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CARBON-FREE EUROPE
A TECHNOLOGY-INCLUSIVE CLIMATE INITIATIVE

CARBON-FREE EUROPE ANNUAL DECARBONIZATION PERSPECTIVE 2023

ABOUT THIS REPORT

This report investigates options for long-term deep decarbonization pathways for Europe and represents the first in series of annual updates that aim to 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.

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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 sophisticated technical analyses of energy systems, are designed to support strategic decision-making for policymakers, stakeholders, utilities, investors, and technology companies.

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I INTRODUCTION

This report aims to explore long-term options for achieving economy-wide net zero emissions in Europe through deep decarbonization pathways. We've developed detailed technical blueprints using sophisticated software modeling to map the infrastructure changes, technologies, and costs required to reach carbon neutrality by mid-century along several alternative pathways while remaining consistent with European policy goals. While this report doesn't focus on specific policy mechanisms, it provides an overview of what policy outcomes and technological advances are necessary to achieve climate goals. It can guide investment planning for capital-intensive businesses, point out critical gaps in research and development, quantify potential land use and socio-economic transition challenges, clarify the risks of over relying on specific technologies, and help focus the energy policy debate on relevant questions. This report builds and expands on analysis conducted in 2022 contributing to the launch of Third Way's Carbon-Free Europe program.

Over the past few years, there has been a growing interest in long-term pathways studies. However, the lack of transparency and standardization across these studies makes it challenging to compare results, methods, data sources, and input assumptions. Existing pathways studies are mostly one-off snapshots of possible futures with little coordination between research efforts or continuity over time.

To address these issues, we're inaugurating a series of annual updates that aim to move pathways analysis beyond isolated proofs-of-concept and make it a practical implementation tool for addressing next-stage challenges in energy and climate change mitigation. We've used the EnergyPATHWAYS and RIO modeling platforms, widely recognized as best-in-class, along with the most current technology cost and performance data. This provides a standard, public benchmark for technical analysis and policymaking and allows year-on-year comparisons that highlight how new developments in technologies, costs, policies, and global markets affect the outcomes of different decarbonization decisions. This report is the first in the series and will serve as a reference point for future updates.

II ANALYSIS FRAMEWORK

The goal of this analysis is to provide answers to two critical questions: (1) what are the infrastructure, spending, and natural resources required to attain carbon neutrality in the EU economy by mid-century, and (2) how would these requirements 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. To answer these questions, we have developed various scenarios and sensitivities through modeling and have compared the results.

Our scenarios depict different decarbonization approaches that reflect societal preferences 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 their differences there is broad agreement about the criticality of some key strategies. This modeling represents pathways for achieving net-zero greenhouse gas emissions by 2050, beginning from the present, for all infrastructure stocks and activities across all major economic sectors and subsectors for each scenario. Our modeling includes temporal granularity at an hourly level for electricity and geographic granularity across more than 30 countries in Europe and North Africa. There are five distinct scenarios, briefly outlined in Table 1 below.

TABLE 1. Scenarios

Scenario	
Core	This is the least-cost pathway for achieving net-zero greenhouse gas emissions by 2050 in the EU + UK with an adherence to existing European policy ambitions expressed in the Fit for 55 package. 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.
High Hydrogen	This net-zero scenario deploys more hydrogen in end-uses where it might be competitive against electrification (we generally assume direct electrification wins this competition where feasible in the core scenario).
No Fossil	This net-zero scenario disallows the use of coal, natural gas, or oil by 2050. It is designed to explore the effects of eliminating fossil fuels altogether on energy infrastructure, electric power, and the production of alternative fuels and feedstocks.
No New Nuclear	This scenario doesn't allow the building of new nuclear generation other than facilities currently under construction.
Slow Consumer Uptake	This net-zero scenario delays by twenty years the uptake of fuel-switching technologies including electric vehicles, heat pumps, fuel-cell vehicles, etc. It is designed to explore the effects of slow consumer adoption on energy system decarbonization, including the impacts on electricity and alternative fuel demand.

Sensitivities begin with the **core** scenario and determine the effects on the energy system of changing a single key variable. There are seven separate sensitivities, described in Table 2 below. Many of these relate to the readiness and expected cost of potentially important technologies (**nuclear breakthrough** and **DAC breakthrough**). Others relate to availability of key decarbonization resources (**limited biomass** and **constrained renewables**) or policy questions (**no flexible load**; **additional policy**; and **net negative**).

TABLE 2. Sensitivities

Sensitivity	
Nuclear Breakthrough	This sensitivity explores the changes in energy system infrastructure and cost when a breakthrough in nuclear technology costs is assumed in the **core** scenario.
DAC Breakthrough	This sensitivity explores the changes in energy system infrastructure and cost when a breakthrough in direct air capture (DAC) costs and performance are assumed in the **core** scenario.
Constrained Renewables	This net-zero scenario limits the deployment of renewable generation due to land and siting constraints. It is designed to explore the effect of societal barriers to the siting of low-carbon energy infrastructure for environmental and other reasons.
Limited Biomass	This sensitivity explores the changes in energy system infrastructure and cost in the **core** scenario when the availability of biomass feedstocks is constrained.
No Flexible Load	This sensitivity explores the changes in energy system infrastructure and cost in the **core** scenario when there is no dynamic coupling between the electricity and fuel-supply sectors, and electric loads and technologies such as electrolyzers and electric boilers operate like many of today's loads, without any signal as to when they should operate to minimize electricity cost. This represents a scenario of poor market and rate design to encourage beneficial load behavior. This extends to end-use loads like space and water heating and vehicle charging as well.
Net Negative	This sensitivity is the least-cost pathway to economy wide net-negative GHGs by mid-century (-500 Mt CO_2e in 2050).
Additional Policy	**Core** scenario plus the inclusion of a representation of additional EU targets in H_2 production (RepowerEU[1]; EU Hydrogen Strategy[2]) and offshore energy[3]; largest impact is in acceleration of hydrogen deployment in the near-term and a reduction in natural gas usage.

