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ENERGY
RESEARCH

CARBON-FREE EUROPE
A TECHNOLOGY-INCLUSIVE CLIMATE INITIATIVE

CARBON-FREE EUROPE ANNUAL DECARBONIZATION PERSPECTIVE 2024

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ABOUT EVOLVED ENERGY RESEARCH

Evolved Energy Research (EER) is a research and consulting firm focused on questions posed by transformation of the energy economy. Their consulting work and insight, supported by complex technical analyses of energy systems, are designed to support strategic decision-making for policymakers, stakeholders, utilities, investors, and technology companies.

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GLOSSARY OF TERMS

Biofuel: A renewable energy source made from organic materials, such as plant biomass, animal waste, or used cooking oil. It serves as an alternative to fossil fuels and can be used in transportation, heating, and electricity generation while reducing greenhouse gas emissions.

Biomass: Organic material, such as wood or agricultural waste, used as a renewable energy source. It can be converted into biofuels for energy production or heating.

Building Shell: The physical structure of a building, including walls, roofs, windows, and doors, which separates the interior of the building from the outside environment. Improving the building shell can significantly enhance energy efficiency by reducing heat loss and improving insulation.

Capacity Factor: A measure of how often a power plant runs at its maximum capacity. It is the ratio of actual energy output over a period of time to the maximum possible output if the plant were running at full capacity all the time.

Carbon Capture and Storage (CCS): A technology that captures carbon dioxide emissions from sources like power plants and stores it underground to prevent its release into the atmosphere.

Combined Heat and Power (CHP): A system that simultaneously generates electricity and useful heat from the same energy source, increasing overall efficiency.

Decarbonization: The process of reducing carbon dioxide emissions through the use of low-carbon technologies, renewable energy, and other mitigation strategies.

Direct Air Capture (DAC): A technology that captures carbon dioxide directly from the atmosphere for sequestration or use in industrial processes.

Dunkelflaute: A German term meaning “dark doldrums,” referring to periods of time with low solar and wind power generation, typically during the winter when there is little sunlight and wind. These periods create challenges for energy systems heavily reliant on renewable energy.

Electricity Balancing: The process of ensuring that the supply of electricity on the grid matches the demand in real time. As electricity cannot be easily stored at large scales, system operators must continuously adjust the output of power plants or the load to keep the grid stable and avoid blackouts. This is especially important in grids with a high share of intermittent renewable energy sources, like wind and solar, which require flexible resources such as batteries, dispatchable power plants, or demand response to maintain balance.

Electrification: The substitution of fossil fuels with electricity in various sectors, such as transport, heating, and industry, to reduce greenhouse gas emissions.

Electrofuels (E-fuels): Synthetic fuels produced by combining hydrogen (from electrolysis powered by renewable energy) with carbon dioxide. They are considered a low-carbon alternative for industries like aviation and shipping.

Electrolysis: A process that uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2). When powered by renewable energy sources like wind or solar, electrolysis produces "green hydrogen," a zero-carbon fuel that can be used in various sectors, such as industry, transportation, and energy storage.

Emissions Trading System (ETS): A market-based approach to controlling pollution by providing economic incentives for reducing emissions of pollutants. The EU ETS is a cornerstone of the EU's policy to combat climate change.

Energy Market Capture Rates: A measure of the revenue a generator earns compared to the average market price of electricity. It reflects how well a particular energy source, such as wind, solar, or gas, can "capture" the value of electricity at different times, depending on when and how much it produces relative to market prices.

Final Energy Demand: The total energy consumed by end users such as households, industries, and transport. It excludes energy losses during generation and transmission.

Energy Transition: The process of shifting from fossil fuel-based energy systems to renewable energy sources like wind and solar to meet climate goals.

Fit for 55: A European Union legislative package aimed at reducing greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.

Geographic Downscaling: A method used in the report to translate country-wide energy model results into high-resolution ($1km^2$) outputs to better visualize local infrastructure needs.

Geologic CO_2 Sequestration: The process of capturing carbon dioxide (CO_2) emissions and storing them underground in geological formations, such as depleted oil and gas fields, saline aquifers, or unmineable coal seams. The CO_2 is injected deep underground, where it is trapped and prevented from being released back into the atmosphere, helping to mitigate climate change by reducing greenhouse gas concentrations.

Geothermal Energy: Renewable energy derived from heat stored in the earth, used for electricity generation or direct heating applications.

Greenhouse Gases (GHGs): Gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) that trap heat in the atmosphere, contributing to global warming.

Heat Pumps: Devices that transfer heat from a cooler space to a warmer one, or vice versa, using electricity. They are more energy efficient compared to traditional heating and cooling systems.

Hydrocarbon: Organic compounds made up of hydrogen and carbon atoms, primarily found in fossil fuels like coal, oil, and natural gas though they can be produced through other processes that don't produce net carbon emissions. Hydrocarbons are burned to release energy, which is used in electricity generation, heating, and transportation.

Land Sink: Natural ecosystems, such as forests, grasslands, and wetlands, that absorb more carbon dioxide from the atmosphere than they release, effectively acting as a "sink" for carbon. Land sinks play a crucial role in offsetting emissions and are integral to strategies aimed at achieving net-zero emissions.

Levelized Cost of Energy (LCOE): A measure of the average cost per unit of electricity produced, which takes into account the total costs of building and operating a power plant over its lifetime.

Long-duration Energy Storage: Energy storage systems designed to store electricity for extended periods (from several hours to days) to balance energy supply and demand, especially during times of low renewable generation.

Multi-day Energy Storage: Energy storage systems capable of providing power over several days, crucial for managing periods of low renewable energy output during high-demand times.

Net Costs: The overall cost of an energy system transition or project, calculated by subtracting any savings (such as from increased efficiency or reduced fuel costs) from the total expenses (including infrastructure investments, technology costs, and operational expenses). In decarbonization Scenarios, net costs reflect the balance between upfront investments in clean energy technologies and long-term savings from lower energy consumption.

Net Load: The difference between the total electricity demand and the amount of electricity being generated by variable renewable energy sources, such as wind and solar. It represents the amount of electricity that must be supplied by dispatchable energy sources (e.g., natural gas, nuclear, or stored energy) to meet the remaining demand.

Net Zero: Achieving a balance between the amount of greenhouse gases emitted and the amount removed from the atmosphere, with the goal of reducing net emissions to zero.

Offshore Wind: Wind power generation located off the coast in bodies of water, which has higher capacity factors and is less visually intrusive compared to onshore wind farms.

Pathway: A modeled trajectory or series of steps that outline how specific goals—such as reducing greenhouse gas emissions or achieving net zero—can be achieved over time. Pathways are the results of detailed analyses that consider various factors like technological advancements, policy interventions, and resource availability. They map out the transformations needed across sectors, providing a roadmap for achieving climate targets.

Power Purchase Agreement (PPA): A contract between an electricity generator and a buyer (usually a utility or large consumer) to purchase electricity at a pre-agreed price, often used to fund renewable energy projects.

Primary Energy Demand: The total amount of energy required to meet a country's or region's energy needs before any conversions or losses in the energy supply chain. It includes energy consumed in the form of raw fuels (like coal, oil, natural gas) and renewable sources before being converted into electricity, heat, or other forms of energy used by end consumers.

Renewable Energy: Energy derived from natural sources that are replenished constantly, such as wind, solar, hydro, and geothermal energy.

Residual Emissions: Emissions that remain after all feasible emissions reduction measures have been implemented, often requiring compensation through offsets or sequestration to achieve net zero.

Scenario: A set of contextual assumptions or situational conditions used to frame the analysis of a pathway. Scenarios define the external factors—such as economic growth, policy constraints, societal preferences, or technological adoption—that shape how the energy system might evolve. Each Scenario explores a different set of conditions to understand how changes in these factors can impact the feasibility and outcomes of different pathways.

Scenario Analysis: The process of modeling different future pathways for energy systems, based on varying assumptions about policy, technology, and societal preferences.

Sequestration: The process of capturing and storing carbon dioxide emissions underground, typically in geological formations, to prevent their release into the atmosphere.

Small Modular Reactors: A type of nuclear reactor that is smaller than traditional nuclear power plants, offering more flexibility in deployment.

Smart Grid: An electricity grid that uses digital technology to monitor and manage the distribution of electricity more efficiently, allowing for better integration of renewable energy and greater system resilience.

Thermal Energy Storage: A technology that stores energy in the form of heat or cold, which can later be used for heating, cooling, or electricity generation. Common methods include storing heat in materials like molten salts, water, or other mediums. This stored thermal energy can be used during periods of high demand or when renewable energy is unavailable, helping balance supply and demand in energy systems.

Uncombusted Fuels: Fuels that are used in processes without being burned or oxidized, thereby not releasing carbon dioxide into the atmosphere. These fuels can be used as feedstock in the production of chemicals, plastics, and other materials, where the carbon remains locked in the product rather than being emitted as a greenhouse gas.

Zero-carbon Fuels: Fuels that do not emit net carbon dioxide during their lifecycle (production to combustion), including hydrogen, ammonia, and synthetic fuels.

ABOUT THIS REPORT

This report investigates options for long-term deep decarbonization pathways for Europe. It represents the third in a series of annual updates that move pathways analysis beyond isolated proofs-of-concept towards becoming a practical implementation tool for addressing next-stage challenges in energy and climate change mitigation, one that is responsive to changing technology, policy, and geopolitical conditions. The report also produces a rich public dataset that can and has been used by European governments and NGOs. This work was conducted for Third Way's Carbon-Free Europe.

I

FOREWORD

We are delighted to introduce our third Annual Decarbonization Perspective (ADP), which provides essential insight into Europe's progress toward net-zero goals.

The report has proved to be a "must-read" analysis for policymakers, industry leaders, and others seeking to understand the different pathways to carbon neutrality, and to assess the long-term policy implications and economic opportunities that each present.

Compiled and written by our partners, Evolved Energy Research, the ADP incorporates the latest data and best technological developments and is a timely and expert evaluation of progress across the European Union (EU) and UK.

We are particularly excited that this year, for the first time, it includes new visual maps to provide a more granular and precise picture of local infrastructure needs and opportunities. The new analyses also reflect how progress towards net zero can support broader economic objectives.

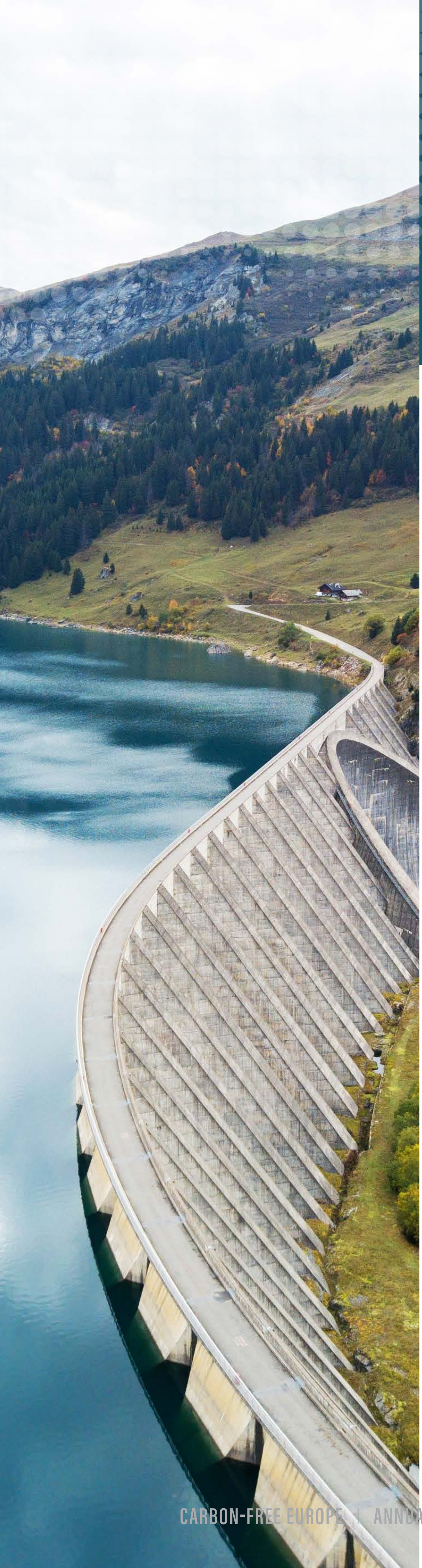
One of the overall conclusions of this year's report is the risk of overly rigid targets that lack the flexibility necessary for effective implementation and delivery at national or local levels, not least because of market realities or supply chain issues.

There is no single, uniform pathway to net zero. With the next European Mandate approaching, we hope that the EU can match its strong ambitions with greater adaptability to accommodate diverse national circumstances and the evolving economic and security challenges facing the continent.

We trust this report continues to provide accurate and impactful insights to all who use it, and that it helps encourage the rapid adoption of clean energy in a sustainable, competitive, and resilient Europe.

Josh Freed
Lindsey Walter

Co-Founders, Carbon-Free Europe



II

INTRODUCTION

This report investigates long-term strategies for achieving net-zero emissions across Europe by developing deep decarbonization pathways. These pathways are detailed technical plans on how Europe can transform the economy to meet emissions reduction targets, created using a model that optimizes investments in and operations of the energy system. We generate multiple pathways under varying situation assumptions to provide an extensive look at how Europe can reach net zero. This report interprets these highly technical and granular analyses into a cohesive narrative with viable actions for European policymakers, industry, and civil society. Our approach complements the European Commission's traditional policy projection models, which emphasize the potential impact of current policy, by offering a dynamic perspective on the risks and opportunities of a wide range of emission's reduction strategies.

The alternative pathways analyzed here provide insights into the diverse investment needs across countries, as well as the requisite levels of research and development in emerging clean energy technologies. They shed light on critical challenges such as land-use constraints and other socio-economic obstacles, the equitable distribution of costs for consumers, and the dependency on specific technologies and emissions-reduction approaches. By exploring these pathways, we highlight the pivotal elements of the energy transition and outline their timeframes—an essential task in light of the anticipated shortfalls in meeting near-term sectoral targets.

The Scenarios in this year's report are aligned with a central theme of "Europe's New Energy Map." Scenarios, for our purposes, represent the contexts of varying policy constraints and societal preferences that affect how technologies and resources are deployed; pathways, on the other hand, comprise the analytical responses to these Scenarios—the solutions to achieving net-zero emissions. As Europe transitions toward a decarbonized economy, the geographical landscape of its energy system shifts dramatically. Countries develop distinct advantages based on their location, resource availability, and societal acceptance of new energy technologies. Additionally, networks are created or repurposed to distribute clean energy, such as electrons and hydrogen, while facilitating the cross-border transmission of captured carbon for storage or reuse. To further enhance our understanding of this evolving energy landscape, this year's report introduces an additional analytical tool known as *downscaling*, which translates the results of our model (operating at a country-wide level) into more granular (kilometer grid cells), high-resolution maps of energy infrastructure. This new component enables us to visualize the energy transition at a finer scale, providing a clearer picture of the future European energy system to inform stakeholders on the local potential and impacts of clean energy deployment.

These Scenarios also have implications for competitiveness, both in terms of energy supply within Europe but also in terms of industrial competitiveness globally. This will come in the form of demonstrating and deploying low-carbon technologies to eventually be used by the rest of the world, but also in terms of policy and market design that can ensure low-cost, low-carbon, and reliable energy supplies.

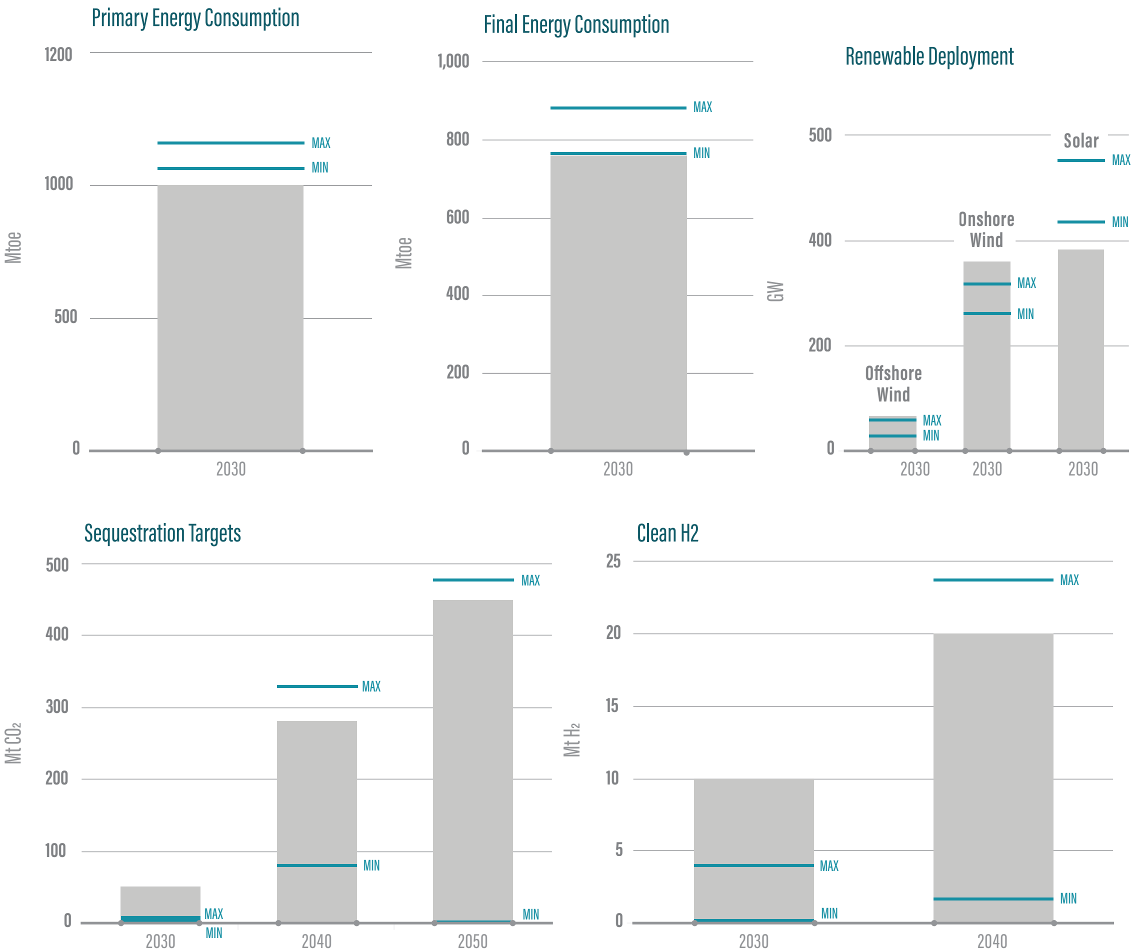
III EXECUTIVE SUMMARY

Prescriptive Policy

In recent years, the EU has made significant advancements in its climate policy, driven by the comprehensive Green Deal agenda. The EU has established a legally binding target to achieve climate neutrality by 2050, aiming to reduce greenhouse gas emissions by at least 55% by 2030, relative to 1990 levels. To achieve this ambitious goal, the "Fit for 55" package was introduced, comprising a series of legislative proposals intended to transform key sectors such as energy, transportation, and industry. This package includes critical reforms such as bolstering the EU Emissions Trading System (ETS), introducing carbon pricing for traditionally exempt sectors like shipping and aviation, and rapidly scaling up renewable energy deployment across all EU Member States. Collectively, these measures form the backbone of the EU's strategy to cut emissions and promote a low-carbon economy.

However, while sector- and technology-specific targets are essential to guiding member states toward meeting these climate objectives, there are challenges with the current approach, as ***Figure 1*** demonstrates. These targets, though not always legally binding, serve as important indicators of progress, yet they often lack the flexibility necessary for effective decarbonization at the national level. Member states may struggle to implement them through their own climate policies if the targets are overly aggressive or rigid. Additionally, technology-specific targets may overlook complex market realities and supply chain issues, creating the false perception that there is a single, uniform pathway to net zero. It is crucial that the EU balances ambition with adaptability, ensuring that its targets are robust yet flexible enough to accommodate diverse national circumstances and the evolving challenges of the green transition.

FIGURE 1. Modeled EU Results vs. Policy Targets[1]



Note: *A comparison of the projected target achievements in all Scenarios (blue lines) with the established policy targets for 2030 and 2050 (grey bars).*

While recognizing the need for market transformation, we specifically question the feasibility of some of the ambitions for clean hydrogen and sequestration in the near term. Supply targets for clean hydrogen outstrip demand in 2030 as use cases in transport and industry are still developing and the principal user of hydrogen today—petroleum refineries—is in decline. Similarly, 2030 sequestration targets have higher than expected deployment of carbon capture technologies. While these 2030 targets are likely more than what is required within the next six years to stay on track for carbon neutrality, these technologies are essential for reaching net zero, and policymakers are right to support creating early markets for their deployment but should also be realistic about near-term prospects.

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[1] Clean H_2 target refers to domestic production targets.

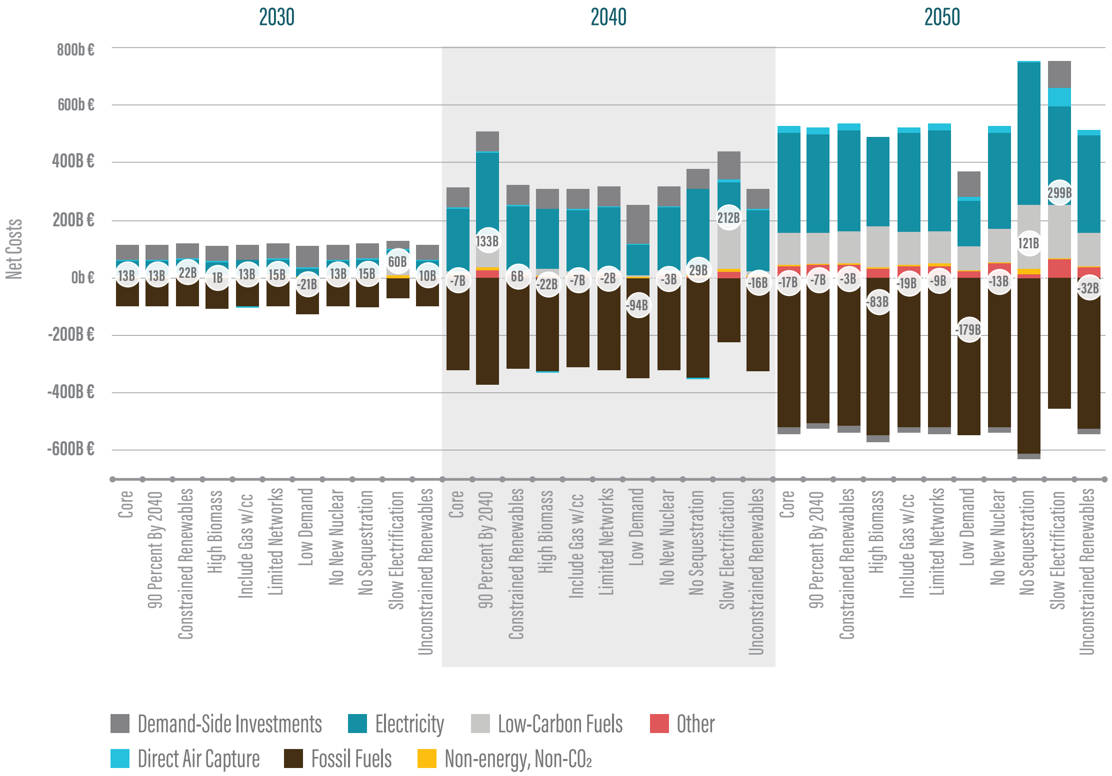
Longer-term targets are generally the right level of ambition, though they are not de facto appropriate in scale, and achievement of some of the targets is highly dependent on choices made elsewhere in the energy system. As policymakers look toward establishing 2040 targets, it is critical to understand where these targets do and do not reflect success in emissions reduction goals and provide EU Member States with a more flexible framework that accounts for the diversity of potential strategies beyond 2030.

The Cost of Inaction

The transformation of the energy system undeniably raises financial concerns for both consumers and governments; however, if executed properly, the journey toward a decarbonized Europe—and the outcome—will ultimately lead to cost savings. In this year's ADP, we examined not only net-zero Scenarios but also a **Baseline** Scenario in which consumer technologies were frozen at their 2021 levels, and no carbon policies were implemented to influence energy supply. This approach allows us to evaluate the full costs of decarbonization, including efficiency and electrification measures, which ultimately reduce costs for consumers.

Achieving a cost-effective transition, however, will require a rapid increase in the capital available. This includes energy investments; ongoing support for research, development, and deployment of key decarbonization technologies; and assistance for consumers with the upfront costs of more expensive vehicles, heating systems, and building upgrades that only deliver savings over time. It will necessitate establishing appropriate market signals to encourage rational private investment. Each of these goals is challenging on its own, and together they are even more demanding. Nevertheless, as seen in ***Figure 2***, our analysis shows that the potential rewards are enormous: a decarbonized economy that saves money.

