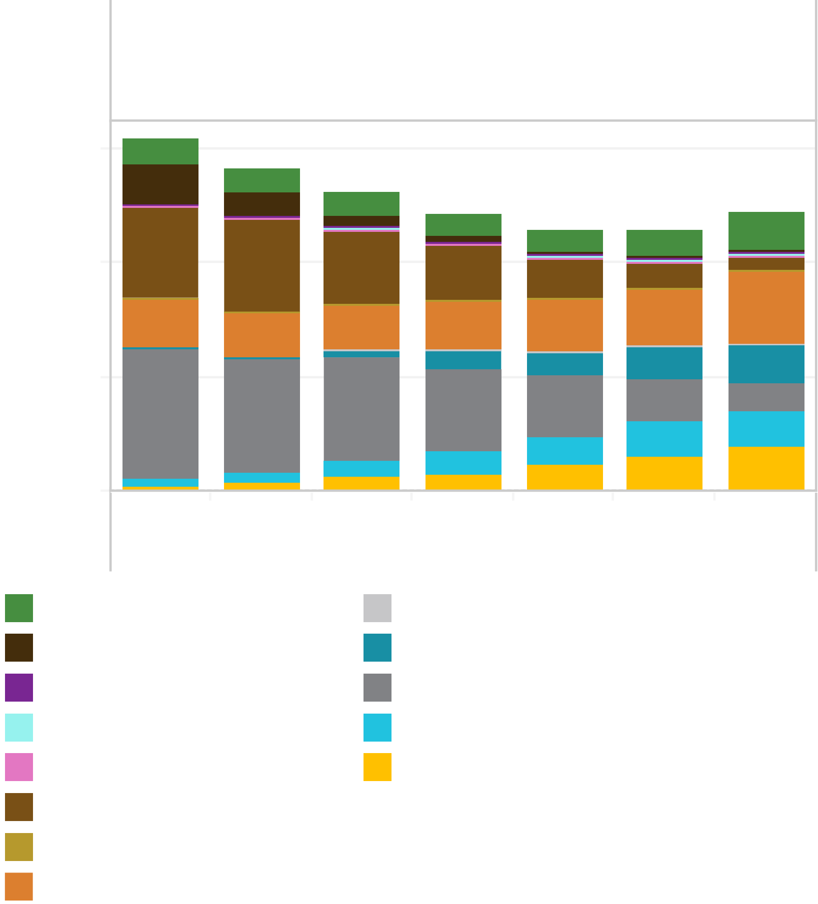
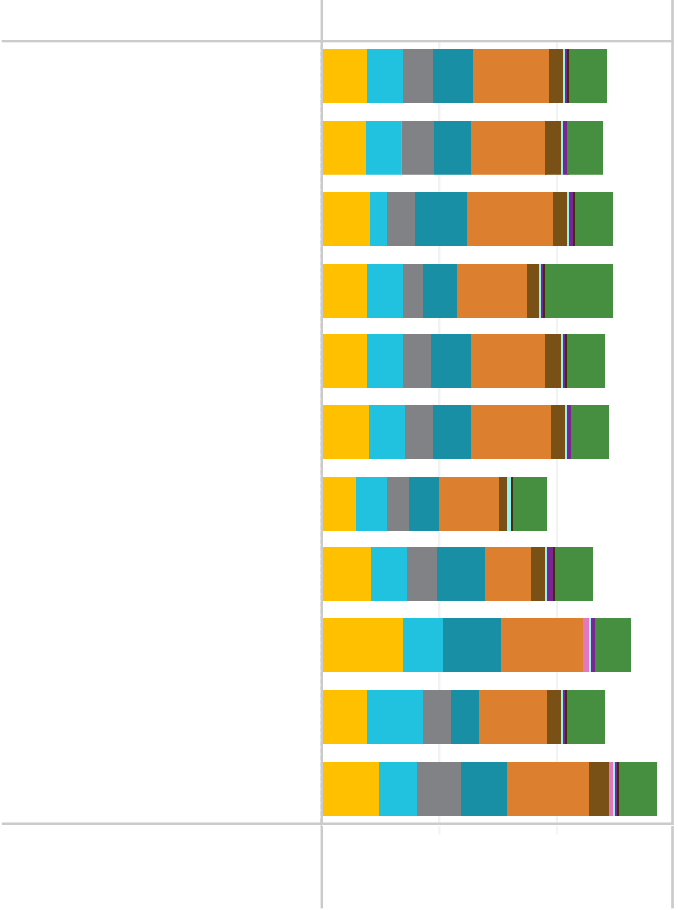
Energy

Primary Energy Demand

- **Primary Energy Demand Variability**
  - Scenarios show differences in primary energy demand, with *Low Demand* reducing service demand, and *No New Nuclear* lowering demand through renewable substitution. *Slow Electrification* and *No Sequestration* require the highest zero-carbon fuel production, highlighting inefficiencies in e-fuel pathway.
- **Challenges of Primary Energy as a Metric**
  - The use of primary energy as a target metric is less informative when comparing different energy sources, as it can favor certain technologies over others.





Final Energy Demand

- **Final Energy Demand Trends**
  - Final energy demand declines are bounded by *Slow Electrification* and *Low Demand* scenarios, with similar levels across other scenarios. Largest reductions occur in refined fuels and pipeline gas, while electricity and hydrogen use increase.
- **Sectoral Declines**
  - Transport and heat see the largest declines, driven by the adoption of electric vehicles and heat pumps replacing boilers.
- **Country-Level Variation**
  - Countries with higher heating demands experience greater reductions in final energy demand by 2050 compared to 2021.