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[1] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

[2] https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en#:~:text=The%20ambition%20is%20to%20produce,in%20energy%2Dintensive%20industrial%20processes

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A741%3AFIN

III MODELING UPDATES

Since last year's analysis, we've 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 the types of modeling improvements we've implemented and discusses the impacts to model results.

Expanded Map

Improvement

We've continued to expand the geographic boundaries of our analysis this year with the inclusion of Ukraine - due to its interconnection with Europe's grid and its long-term renewable resource potential — as well as the addition of Turkey as a potential importer of both clean electricity and hydrogen due to its abundant renewable resources (wind, solar, and geothermal).

The map below shows the country representations and the level of fidelity with which we model each country:

1. Full energy system representation: this includes representation of all producing, converting, delivering, and consuming energy infrastructure in the country.
2. Electricity system representation: this includes a representation of overall electricity loads; existing generation; and potential for new generation; as well as inter-regional transmission infrastructure.
3. Clean energy export: this includes a representation of clean energy production potential for either direct electricity export or in the form of clean fuels (hydrogen, e-fuels, etc.)

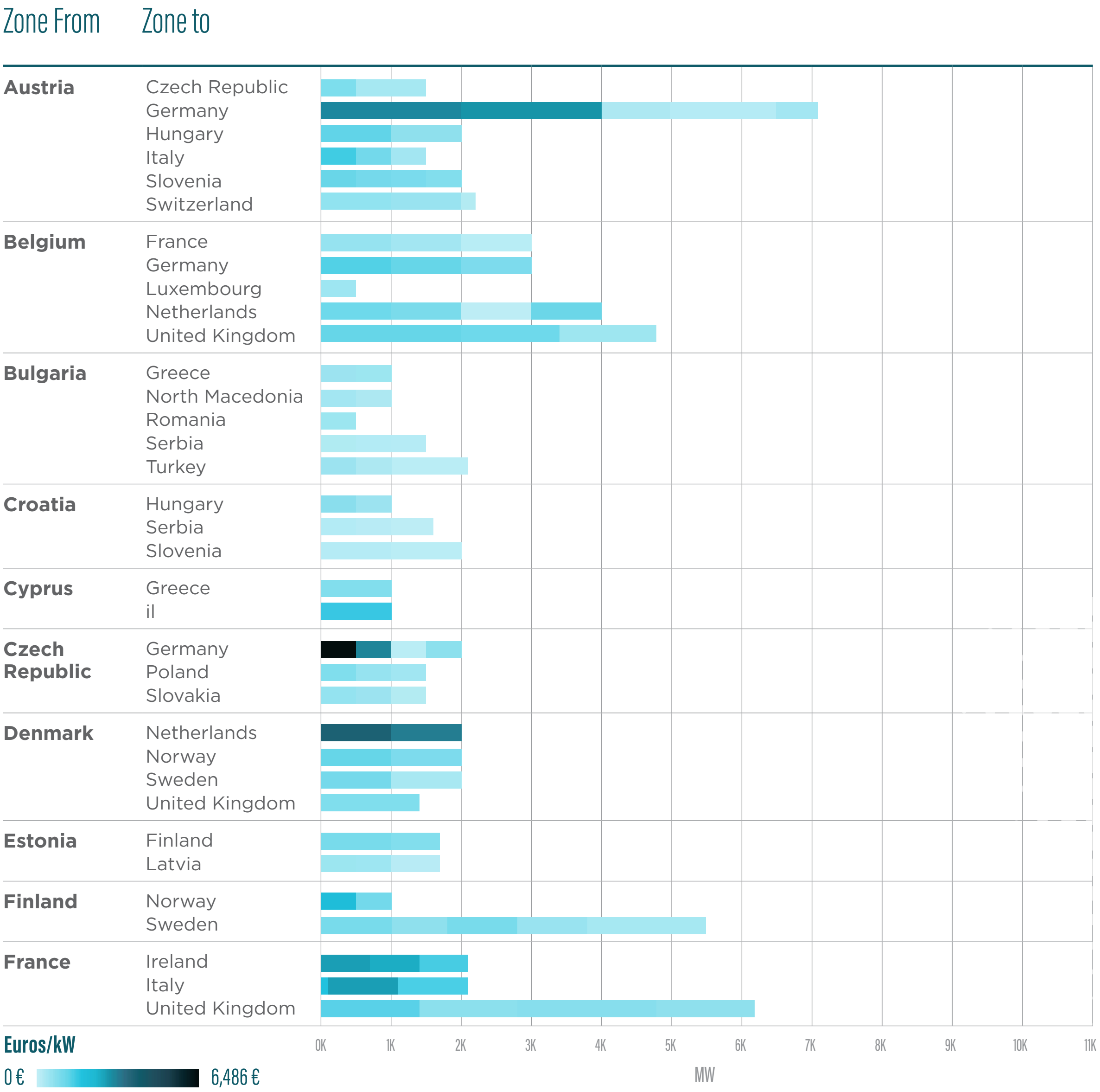
FIGURE 1. Zonal representation in the model