FIGURE 2. Net Costs from Baseline Scenario



Note: *A graph illustrating the cost differences between the **Baseline** Scenario (no new decarbonization efforts) and the net-zero Scenarios, showing potential long-term savings from a decarbonized economy.*

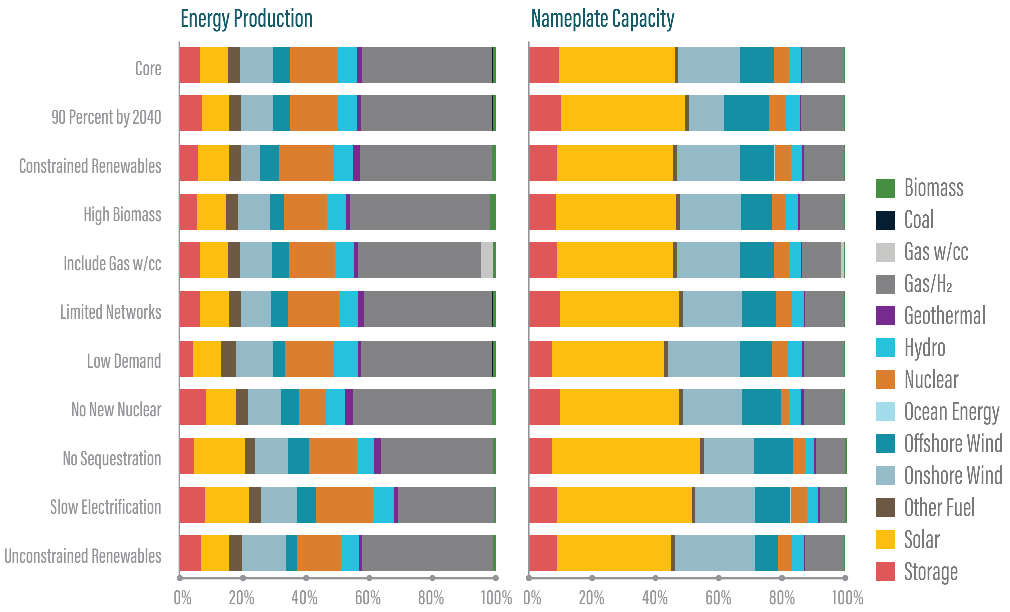
Winter Is Coming

In the long run, Europe is likely to face a distinctly winter-peaking electricity demand due to the widespread electrification of heating systems. This seasonal peak presents a significant challenge, as the periods of highest demand often coincide with some of the lowest renewable energy generation capacity, particularly during winter months. Solar energy, which is a key resource in many high-load countries, tends to contribute very little during these times, sometimes for sustained periods. This dynamic makes it difficult to rely solely on renewables during high-demand winter periods, and it highlights the complexity of meeting sustained high net-load events (demand minus renewable generation). It also underscores the need to move beyond simplistic resource comparisons based on metrics like Levelized Cost of Energy (LCOE) and to recognize that resource competitiveness will evolve as the grid and market conditions change.

To address these challenges, our results suggest the need for a diverse portfolio of energy resources. In addition to deploying hundreds of gigawatts of short-duration energy storage to manage daily fluctuations, there is a growing role for multi-day energy storage systems, capable of providing power over several days when renewable output is low. An expanded nuclear fleet will provide baseload carbon-free power. Furthermore, up to 250 gigawatts of new backup generators—designed to be fuel-flexible (capable of running on fossil gas, hydrogen, or biogas) and running at less than 15% of the time—are necessary to ensure electricity reliability.

Figure 3 shows a comparison of the share of each resource's energy production during a winter reliability event (defined here as the day with the highest net load across Europe) to the nameplate capacity (maximum potential output of a generator). This illuminates that despite huge increases in renewable capacity, the reliability events are triggered during periods of their lowest production and thus will require complementary reliability resources. This is not a reason to forego renewables (our model chooses multiple terawatts of these resource economically) but it is an argument to be clear about what other types of resource will be necessary to support them.

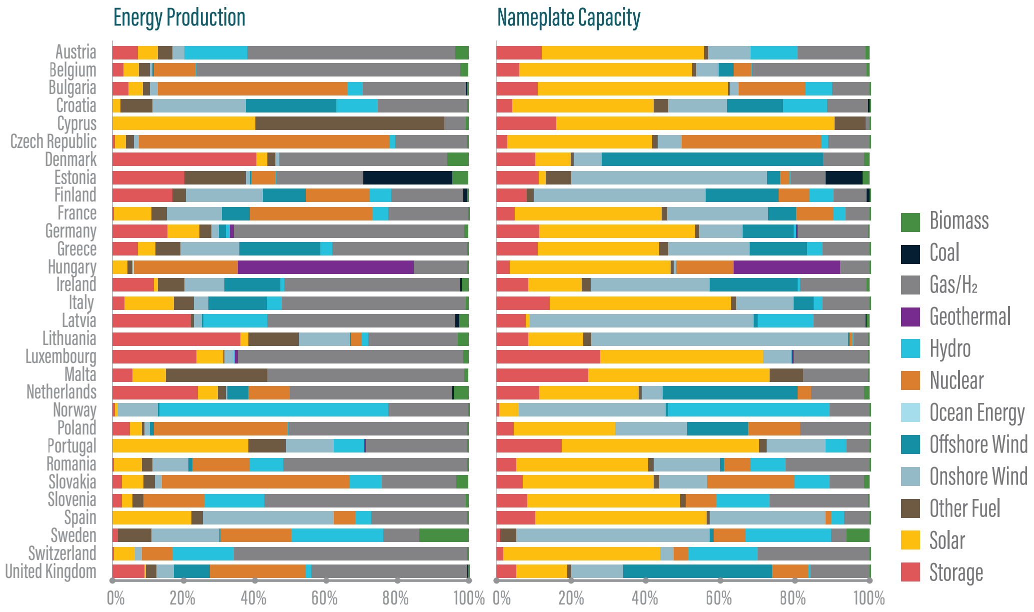
FIGURE 3. Comparison of Resource Performance During Peak Winter Day Across Europe



Note: *Performance comparison of different energy resources during Europe's highest net-load winter event, highlighting the role of renewable and backup power sources.*

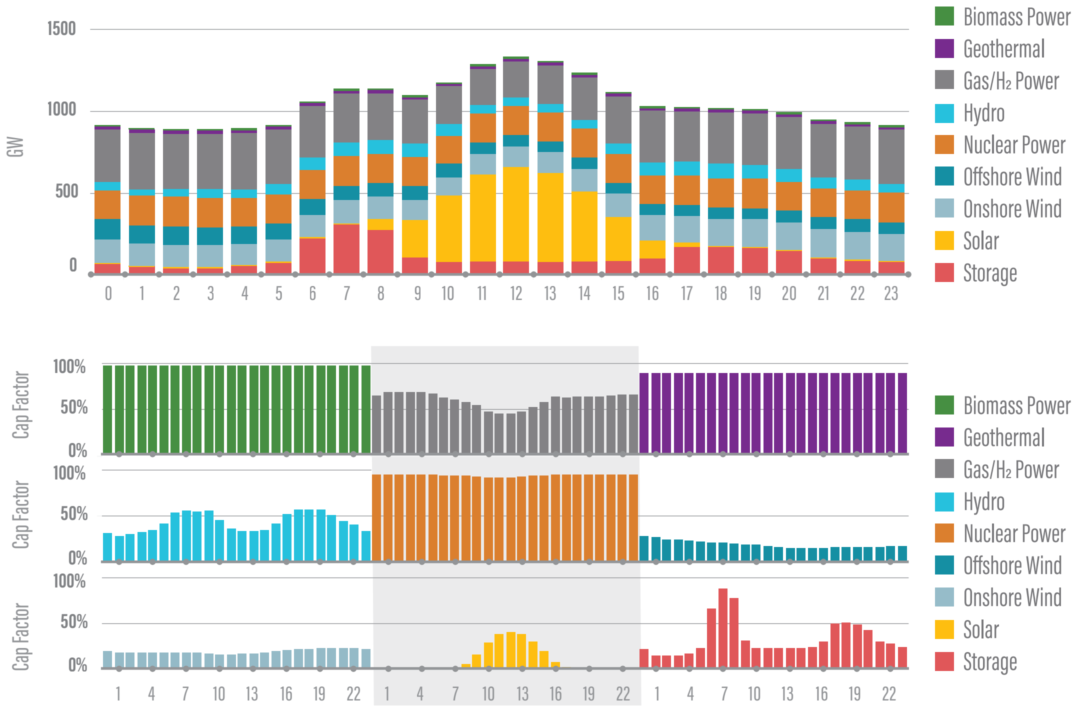
Figure 4 below illustrates the same metric regionally, showing how the resources are generating during the system's most constrained day in each country for the **Core** Scenario. While some countries see continued availability of renewables during a winter reliability event, most experience the fundamental challenge of persistent under-generation of renewable resources, highlighting the benefits of a diverse clean energy approach. Regional reliability is supported with a significant contribution from thermal resources and some long-duration storage. ***Figure 5*** delineates this performance by hourly usage and collapses data across Europe.

FIGURE 4. Comparison of Resource Performance During Peak Winter Day by Country



Note: *Regional breakdown of energy resource performance during peak winter demand, illustrating resource diversity and reliability across Europe.*

FIGURE 5. Hourly Resource Performance During Peak Winter Day in 2050 Across Europe

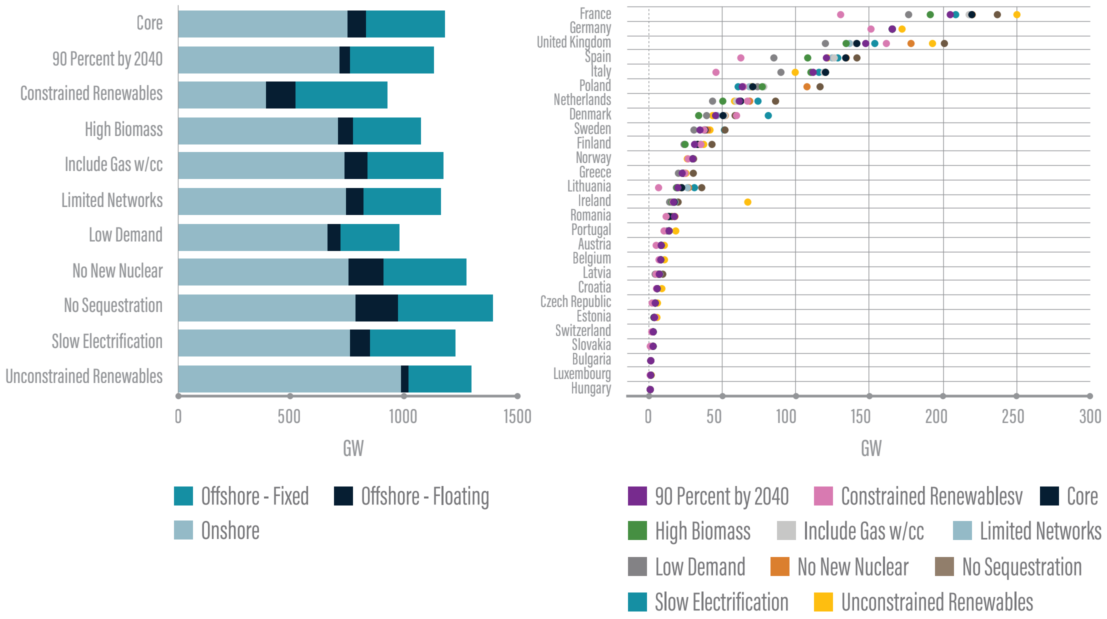


Note: *Metrics that illustrate the hourly energy usage across Europe, first combined to show total production in average gigawatts across each hour, then delineated to show percentage of maximum capacity factor by resource.*

Where the Wind Blows

This analysis underscores the critical importance of expanding Europe's wind resources, with all Scenarios projecting over 900 GWs of combined onshore and offshore wind capacity by 2050. Although this capacity is expected to be lower than overall installed solar capacity, wind provides significantly more energy due to its higher capacity factors. Additionally, the energy generation profiles of wind offer more seasonal consistency than solar, making it a more reliable contributor to the energy mix during winter months when solar output is minimal. Even when assumptions regarding the resource potential of wind are drastically changed, the model compensates by increasing reliance on offshore wind, showcasing wind's desirability in various geographical and resource conditions. This dynamic is exemplified in ***Figure 6***.

FIGURE 6. European Wind Capacity in 2050

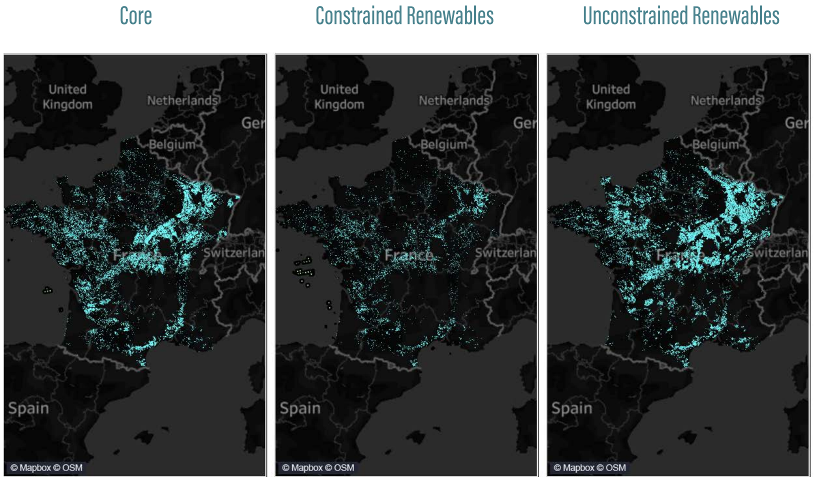


Note: *A projection of onshore and offshore wind capacity across Europe in 2050 under various decarbonization Scenarios, demonstrating wind energy's critical role.*

The pivot from onshore towards offshore wind would significantly alter the spatial distribution of wind resources across Europe. Unlike the aggregate totals, which may appear uniform, there is considerable variability in wind deployment at the national level. The determining factor in the expansion of wind resources lies in where they can be developed most cost-effectively. In the long term, this geographic flexibility becomes crucial for supporting locationally agnostic electricity loads, such as electrolysis, industrial electrification, direct air capture, and possibly data centers and server loads. Wind resources developed in these optimal locations will help drive the future decarbonization of industries and facilitate Europe's transition to a cleaner energy system.

Figure 7 shows the wind buildout in 2050 in France under the different Scenarios of renewable siting. In the **Constrained Renewables** Scenario, we see only 63 GWs of total wind; in the **Core** Scenario we see 170 GWs and the **Unconstrained Renewables** Scenario we see 223 GWs. The differences in the onshore wind availability are offset by differing builds of offshore wind (67 GW in Constrained Renewables vs. 27 GWs in Unconstrained Renewables), in addition to the construction of 20 GW of new nuclear capacity.

FIGURE 7. Downscaled Wind Capacity in France in 2050[2]


Core

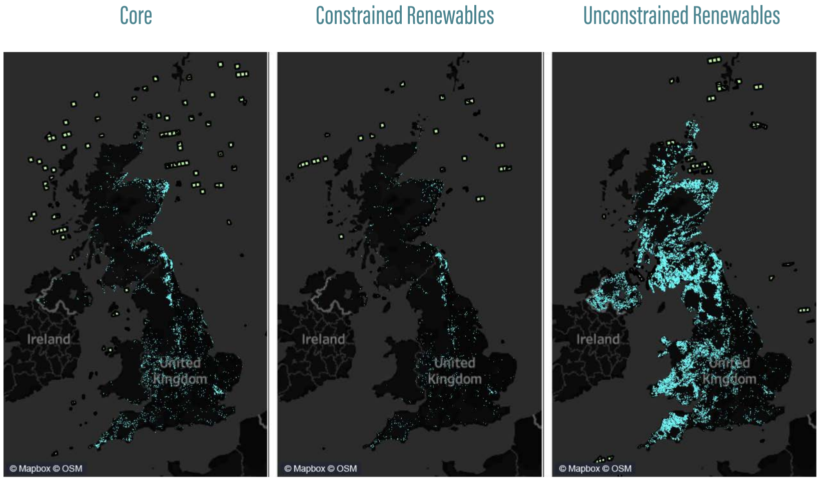
Constrained Renewables

Unconstrained Renewables

Note: *Offshore wind is shown in green and onshore wind is shown in blue across the three Scenarios.*

In ***Figure 8***, we see a similar dynamic in the U.K, with restriction on offshore siting forcing the development of additional offshore wind resources (as well as additional nuclear powerplants).

FIGURE 8. Downscaled Wind Capacity in the UK in 2050


Core

Constrained Renewables

Unconstrained Renewables

Note: *Offshore wind is shown in green and onshore wind is shown in blue across the three Scenarios.*

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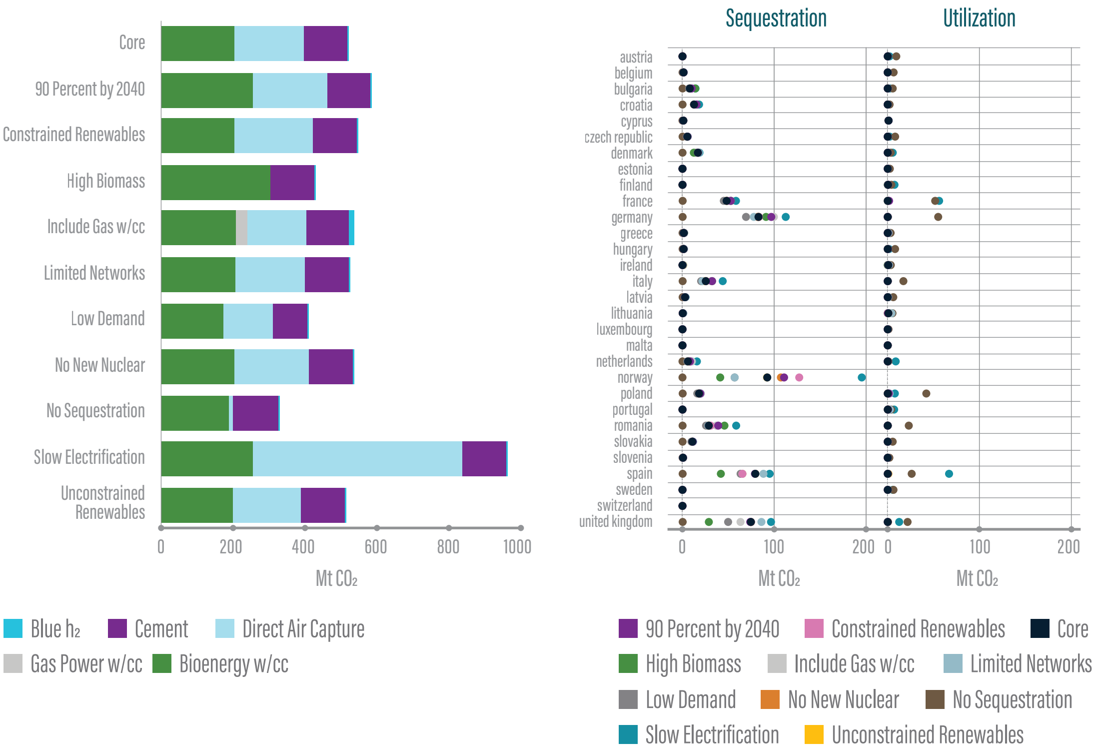
[2] Full downscaling results available at: carbonfreeeurope.org/modelling

What to Do with the CO$_2$

Achieving net-zero emissions necessitates a significant expansion of carbon capture technologies, with industry, biofuels, and direct air capture emerging as the primary opportunities in our modeling, as illustrated in ***Figure 9***. However, the fate of the captured carbon remains uncertain and is contingent on a variety of factors including technological advancement, policy frameworks, and public acceptance. Captured carbon can either be sequestered in geological formations, such as depleted oil and gas fields, coal seams, or saline aquifers, or it can be utilized to produce substitutes for liquid and gaseous fossil fuels. The feasibility of each pathway depends on advancements in related technologies such as electrolysis, e-fuel synthesis, and the ability to securely inject and monitor carbon for sequestration.

FIGURE 9. Carbon Capture, Utilization, and Sequestration in 2050



Note: *Projected deployment of carbon capture technologies across Europe, with the right panel showing how captured carbon could be sequestered or utilized in different countries under different Scenarios.*

In countries where sequestration is prioritized, geological conditions determine viability, with certain areas having more suitable formations for long-term carbon storage. Proximity to carbon capture sources is also a critical factor in determining the level of sequestration since shorter distances lower transportation costs. On the utilization side, the development of renewable resources plays a decisive role. The availability of surplus renewable energy—beyond what is needed for direct consumption—makes it possible to produce carbon-based fuels, thus making utilization more attractive in countries with abundant renewable energy potential. We don't model the totality of carbon dioxide removal approaches that might be available due to a lack of data inputs on costs and potential, but pursuing these approaches might be able to reduce the amount of infrastructure devoted to things like DAC or provide additional emissions offsets benefits to the rest of the economy.

Electricity Market Evolution

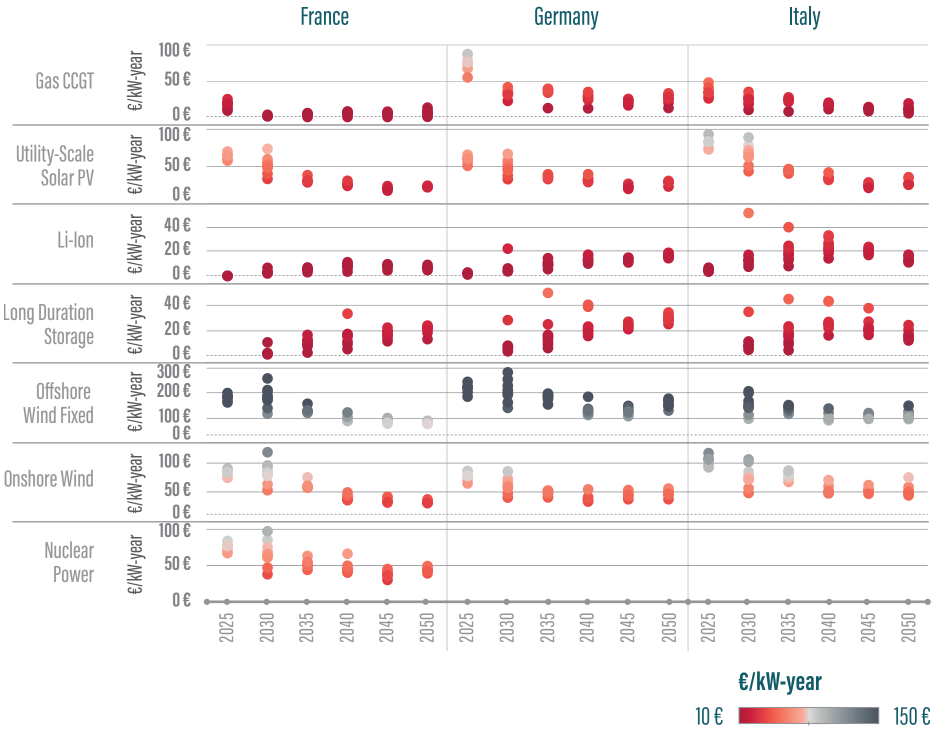
Electricity markets are systems where electricity is bought and sold between generators and consumers, often mediated by market operators. These markets ensure the efficient transaction of electricity and set prices based on supply and demand dynamics. Traditionally, power generation has relied on hydro and nuclear energy as well as fossil fuels like coal and natural gas, but the growth of renewable energy sources like wind and solar has significantly impacted these markets. Unlike conventional power plants, renewables have no variable costs once installed, leading to them bidding into the market at very low or even negatives prices. This influx of low-cost energy from renewables can drive down the overall market price of electricity.

However, while the addition of more renewables can lower market prices, it also introduces new challenges concerning the reliability and stability of the power grid. To ensure a stable electricity supply, capacity resources like batteries, gas plants, and other dispatchable power sources are still needed to balance the grid during periods of low renewable output. The current market structures often undercompensate these capacity resources, as they are primarily paid for according to the energy they provide rather than their availability to meet peak demand. This highlights the need for market reforms that appropriately value and compensate the capacity resources for the crucial role they play in ensuring grid reliability, even as we transition to cleaner energy sources.

If deployment of low-marginal cost generators outpaces electricity market reform, we could see the retirement of resources that will eventually be needed to support longer-term electrification. Specifically, resources like existing nuclear power plants may be at risk given their more limited operational flexibility, and with it, the inability to avoid low or negative-price market periods.

In ***Figure 10*** we show the average energy market revenues by generator type for the years 2025-2050 in three keys countries: France, Germany, and Italy. Figure 10 illustrates the projected decline in energy market revenues across cases for most resource types (other than storage). Maintaining the portfolio of resources necessary to support decarbonization in this context will require additional products to be developed and monetized to compensate generators for when they are needed most.