Electricity Demand

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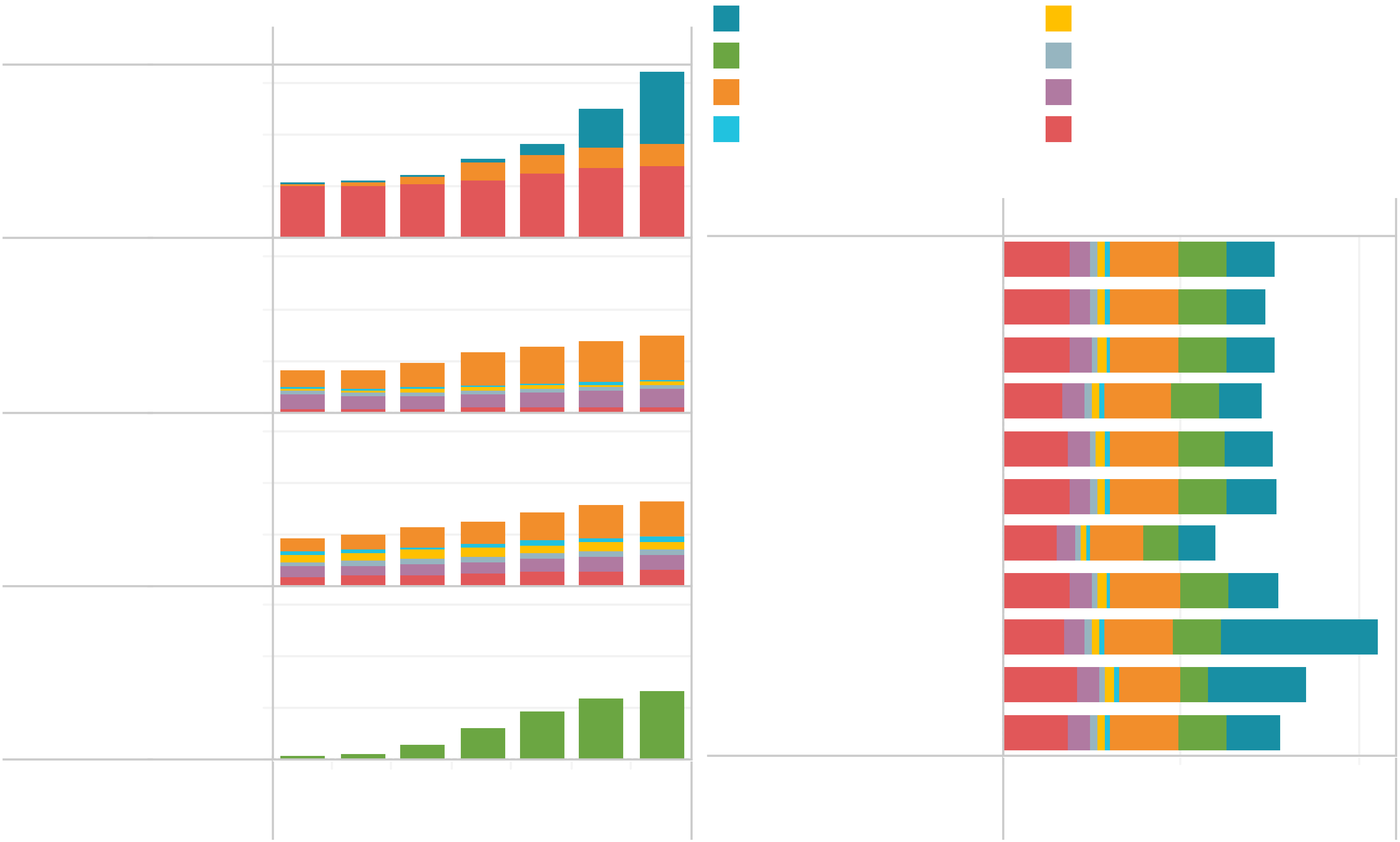
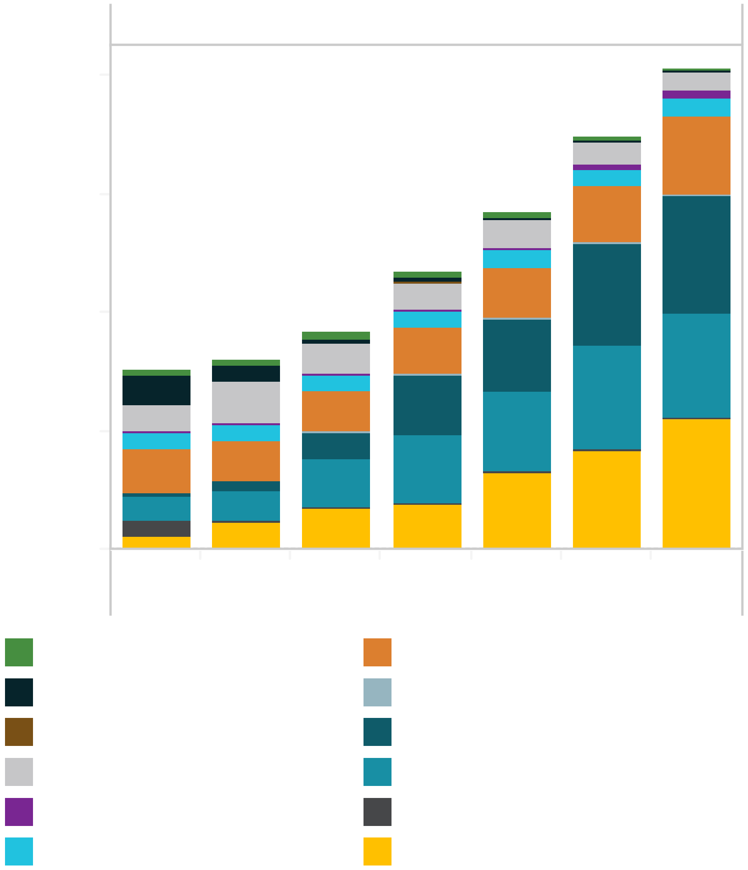
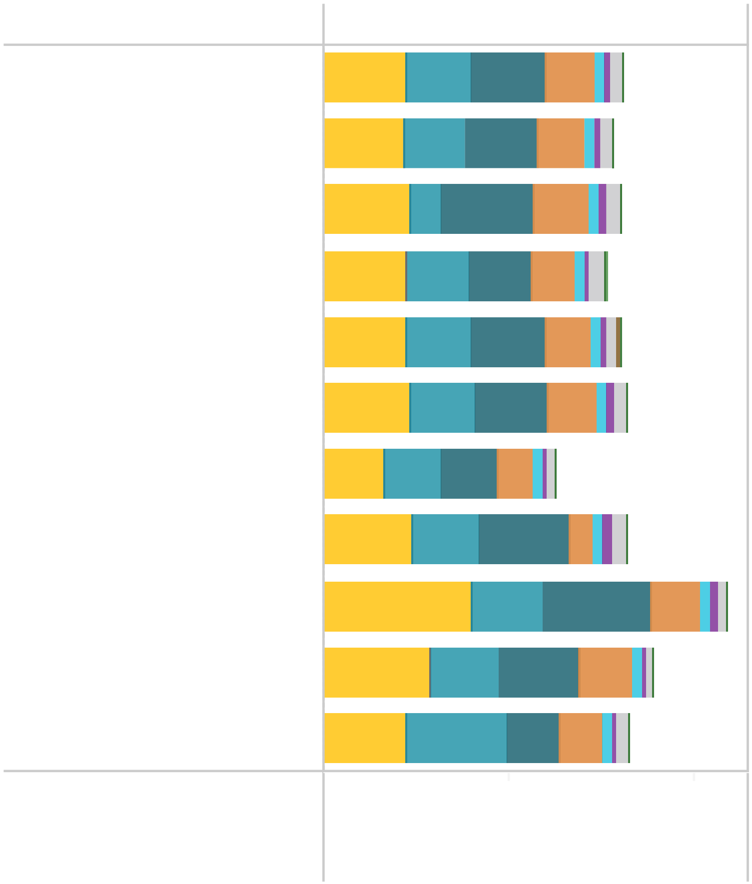
- **Electricity Demand Growth**
  - Significant increases in electricity use through 2050 occur in building heating, industrial processes, e-fuel production, and transportation, with overall electricity load increasing ~2.5x from 2021
- **Shifting Load Characteristics**
  - Transportation and e-fuel production offer flexible, location-independent loads, while building heating concentrates demand during cold periods, straining distribution and generation systems.
- **Sector Coupling for Renewable Integration**
  - Flexibility in load timing and location supports higher renewable energy penetration (75-85% across scenarios), enhancing cost-effectiveness in the energy transition.



Electricity Generation

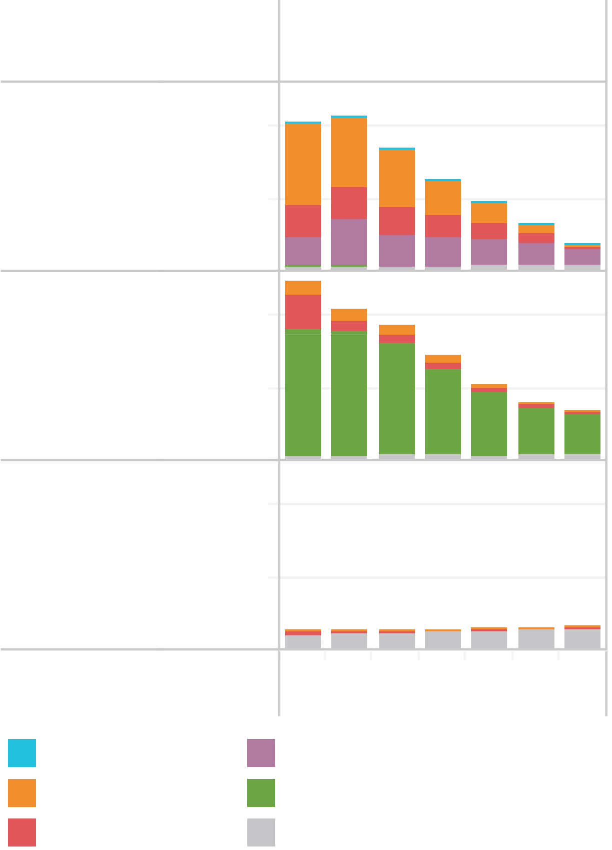
- **Generation Variability by Scenario**
  - The overall scale of electricity generation varies across scenarios, influenced by energy service demand and the need for zero-carbon e-fuels and DAC support.
- **Dominance of Wind Energy**
  - Wind energy provides the majority of electricity by 2050, with variability in location and type (onshore, fixed offshore, floating offshore) across scenarios.
- **Role of Floating Offshore Wind and Nuclear**
  - Floating offshore wind and nuclear serve as backstop resources, particularly in scenarios with siting constraints for onshore wind