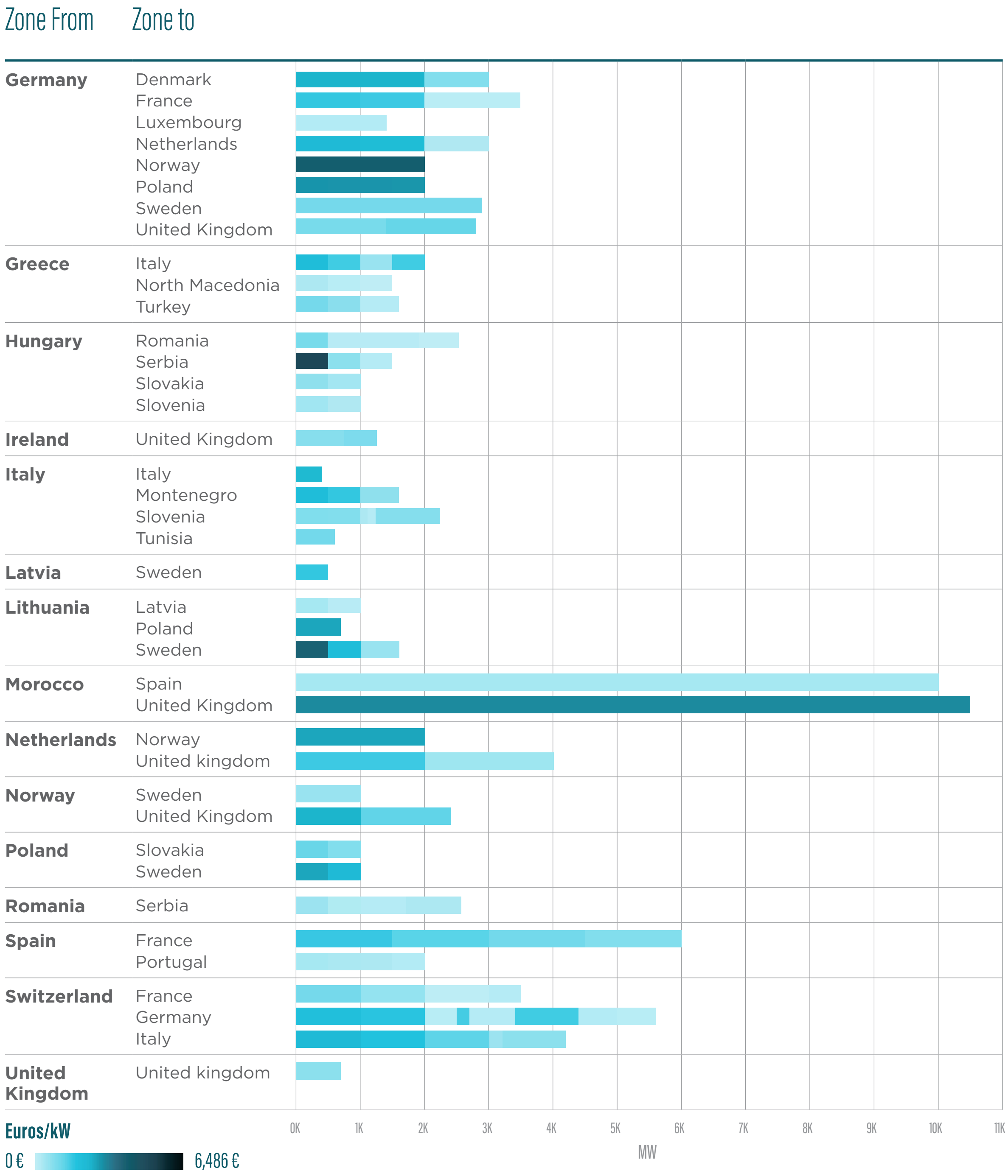
Transmission and Pipeline modeling

Improvement

We've updated the transmission line supply curves from the most recent Ten-Year Network Development Plan (TYNDP) from ENTSO-E and supplemented with some project-level segments not represented in the supply curve (i.e., Morocco — to UK underwater transmission cable).