FIGURE 10. Energy Market Capture Rates



Note: *Analysis of energy market revenues by generator type for France, Germany, and Italy from 2025 to 2050, highlighting revenue trends under decarbonization Scenarios. These would be reflective of day-ahead energy market capture and do not include ancillary service revenues; capacity market revenues; or any flexibility payments. They also do not include resource bidding behavior or contractual structures that would influence offer prices (e.g. PPAs).*

FROM STORAGE TO BALANCING

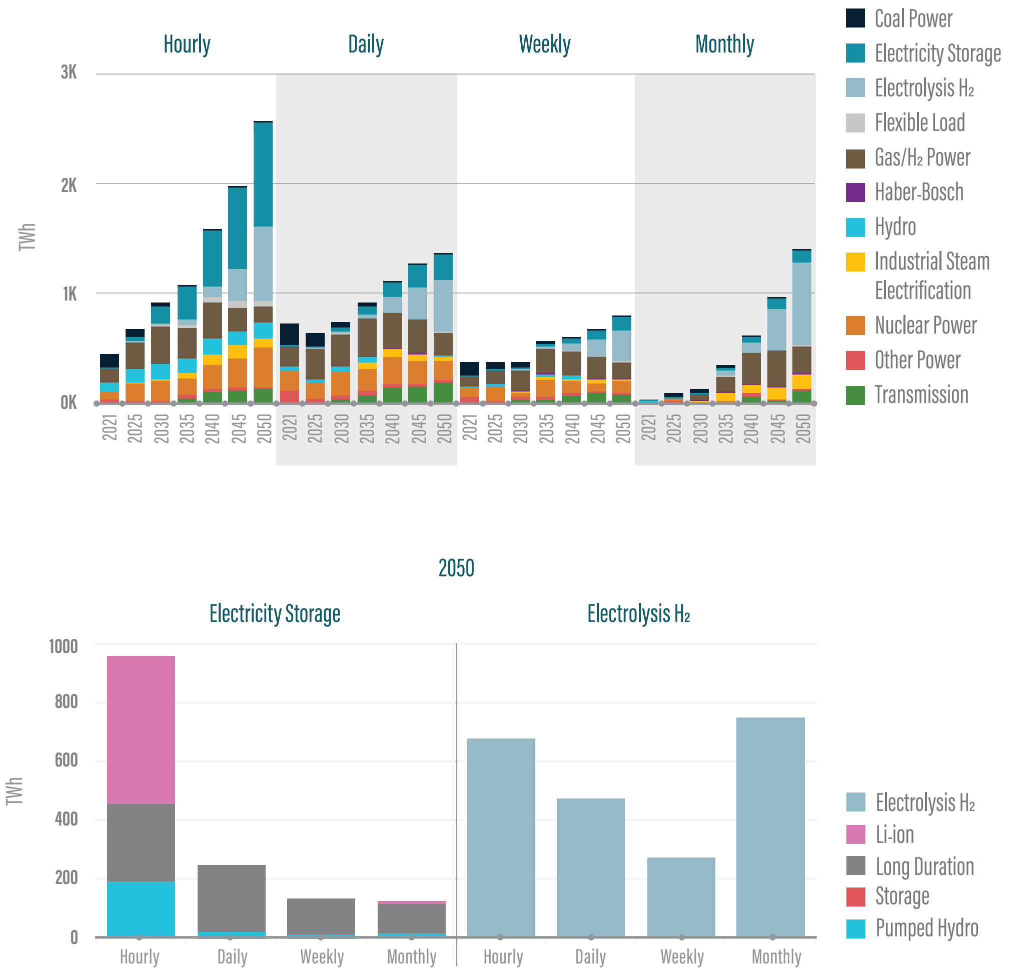
In addition to the need to move more of the compensation of generators out of the traditional energy market and into capacity and flexibility markets, the nature of these will also have to be continuously evolving as the needs of the system evolve. As discussed in the previous section, the economic and reliability challenges of a highly renewable grid occur during net-load deficits and surpluses. Deficits occur when there are not enough renewables to meet load; surpluses occur when potential generation exceeds demand. These surpluses, with increasing penetrations of renewables, tend to persist over longer periods of time (e.g., solar overgeneration that might begin only at the peak of the day but start to extend over all daylight hours). Deficits, even with increasing penetrations of renewables, remain stubbornly long. Adding more and more renewables in fallow periods does little to address the problem. These persistent periods of renewable under-generation are often referred to with the German term *Dunkelflaute*. Meeting them requires generators with the ability to dispatch on a sustained basis, up to multiple days in a row.

The easiest technology to imagine performing this function is very long-duration energy storage, or multi-day energy storage but this is not always the most cost-effective resource given its cost and projected inefficiencies. Backup thermal generators such as gas plants can also perform this function, limiting their generation to only the most critical periods. Resources like nuclear can be counted on to produce during these periods, but once constructed, they are economically operated at high-capacity factors. As a result, the issue of balancing between over-and under-generation of renewables is not ameliorated when they are operating as baseload resources.

Our model tends to solve these balancing challenges with a portfolio approach. We deploy electrolysis to operate during periods of plentiful renewables, reducing the overgeneration hours of renewables and allowing more economic deployment (because the load has shaped itself against a renewable profile). This hydrogen resulting from electrolysis can be stored in low-cost underground reservoirs in lieu of electricity storage. In addition, we deploy electrified steam technologies that operate when there are sufficient renewables (and otherwise use fuel boilers), reducing the demands for electricity and addressing seasonal imbalances of load and supply. These electricity loads that operate seasonally mean that during periods of low renewable generation, they can be turned off, reducing the overall scale of the under-generation period. The remaining *Dunkelflaute* is addressed with long-duration storage, hydro, thermal plants (burning zero-carbon fuels if necessary), and potentially the intelligent scheduling of nuclear maintenance so that fewer nuclear plants are offline during winter periods.

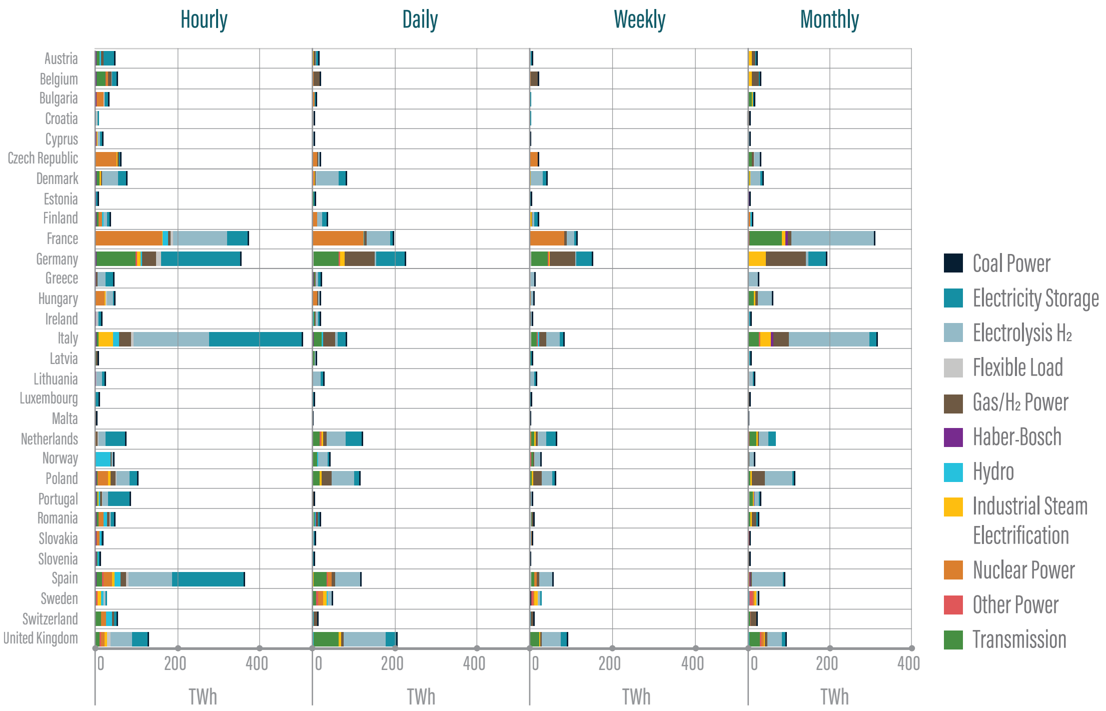
Figure 11 shows both the overall increase in the need for balancing energy at different timescales as we move towards higher renewable systems as well as the contribution to balancing over- and under-generation at different timescales made by each resource type. Specific note should be paid to the increase in hourly balancing (principally driven by the solar overgeneration in the middle of the day) which is solved with electrolysis, short-duration battery storage, and flexible loads like industrial electrification and smart EV charging. Monthly balancing increases even more dramatically and this is where we see the impact of electrolysis (downward balancing during periods of over-generation) and the thermal fleet (upward balancing during periods of under-generation) in addressing the monthly imbalances in net load. ***Figure 12*** shows the different balancing portfolios by region.

FIGURE 11. Total Balancing Contribution – Core Scenario



zloads) *in the* ***Core*** *Scenario, showing how the grid will manage over- and under-generation of renewable energy.*

FIGURE 12. Total Balancing Contribution by Country in 2050 – Core Scenario



Note: *Regional analysis of balancing contributions by resource type in 2050 under the* ***Core*** *Scenario, illustrating the diversity of flexibility approaches with different resource portfolios across countries.*

IV ANALYSIS FRAMEWORK

The analysis addresses two critical questions: (1) what are the infrastructure, spending, and natural resources required to attain carbon neutrality in the European economy by mid-century, and (2) how would these be impacted if we take into account "Factor X," a broad range of variables that could affect decarbonization efforts, such as technological advancements, consumer adoption rates, and societal constraints.

Our Scenarios depict different decarbonization approaches that reflect societal preferences and/or policy constraints concerning the technologies and resources that can be employed. These Scenarios may or may not include elements like new nuclear power or geologic sequestration, but despite any differences, there is broad agreement about the criticality of some key strategies. This modeling represents economy-wide pathways for achieving net-zero greenhouse gas emissions by 2050, beginning from the present, and includes temporal granularity at an hourly level for electricity and geographic granularity across more than 30 countries in Europe and North Africa.

TABLE 1 Scenarios

Scenario	Description
Core	This is the lowest cost pathway[3] for achieving net-zero greenhouse gas emissions by 2050 in the EU + UK with an adherence to existing European policy ambitions expressed in Fit for 55. This net-zero target is economy-wide and includes targets for energy and industrial CO_2, non-CO_2 GHGs, and the land CO_2 sink. It is built using a high electrification demand-side case, and on the supply-side has the fewest constraints on technologies and resources available for decarbonization along with core assumptions on technology cost.
90% by 2040	This is the only Scenario that alters the net-zero trajectory, with a what-if of imposing a 90% reduction by 2040, a target currently under consideration by the EU.
Constrained Renewables	The technical renewable resources available in countries is knowable. The available resource potential from a societal preference standpoint is not, with many jurisdictions worldwide rejecting the deployment of renewables even in the most resource-rich areas. This Scenario reflects increased scrutiny on siting, with additional restrictions on siting on farmland, lands with limited levels of current human modification, and near population centers.

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[3] Excepting Low Demand which uses a different trajectory of energy service demands.

Scenario	Description
High Biomass	This year's analysis now uses the "low" case from ENSPRESO[4] for a default input. This change was made to reflect the uncertainty around biomass emissions accounting and qualification and a general hesitance to leverage biomass resources too heavily in achieving net zero. This Scenario expands the biomass potential (using the "high" case) to examine the potential impacts of a higher level of zero-carbon primary biomass available to the energy system.
Include Gas with Carbon Capture	With the recent gas crisis and the push to both expand supply (through the imports of LNG) as well as reduce demand, there is understandable caution for building out gas with carbon capture (in electricity and hydrogen) and committing to gas as a long-term energy vector. We do not include these technologies in our other Scenarios to reflect this caution, but this Scenario does examine a what-if wherein the technology is allowed to be deployed economically.
Limited Networks	Resource endowments of primary energy (solar, onshore and offshore wind) and geologic storage (for CO_2 as well as hydrogen) dictate the development of new networked infrastructure to match supply with demand. This Scenario increases the cost of these interconnections by 3x above their base value, reflecting a societal preference for domestic supply and a rejection of new transmission and pipeline infrastructure.
Low Demand	This net-zero Scenario imagines a reduction in energy demand, not through additional efficiency, but through the reduction in energy service demand. This includes less industrial activity, less travel demand both on road and air travel, and reduced conservation in household energy services like space conditioning and water heating. These in turn reduce the overall scale of necessary clean energy infrastructure build.
No New Nuclear	This Scenario does not allow the building of new nuclear generation other than facilities currently under construction. This necessitates the substitution of otherwise economic nuclear deployment with additional renewables.
No Sequestration	This Scenario reflects a societal preference and/or a technology failure of geologic sequestration. It requires more direct displacement of fossil fuels with biofuels and e-fuels to achieve the same emissions outcomes.
Slow Electrification	This net-zero Scenario delays by twenty years the uptake of fuel-switching technologies, including electric vehicles and heat pumps. It is designed to explore the effects of slow consumer adoption on energy system decarbonization, necessitating a drop in fuels or offsetting approach to achieve the emissions targets.
Unconstrained Renewables	This Scenario reflects reduced scrutiny on siting, with the easing of restrictions on siting on farmland, lands with limited levels of current human modification, and near population centers. This tends to increase the available resource potential of onshore wind.

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[4] See https://www.sciencedirect.com/science/article/pii/S2211467X19300720#appsec1

IV MODELING UPDATES

Since last year's analysis, we have been responsive to stakeholder feedback as well as our own internal deliberations about how to improve our representation of the European energy system. To that end, this section illustrates key modeling improvements we have implemented in addition to our annual input data update process.

Updated Demand-Side Representation

Improvement: The Joint Research Center's Integrated Database on the European Energy System (JRC-IDEES) was updated this year so as to better understand the past and create a robust basis for future policy assessments. JRC-IDEES provides a consistent set of disaggregated energy-economy-emissions data for each Member State of the European Union, covering all sectors of the energy system for the 2000-2021 period. This data complies with Eurostat energy balances while providing a plausible decomposition of energy consumption into specific processes and end uses. In each sector, JRC-IDEES uses a vintage-specific approach to quantify the characteristics of the energy-using equipment in operation, along with the average operation of the equipment stock. It accordingly identifies different drivers and provides insights on their role by sector while accounting for structural differences across countries. As such, JRC-IDEES has several key applications for energy system modeling, research, and policy analysis, such as the parameterization of energy models and the assessment of past and prospective policies.

JRC-IDEES is freely accessible to the general public since 2018. This report documents the 2024 update (JRC-IDEES-2021) to include a granular disaggregation of European energy demand through 2021. This allows us to both update our base year in the modeling and to calibrate and project using up-to-date trends, such as electric vehicle adoption. We also include demand technology costs this year, allowing for comparisons of total energy system cost between Scenarios in ***Table 1*** and the 2021 **Baseline** Scenario, which freezes demand-side technology adoption and progress and leaves the system unconstrained with regards to emissions.

Expanded Emissions Scope

Previous ADPs only include a representation of energy and industrial CO_2 emissions and relied on exogenous assumptions about the trajectory of land-use and non-CO_2 emissions. We now specify land-use reduction opportunities within the model and have a supply curve of non-CO_2 emission reduction measures. This allows for tradeoffs between energy and other sectors in different Scenarios as well as a fuller representation of overall emission reduction contributions from various sectors.

Geographic Downscaling

To make our results more accessible and impactful, we have undertaken an additional analytical step this year called *downscaling*, which takes our power sector outputs at the country level and sharpens them into higher resolution (1km2) outputs across Scenarios and timesteps. The downscaling process is broken into two parts: 1) Candidate Project Areas (CPAs) creation and scoring and 2) CPA selection and mapping.

The CPA creation and scoring step either imports pre-existing sites that have already been determined as suitable for energy development or identifies and uses new potential locations. This step then also assigns a prediction score to each CPA that is derived from a machine learning algorithm. The prediction score measures the likelihood that a given parcel of land will be selected for development based on the characteristics of existing energy generation sites. The algorithm takes the following environmental variables and uses them in a random forest classifier:

- Capacity factor
- Slope
- Land use
- Proximity to roads and electrical substations
- Population density and population center proximity
- Proximity to water (thermal energy only)
- Proximity to saline aquifers (CCS only)
- Geothermal heat flux (geothermal energy only)

The CPA selection and mapping step takes the prediction scores and establishes a ranked list of CPAs. CPAs are first thinned to reduce clustering (in the case of wind and solar) and then are selected descending from highest prediction score to fill the capacity demand threshold for a given country and year in a Scenario. Thermal generation sites/CPAs have two additional steps. Once a site/CPA is selected, a discount is applied for further away locations to discourage over-clustering. After selection is complete, proximal locations are combined to simulate multiple generators housed within a single facility. Finally, all results are mapped using rendering software.

V RESULTS

Core Scenario

The **Core** Scenario reflects our central estimates for technology cost and availability, resource availability (biomass, sequestration, renewables), and demand-side adoption. It follows a straight-line trajectory to net zero from the 2030 emissions target. It represents a high-renewables and high electrification future, but it does not go to 100% renewable energy and does not electrify everything. Instead, it applies electrification in end-uses where efficiency gains are high (on-road transport, space and water heating, industrial steam production, etc.) and substitutes zero-carbon fuels in difficult-to-electrify end-uses (aviation, shipping, high-temperature heat). It achieves rapid reductions in primary and final energy and emissions across all sectors. It requires an accelerated expansion of the electricity system to accommodate electrification rates; the deployment of carbon capture across the economy including biomass applications, industry, and direct air capture; drop-in replacements for fossil fuels with zero-carbon substitutes; and the scaling of a new clean hydrogen network. Even with this new infrastructure investment, it promises a reduction in overall economy-wide costs from a **Baseline** Scenario that maintains a heavy dependency on fossil fuels.

As seen in ***Figure 13*** below, some highlights of the **Core** Scenario include: a net savings of €10 billion, over 400 million new zero-emission vehicles on European roads, almost 200 megatonnes of CO_2 reduced through direct air capture with geologic sequestration, 86 gigawatts of new nuclear power, 3 kw of solar PV for every person in Europe, and zero CO_2 net emissions.

Key elements of this Scenario include:

- **Electrification:** A major push toward electrifying heating systems, transportation, and industrial processes, reducing the reliance on fossil fuels and increasing demand for renewable electricity.

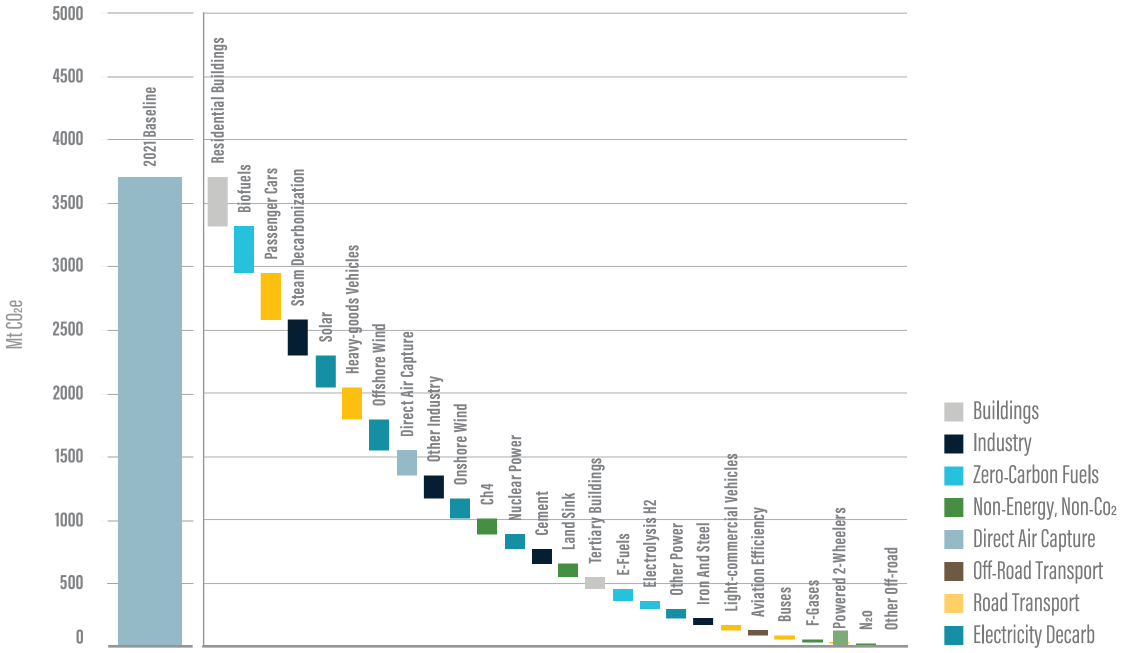
- **Energy Storage:** The integration of multi-day energy storage systems to ensure grid reliability, especially during periods of high demand and low renewable generation, such as winter months.
- **Carbon Capture and Sequestration:** The use of CCUS technologies to capture and store emissions from sectors where decarbonization is challenging, particularly in industrial processes.
- **Renewable Energy Expansion:** Large-scale deployment of renewable energy technologies, particularly wind and solar, with minimal geographic or societal constraints on their development.

This Scenario reflects a balanced approach, utilizing a diverse portfolio of clean energy technologies to meet decarbonization targets while prioritizing economic efficiency and technological feasibility. It forms the basis for comparison with other Scenarios that incorporate variations in policy, technological constraints, and societal preferences. Although the **Core** Scenario provides an idealized and efficient path to a decarbonized Europe, the reality dictates that the pathway will deviate from this version. As such, our Analytical Framework reflect multiple realistic and adaptable Scenario pathways to net zero, with **Core** serving as a comparison point for these alternative Scenarios.

FIGURE 13. Key 2050 Core Scenario Numbers

67 % Electric Final Energy Share	**80** % Renewable Electricity Share	**-10** Billion Euros Net Costs	**1,230** GW Heat Pumps Installed
297 GW New Electricity Storage	**86** GW of New Nuclear Power Plants	**3** kW Solar PV per Person	**447** Million ZEVs on the Road
2 MMB/D Zero-Carbon Fuels	**196** Mt CO_2 Captured from DAC	**514** Mt CO_2 Geologic Sequestration	**359** Mt CO_2 Land Sink Offsets
0 Mt CO_2e Net Emissions	**23** Mt H_2 Clean Hydrogen	**763** Mtoe Final Energy	**1,215** Mtoe Primary Energy

FIGURE 14. Emissions Reductions in Core Scenario

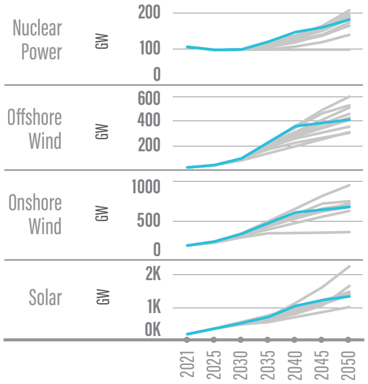


Note: *Breakdown of the emissions reductions by category according to the* ***Core*** *Scenario, when compared to the 2021* ***Baseline****.*

Scenario Impacts

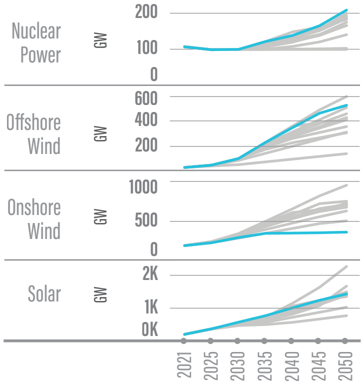
90% by 2040

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.



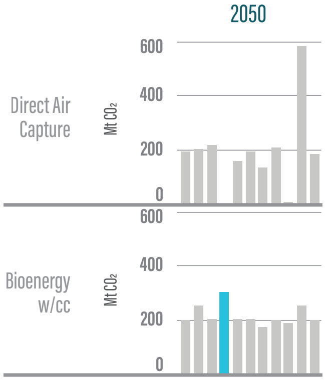
Constrained Renewables

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).



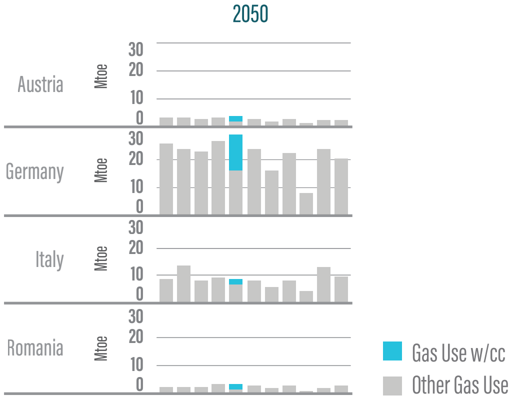
High Biomass

Low-carbon biomass is a valuable resource in a net-zero economy, both as a fuel feedstock as well as a source of CO_2 for sequestration. Its use must be balanced against its overall emissions impact, competition with food production, and land-use concerns; but if it were more readily available, the model uses more of it and reduces the need for technical carbon capture (DAC).



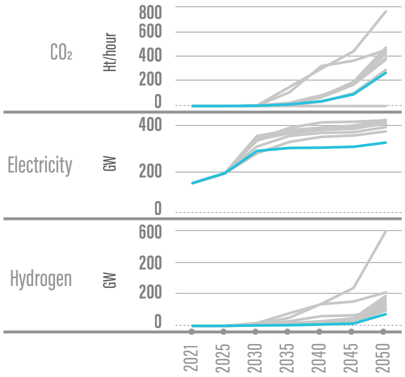
Include Gas with Carbon Capture

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.



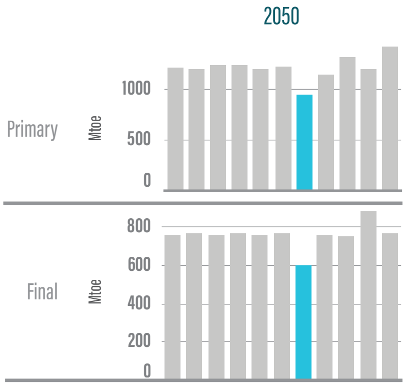
Limited Networks

Increasing the costs of interconnection for new electricity, hydrogen, and CO_2 pipeline in the modeling reduces overall build of all three, forcing the model to rely on lower quality renewable resources, to increase the share of nuclear capacity, and to increase the amount of electricity storage for balancing. In general, this infrastructure is not cost sensitive; the economics of building it is robust against significant cost increases.