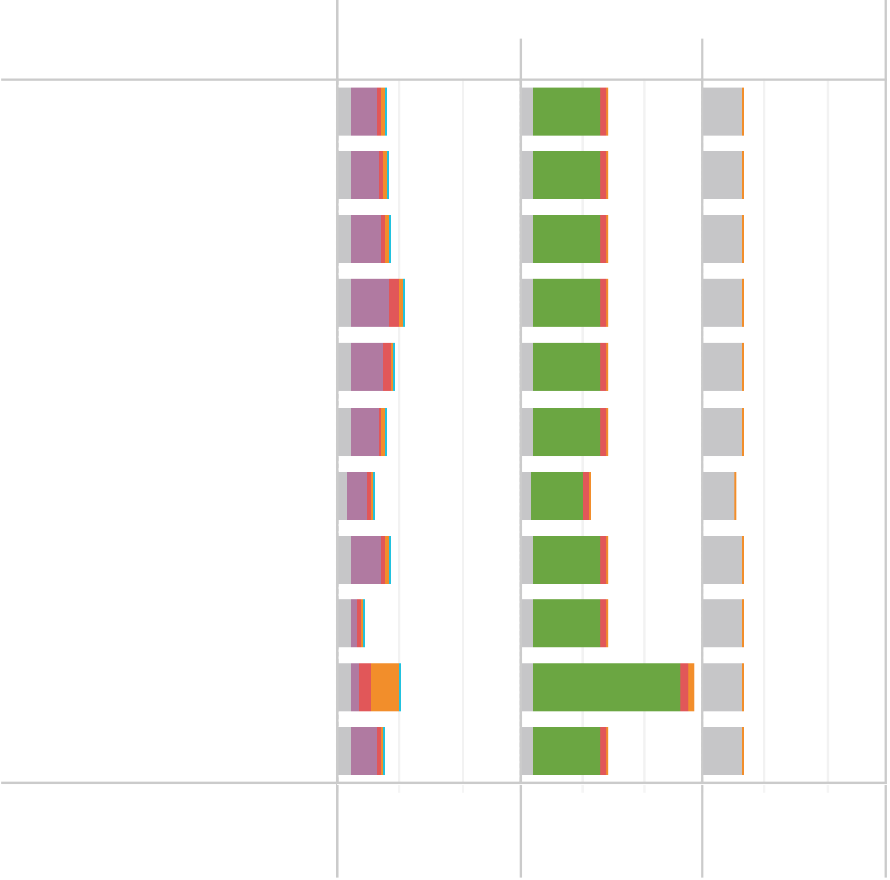




Hydrocarbon Demand

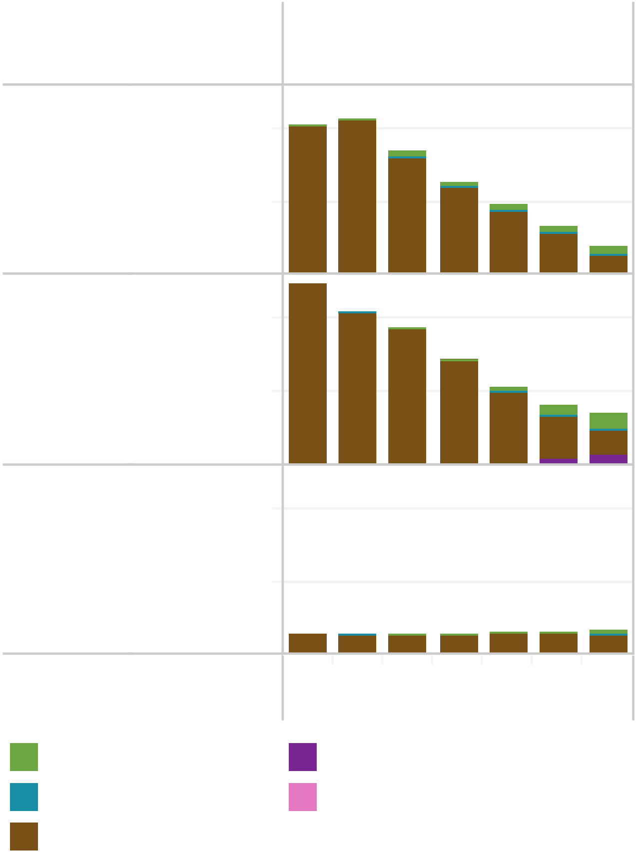
- **Hydrocarbon Fuel Use Today**
  - The current energy system heavily relies on hydrocarbon fuels, especially for heat and transport.
- **Electrification Reduces Fuel Use**
  - By 2050, electrification of heat and transport eliminates most fuel use in these sectors, with residual fuel use for hard-to-electrify areas like aviation, bunkering, and chemical feedstocks
- **Slow Electrification Scenario**
  - While transport and heat fuel use remains higher, reduced fuel demand in power mitigates the overall impact, with biofuels, e-fuels, and DAC offsetting residual emissions.





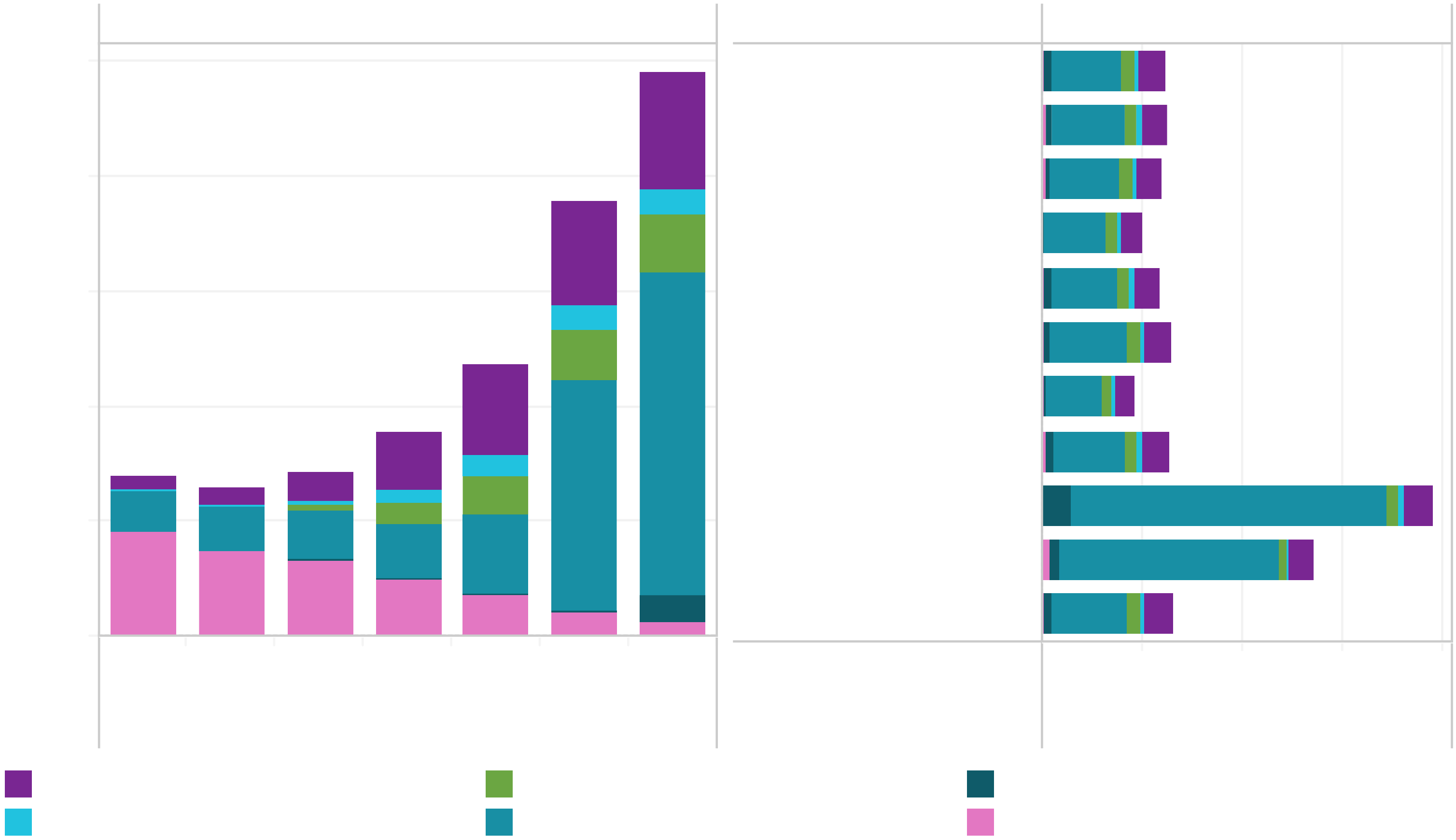
Hydrocarbon Supply

- **Dry Biomass Use**
  - Dry biomass feedstocks, such as herbaceous and woody wastes, are primarily used to displace petroleum-based liquid fuel in the model
- **Wet Biomass Use**
  - Wet biomass, like manure and wastewater, is utilized for pipeline decarbonization through anaerobic digestion.
- **E-fuels and No Sequestration**
  - E-fuels are used sparingly due to high costs, but in the No Sequestration Scenario, significant volumes of e-fuels are employed across all fuel types to offset the lack of carbon sequestration.