FIGURE 2. Electricity transmission supply curve

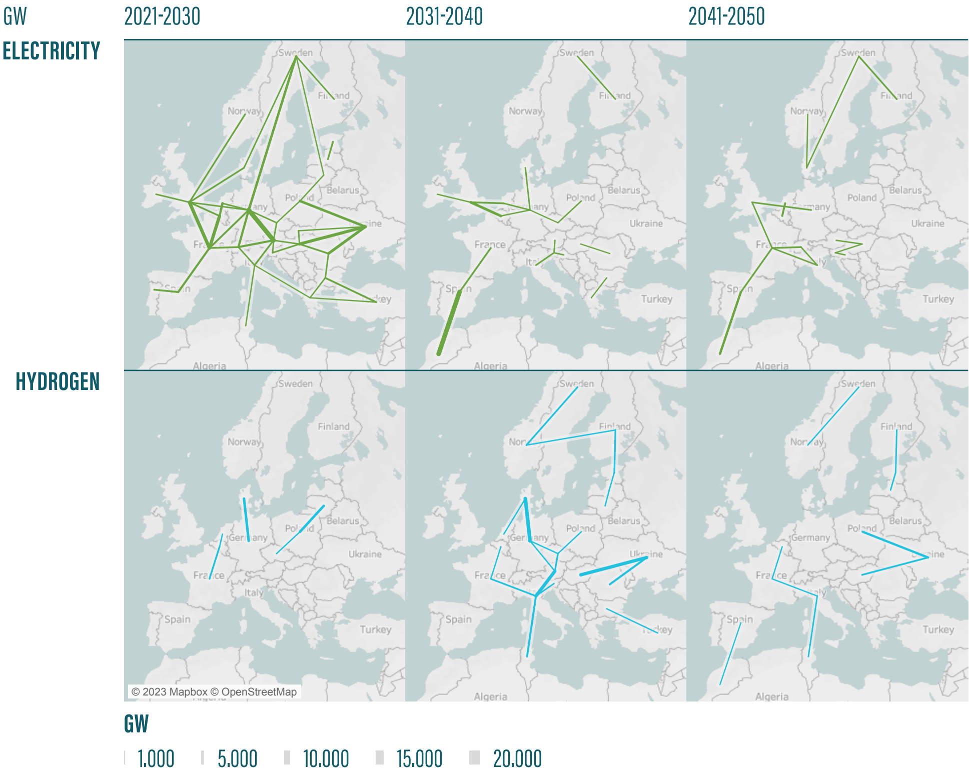




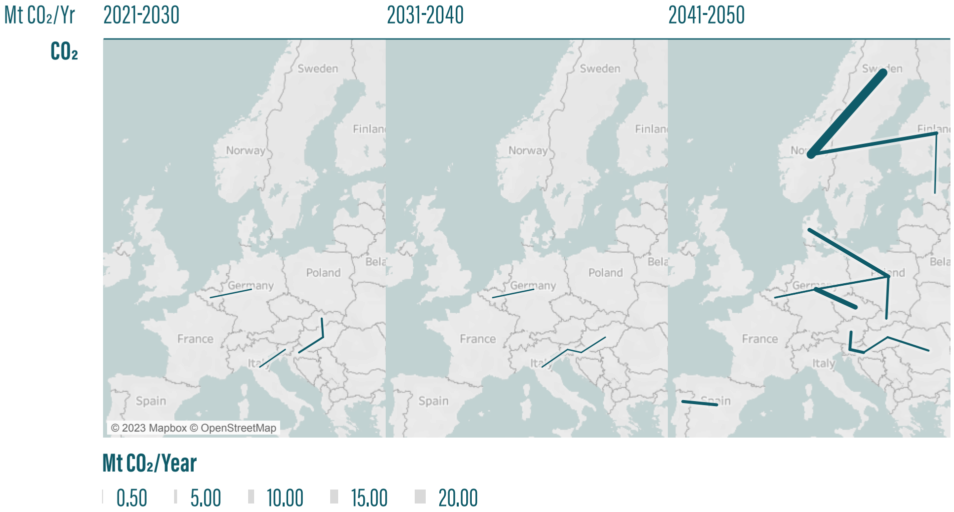
In addition to updating the electricity transmission representation, we continue to allow for the construction of hydrogen pipelines between zones and additionally allow for the construction of CO_2 pipelines. This allows for the cross-border transport of CO_2 to address spatial mismatches between points of capture (industry, biofuels, direct air capture) and sequestration opportunities.

FIGURE 3. Transmission and Pipeline Maps, Core Scenario. Colored lines show new transmission or pipelines between zones built between years (e.g. 2030 represents all new infrastructure from today — 2030). The thickness of the line indicates the size of the connection either in power terms (GW) or CO_2 transfer capacity annually (Mt CO_2)

New Energy Delivery Infrastructure



New CO_2 Delivery Infrastructure



Result

Intra-regional infrastructure to deliver both energy and CO_2 from where it is produced to where it can be used or stored is critical to net-zero decarbonization pathways. Hydrogen pipelines and electricity transmission compete as a means of delivering renewable energy and balancing diversity of load and supply. CO_2 pipelines are used to access lower cost geologic sequestration that is not co-located at the point of capture for cement, BECCS, and DAC facilities.

Nuclear Technologies

Improvement

We have expanded the representation of nuclear technologies to include multiple reactor types and sizes as well as potential integration with heating needs.