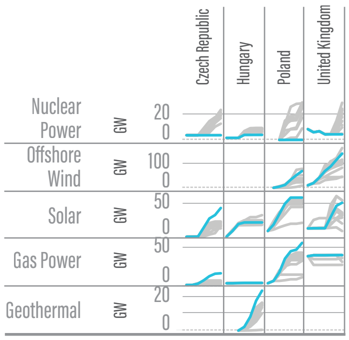
Low Demand

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.



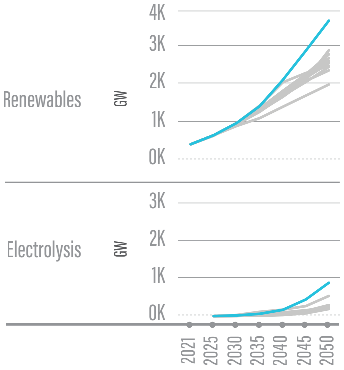
No New Nuclear

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.



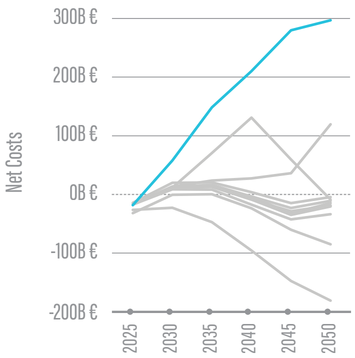
No Sequestration

Disallowing sequestration necessitates significant volumes of zero-carbon fuels and the use of large quantities of hydrogen as a feedstock. This puts a strain on Europe’s available renewable resources and may necessitate more imported fuels.



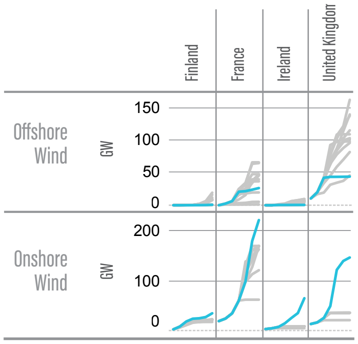
Slow Electrification

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.



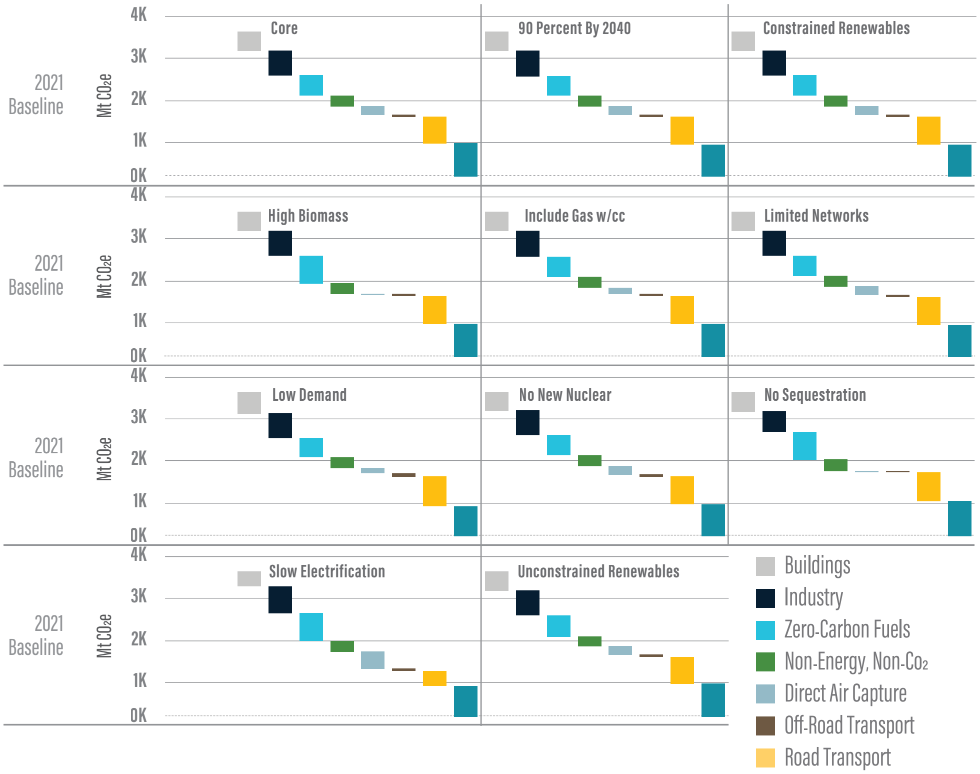
Unconstrained Renewables

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



Note: *All scenarios are shown in the above figures in grey with the highlighted Scenario identified in blue.*

FIGURE 15. Emissions Reductions in All Scenarios



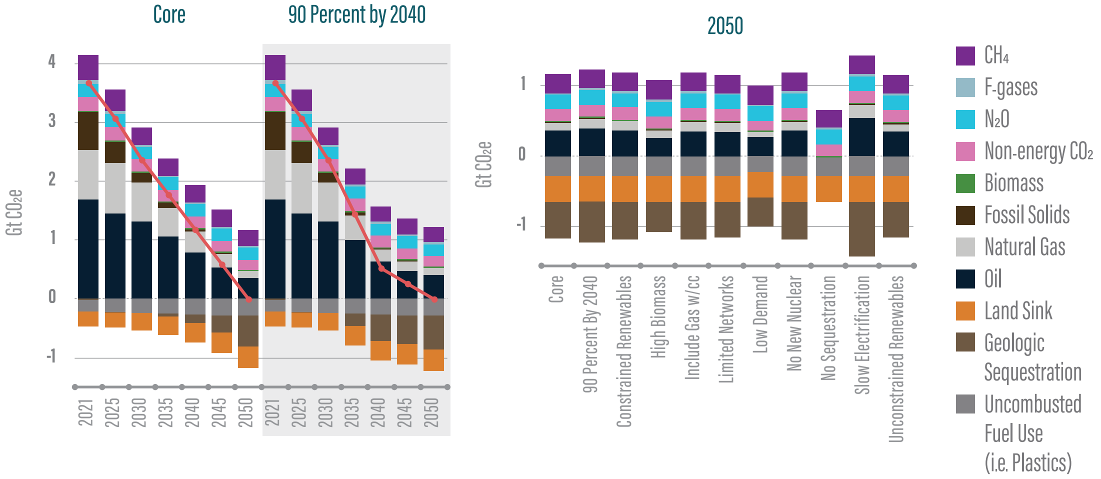
Note: *A detailed look at the breakdown of the emissions reductions across sectors in all Scenarios.*

Emissions

Total Emissions

Total emissions by source category are illustrated in ***Figure 16***, with annual detail provided for the two different emissions trajectories enforced in the model: our net-zero trajectory that operates on a straight-line from 2030 to 2050, and our **90% by 2040** trajectory that adds the additional interim requirement of a 90% reduction from 1990 levels by 2040. 2050 emissions balances are shown for all Scenarios, with residual fossil fuel use and non-CO_2 emissions offset by uncombusted fuels (e.g., sequestration in durable goods like plastics) as well as geologic sequestration and contributions from the land sink. The most materially different emissions balances from the **Core** Scenario are found in the **No Sequestration** and **Slow Electrification** Scenarios. **No Sequestration** requires the reduction of all fossil use (through the substitution of low-carbon fuels). **Slow Electrification** has a larger share of residual fossil fuel use and has a higher level of offsetting from geologic sequestration.

FIGURE 16. Total Emissions by Source Category

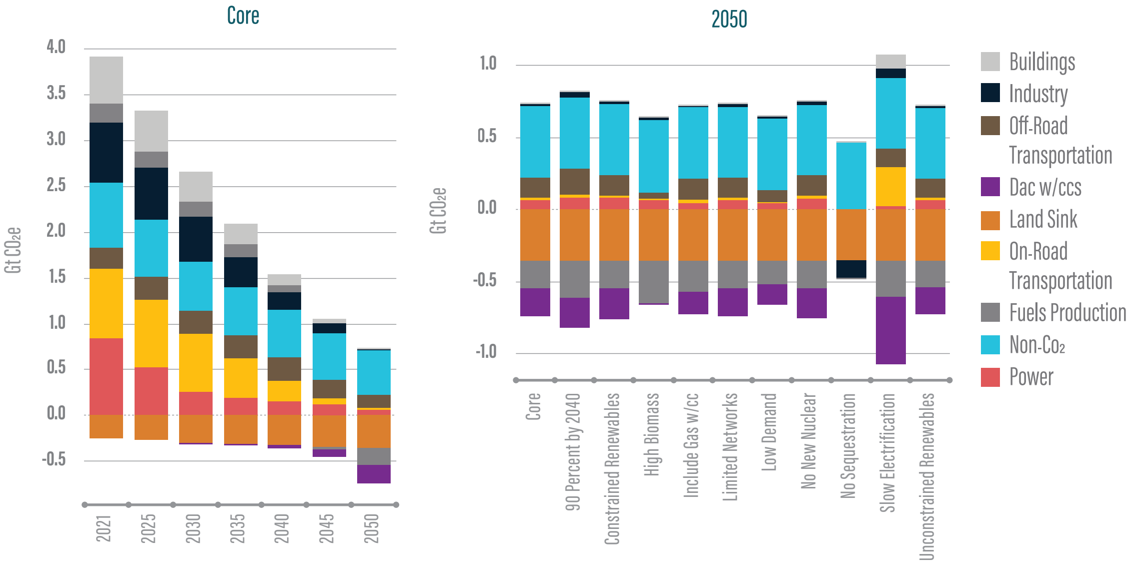


Note: *A detailed graph showing total emissions across key source categories under both the net zero and 90% by 2040 trajectories, comparing reductions achieved in various sectors.*

Sector Emissions

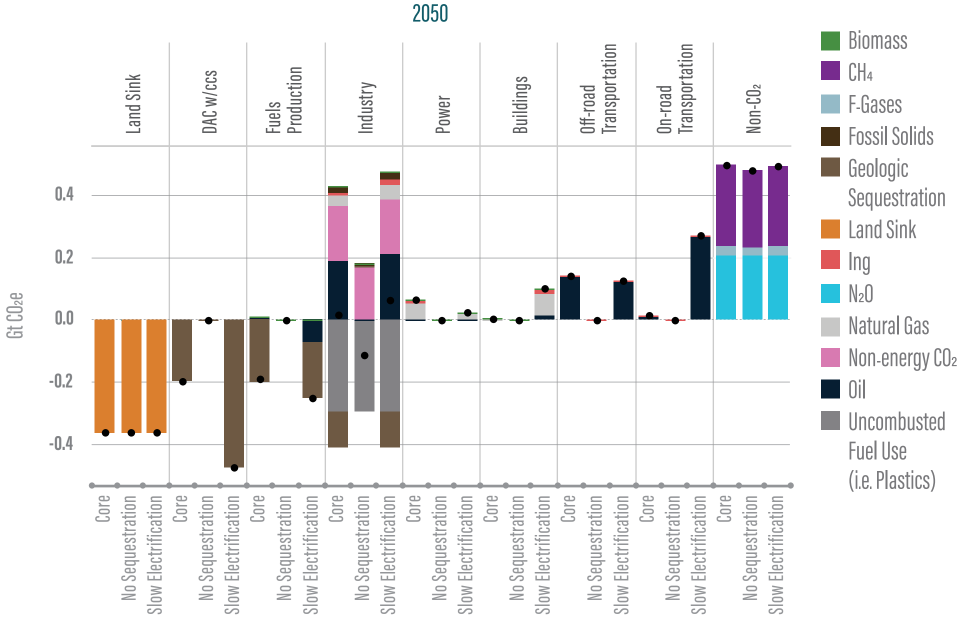
Figure 17 and ***Figure 18*** provide further breakdowns of emissions by sector, showing more significant variability between Scenarios, but the most significant emissions differences are again in the **No Sequestration** and **Slow Electrification** Scenarios. Failure to electrify by 2050 results in more point-source combustion emissions in buildings, transport, and industry, which necessitates cleaner electricity generation and more offsets from DAC. **No Sequestration** uses zero-carbon fuels across all these point-sources (including electricity generation) to balance emissions without geologic sequestration.

FIGURE 17. Total Emissions by Sector



Note: *Breakdown of emissions reductions by sector under the* ***Core*** *Scenario, highlighting key contributors to decarbonization by 2050.*

FIGURE 18. 2050 Emissions Comparison



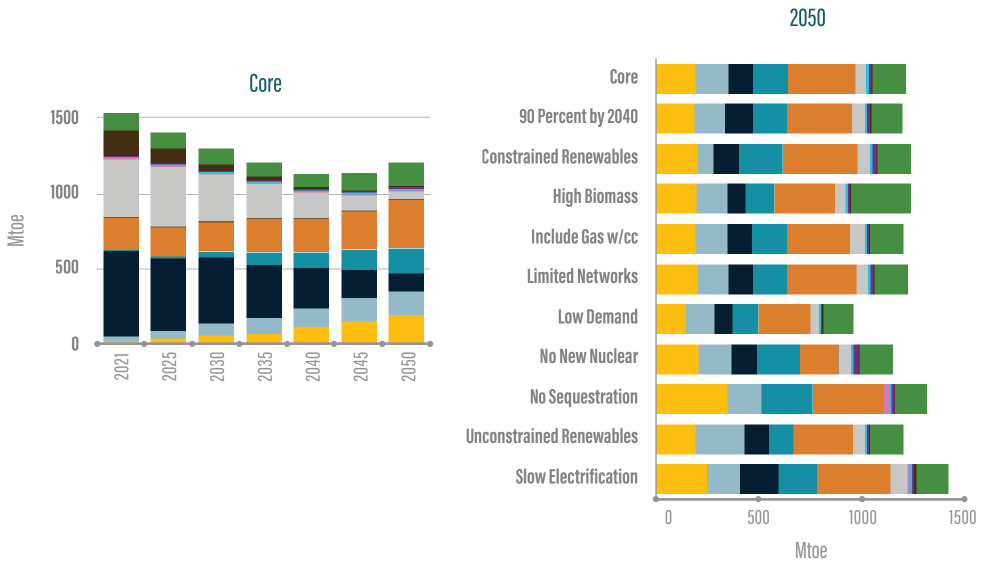
Note: *Comparison of source category and sector emissions in 2050 across different decarbonization Scenarios, illustrating how policy and technology choices impact emissions allocation.*

Energy

Primary Energy

Figure 19 demonstrates that Scenarios show some variability in overall primary energy demand, with the **Low Demand** Scenario leveraging a reduction in service demand for a commensurate decline in primary energy requirements. **No New Nuclear** has lower primary energy demand due to the substitution of renewables for nuclear heat as a primary energy source (with reduced thermodynamic losses). That said, this dynamic illustrates the flaw of the metric when comparing across disparate energy sources and illustrates why targets established at the primary energy level are not the most informative. **Slow Electrification** and **No Sequestration** have the highest levels of zero-carbon fuel production and the highest overall energy demand, illustrating the importance of electrification and the challenge of relying too heavily on e-fuels pathways with their overall inefficiency. This comparison is also illustrative since some EU targets focus on primary energy as a metric. We find substantively different pathways that meet the emissions goals with different primary energy outcomes. It is worth considering whether the primary energy targets are useful in this context, given that they preference certain technologies over others.

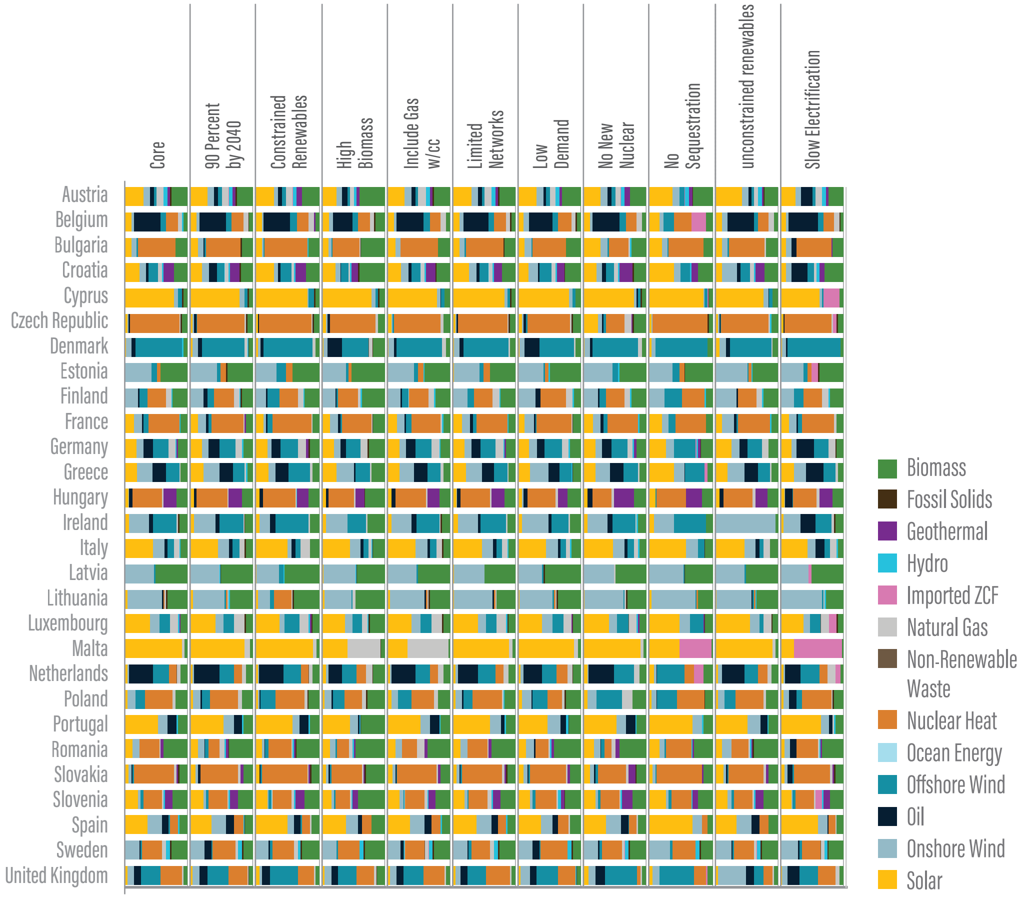
FIGURE 19. Primary Energy Demand



Note: *A projection of primary energy demand across Scenarios, showing how the demand for different energy sources evolves under decarbonization efforts.*

At the country level, Scenarios have a more substantial impact on primary energy, as seen in ***Figure 20***. Restricting new nuclear is hugely impactful for eastern European countries like the Czech Republic and Poland. Including gas with carbon capture provides an important, though overall-limited, share of primary energy for countries like Germany and Austria. The **Constrained Renewables** Scenario pushes wind offshore in Ireland, the U.K, and France and increases the need for new nuclear reactors in France whereas **Unconstrained Renewables** pushes in the other direction, reducing the need for offshore wind and nuclear in these countries.

FIGURE 20. Primary Energy Demand Share in 2050 by Country

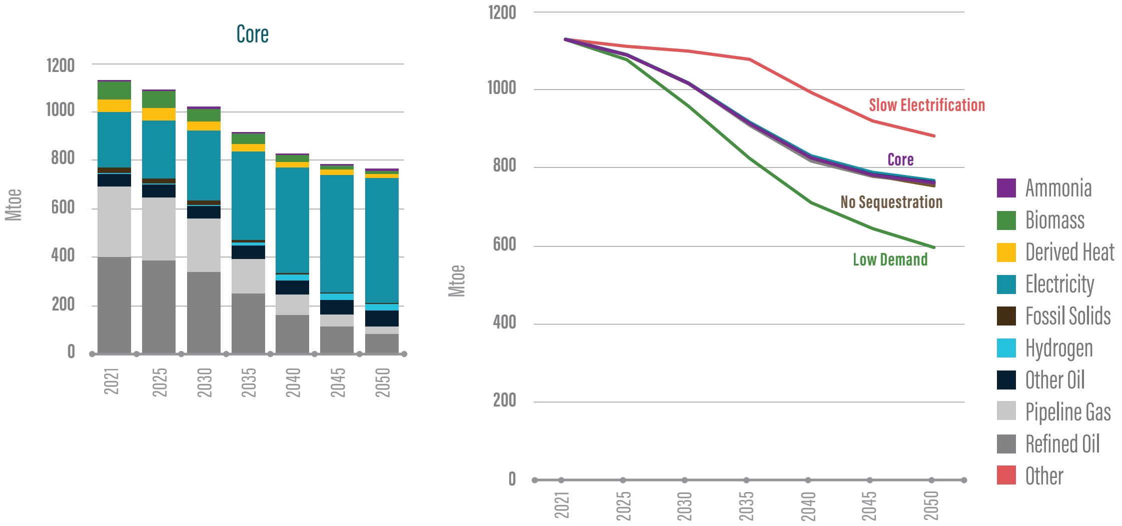


Note: *Country-level analysis of primary energy demand share in 2050, showing the variation in energy use across European countries depending on energy sources and decarbonization strategies.*

Final Energy

Figure 21 demonstrates that overall final energy declines are bounded by the **Slow Electrification** and **Low Demand** Scenarios, with other Scenarios having very similar overall levels of final demand. The largest declines are seen in refined fuels and pipeline gas, with increases (though not commensurate) seen in electricity and direct hydrogen use.

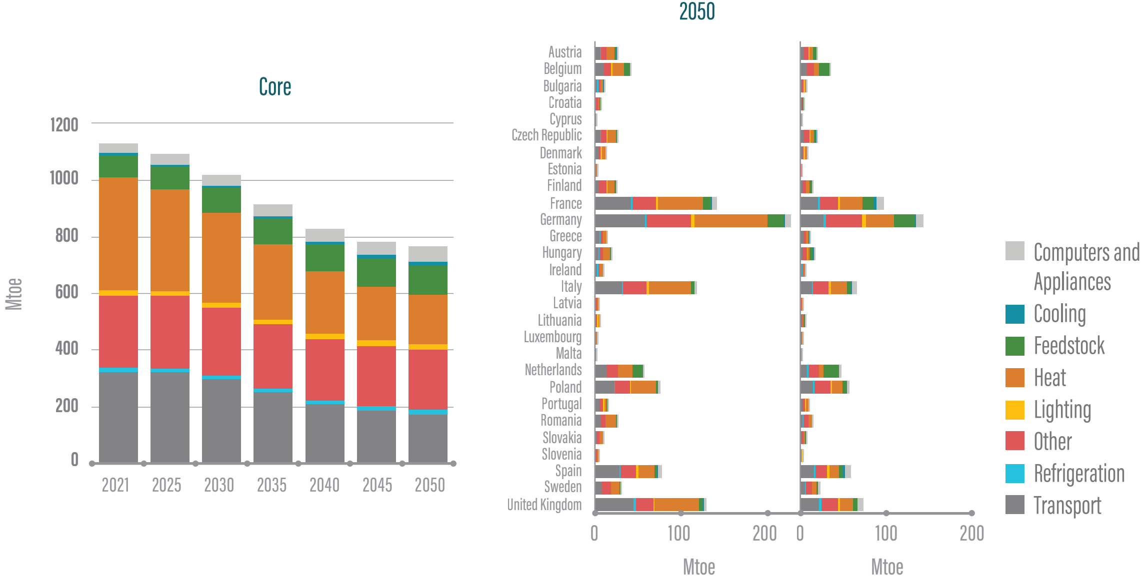
FIGURE 21. Final Energy Demand



Note: *A comparison of final energy demand across all scenarios, highlighting the trajectory of the* ***Core, Slow Electrification****, and* ***Low Demand*** *Scenarios which have the largest differences in final energy demand.*

The largest overall decline in end-use categories is seen in transport and heat, with the substitution of electric vehicles for internal combustion engines and the substitution of heat pumps for boilers. ***Figure 22*** shows this both at an aggregate level as well as with a country-level comparison from 2021 to 2050. Countries with larger heating demands as a share of their overall loads show larger overall declines in final energy demand through 2050.