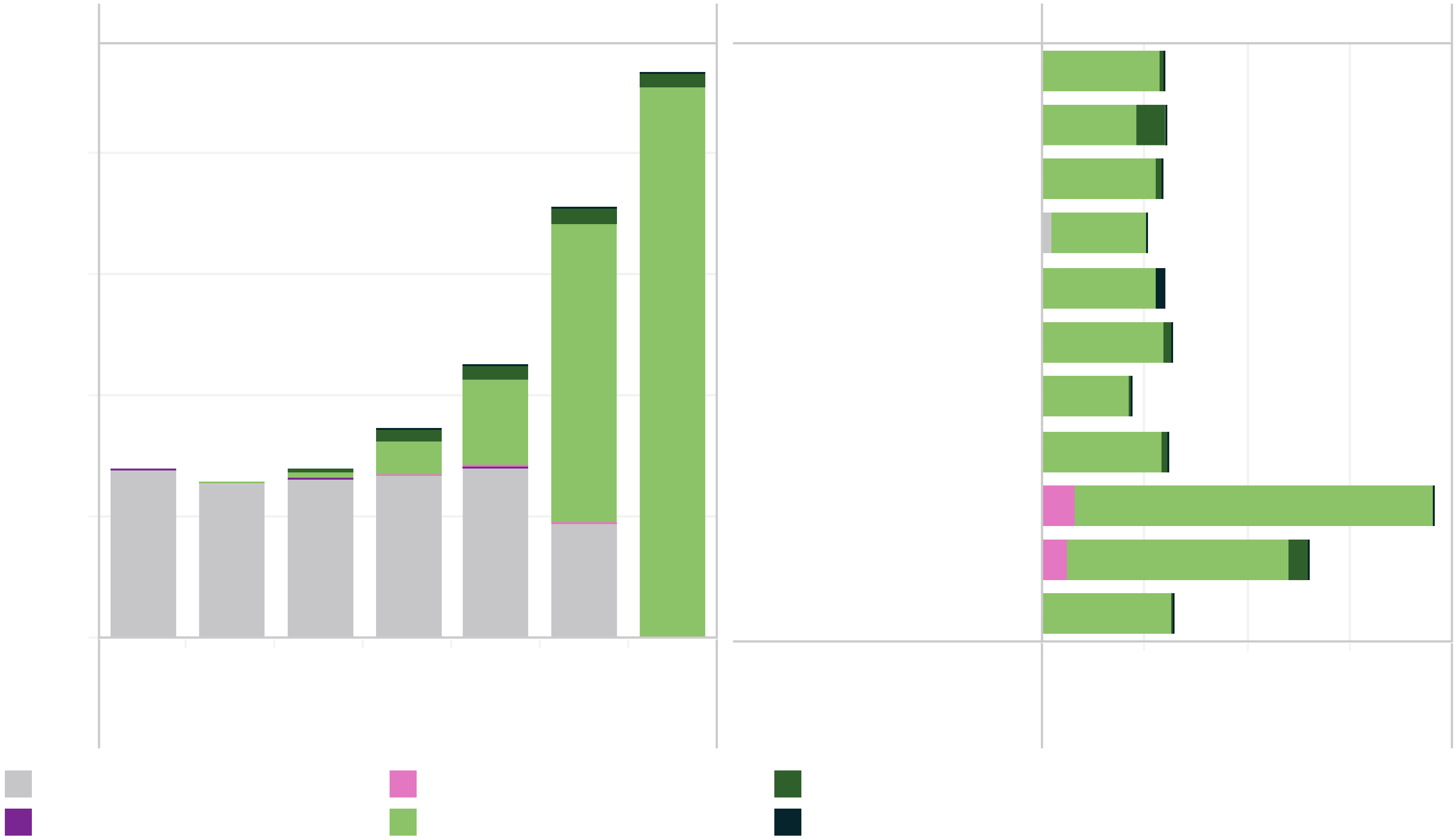
Hydrogen Demand

- **Hydrogen Demand Pre-2030**
  - Hydrogen demand remains steady through 2030, with declining refinery use balanced by increases in transport and chemical production (e.g., ammonia)
- **Post-2030 Growth**
  - Significant hydrogen demand growth occurs after 2030, driven by its use in ammonia production (for bunkering), the iron and steel industry, and some long-haul transport
- **Limited Role in Power Generation**
  - Hydrogen plays a minimal role in power generation until 2050, used primarily as a backup fuel due to its high cost, rather than for regular thermal power plant operations.



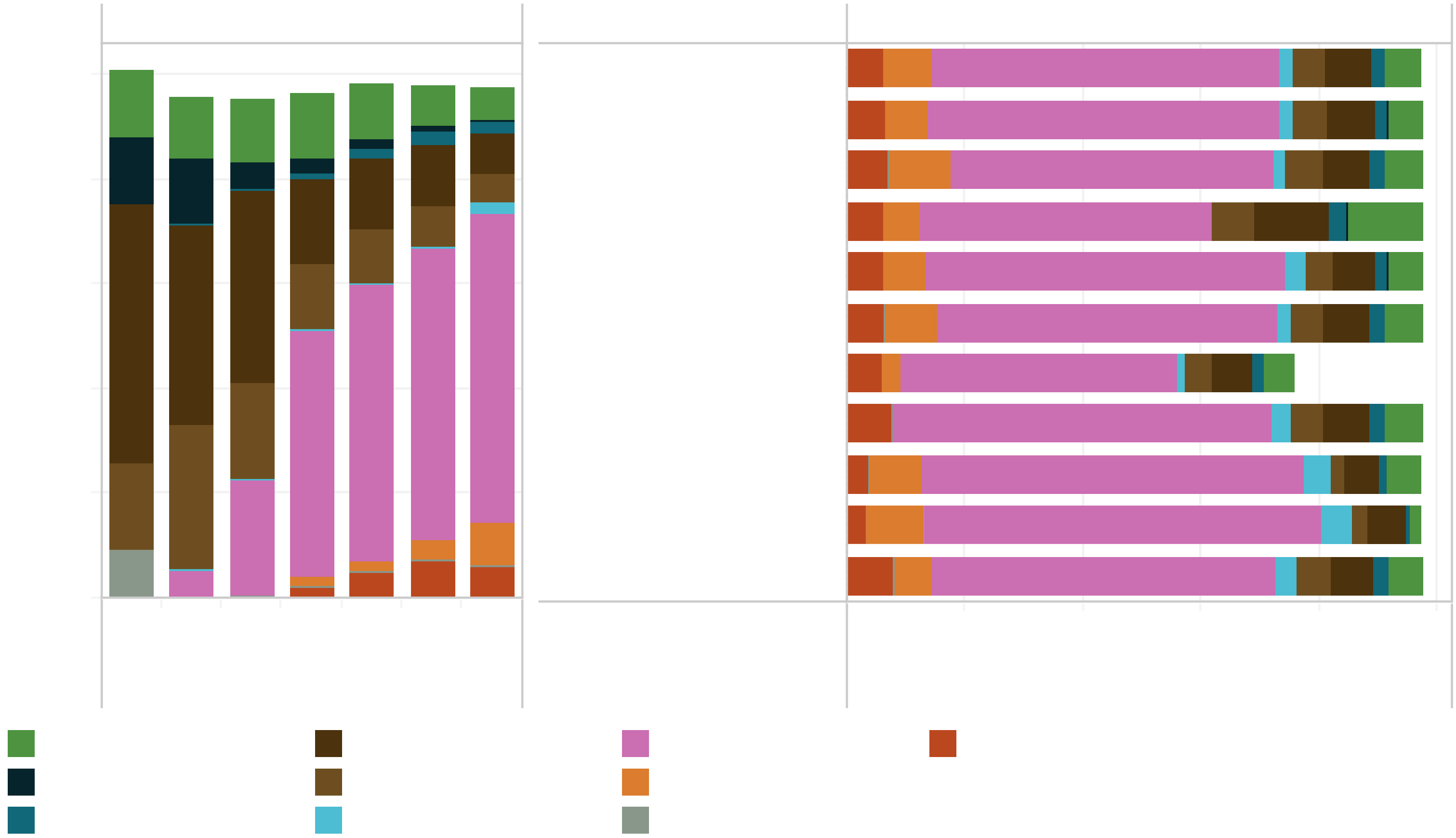
Hydrogen Supply

- **Post-2030 Clean Hydrogen Deployment**
  - Significant clean hydrogen resource deployment occurs after 2030, driven by economic factors favoring renewables for thermal generation displacement before increasing hydrogen production.
- **Electrolysis For Majority of Production**
  - Most clean hydrogen is produced via low-temperature electrolysis, with some nuclear high-temperature electrolysis in *Slow Electrification* and *No Sequestration* scenarios
- **Diverse Hydrogen Production Methods**
  - Most scenarios include some BECCS hydrogen, with blue hydrogen produced through autothermal reforming in the Include Gas with Carbon Capture scenario.



Steam Supply

- **Steam's Role in Decarbonization**
  - Steam remains essential for building heating and industrial processes, with the imperative for early decarbonization driven by the retirement of fossil CHP facilities and the need to replace this production.
- **Shift to Heat Pumps**
  - Decarbonization is accelerated by the economic benefits of heat pumps, driven by efficiency gains and high fuel prices.
- **Flexible Electric Technologies**
  - As renewable energy penetration grows, technologies like thermal energy storage and electric boilers gain traction, allowing heat production during low-priced electricity periods, while small modular nuclear reactors support nuclear CHP.