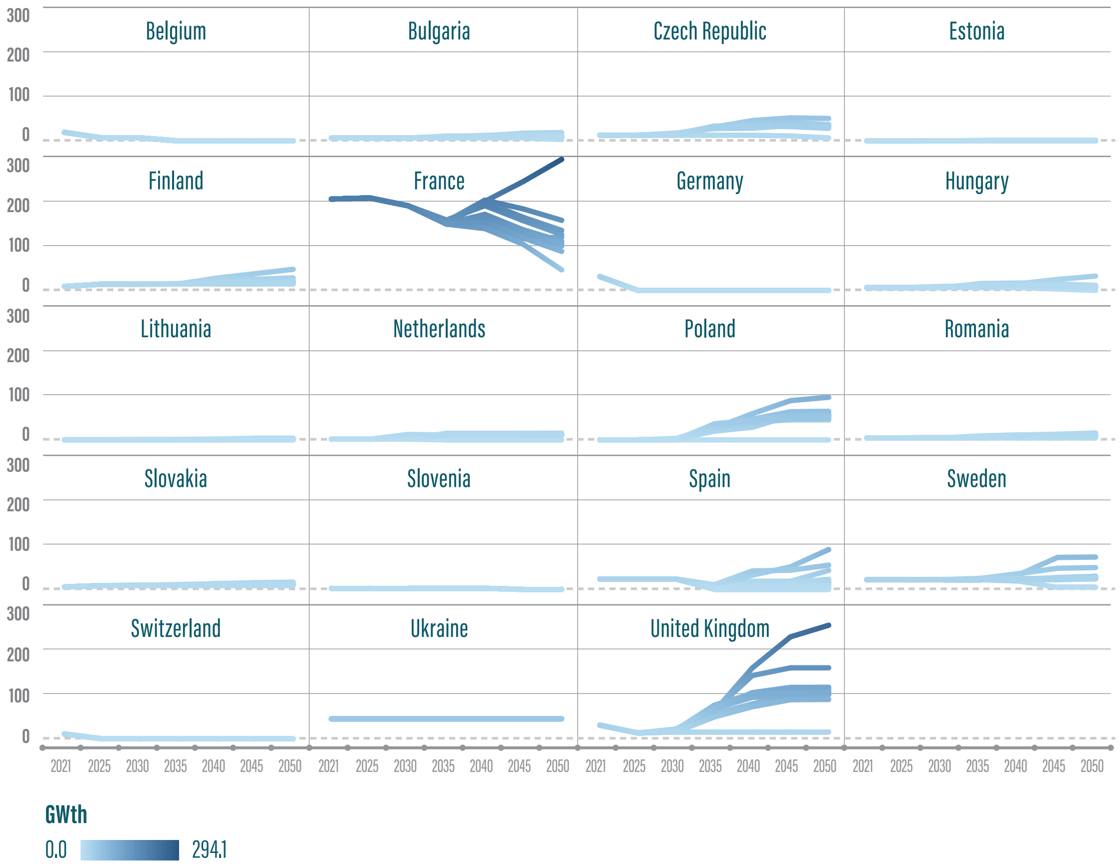
1. **Light-Water Reactors.** These nuclear plants are modeled as operating at conventional light-water reactor temperatures and flexible in size (representing the potential for small modular designs). Capacity allocation and operational decisions among reactors, thermal storage, and steam turbine generators are independent in the model, allowing for flexible system designs depending on electricity system needs. Steam turbine generators can also be constructed as CHP facilities, improving the overall efficiency, and allowing the provision of heat to buildings and industry.

2. **High temperature gas-cooled reactors.** HTGRs are modeled as producing heat at sufficiently high temperatures (>750 °C) to power highly efficient steam cycles, support high-temperature electrolysis, and provide thermal inputs for direct air capture. In the model, these reactors can also be built in conjunction with thermal energy storage. This allows for a variety of plant configurations that can variously generate clean electricity, produce carbon-free hydrogen, and/or capture atmospheric CO_2. We also allow the steam turbine generators to be constructed as CHP facilities, similarly improving the overall efficiency of the plant and allowing lower-temperature heat provision to buildings and industry.

Result

The model improvements show an expanded economic potential for nuclear generators. This results from including additional applications (hydrogen production and direct air capture), and temporal flexibility (allowing for thermal energy storage of produced heat) that are critical to nuclear economics in systems with high levels of low-cost renewables.

FIGURE 4. Range of nuclear reactor capacity (GW thermal) by country (where there is existing nuclear or nuclear is eligible to be constructed).



Industrial Heat Decarbonization

Improvement

We have added complexity to the modeling of industrial heat, so that we now can decarbonize industrial steam supply by employing four strategies that can be applied separately or in combination:

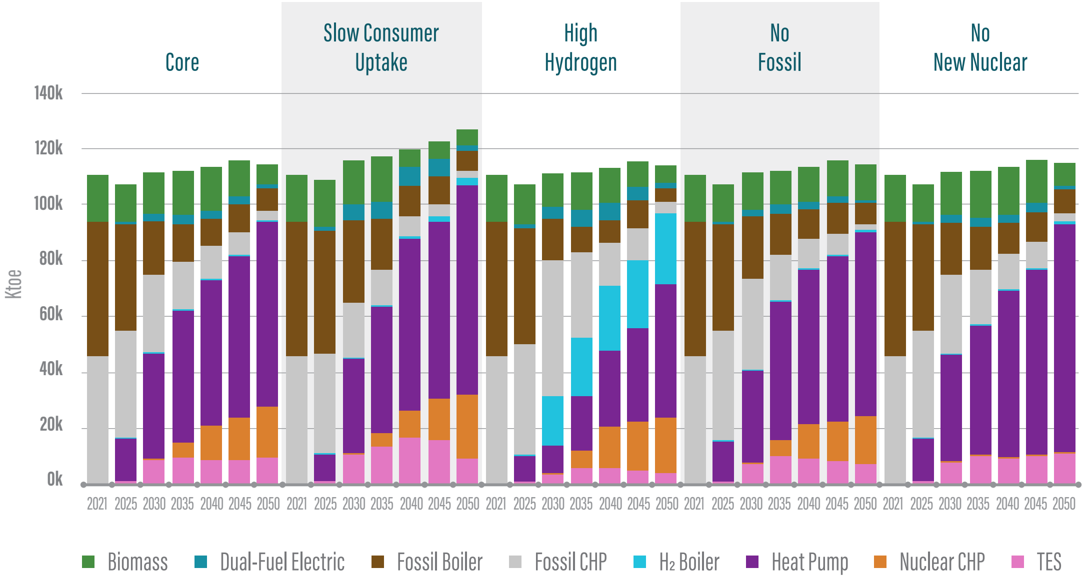
1. **Hybridization:** Hybridization builds redundancy into industrial boiler systems in the form of 'dual-fuel' boilers, where electric boilers are operated when electricity system conditions support their use (i.e. when renewable energy is available) and switching to fuel boilers (sometimes hydrogen) during the limited hours where their use would be supported by thermal generators. Our previous work used this strategy. **Result:** This strategy enhances reliability for both steam and electricity supply.