FIGURE 22. Final Energy by End-Use Category

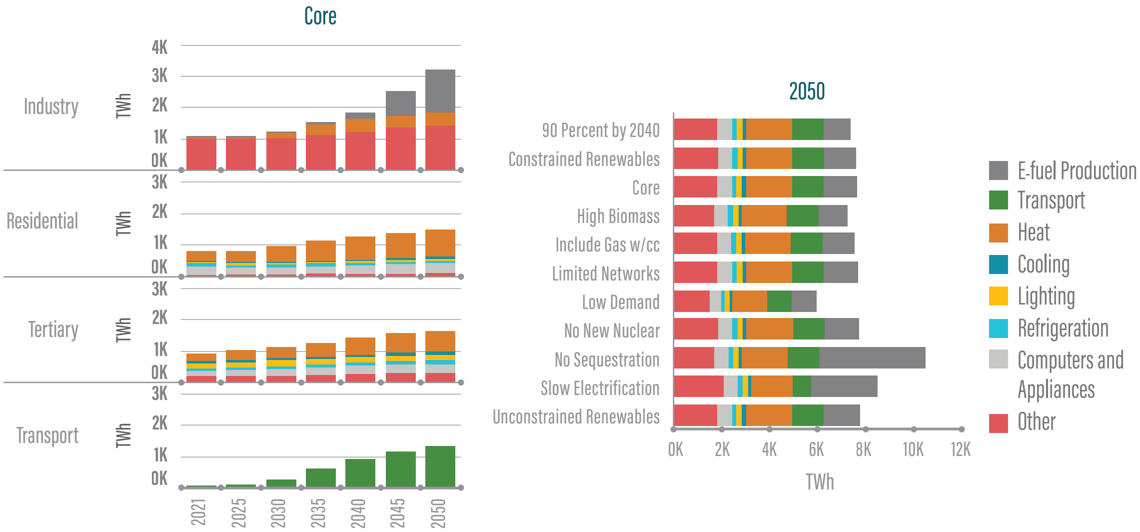


Note: *Breakdown of final energy use in key applications from 2021 to 2050, highlighting how energy demand changes with decarbonization.*

Electricity

The most significant increases in electricity use through 2050 are in building heating, industrial process heating and steam production, e-fuel production, and on-road transportation (***Figure 23***). Overall electricity load increases ~2.5x from 2021 through 2050, yet the nature of this load changes even more dramatically. Transportation loads are new loads delivered through millions of charging points with the opportunity to flex their charging to manage grid conditions; e-fuel production comprises loads that can be co-located with renewable resources or even off-grid, reducing transmission and distribution requirements; and building heat is a load concentrated in the coldest hours, putting strain on both distribution systems and generation fleets to meet its demand. The when and where of electricity load is equally important to the "how-much" and in many cases these loads are flexible enough to co-evolve with the generation portfolios. This sector coupling is critical to the cost-effectiveness of the energy system transition and allows for higher penetrations of variable renewable energy (wind and solar) than would otherwise be economically optimal (75-85% across Scenarios as shown in (***Figure 24***).

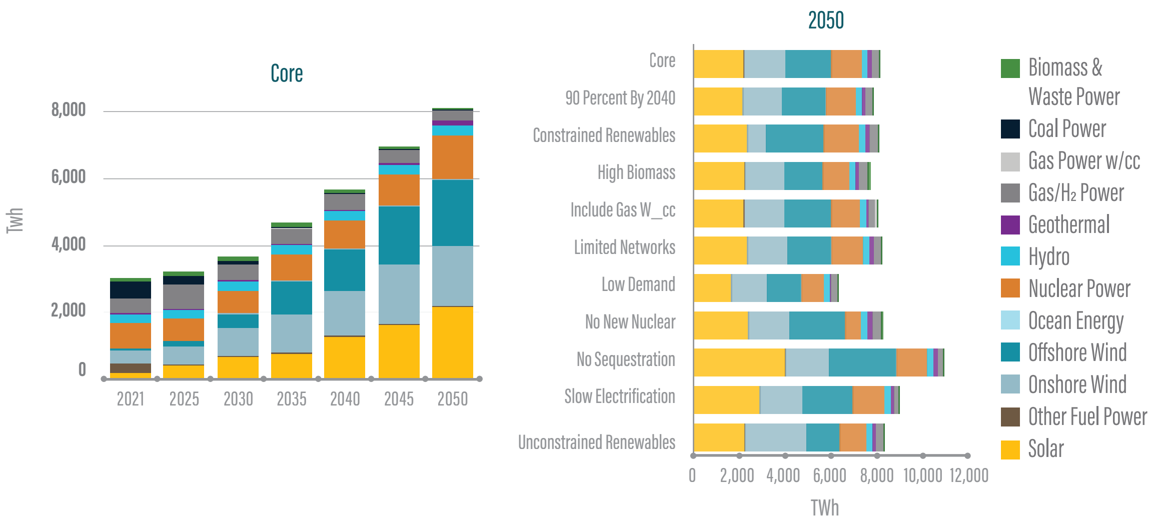
FIGURE 23. Electricity Demand



Note: *Projected electricity demand through 2050 by sector and end-use, showing the growing role of electrification of heat in buildings and industry and the growing share of electricity used in mobility for direct electrification and e-fuel production.*

The scale of overall generation varies significantly across scenarios. This scale is determined by estimates of energy service demand, levels of electrification, and the necessity to produce zero-carbon e-fuels and support the electricity load of DAC. Wind, across Scenarios, makes up most of the electricity supply by 2050, with variations in the geographic location and type—onshore, fixed offshore, and floating offshore. Floating offshore and nuclear are the backstop resources in these Scenarios, both regionally and for Europe as a whole, and they are utilized most when onshore wind deployment is limited by siting constraints (**Constrained Renewables**). Nuclear plays a significant role in the overall mix in all Scenarios excepting **No New Nuclear**, with the model choosing to maintain the nuclear fleet, to the extent feasible, and build new plants to support up to 1500 TWh of generation.

FIGURE 24. Electricity Generation

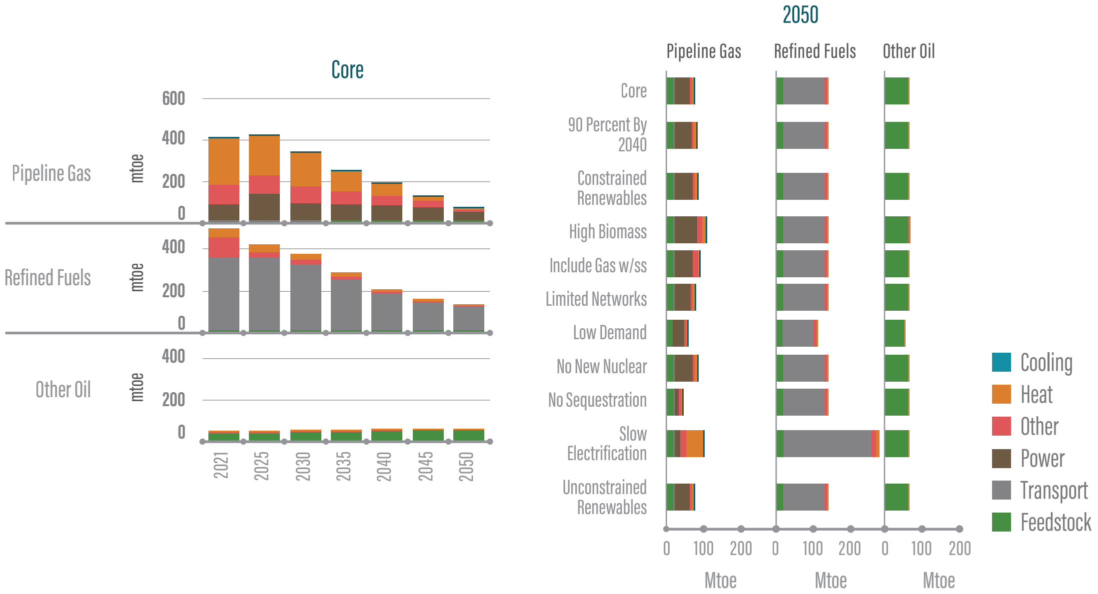


Note: *Energy mix for electricity generation by 2050, with a focus on the decline of fossil generation and the increase in renewable energy sources and nuclear energy.*

Hydrocarbon Fuels

The current energy system uses an enormous volume of hydrocarbon fuels (liquid and gaseous), principally for heat and transport, as exemplified in ***Figure 25***. In most Scenarios, the electrification of heat in buildings and industry indicates that the use of fuel in these applications is almost entirely gone by 2050. Electrification of vehicles indicates that most of the fuel use in transportation is converted by 2050, with the residual fuel going to hard-to-electrify uses like aviation and bunkering. Other residual fuel use in 2050 is primarily in power (used for backup power during periods of under-generation) and the use of fuel as feedstocks for bulk chemical production. In the **Slow Electrification** Scenario, additional fuel use in transport and heat results is slightly mitigated by lower fuel demand in power. Principally, however, the impacts are on the supply side, with changing volumes of biofuel and e-fuel use (in addition to direct air capture being used to offset residual fuel emissions).

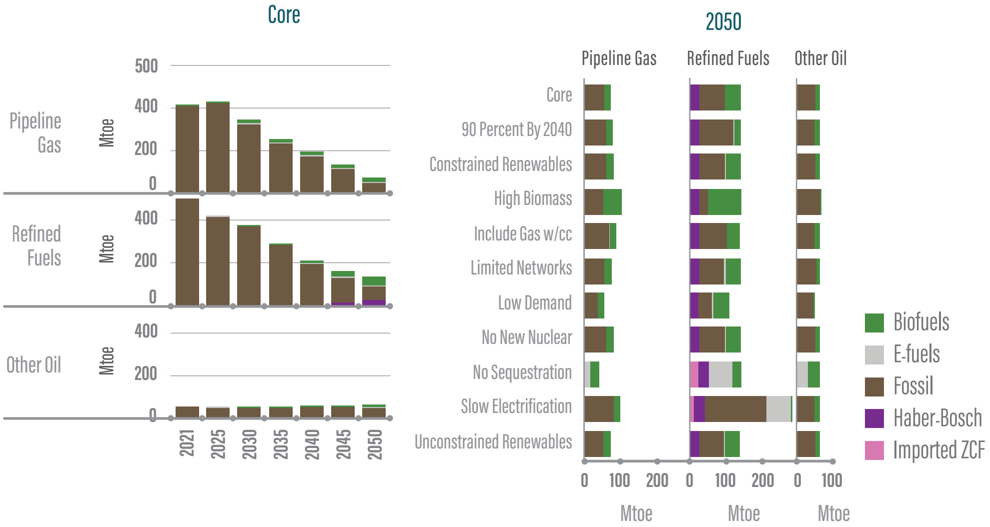
FIGURE 25. Hydrocarbon Demand



Note: *Graph showing the projected decline in hydrocarbon demand across sectors as electrification and renewable energy adoption increase.*

Dry biomass feedstocks (e.g. herbaceous or woody wastes) are principally used to displace liquid alternatives in the modeling. Wet biomass feedstocks (e.g. manure, wastewater, and landfill feedstocks for anaerobic digestion) are used to decarbonize the pipeline. We represent Haber-Bosch here as a refined fuel here as it displaces fuel oil traditionally used in bunkering applications. Other e-fuels are used sparingly due to the expense and the alternative of directly sequestering carbon (instead of utilizing it), but in the **No Sequestration** Scenario, we see a significant volume across all fuel types, as seen in ***Figure 26***.

FIGURE 26. Hydrocarbon Supply

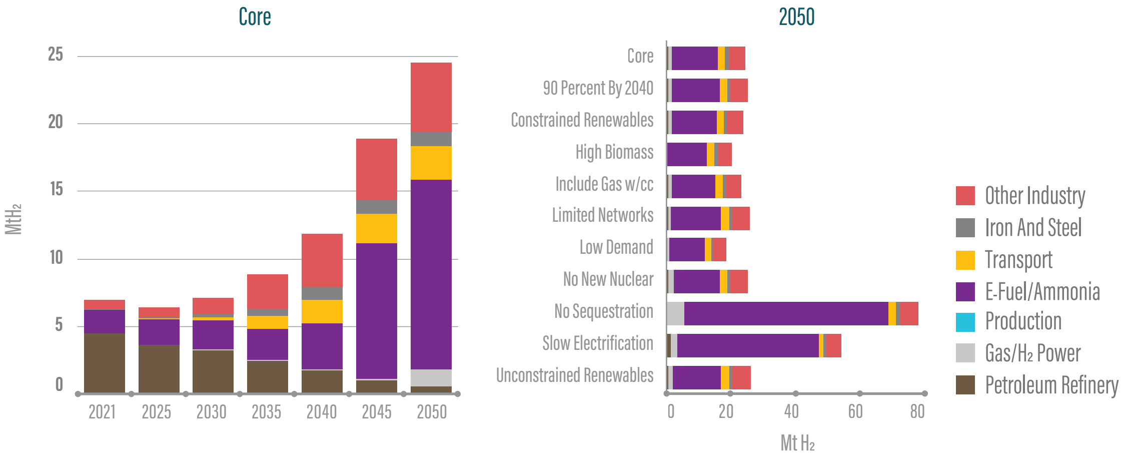


Note: *Projected supply of hydrocarbons in 2050, showing the role of biofuels and e-fuels as fossil fuel alternatives in a decarbonized energy system.*

Hydrogen

Hydrogen demand in the model, as seen in ***Figure 27***, stays relatively flat through 2030, with declining refinery output offset by an increase in transport and the production of ammonia and other chemicals. Significant growth occurs after 2030, with the expansion of 1) hydrogen's use as a feedstock for ammonia (which is used in bunkering), 2) growth in the iron and steel industry (hydrogen-based direct reduced iron), and 3) some long-haul on-road transportation. It does not make significant in-roads into power generation until 2050, and even then, it only does so on a limited basis because hydrogen remains prohibitively high-cost as a fuel to support regular operations of thermal powerplants, instead being used as a backup fuel in lieu of fossil gas.

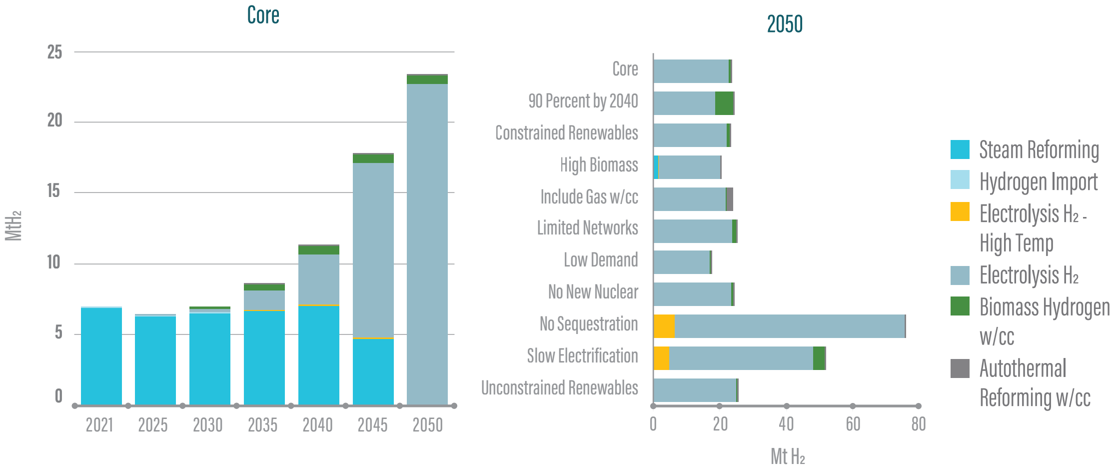
FIGURE 27. Hydrogen Demand



Note: *Projected hydrogen demand by sector through 2050, with a focus on industry, transport, and e-fuel production applications.*

Figure 28 shows that the deployment of clean hydrogen resources accompanies this post-2030 growth. This timing is explained by the high costs of electrolysis and the economic preference to deploy renewables to displace thermal generation initially before adding a significant amount of new load. Our conclusion contradicts some of the policy goals expressed by the EU, which would need more rapid expansion of renewables through 2030 than we anticipate here. The majority of clean hydrogen is produced through low-temperature electrolysis, with **Slow Electrification** and **No Sequestration** also producing some of its hydrogen through nuclear high-temperature electrolysis. Some BECCS hydrogen is produced in most Scenarios, and **Include Gas with Carbon Capture** also produces some blue hydrogen through an autothermal reforming process.

FIGURE 28. Hydrogen Supply

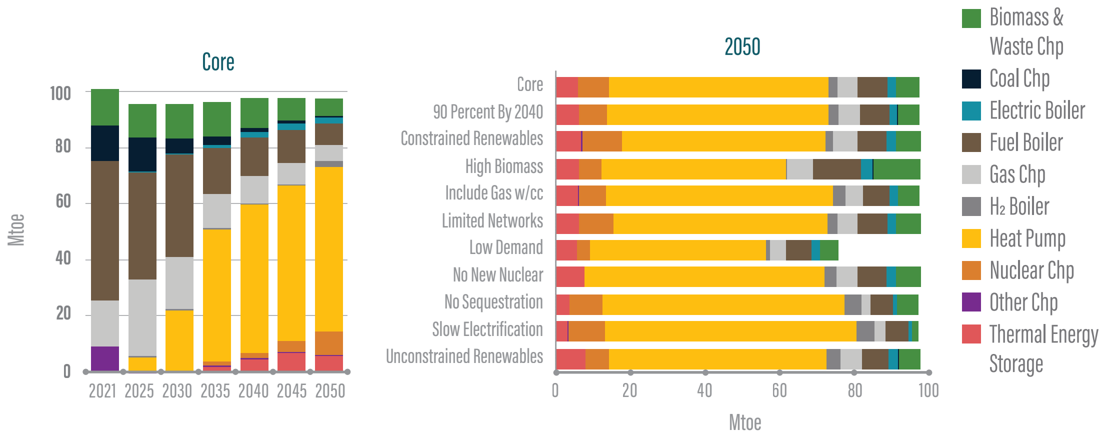


Note: *Graph showing the portfolio of hydrogen production through 2050 with a focus on electrolysis production.*

Steam

Steam remains an important energy vector through 2050, supplying both building heating as well as industrial processes, with potential for decarbonization demonstrated in ***Figure 29***. Currently, dedicated fuel boilers, or Combined Heat and Power (CHP) facilities, produce almost all of Europe's steam. The model chooses a rapid decarbonization of steam for two reasons. First, many of these CHP facilities will be retired for economic reasons in a decarbonizing electricity grid with more limited need for steam's relatively inflexible generation, leaving a gap in the supply of steam that will need to be filled with new technologies. Second, the efficiency gains of heat pumps when combined with relatively high fuel prices create favorable economic conditions for industrial heat pump deployment. In the longer term, with higher levels of renewable penetration in electricity, we see more deployment of flexible electric technologies. For instance, a technology like thermal energy storage leverages heat storage to allow it to produce heat with electricity during low-priced periods and use it during high-priced periods, whereas a technology like electric boilers (which does not utilize thermal storage, operates in a dual-fuel capacity with fuel boilers, running only during low-priced periods and switching with fuel boilers during high-priced electricity periods). We also see the deployment of nuclear CHP, with smaller plants (small modular reactors) more easily being matched with the scale of existing heating loads than large plants.

FIGURE 29. Steam Supply

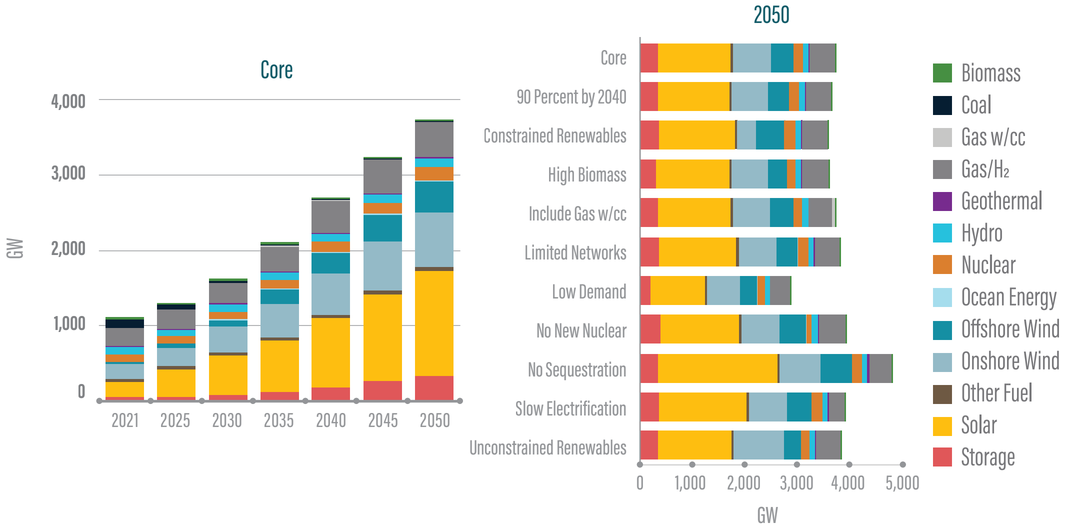


Note: *Analysis of steam supply for heating and industrial processes by 2050, showing the role of electrified steam technologies and nuclear CHP.*

Infrastructure

Figure 30 demonstrates that, in the **Core** Scenario, generation capacity across the EU and UK expands ~3.5x from 2021 levels, with a huge shift by 2030 from a primarily thermal system to one that is primarily renewable . This renewable expansion accounts for most capacity increases, with parallel deployment of battery storage and backup thermal capacity to support reliability even with existing coal and nuclear retirements. Nuclear expansion begins to occur at scale only in the 2030s. **No New Nuclear** has an expansion of offshore wind and a larger amount of backup thermal and battery storage compared to other Scenarios. **Constrained Renewables** substitutes additional nuclear capacity and offshore wind for a limited onshore wind resource. **Include Gas with Carbon Capture** adds gas with carbon capture in power, replacing other backup thermal generators (unabated gas plants). **No Sequestration** adds an additional TW of renewables to produce e-fuels. **Unconstrained Renewables** adds additional onshore wind in lieu of offshore wind.

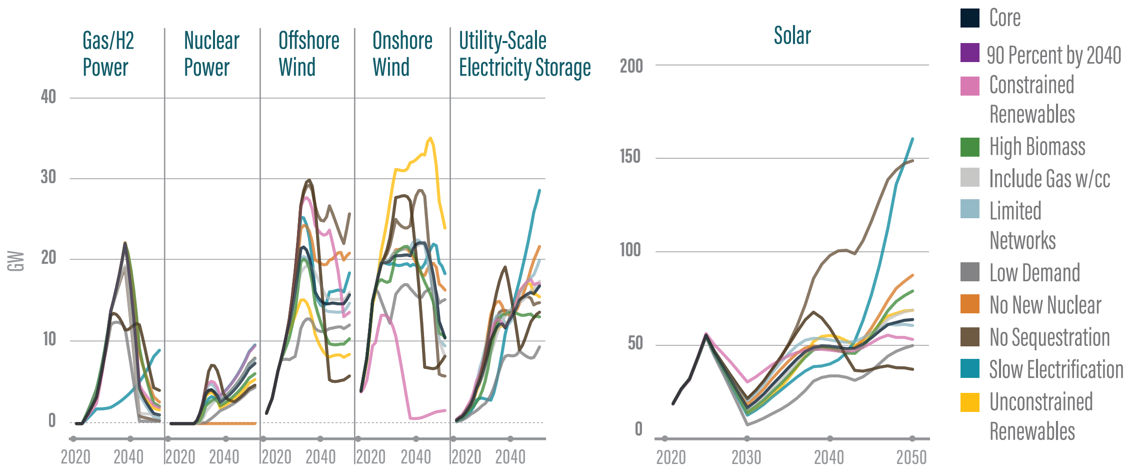
FIGURE 30. Electric Generation Capacity



Note: *Projected growth of electric generation capacity through 2050, with a focus on renewables, nuclear, storage, and backup thermal power.*

Electricity build rates (shown annually by resource category on a standard and logarithmic axis in ***Figure 31***) demonstrate the necessity to accelerate deployment across resource categories. Offshore wind peaks across Scenarios at 30 GWs in 2035, onshore wind peaks at 35 GWs in 2045, and solar increases to almost 155 GWs by 2050 to support e-fuel production in the **Slow Electrification** Scenario. Nuclear power peaks in 2050 above 9 GWs. Controversially, we see the deployment of over 20 GWs per year of backup thermal generation to support the load growth of electrification and the retirement of existing thermal power plants (coal and lignite primarily). Despite market pressures and current trends, short-duration batteries are not able to meet these evolving reliability needs, and long-duration storage is not economic or available at the requisite scale to satisfy this reliability need in this timeframe.

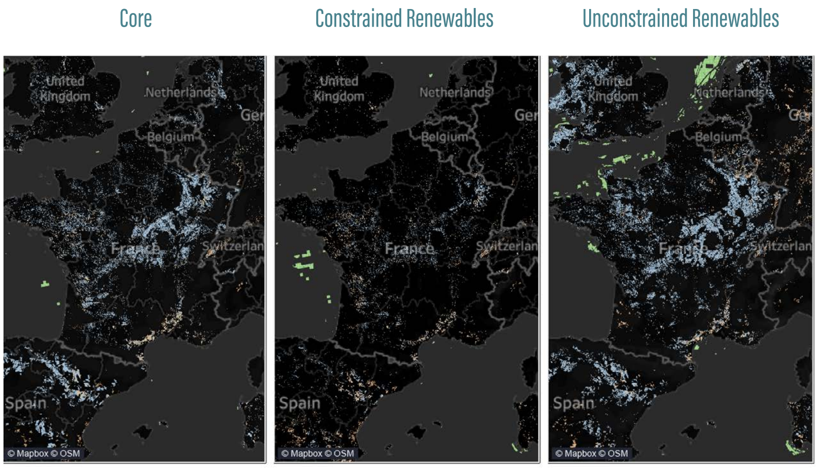
FIGURE 31. Annual Capacity Build Rates[5]



Note: *A graph showing the rate of new capacity build-out for renewables, storage, and thermal power plants between 2025 and 2050, illustrating the scale of infrastructure deployment required.*

This year's ADP also produced downscaled maps of all our Scenarios for utility-scale solar, onshore wind, offshore wind, nuclear, geothermal, and gas with carbon capture. ***Figure 32*** shows the example for France of the evolution of renewable siting from 2030 — 2050 in the **Core** Scenario. Renewable CPAs are reflected on the map as polygons, representing the land selected in each Scenario.