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Infrastructure

Electric Generation Capacity

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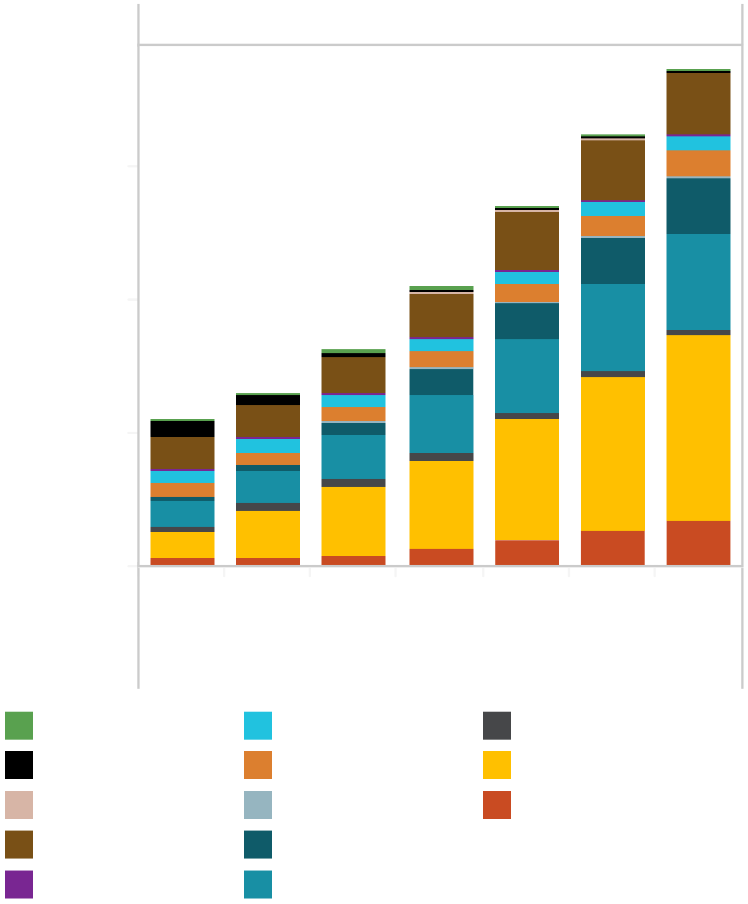
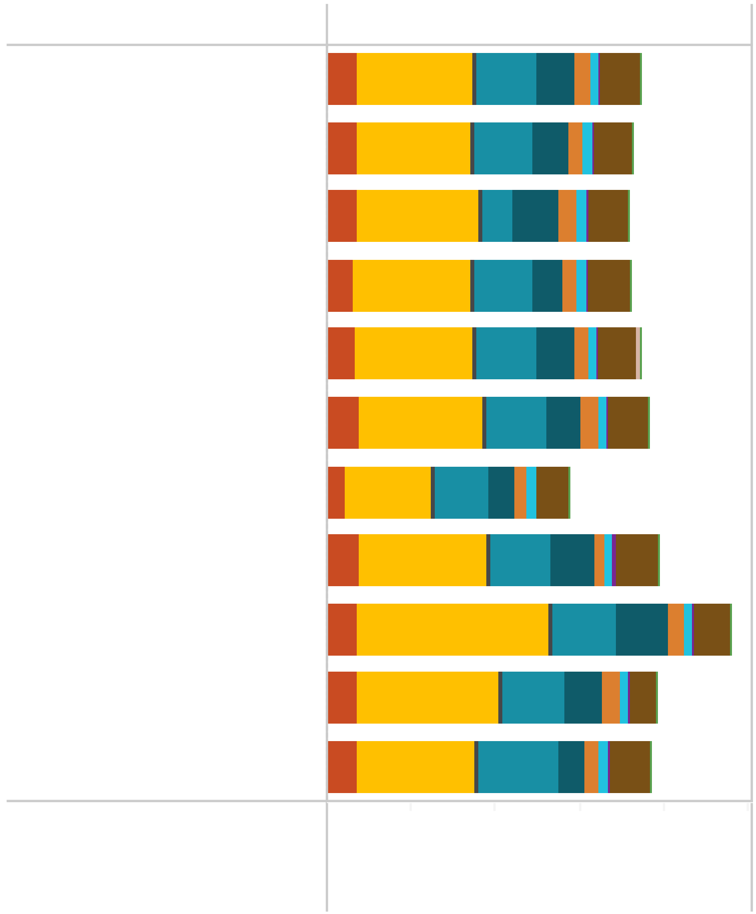
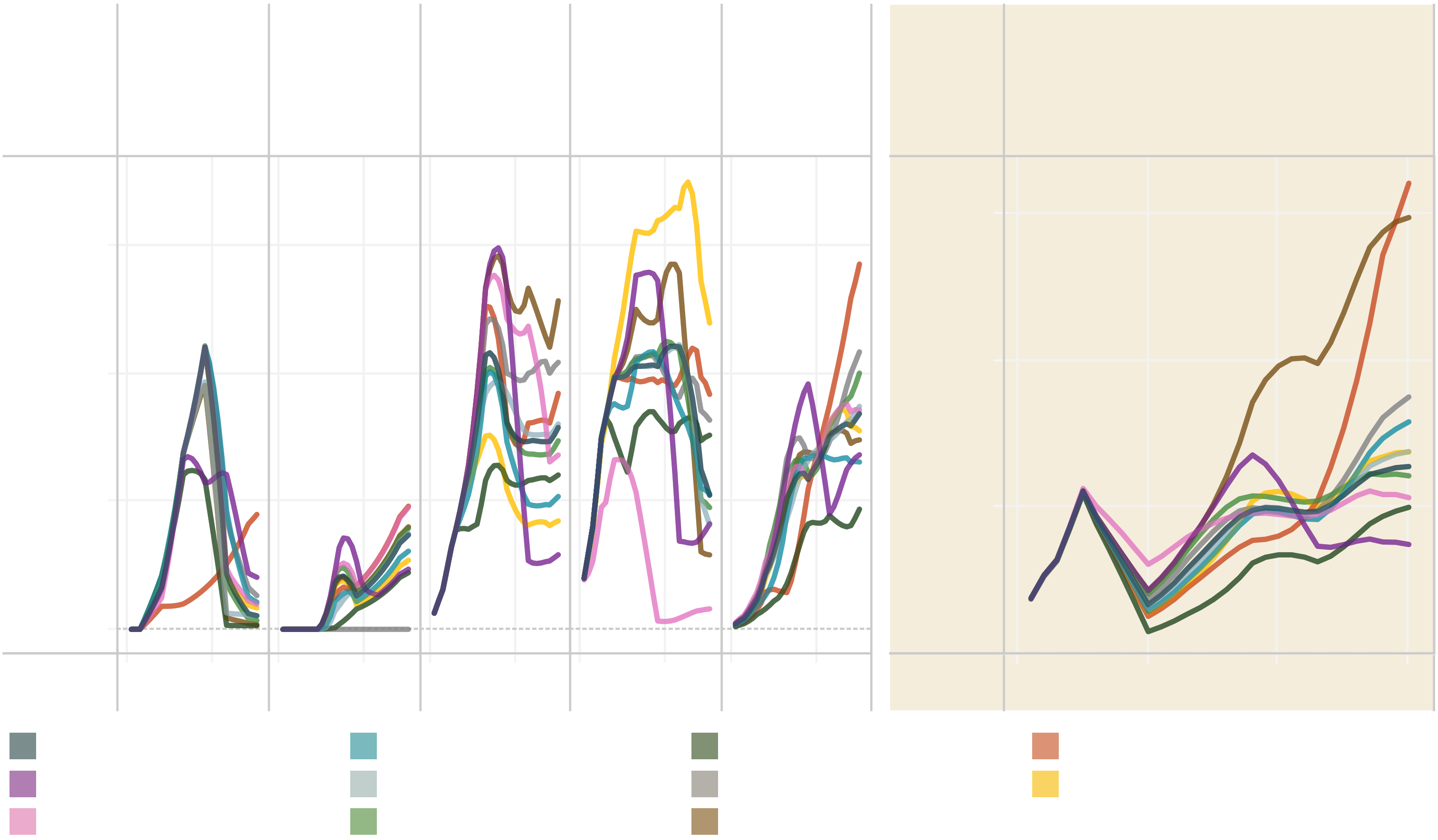
- **Generation Capacity Expansion**
  - In the *Core* Scenario, EU and UK generation capacity grows ~3.5x from 2021 to 2050, shifting from a thermal-based system to a predominantly renewable one by 2030, supported by battery storage and backup thermal capacity
- **Scenario-Specific Adjustments**
  - *No New Nuclear* relies on offshore wind and more backup thermal/battery storage, while *Constrained Renewables* substitutes offshore wind and nuclear for limited onshore wind resources.
- **Other Scenario Variations**
  - *Include Gas with Carbon Capture* integrates gas with carbon capture, *No Sequestration* adds 1 TW of renewables for e-fuel production, and *Unconstrained Renewables* favors onshore wind over offshore wind.





Annual Capacity Build Rates

- **Accelerated Deployment Across Resources**
  - Significant increases in electricity build rates are required, with offshore wind peaking at 30 GW in 2035, onshore wind at 35 GW in 2045, and solar reaching nearly 155 GW by 2050 in the Slow Electrification Scenario.
- **Nuclear and Backup Thermal Generation**
  - Nuclear power peaks at 9+ GW in 2050, and backup thermal generation reaches over 20 GW per year to support electrification and replace retiring coal and lignite plants.
- **Challenges with Storage**
  - Short-duration batteries cannot meet reliability needs, and long-duration storage is neither economically viable nor scalable to satisfy reliability demands in the required timeframe.