2. **Thermal Energy Storage:** Adding thermal storage allows for the ‘charging’ of heat when there is a plentiful supply of renewable energy and ‘discharging’ it when heat is needed and electricity system conditions are less advantageous. **Result:** Thermal storage is cheaper than electricity storage and provides renewable energy balancing at lower cost.

3. **Heat Pumps:** When renewables are constrained or the use of steam production as a renewable balancing load is less attractive economically, heat pumps can reduce the overall amount of electricity needed to produce heat, using either ambient air or waste heat (which the heat pump upgrades to necessary temperatures). **Result:** High capital costs combined with low capacity factors limit the value of heat pumps in applications calling for flexible operation though they are still used as efficient electric heating sources; technology progress that reduces their upfront costs would encourage their deployment.

4. **Nuclear CHP:** referenced above, we allow the use of nuclear waste heat from electricity production to be integrated into buildings and industry. In areas with significant new deployment of nuclear generation, this is modeled as a cost-effective option, though challenges remain in terms of matching heat production to loads both in terms of reactor scale and geographic proximity.

FIGURE 5. Steam Production



Improved Direct Air Capture Technology Representation

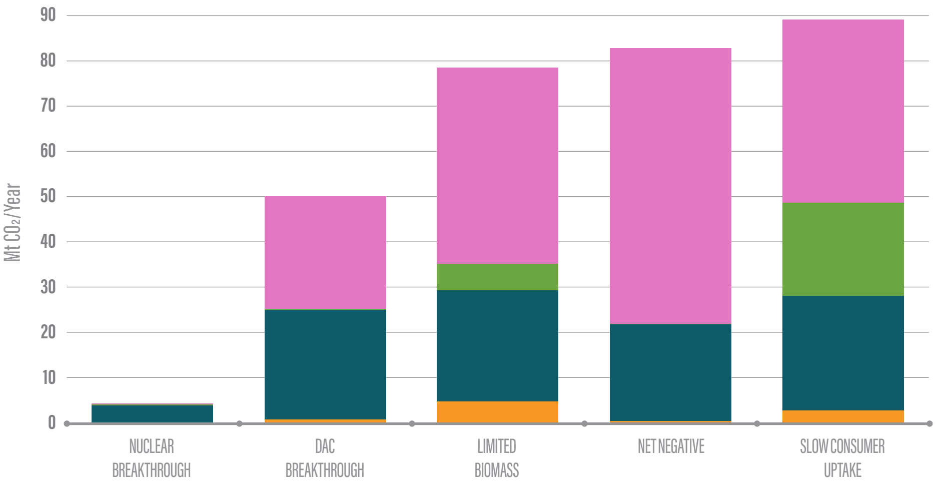
Improvement

Instead of modeling a single generic direct air capture technology, we explicitly model the technical characteristics of both solid sorbent and liquid solvent technologies, which have very different performance characteristics depending on the prevailing climactic conditions. This allows for a higher-fidelity representation of critical opportunities for DAC as well as a more realistic appraisal of potential operations depending on location of operation.

Result

DAC technology was deployed in four cases and in each, the solid sorbent technology was deployed. The efficiency advantage offered by using heat pumps to provide low-temperature heat to the solid sorbent technology was a significant advantage (at similar capital costs). The ultimate costs of each DAC technology is highly uncertain and the ultimate competition is likely to be more nuanced. The location of the DAC technologies deployed was significantly related to availability of electricity resources (principally offshore wind and an ability to build nuclear facilities) as well as the availability of geologic sequestration. This led to its concentration in the United Kingdom and Denmark due to their residual availability of offshore wind and offshore sequestration potential; and in Spain, for its ability to construct nuclear and its onshore geologic sequestration.

FIGURE 6. 2050 DAC Capacity (Mt CO_2/Year)