FIGURE 32. Locations of Downscaled Renewable Projects (offshore wind, onshore wind, solar) – Core Scenario


Core
Constrained Renewables
Unconstrained Renewables

Note: *Offshore wind siting shown in green across Scenarios.*

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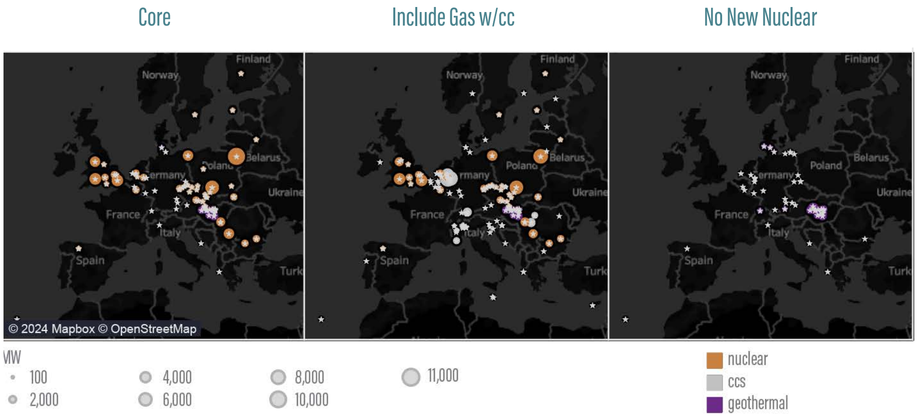
[5] We smooth the modeled build-rate using a 5-year moving average to better illustrate trends

Figure 33 illustrates siting for nuclear, CCS, and geothermal technologies in 2050 in the **Core, Include Gas with Carbon Capture**, and **No New Nuclear** Scenarios. Our downscaling process sites these at "point" locations, with the size of the bubbles representing their capacities. As shown, some points able to site multiple projects or larger capacity facilities.

FIGURE 33. Downscaled Nuclear, CCS, and Geothermal in 2050

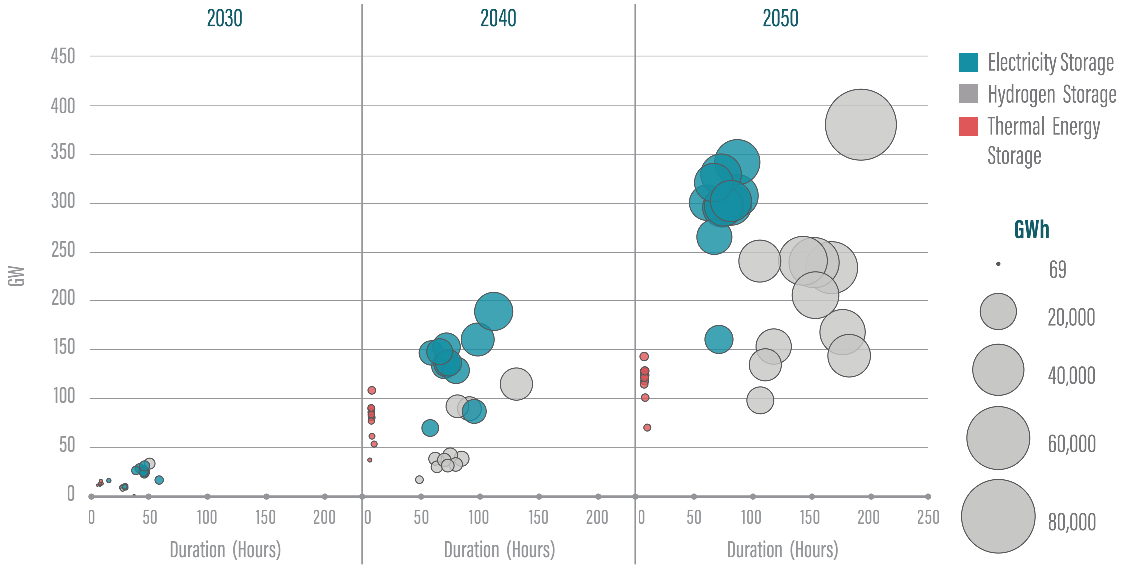


Storage

The current energy system relies on an enormous volume of fossil fuel storage, which, as the energy system transitions away from fuel, will lose some of its usefulness in balancing supply and demand. Some of the residual fossil fuel storage can be leveraged for storing synthetic fuels, but these volumes are small. Instead, balancing supply and demand for energy, which is exacerbated by moving primary energy supplies towards renewable sources, necessitates storage in new forms.

We define storage here as the input-to-output energy carrier of the storage medium. Electricity storage therefore would apply to batteries (of any type) or pumped hydro. Thermal storage refers to storing thermal energy in a medium like molten salt. Hydrogen storage refers to the storage and extraction of hydrogen from storage tanks, underground pipes, or underground reservoirs. The interesting dynamics here involve the evolution in storage duration as the grid becomes more renewable and overgeneration periods begin to persist for longer periods of time. ***Figure 34*** shows an increase in storage over time for each of the storage mediums detailed above. The y-axis represents storage charge capacity. The duration is shown on the x-axis and the bubble size is the total storage (energy) capacity.

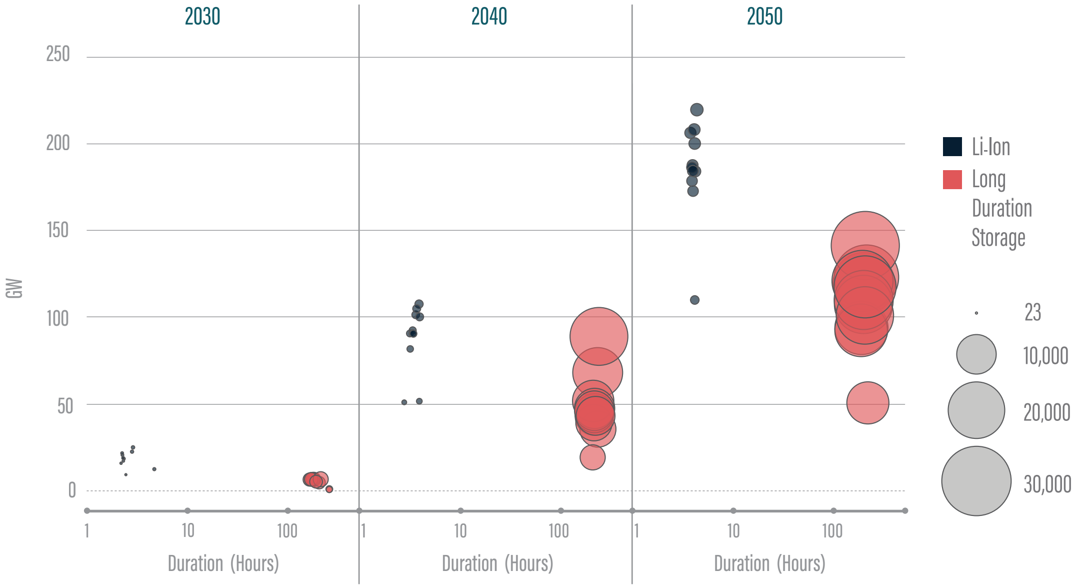
FIGURE 34. New Energy Storage



Note: *Projected growth in new energy storage through 2050, comparing electricity storage, hydrogen storage, and thermal energy storage solutions.*

Storing this amount of energy, specifically in electricity storage, will only be economic at costs that are multiples below current costs. In 2030, a multi-day energy storage device (100 hours) in our modeling is €1488/kW. By 2050, this declines to €734/kW. If these cost targets are not feasible, we would see significantly less electricity storage, more thermal backup (including from nuclear), and more hydrogen storage to compensate. ***Figure 35*** illustrates the bifurcation of storage, with li-ion providing the bulk of the storage power capacity at shorter durations (~4 hours as a fleet average) and long-duration storage providing most of the storage energy. Thermal energy storage is economic for storage durations of 8-10 hours in the modeling.

FIGURE 35. New Electricity Storage

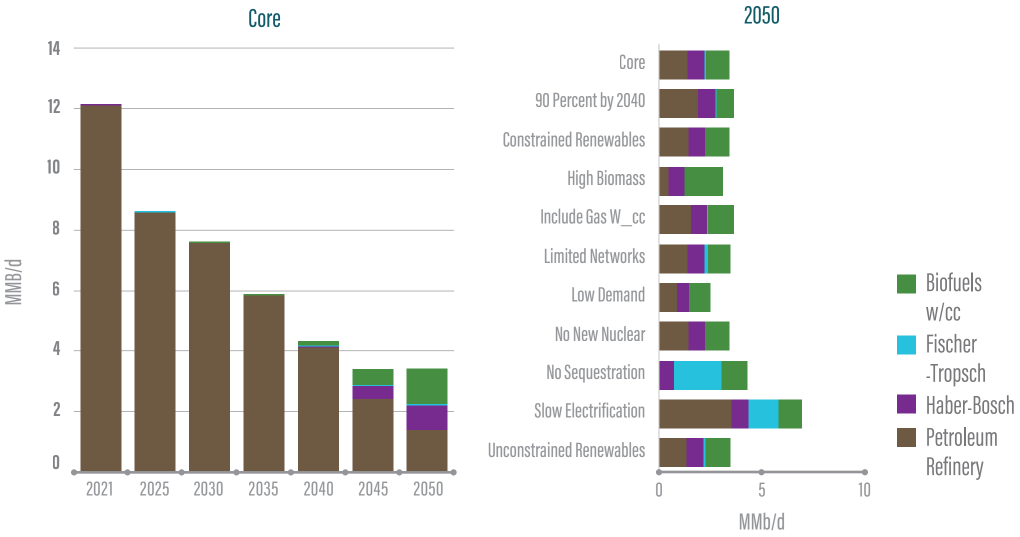


Note: *Analysis of the contribution of new short- and long-duration electricity storage technologies to the energy system by 2050, highlighting the differentiated builds (capacity and energy) of short-duration and long-duration technologies. X-axis is shown on a logarithmic scale.*

Fuels

Fuels production capacity declines overall with electrification, with the biggest fuel impact being the retirement of petroleum refining with decreasing demand. In the long term, some of this capacity is replaced with e-fuels (ammonia and Fischer-Tropsch or methanol) and biofuels. Still, the overall fuel production capacity in the modeling declines by >50% in all Scenarios except for **Slow Electrification**, as seen in ***Figure 36.***

FIGURE 36. Fuels Production Capacity[6]



Note: *Projected decline in fossil fuel processing capacity by 2050, with growth in biofuels and e-fuels to meet decarbonization goals.*

Transmission

We use included transmission line segments from ENTSO-E[7] to populate a supply curve of potential transmission expansion. Economic buildout in the model, selecting from these segments, is relatively consistent across Scenarios, as seen in ***Figure 37***. Only **Limited Networks** (which increases the cost to the model of transmission by 3x), **Low Demand**, and **High Biomass** result in significantly less transmission build than other Scenarios. **Low Demand** reduces transmission due to the reduction in overall electricity system size. This Scenario has significant reductions electric space heating, which reduces overall system peak even more than overall electricity demand and reduces the need for transmission to supply electricity reliably during critical winter peaks. **High Biomass** reduces the need for DAC and its associated electricity load, reducing the need for transmission. Not all load impacts the need for transmission equally. While residential space heating load and DAC increase the need for transmission, electrolysis does not. Despite the **No Sequestration** Scenario having significantly more overall electricity load than other Scenarios, the share that is electrolysis actually reduces overall transmission need. The electrolysis can be sited with regards to renewable resources, and hydrogen pipelines can substitute for moving energy between countries.

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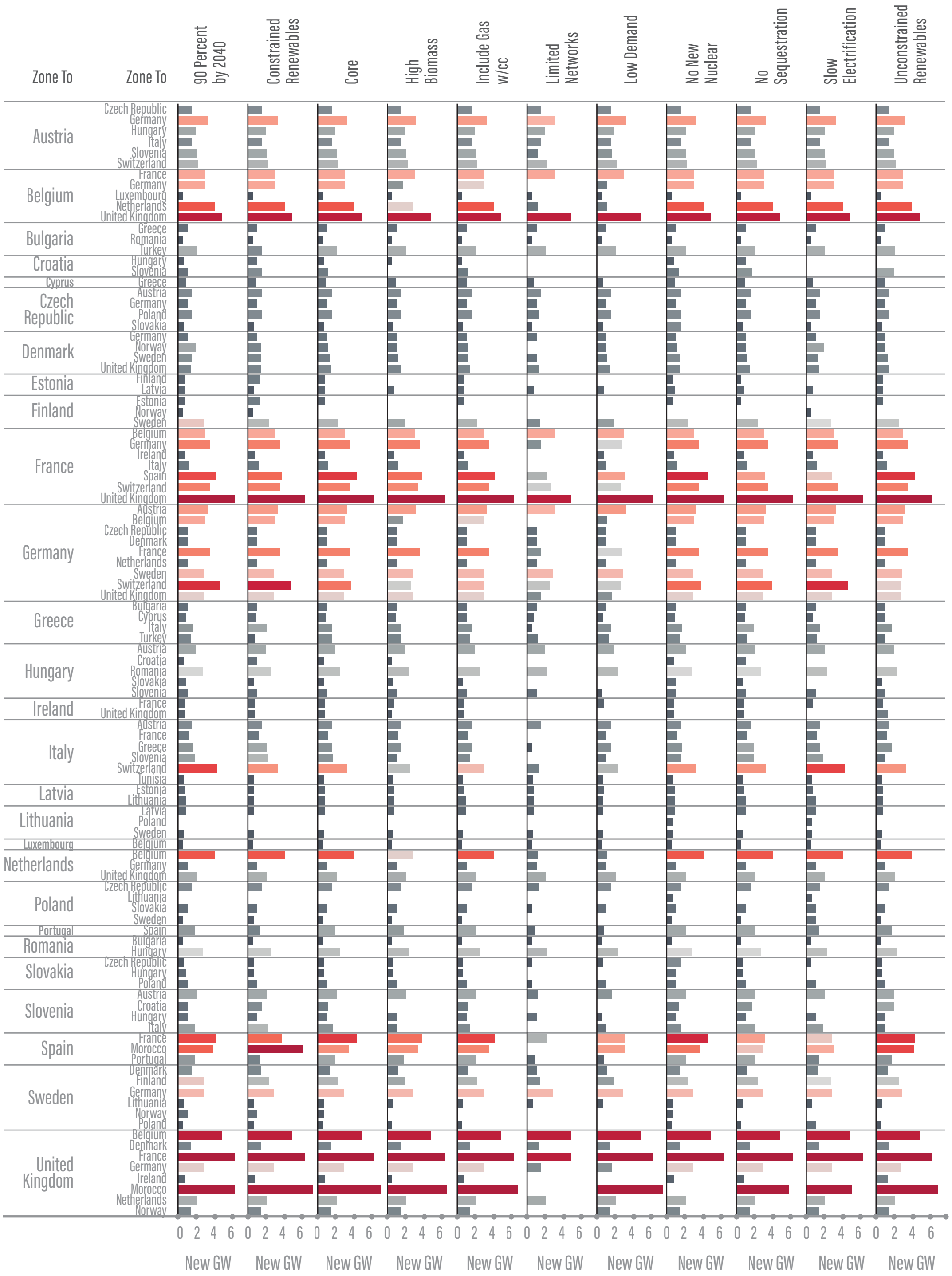
[6] Early year declines are driven by retirement of petroleum refineries to reach "optimal" utilization factors, which ignores some near-term dynamics of fuel markets. This doesn't impact longer-term trends.

[7] https://tyndp.entsoe.eu/

FIGURE 37. Transboundary Electric Transmission Capacity in 2050



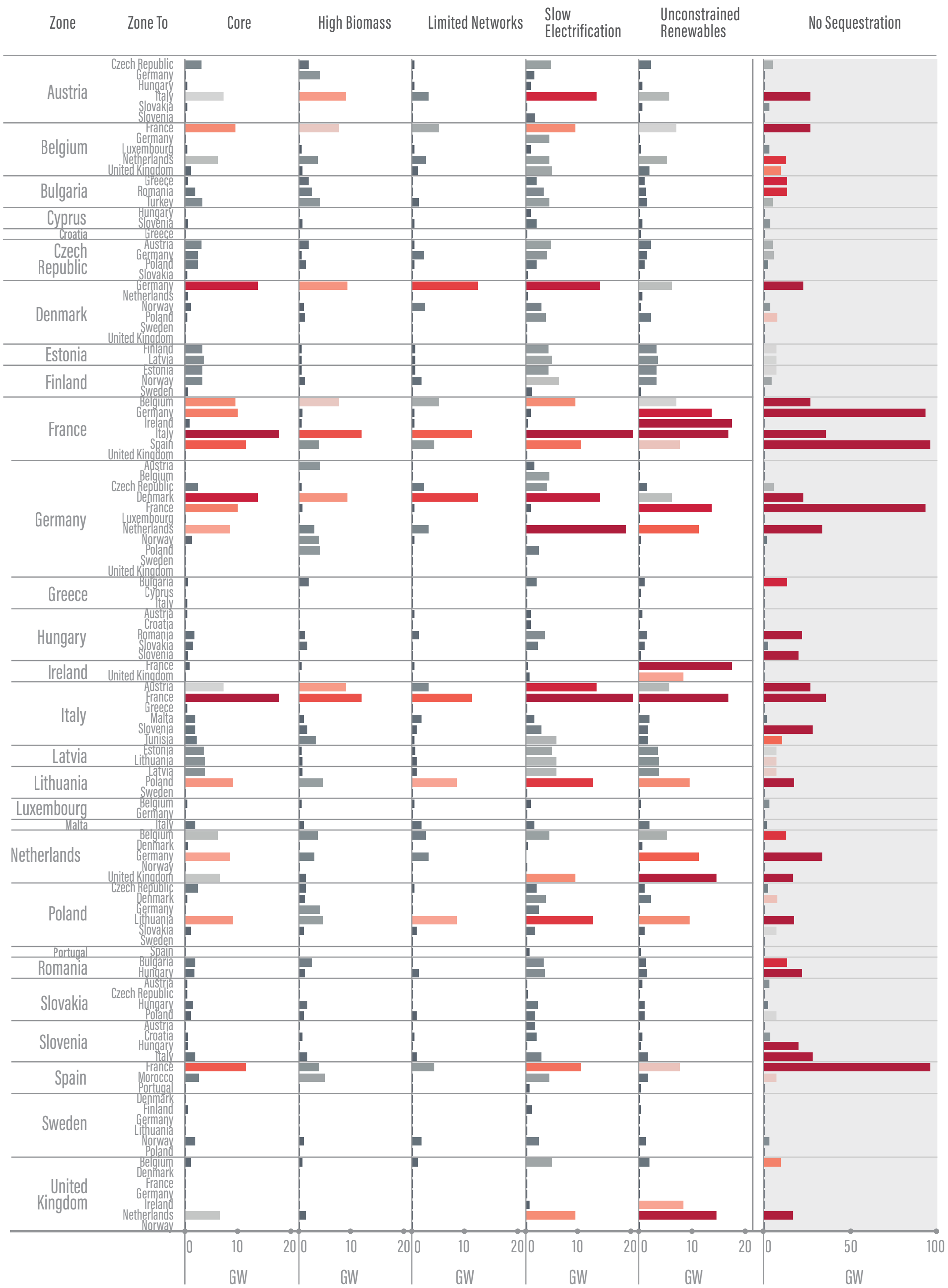
Note: *Projection of electric transmission capacity between countries in 2050, showing the cross-border infrastructure required to balance supply and demand.*

Pipelines

Hydrogen

Figure 38 shows the pipeline capacity among countries for six different Scenarios that have the largest impact on the pipeline network: **Core, High Biomass, Limited Networks, No Sequestration, Slow Electrification**, **and Unconstrained Renewables**. The pipeline network develops to move hydrogen between countries with plentiful renewables to countries with significant demand. **No Sequestration** and **Slow Electrification** increase the need to distribute hydrogen to countries for e-fuel production. **Limited Networks** increases the cost of distributing hydrogen by backbone pipeline, causing the model to rely on lower quality renewables (and higher cost production), reducing the need for inter-regional flows. **High Biomass** decreases the demand for hydrogen, specifically in e-fuel production.

FIGURE 38. Transboundary Hydrogen Pipeline Capacity in 2050

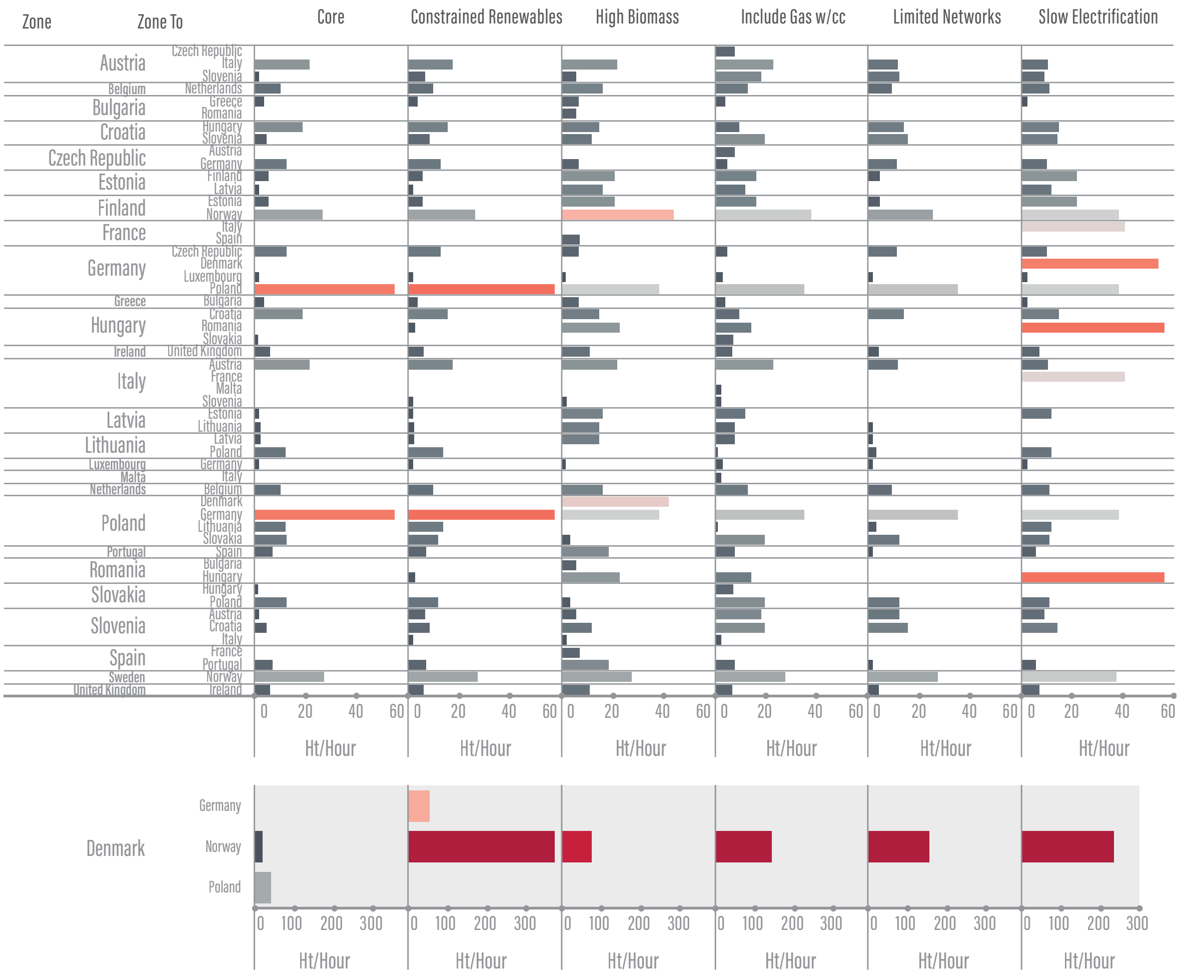


Note: *A graphic showing the projected hydrogen pipeline network across Europe in 2050 across Scenarios.* ***No Sequestration*** *shown on a separate scale to the right for clarity.*

CO2 Pipelines

Figure 39, on the other hand, shows the pipeline capacity between countries for six different Scenarios that have the largest impact on the CO_2 pipeline network: **Core, High Biomass**, **Include Gas with Carbon Capture**, **Limited Networks, Slow Electrification**, and **Unconstrained Renewables. High Biomass** increases the supply of CO_2 from Eastern Europe and parts of Scandinavia (Finland, Sweden) and necessitates increased pipeline capacity to Germany, Denmark, and Norway. It also reduces the need for DAC and the necessity for pipelines to move carbon from the point of capture (powered by offshore wind resources) to the point of sequestration in the North Sea (Denmark to Norway). **Include Gas with Carbon Capture** has a modest impact on transboundary pipelines as most gas with carbon capture (power and hydrogen) facilities are built in Germany with ample access to storage, though it does increase some pipelines between Hungary and Romania, and between Austria and Slovenia. **Limited Networks** reduces overall pipeline build across countries, with the most significant impact to the North Sea corridor (Denmark to Norway). **Slow Electrification** has the opposite effect, with the demand for offsets driving an increase in the CO_2 stored from offshore wind powered DAC in the North Sea and the capacity of the concomitant pipeline network. This is also observed in **Constrained Renewables**, which increases the concentration of DAC in the North Sea. **Slow Electrification** expands DAC overall, which also induces new pipelines from Denmark to Germany and France to Italy for the same purpose.