New Energy Storage

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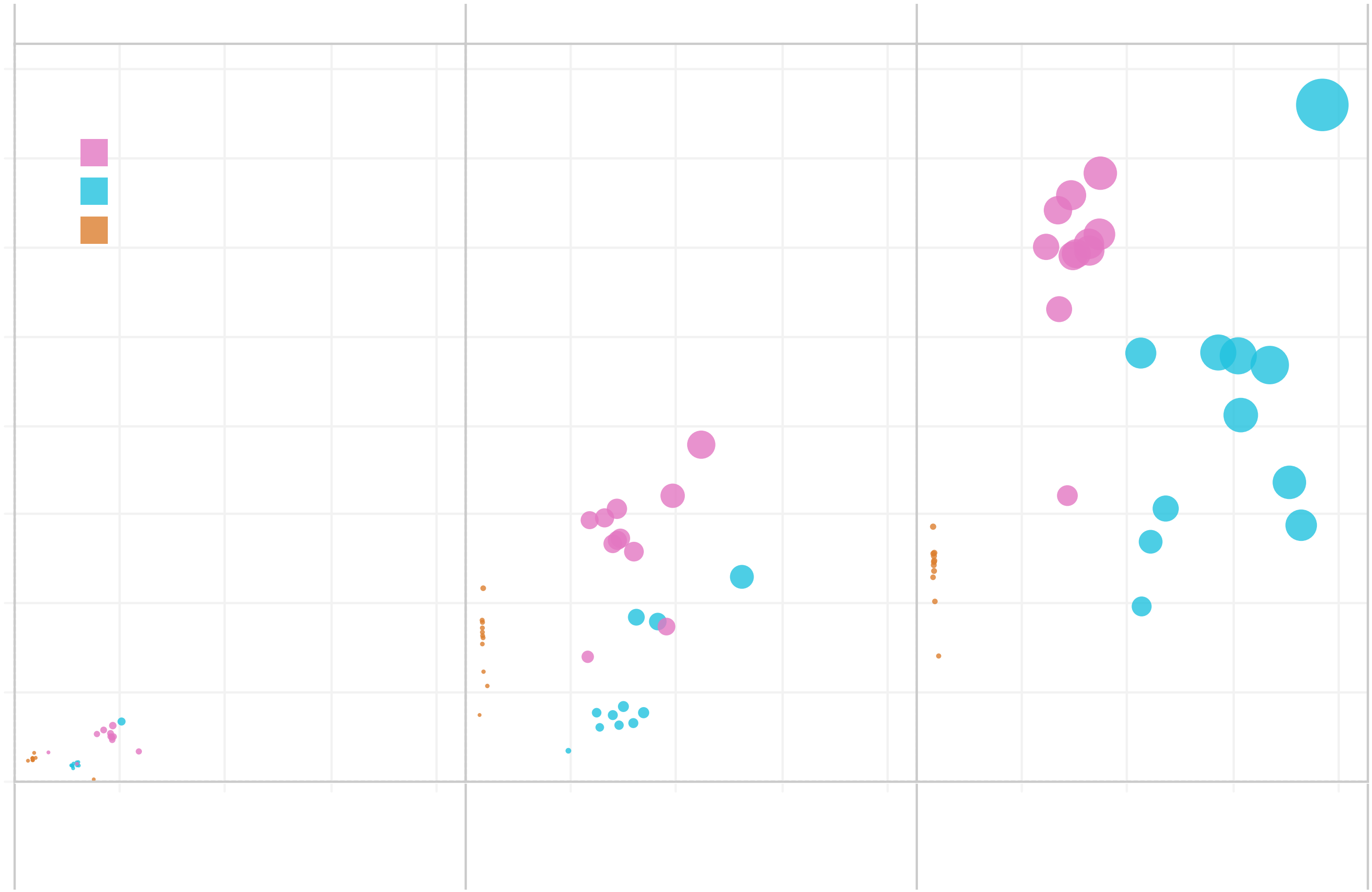
- **Figure Explanation**
  - This figure shows bubbles of storage energy capacity against a y-axis of charge capacity and an x-axis of duration. Each bubble represents a storage type for a scenario.
- **Storage Definitions**
  - Storage is categorized by its input-to-output energy carrier: electricity storage (batteries, pumped hydro), thermal storage (e.g., molten salt), and hydrogen storage (tanks, underground reservoirs).
- **Evolution of Storage Duration**
  - As the grid becomes more renewable, storage duration increases to manage longer periods of overgeneration. More “charge” capacity is in electricity storage but generally more stored energy capacity is in hydrogen storage.



New Electricity Storage

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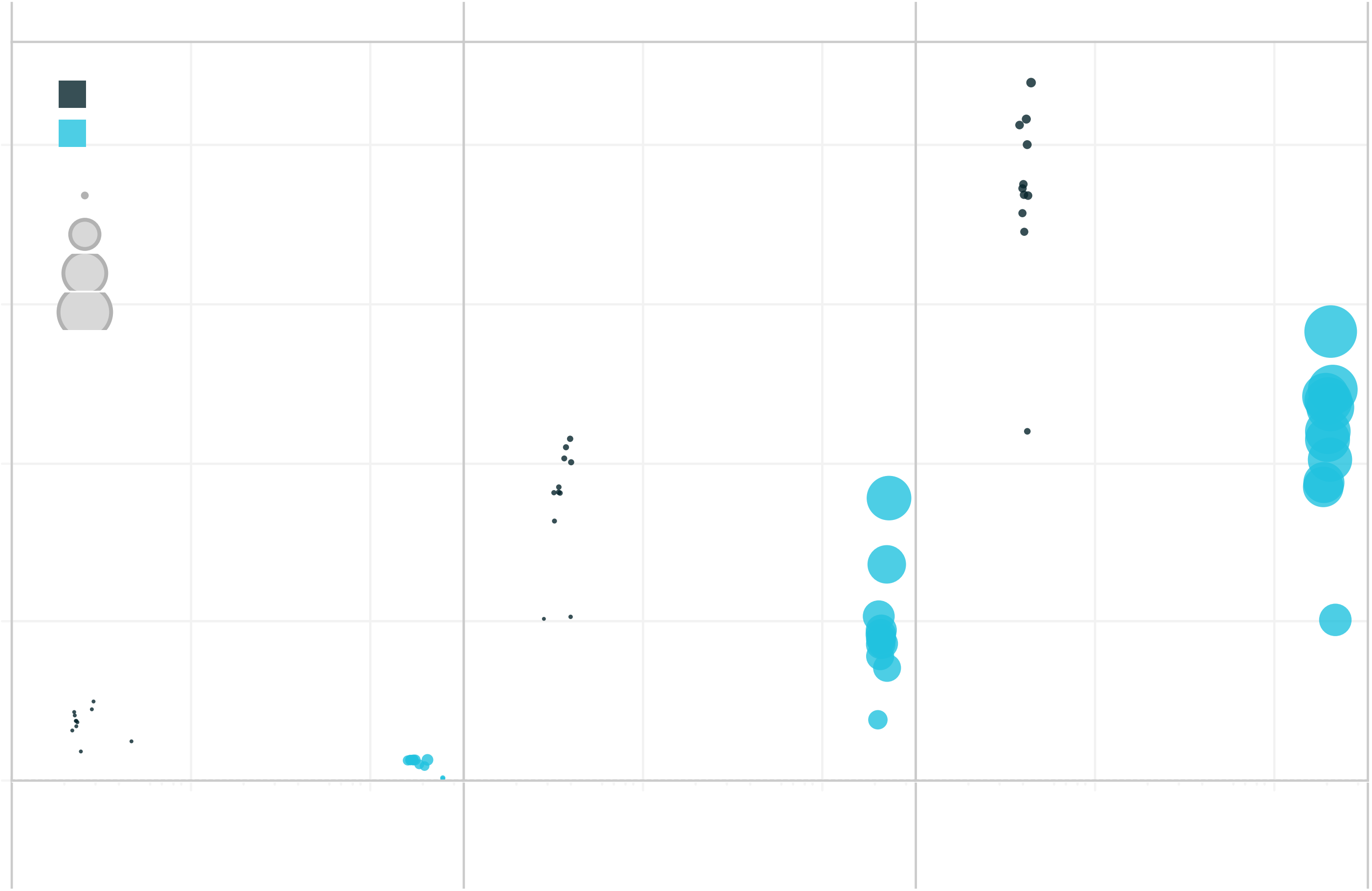
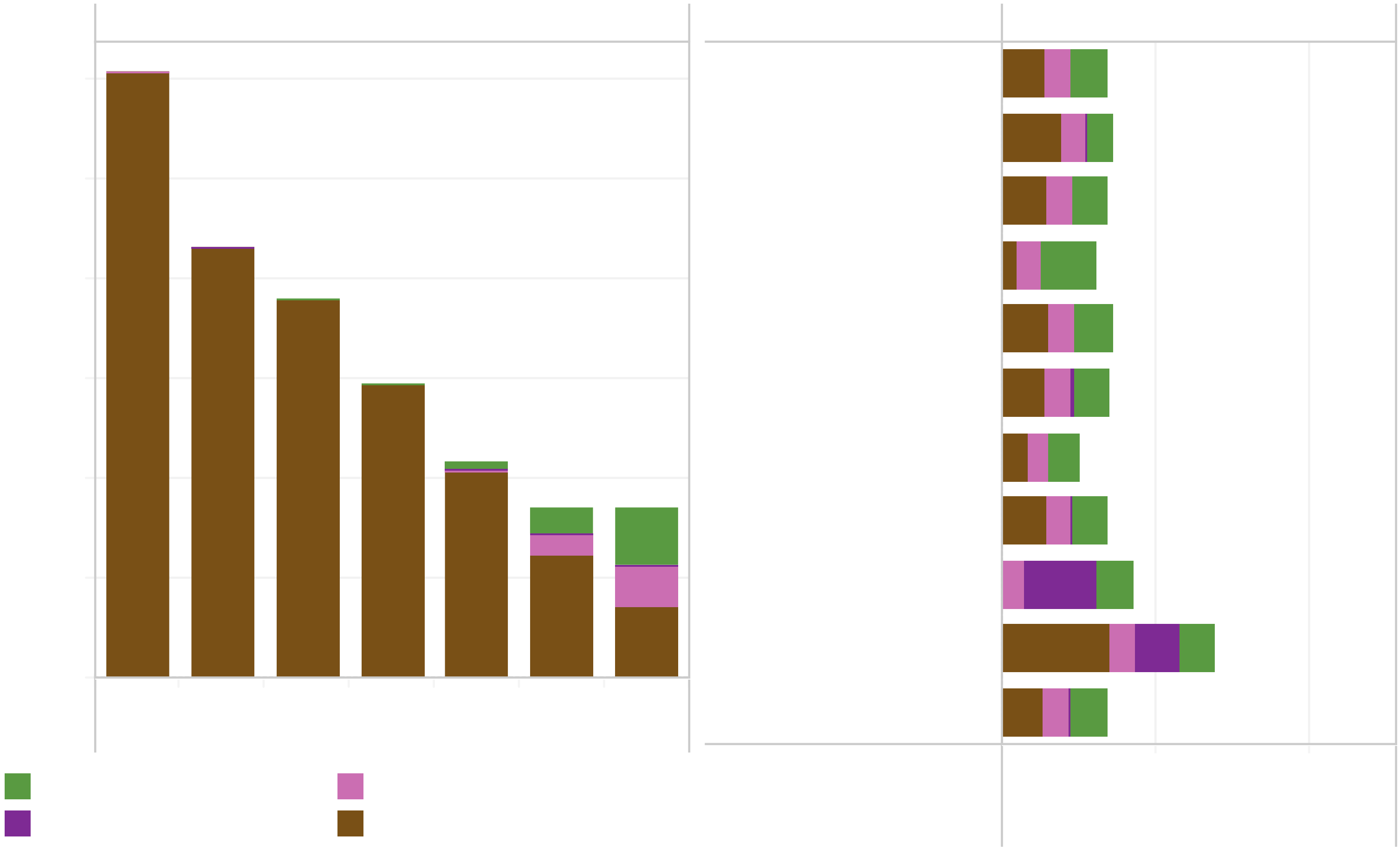
- **Economic Challenges of Electricity Storage**
  - Large-scale electricity storage will only be viable if costs drop significantly, with multi-day storage modeled to decrease from €1488/kW in 2030 to €734/kW by 2050.
- **Impact of Unmet Cost Targets**
  - If cost reductions are not achieved, there will be less electricity storage, with increased reliance on thermal backup (including nuclear) and hydrogen storage.
- **Storage Technology Differentiation**
  - Li-ion batteries dominate shorter durations (~4 hours), while long-duration storage dominates in terms of energy storage GWh