Gas System Representation

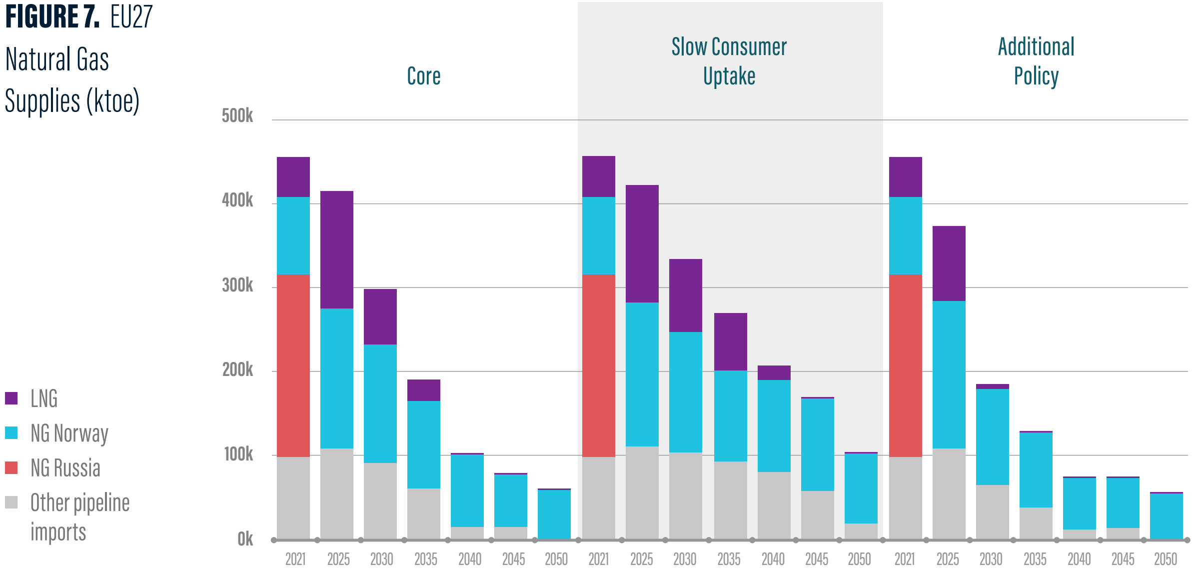
Improvement

Fossil energy is often represented in ours and other energy models as an exogenous commodity at a price; in other words, fossil energy is always available at a willingnes–to–pay. The war in Ukraine and the subsequent reduction in Russian gas supply has rendered that basic assumption incompatible with modeling in Europe. In this analysis, we've included a physical representation of gas supply to Europe including extraction potentials, pipelines, storage, and LNG facilities in order to be able to answer relevant near-term questions about the ability of Europe to meet its energy demands across all hours of the year.

Result

This improvement allows us to represent reduced availability of Russian imports as well as constraints in the gas system seasonally and locationally. The transition of natural gas supplies is shown in the chart below for three cases with substantially different near-term gas requirements. The deployment of renewables and heat pumps in the core case reduces overall gas demand substantially by 2030 (to 300 ktoe) with natural gas from Russia replaced by LNG imports and an expansion of gas from Norway and other importing countries.

FIGURE 7. EU27 Natural Gas Supplies (ktoe)



Policy Clarity

Improvement

Over the past year, the specifics of the EU's Fit for 55 package have come into focus with clarified targets in energy efficiency; renewable energy; transport; sustainable fuels; methane; and land use, land use change, and forestry as well as country-level. This allows for direct representation and comparison in our model to the EU's sectoral and geographic ambitions for emissions reductions.

TABLE 2. EU Policies Modeled

Binding	Core	Additional Policy
REPowerEU (binding)	✓	
Energy Efficiency Directive	✓	
Renewable Energy Directive (REDIII)	✓	
RefuelEU (sustainable air transport)	✓	
FuelEU (renewable & low-carbon fuels in the maritime sector)	✓	
Effort Sharing Regulation	✓	
Land Use, Land Use Change & Forestry (LULUCF)	✓	
CO_2 for cars & vans	✓	
Energy Performance of Buildings Directive	✓	
Non-Binding		
Hydrogen Strategy		✓
EU Offshore Strategy		✓
REPowerEU communication		✓
EU Solar Energy Strategy		✓

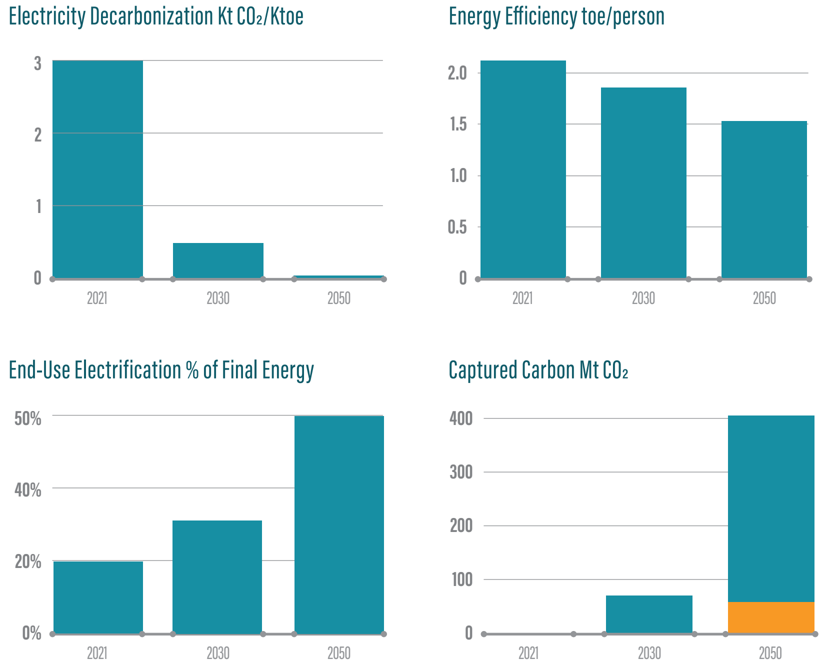
IV HIGH-LEVEL RESULTS

The high-level results of this analysis are described below, organized into four sections: energy system decarbonization, infrastructure requirements, costs and investment, and scenario highlights. Significant new insights that derive from methodological changes, including increased spatial and sectoral resolution in modeling, and from sensitivities that cover a wide range of assumptions about technologies and other critical variables, are discussed in subsequent sections.

Energy System Decarbonization

Energy system decarbonization is based on four strategies: using energy more efficiently, decarbonizing electricity, electrifying end uses, and capturing carbon, which is either sequestered geologically or used to make carbon-neutral fuels. Benchmark values for each of these strategies are shown in Figure 8 for the **core** scenario, in comparison to the European energy system today. (1) The carbon intensity of electricity is 99% lower (2) Energy intensity is 30% lower on a per capita. (3) The electricity share of end use energy is 57%, or 3 times higher. (4) Carbon capture is almost 440 Mt CO_2/year, of which approximately 10% is utilized to create zero-carbon fuels and 90% is geologically sequestered. Current carbon capture is negligible.