FIGURE 39. Transboundary CO_2 Pipeline Capacity in 2050

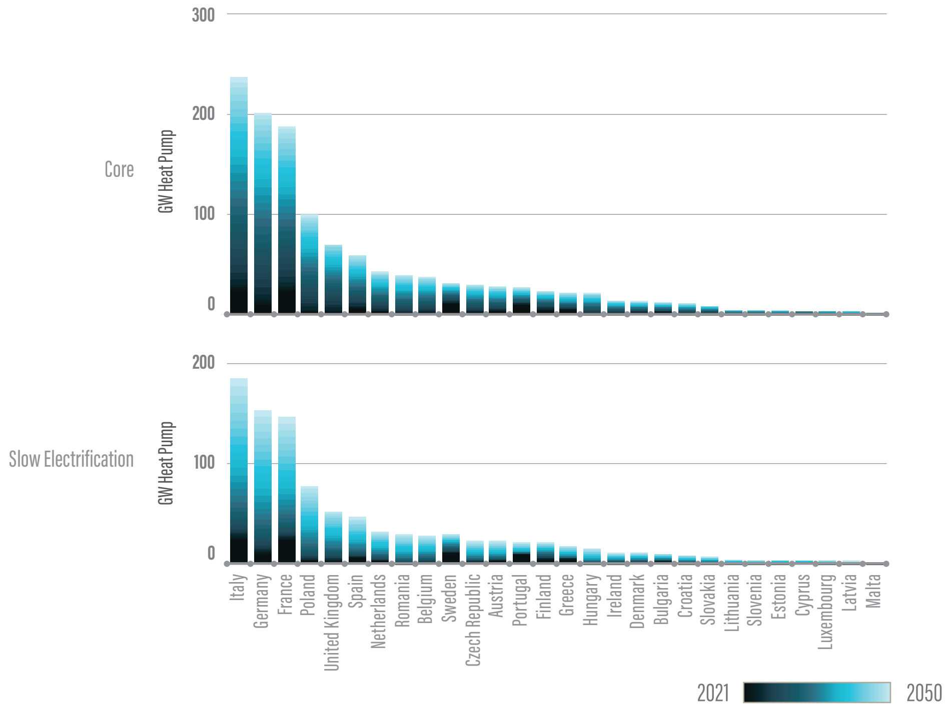


Note: *A graphic of the CO_2 pipeline network by 2050, showing how captured carbon will be transported across Europe for sequestration or utilization across Scenarios.* **Denmark** *shown on a separate scale at the bottom for clarity.*

Buildings

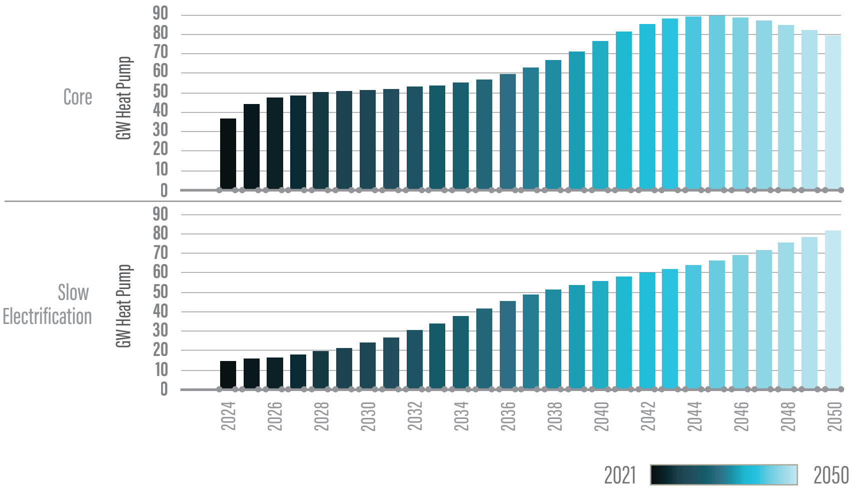
The most significant change in the building stock, in addition to upgrades to building envelopes, comes in the deployment of heat pumps across Europe for space heating. This has impacts, as discussed, on electricity sector generation planning, but it is also necessary to understand the electricity distribution impacts as well as the necessity to scale up the heat pump market in these countries as hundreds of new GWs of heat pumps are installed throughout Europe. ***Figure 40*** illustrates the installed heat pump stock in buildings by year and country while ***Figure 41*** shows the overall heat pump sales in the EU and UK by year.

FIGURE 40. Heat Pump Capacity Installed



Note: *Projected growth of heat pump installations across Europe through 2050, highlighting the role of heat pumps in reducing emissions from heating.*

FIGURE 41. Heat Pump Sales

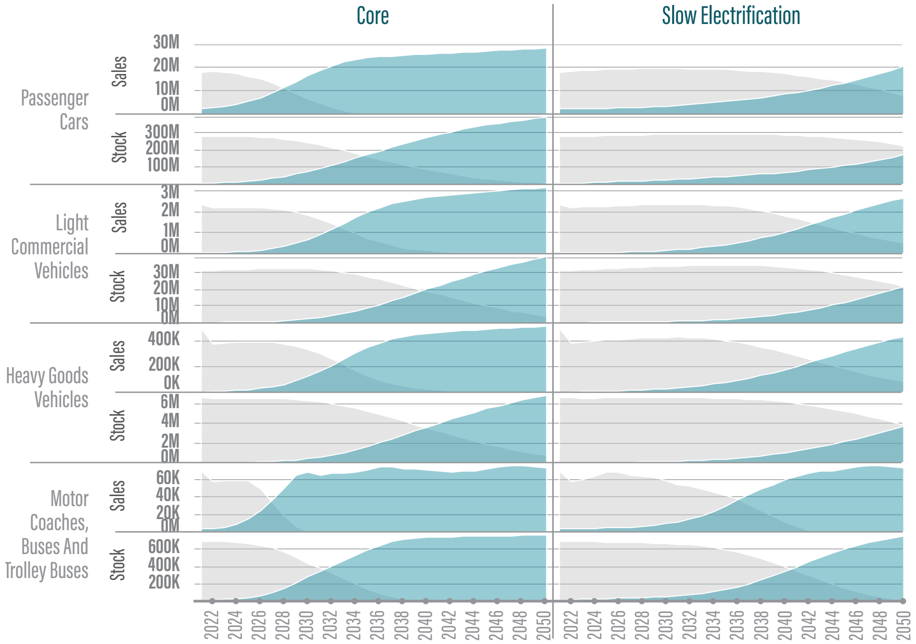


Note: *Heat pump sales in the EU and UK through 2050, reflecting the increasing market adoption of this technology for building decarbonization.*

Transport

Figure 42 shows the on-road zero-emission vehicle (ZEV) growth by cost category and Scenario (**Core** and **Slow Electrification**). **Slow Electrification,** with much slower sales growth, results in only half the ZEVs on the road in 2050 as does the **Core** Scenario, necessitating a large volume of zero-carbon fuels.

FIGURE 42. Zero-Emission Vehicle Stock and Sales for Core and Slow Electrification



Note: *Comparison of the growth of zero-emission vehicles (ZEVs) under the* ***Core*** *and* ***Slow Electrification*** *Scenarios through 2050.*

Costs

In this year's analysis, we included costs for demand-side equipment and energy efficiency investments so that we could calculate a net energy system costs metric (***Figure 43***). This represents the levelized societal costs for energy producing, converting, delivering, storing, and consuming infrastructure as well as the commodity costs of things like oil and natural gas. When compared against our **Baseline** Scenario, this represents the additional costs and savings associated with efficiency, electrification, electricity and fuel decarbonization,[8] non-CO_2 mitigation, etc. Decarbonization

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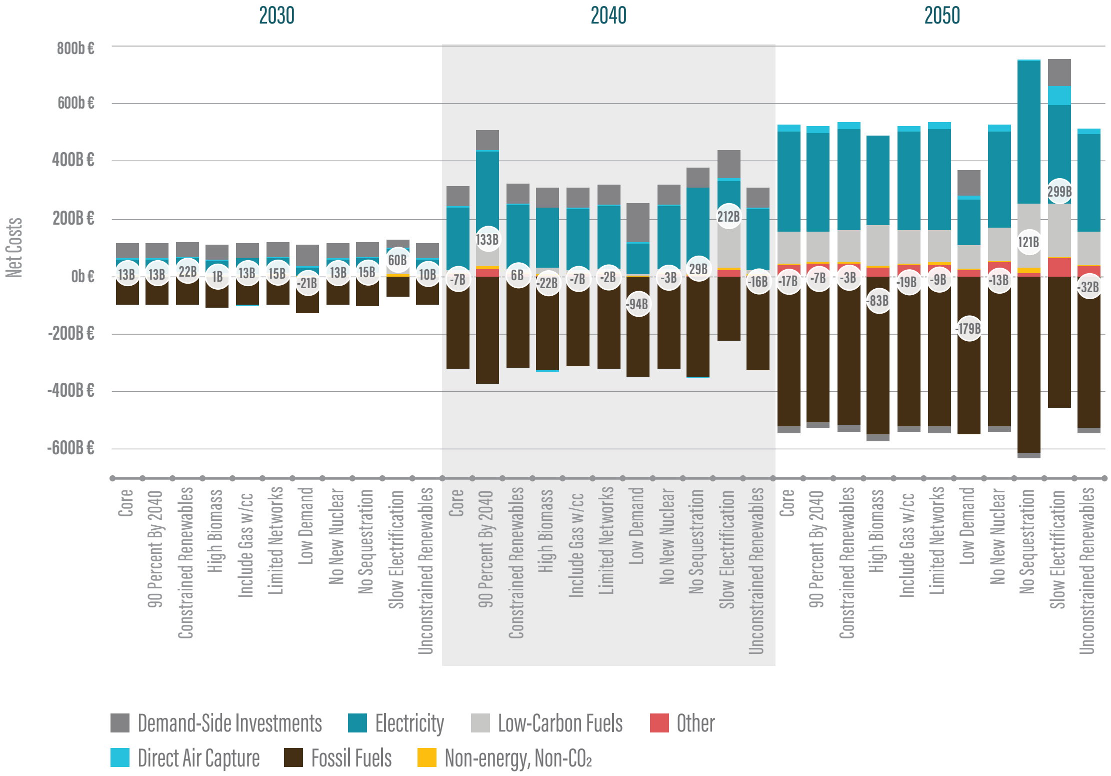
[8] We do not have economic cost impacts associated with additional land sector contributions

increases the costs of electricity (grid investments, low-carbon generation, storage, etc.), low-carbon fuels, non-CO_2 mitigation, and direct air capture. Overall demand-side investment costs only increase in the near-term (building shell, ZEV purchases, etc.); in the long term, declining vehicle costs means a transition to EVs saves money on vehicle purchases and thus reduces the overall demand-side equipment cost in the aggregate.

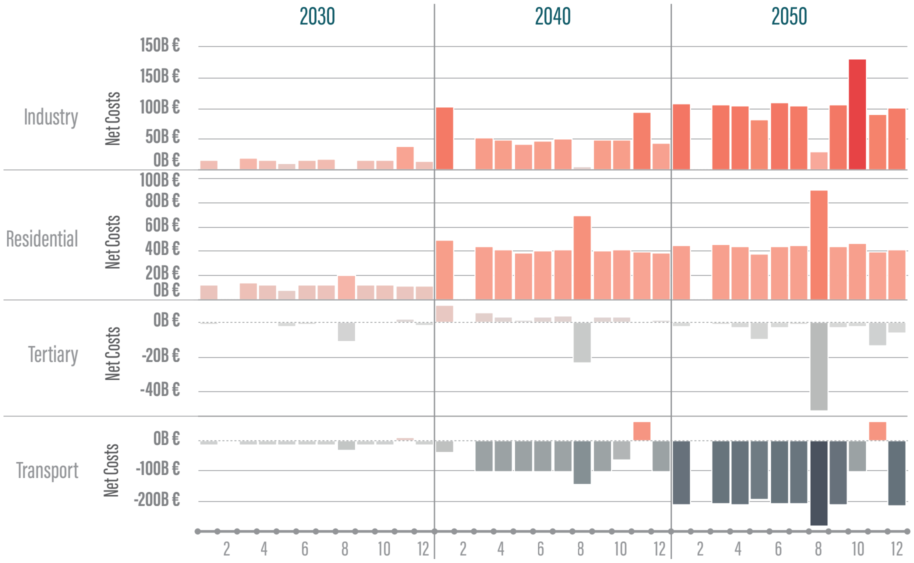
FIGURE 43. Net Costs from Baseline Scenario



Note: *A graph showing the net costs of decarbonization efforts compared to the* ***Baseline****, highlighting the economic benefits of a decarbonized economy.*

Importantly, these costs and savings are not allocated equally across sectors, which has implications for consumers as well as for European competitiveness. ***Figure 44*** shows that much of the increase in costs is borne by industry and residences, with large savings primarily in transportation, and with the electrification of on-road transportation as the most significant source of cost savings in the long run.

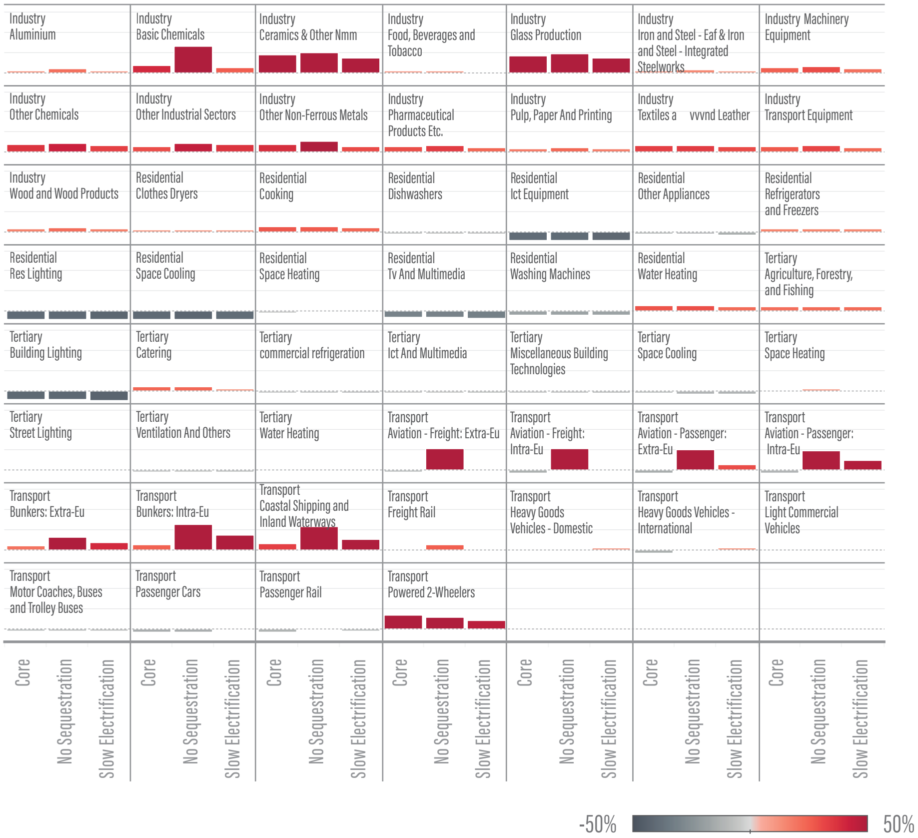
FIGURE 44. Net Costs from Baseline Scenario by Sector



Note: *Sectoral breakdown of the net costs of decarbonization, showing where costs and savings will occur by 2050.*

Diving in deeper, at the end-use level, ***Figure 45*** demonstrates that the variability in cost is large driven principally by an end-use's ability to electrify and the efficiency of that electrification process. Broadly, where large efficiency gains are possible (heat pumps in space conditioning and EVs) then costs can be mitigated. Where there is a lower efficiency gain (cooking, industrial end-uses, etc.) then decarbonization increases costs above the **Baseline**. If electrification is not possible at all, the cost of zero-carbon fuels also increases costs above the **Baseline**.

FIGURE 45. Net Cost Impact (%) from Baseline Scenario in 2050



Note: *A comparison of net cost impacts (%) across end-uses in 2050, showing which sectors will experience the largest cost reductions or increases.*

VI CONCLUSIONS

This report underscores the critical importance of adopting flexible, multi-faceted strategies to achieve net-zero greenhouse gas emissions by 2050 across Europe. Key updates in this year's analysis include a refined modeling approach that integrates more granular geographic downscaling analyses and maps, expanded emissions scope, and updated demand-side representation. These enhancements offer a more accurate and comprehensive view of the infrastructure, technological advancements, and societal shifts necessary for deep decarbonization. The Scenarios explored in this report highlight the varying pathways and their implications, emphasizing that there is no one-size-fits-all solution; instead, presented above is a balanced and adaptable approach tailored to regional strengths, resource availability, and societal preferences.

The report's findings indicate that while electrification and renewable energy deployment remain central to decarbonization, achieving these goals will require substantial investments in infrastructure—particularly in energy storage, transmission networks, and hydrogen pipelines. Additionally, the evolving energy landscape calls for robust policy frameworks that can adapt to changing technological and market conditions, ensuring that targets are both ambitious and flexible enough to accommodate diverse national circumstances. The necessity is clear for ongoing innovation, particularly in carbon capture, utilization, and storage, as well as in the development of low-carbon fuels.

As Europe advances toward its decarbonization goals, the next steps involve accelerating renewable energy deployment, enhancing energy efficiency, and addressing the economic implications of these transitions. Policymakers must create a supportive environment for investment in innovative technologies while ensuring equitable distribution of benefits. This report serves as a critical guide for stakeholders, offering actionable insights and a clear path forward to achieving a sustainable and resilient net-zero future for Europe.

Key Contributions

- **Geographic Downscaling:** High-resolution mapping (1 km2) of energy infrastructure, allowing for a more precise visualization of local and regional energy needs and opportunities.
- **Expanded Emissions Scope:** Inclusion of land-use and non-CO_2 emissions within the modeling framework, providing a more holistic approach to achieving net-zero targets.
- **Scenario-Based Analyses:** Exploration of multiple, diverse pathways to net zero, reflecting different societal preferences & pressures, policy constraints, and technological advancements, offering a dynamic perspective rather than a one-size-fits-all approach.
- **Detailed Sectoral Insights:** Comprehensive breakdown of impacts on key sectors such as electricity, transport, industry, and buildings, highlighting the interplay between different energy vectors and technologies.
- **Comprehensive Emissions Scope:** Expands the analysis to include land-use changes and non-CO_2 emissions, allowing for a more holistic understanding of how to achieve net-zero targets across multiple sectors.
- **Innovative Solutions for Energy Balancing:** Emphasis on multi-day energy storage, flexible generation, and sector coupling to manage the complexities of a renewable-heavy grid, particularly during peak winter demand.
- **Policy Adaptability:** Recommendations for flexible policy frameworks that balance ambition with the need for adaptability, ensuring effective implementation at both national and local levels.