Fuels Capacity

- **Decline in Fuel Production Capacity**
  - Electrification leads to a significant reduction in overall fuel production capacity, driven by the retirement of petroleum refining due to decreasing demand.
- **E-fuels and Biofuels Replace Some Capacity**
  - In the long term, e-fuels (ammonia, Fischer-Tropsch, methanol) and biofuels partially replace the retired capacity.
- **>50% Decline in Most Scenarios**
  - Fuel production capacity declines by more than 50% in all scenarios except *Slow Electrification*.



Building Heat Pumps

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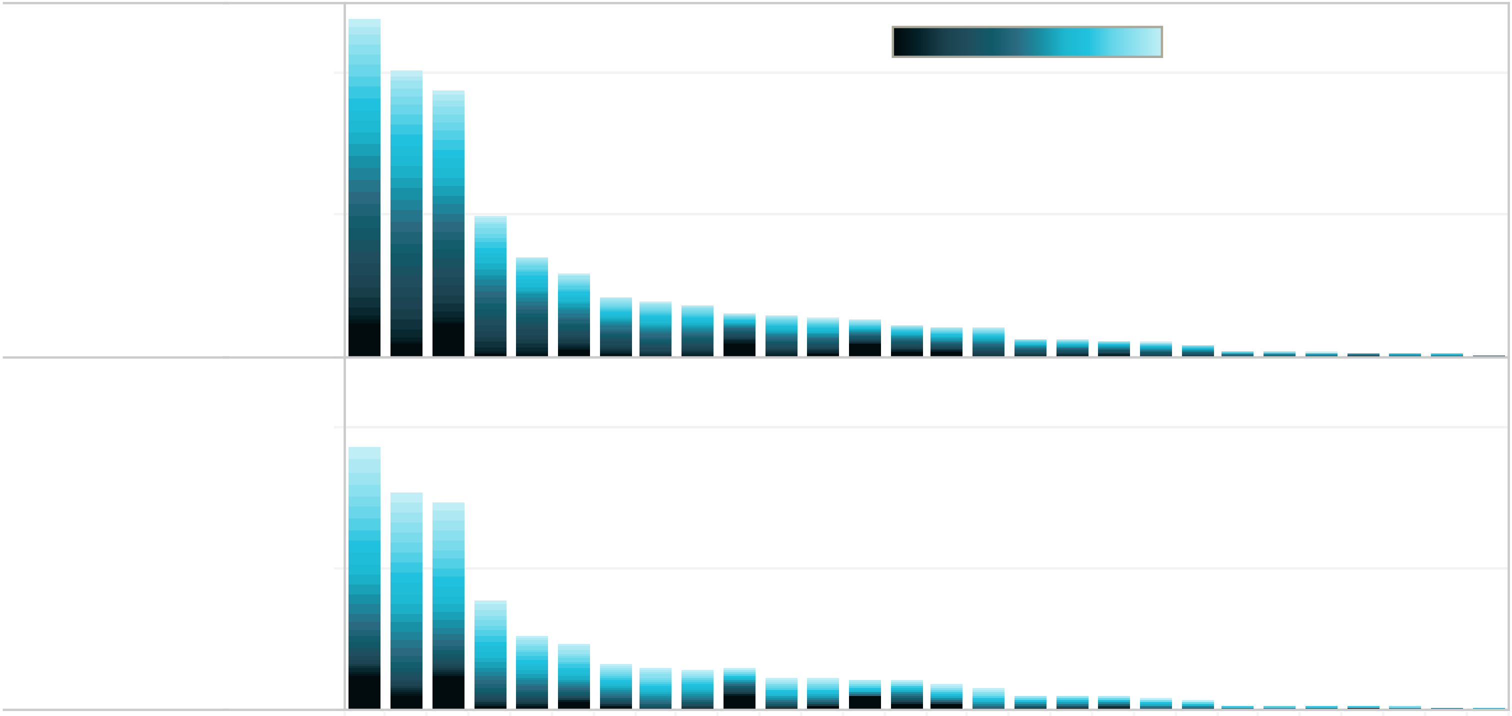
- **Boilers to Heat Pump Transition**
  - The largest change in building stock involves widespread deployment of heat pumps for space heating across Europe, alongside building envelope upgrades.
- **Scaling the Heat Pump Market**
  - Hundreds of new GWs of heat pumps will need to be installed across Europe requiring a significant scale-up in the heat pump market, with installation growth illustrated by country and year.
- **Impacts on Electricity and Distribution**
  - This shift affects electricity generation planning and distribution networks due to the significant increase in electricity demand.



Zero-Emissions Vehicles

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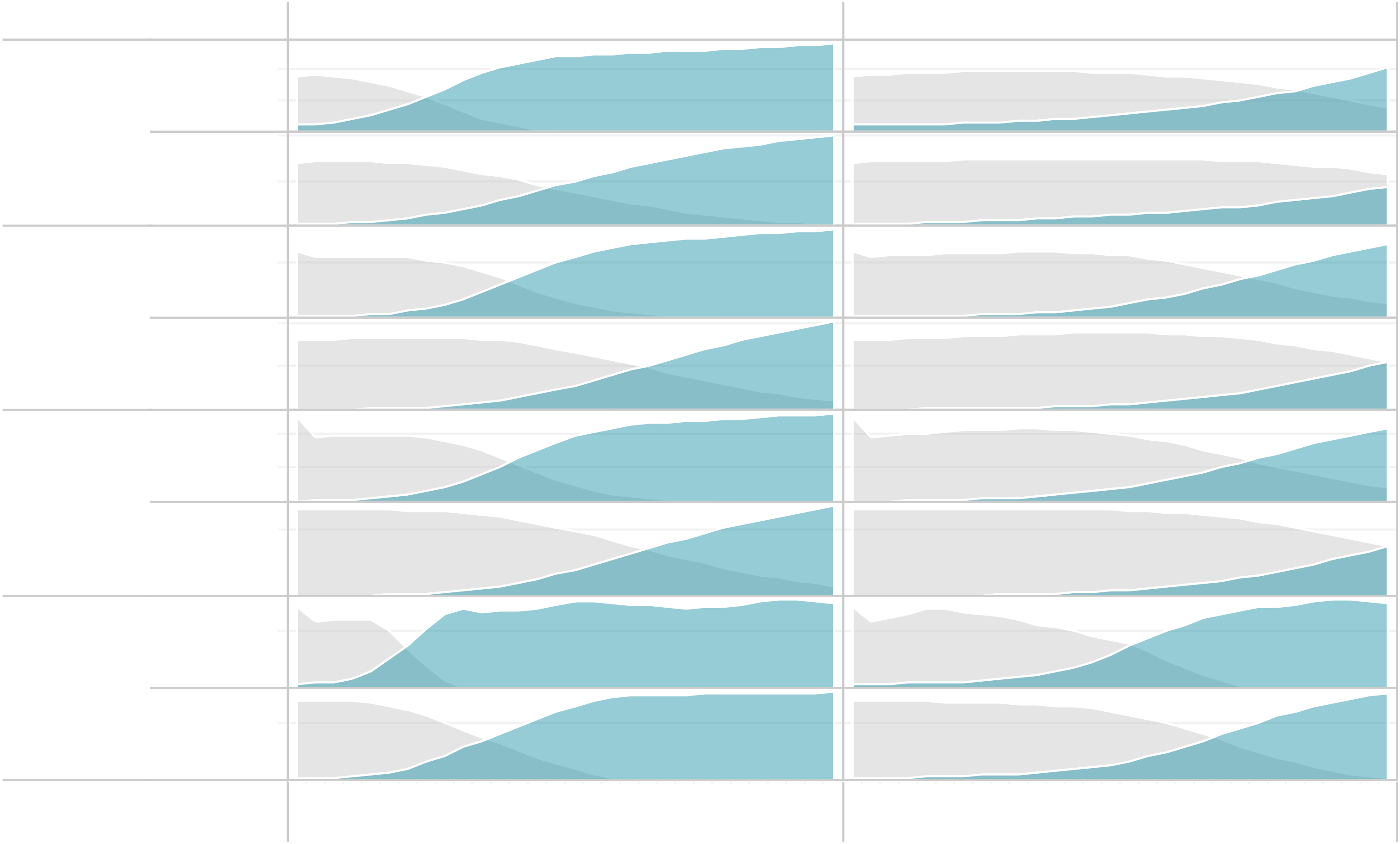
- **ZEV Growth by Scenario**
  - On-road zero-emission vehicle (ZEV) growth varies by Scenario, with the *Core* scenario achieving significantly higher ZEV adoption by 2050 compared to *Slow Electrification.*
- **Impact of Slow Electrification**
  - In this scenario, slower ZEV sales growth leads to only half the ZEVs on the road by 2050 compared to the *Core* scenario.
- **Need for Zero-Carbon Fuels**
  - Slow ZEV adoption in *Slow Electrification* increases reliance on zero-carbon fuels to meet emissions targets.



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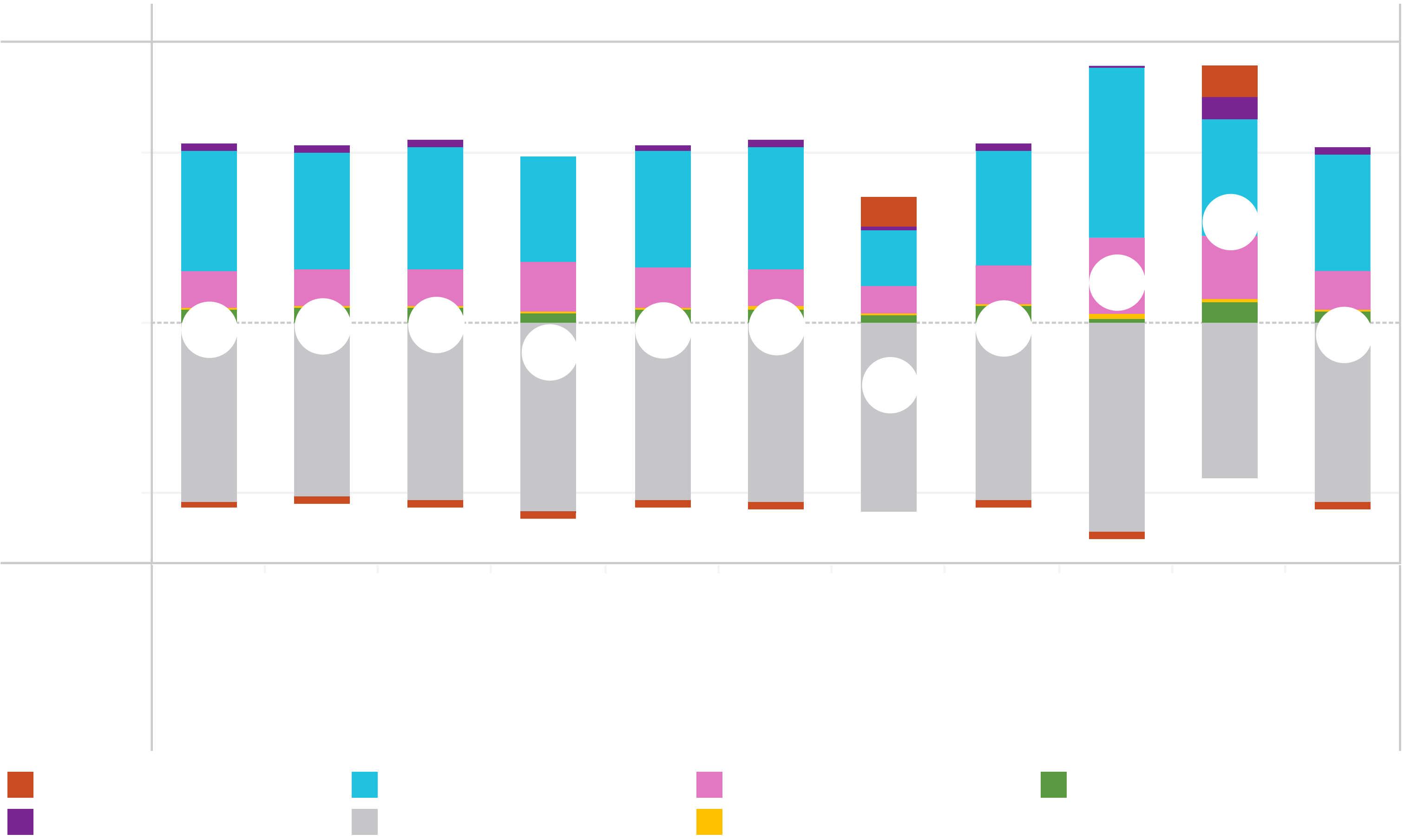
Costs

Net Costs in 2050

- Net Energy System Costs
  - This analysis includes costs for demand-side equipment and energy efficiency investments, calculating the levelized societal costs of producing, delivering, and consuming energy, as well as commodity costs like oil and natural gas. The metric calculates costs and savings from decarbonization efforts (net of the *Baseline)*, including efficiency, electrification, low-carbon fuels, and non-CO_2 mitigation.
- Cost Drivers
  - Decarbonization raises costs for electricity (grid, generation, storage), low-carbon fuels, and mitigation, while demand-side investments (e.g., building upgrades, ZEVs) increase short-term costs but lead to long-term savings with cheaper EVs.



Net Costs by Sector

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- Unequal Cost Distribution
  - The costs and savings from decarbonization are unevenly distributed across sectors, impacting consumers and European competitiveness.
- Industry and Residential Costs
  - Much of the cost increase is borne by the industrial and residential sectors
- Transport Savings
  - The largest savings come from the transport sector, particularly from the long-term electrification of on-road transportation.

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Conclusions

Conclusions

- This year's report integrates more granular geographic downscaling analyses and expanded emissions scope for a comprehensive view of decarbonization.
- The refined modeling highlights the need for infrastructure, technological advancements, and societal shifts to reach deep decarbonization.
- The Scenarios emphasize that there is no one-size-fits-all solution, advocating for regionally tailored approaches.
- Significant investments in infrastructure, especially energy storage, transmission networks, and hydrogen pipelines, are critical to decarbonization.
- Robust and adaptable policy frameworks are necessary to meet ambitious decarbonization targets under changing technological and market conditions.
- This report provides stakeholders with actionable insights for achieving a sustainable and resilient net-zero future in Europe.

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Modeling Resources

Modeling Resources

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	Format
Summary Model Results	Online Tableau (also downloadable)
Country Model Results	Online Tableau (also downloadable)
Downscaling Maps	Online Tableau (also downloadable)
Data Input Catalog	Excel
Technical Documentation	Word
Additional Data	.csv files (available on request)

THANK YOU

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