VII SUPPLEMENTAL RESULTS

FIGURE 46. Supplemental: Total Emissions by Source Category

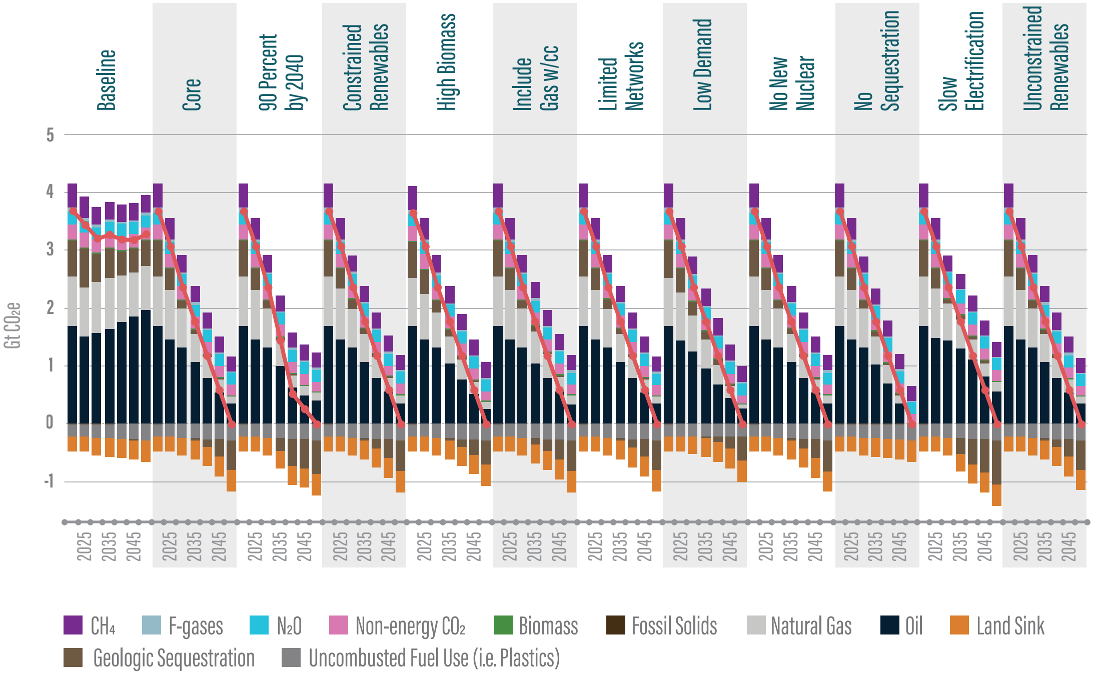


FIGURE 47. Total Emissions by Sector

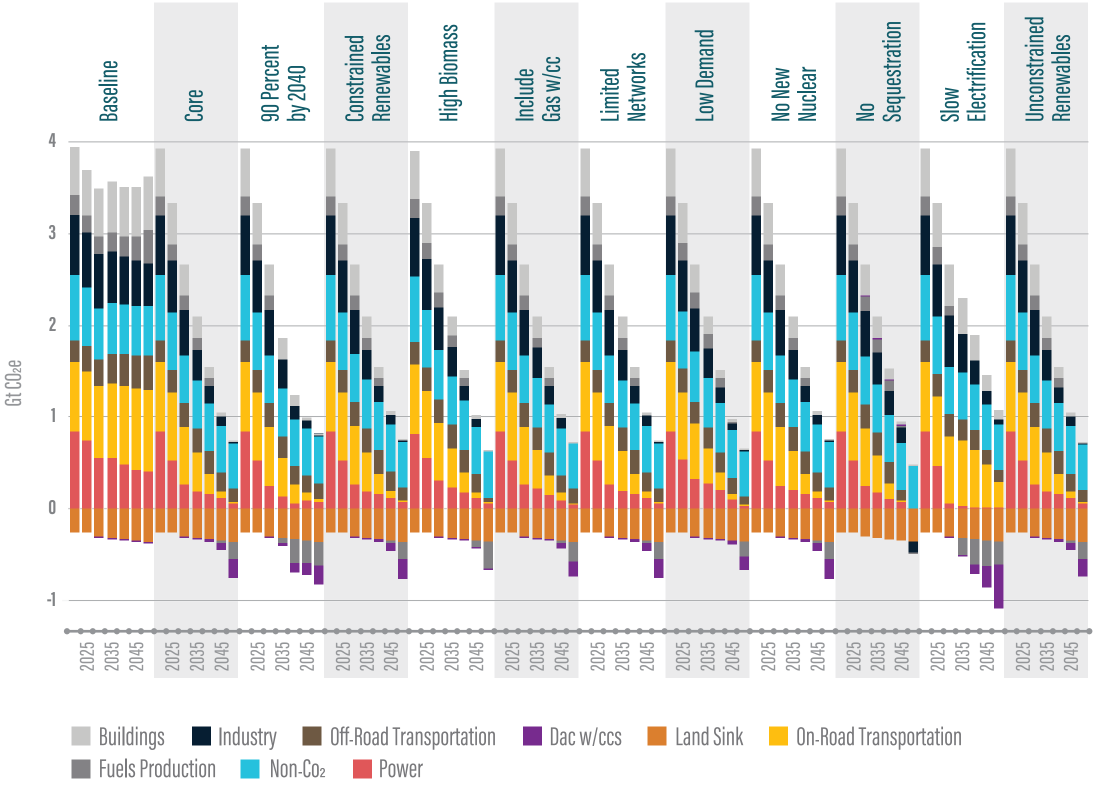


FIGURE 48. Supplemental: Primary Energy Demand

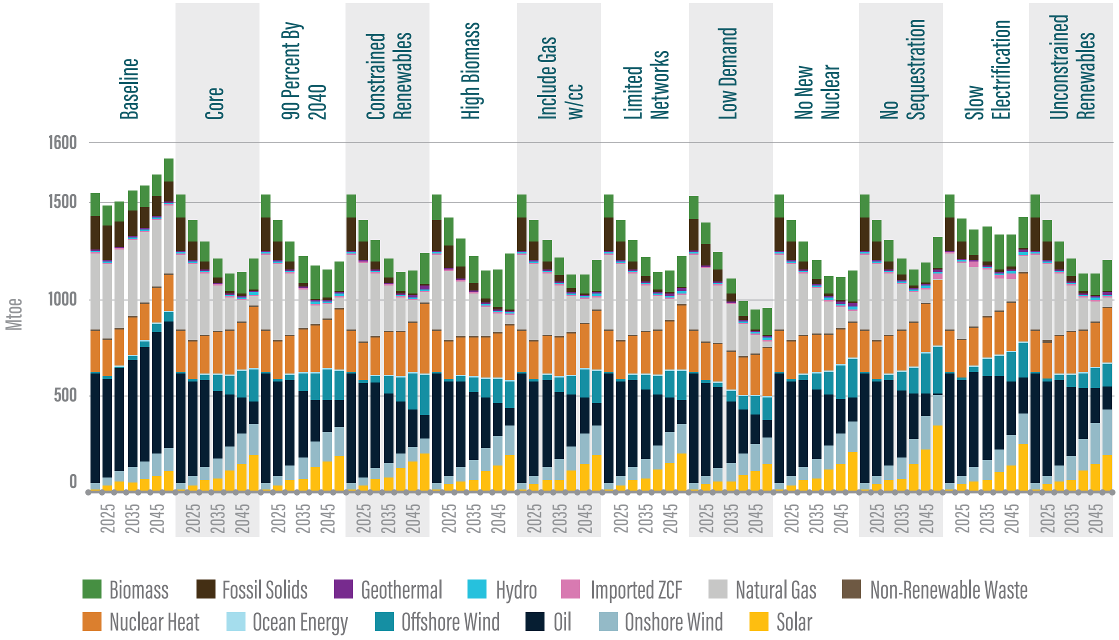


FIGURE 49. Supplemental: Final Energy Demand

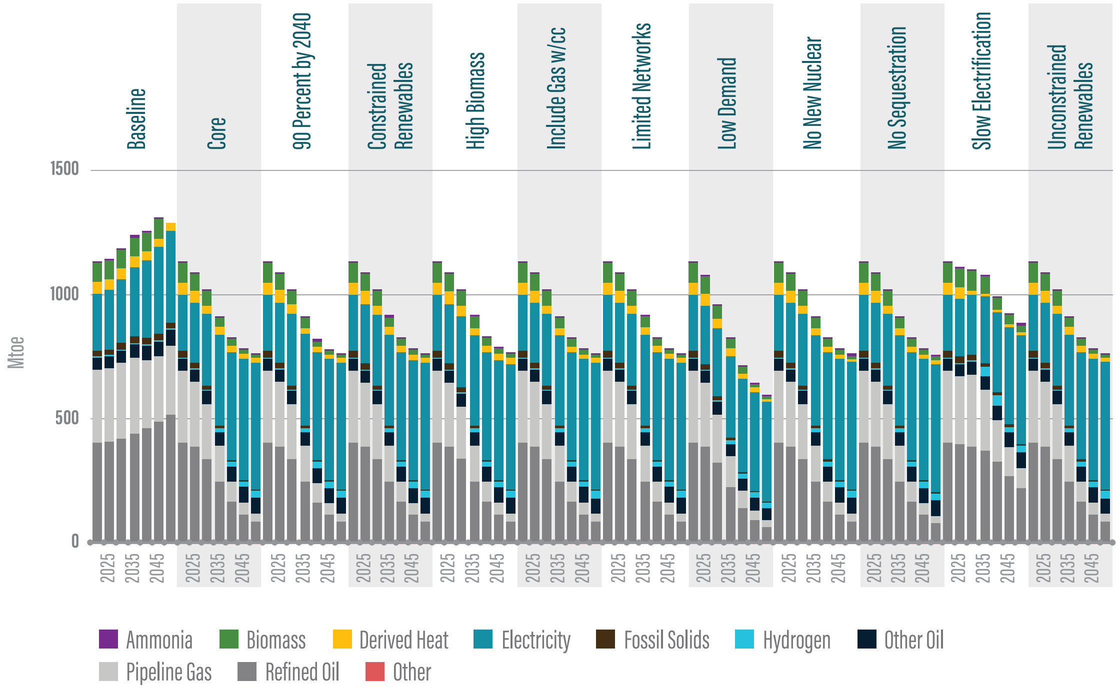


FIGURE 50. Supplemental: Electricity Demand

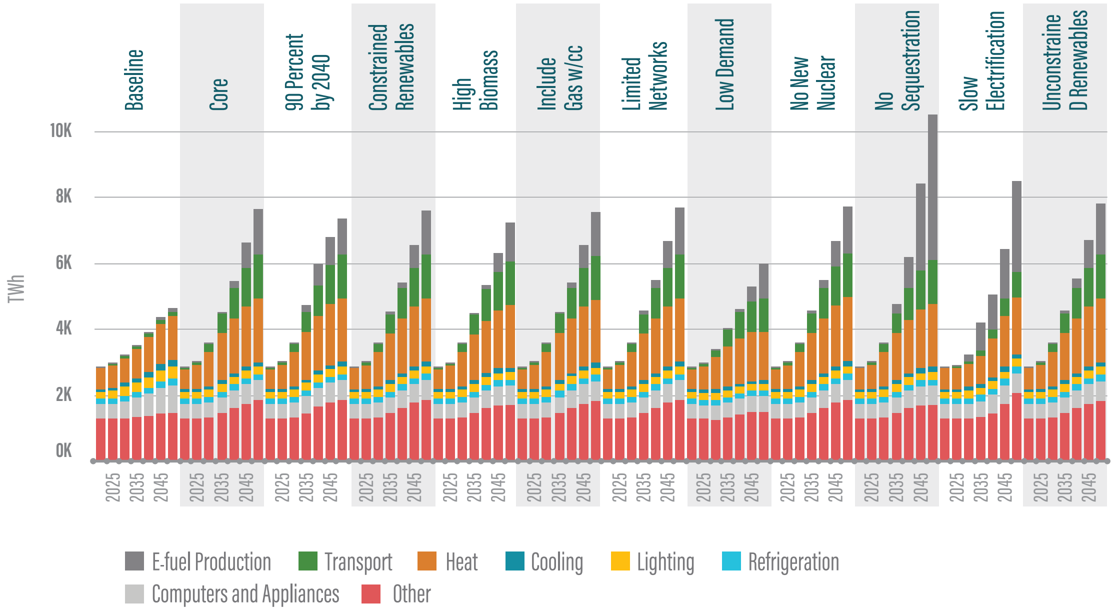


FIGURE 51. Supplemental: Electricity Generation

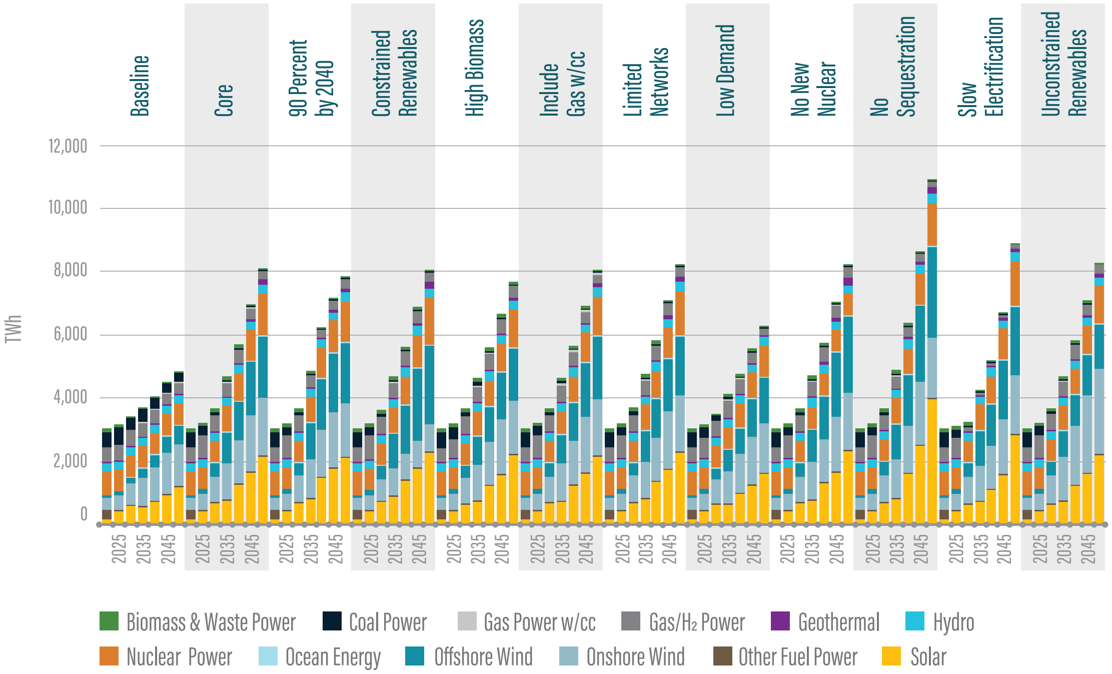


FIGURE 52. Supplemental: Hydrocarbon Demand

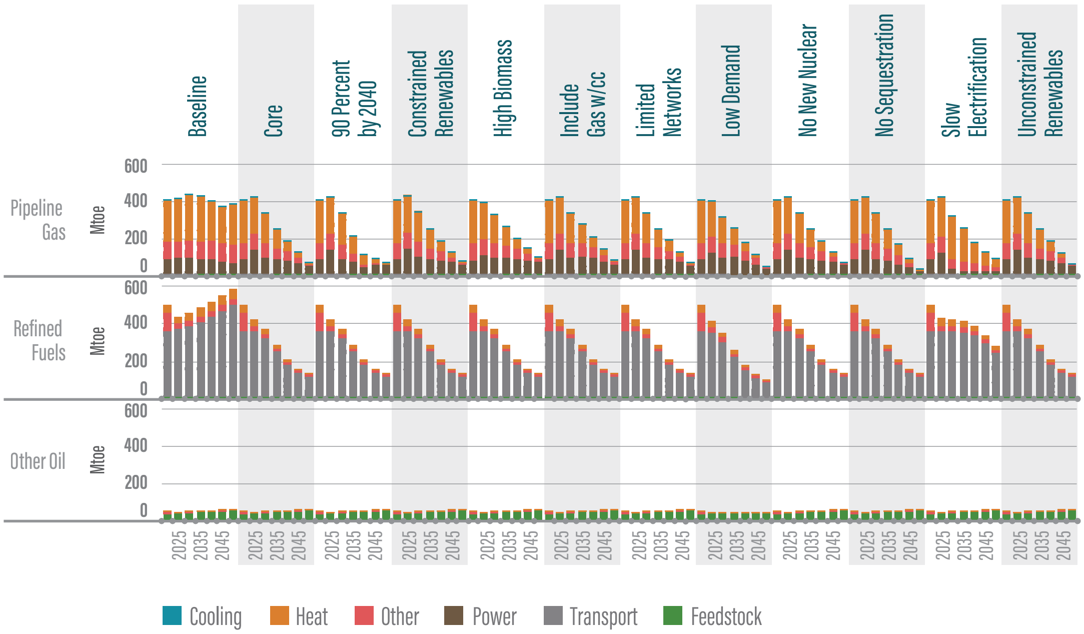


FIGURE 53 Supplemental: Hydrocarbon Supply

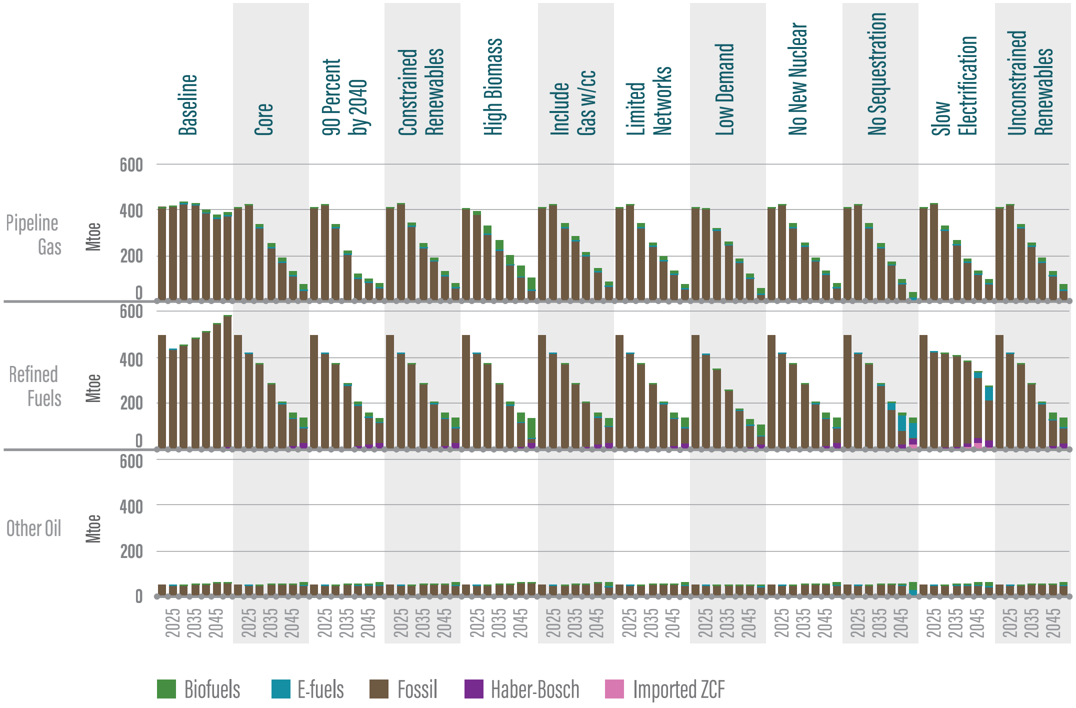


FIGURE 54 Supplemental: Hydrogen Demand

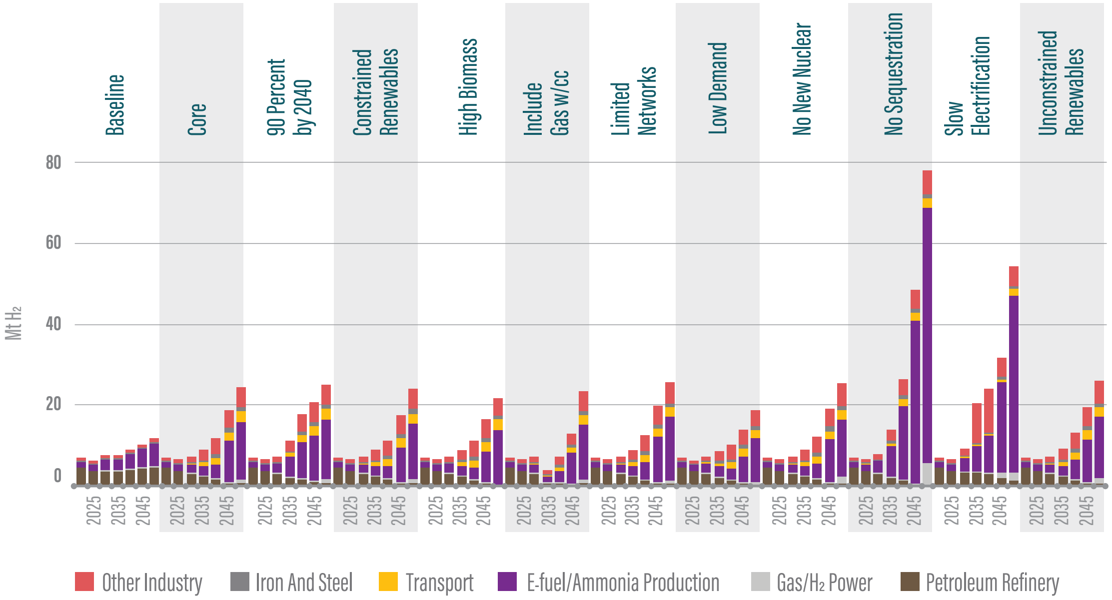


FIGURE 55. Supplemental: Hydrogen Supply

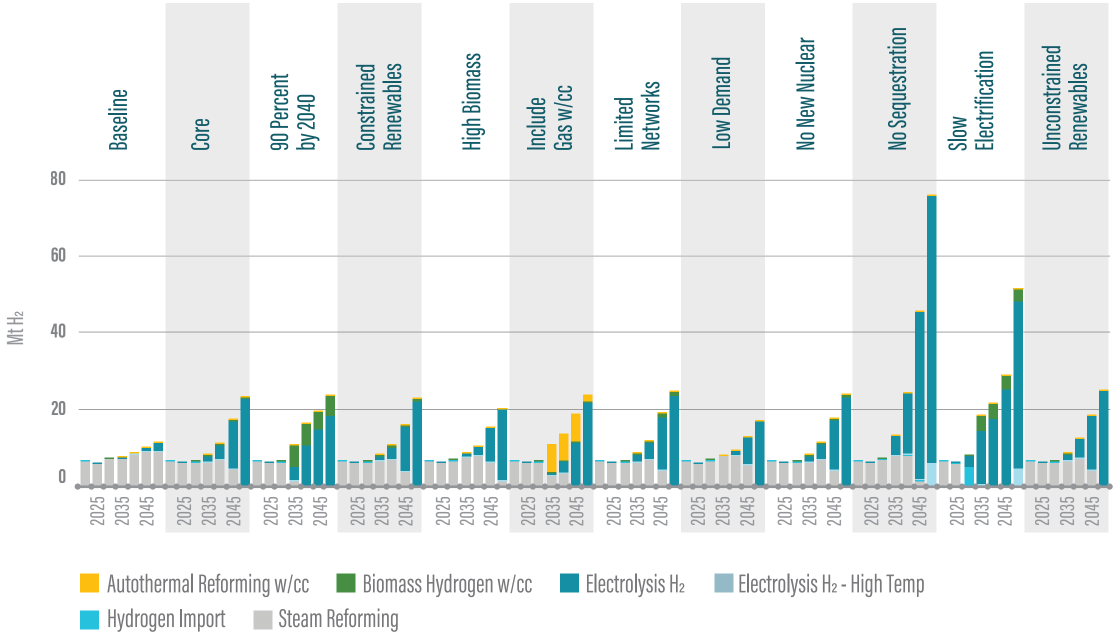


FIGURE 56. Supplemental: Steam Supply

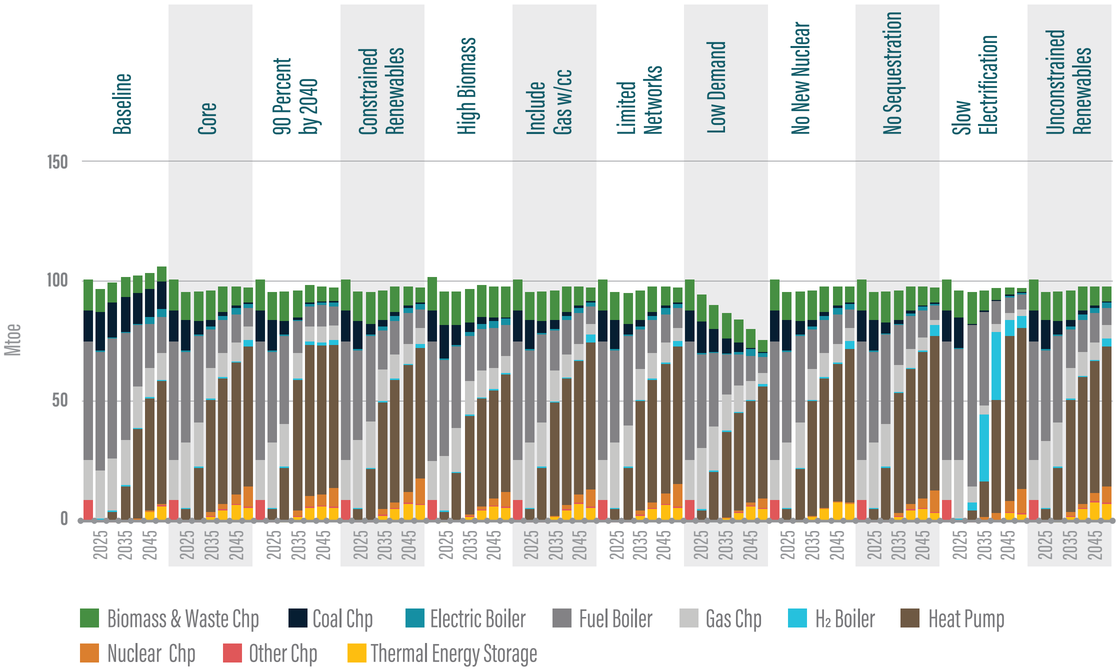


FIGURE 57. Supplemental: Electricity Generation Capacity

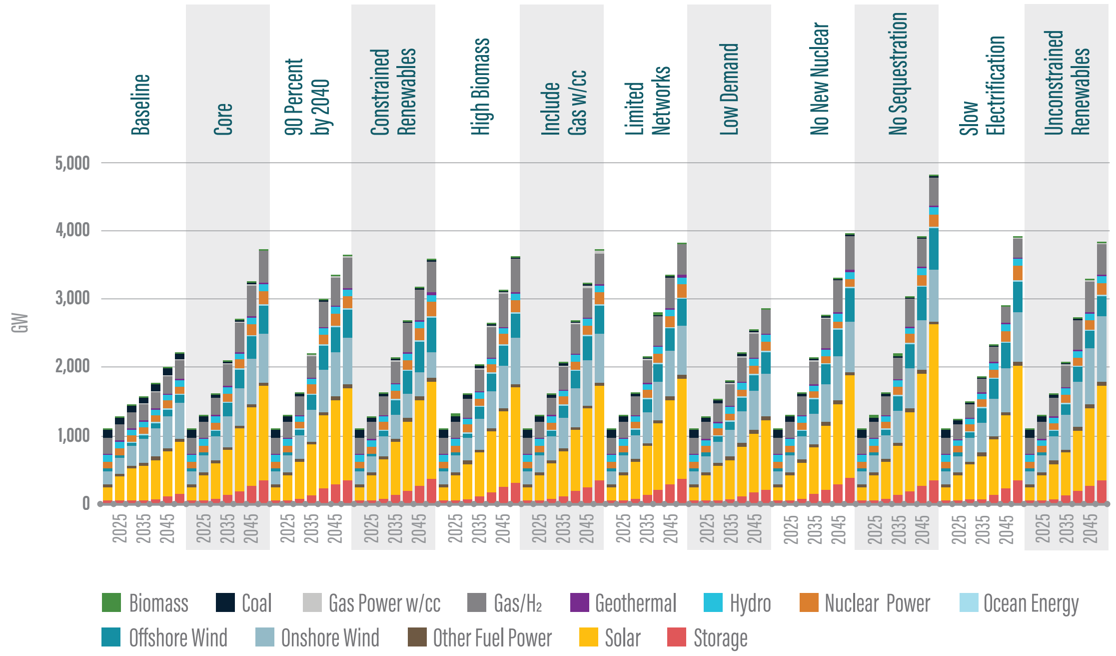
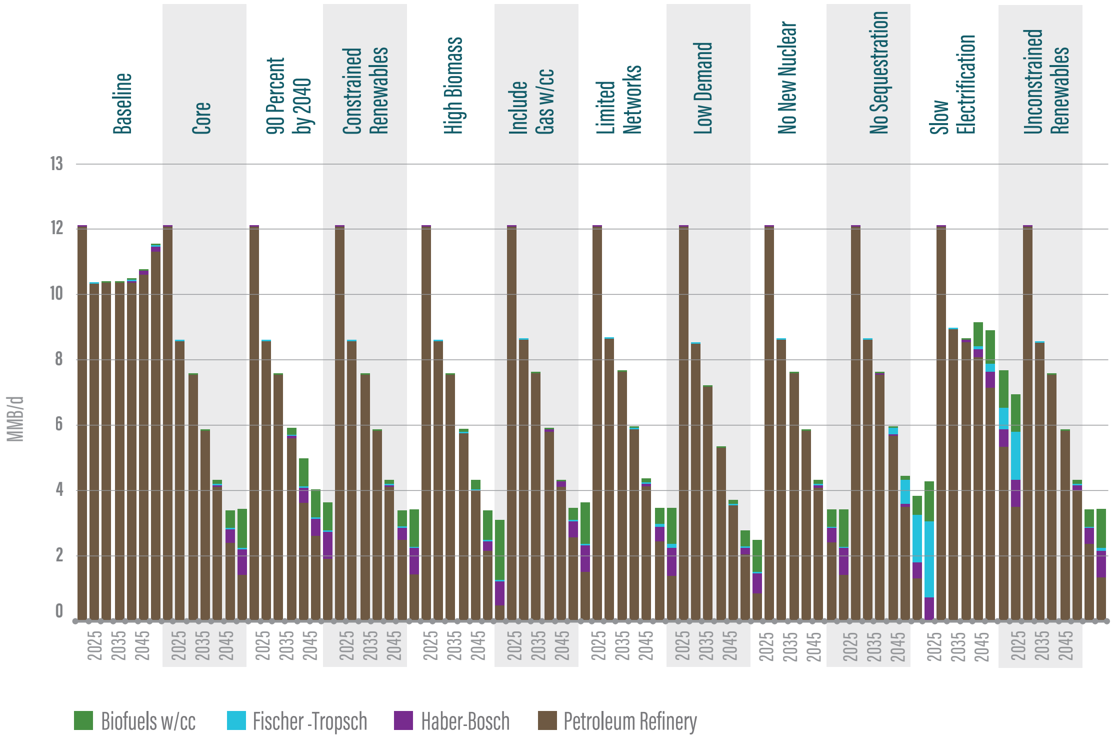


FIGURE 58. Supplemental: Fuels Production Capacity



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