FIGURE 8. Metrics for the four main strategies of deep decarbonization, core scenario compared to current levels



- ■ Geologic sequestration
- ■ Utilization

Figures 9 through 12 illustrates the transformation of the European energy system resulting from the strategies discussed above. The figure compares the energy system in 2021 with three different 2050 net-zero scenarios. In the current system, petroleum refining and thermal power generation dominate as intermediate energy conversion forms, as depicted in Figure 9. However, in all net-zero scenarios, both primary and final energy use are lower than in the present system, thanks to efficiency improvements that surpass higher energy service demand caused by population and GDP growth. Electrification plays a critical role in reducing the share of combustion fuels and increasing the share of electricity in final energy, alongside the overall reduction in final energy demand. Furthermore, the production of hydrogen and synthetic fuels from biomass and electricity, which are currently of minimal importance, become essential components of the net-zero systems. The **core** scenario (Figure 10) is flanked by two alternative scenarios: the **no fossil** (Figure 11) and **slow consumer uptake** (Figure 12) scenarios, which represent the extremes as to the residual role of fuels in a net-zero energy system.

FIGURE 9. Sankey diagram for 2021

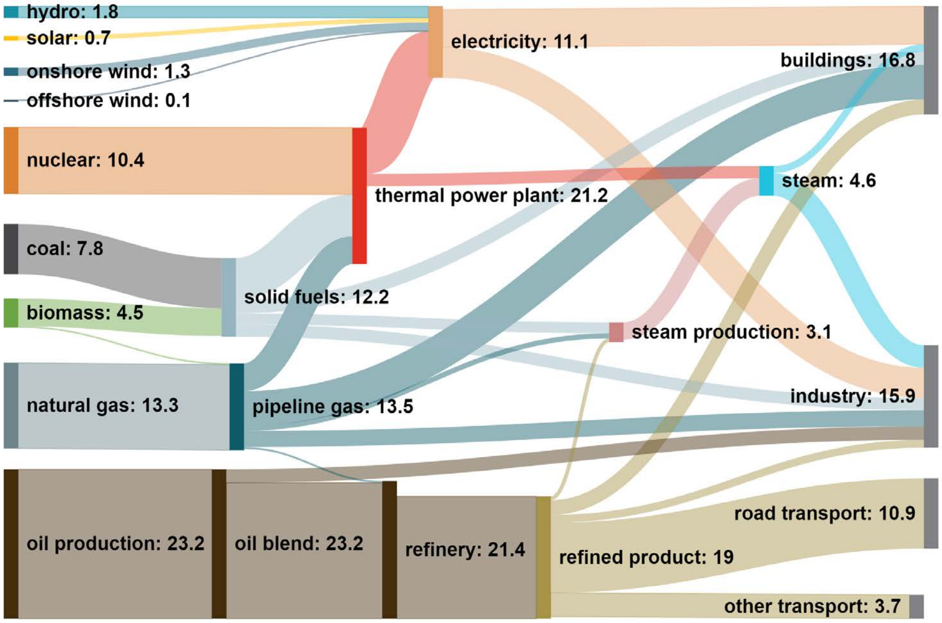


FIGURE 10. Sankey diagram for core 2050

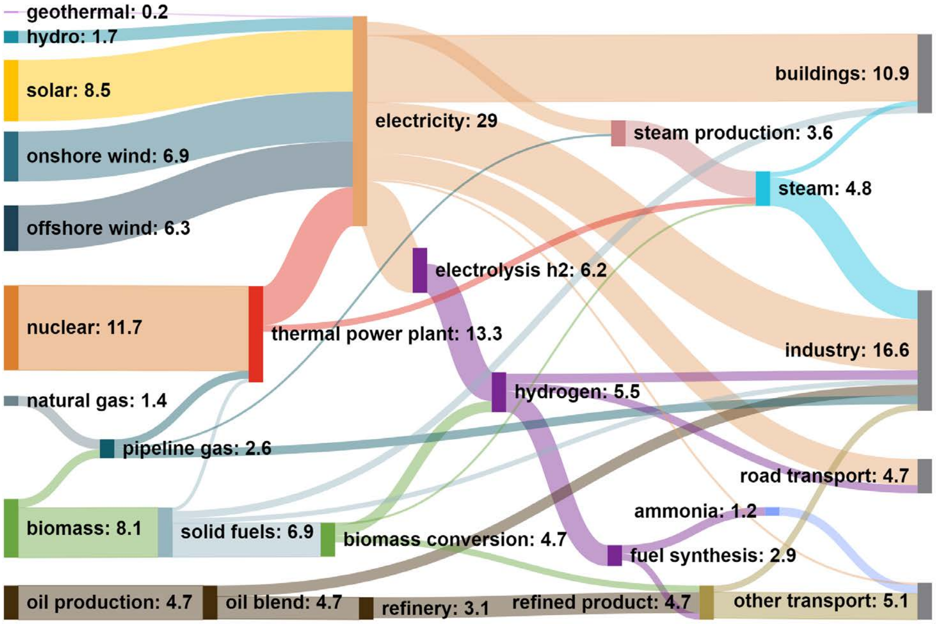


FIGURE 11. Sankey diagram for no fossil 2050

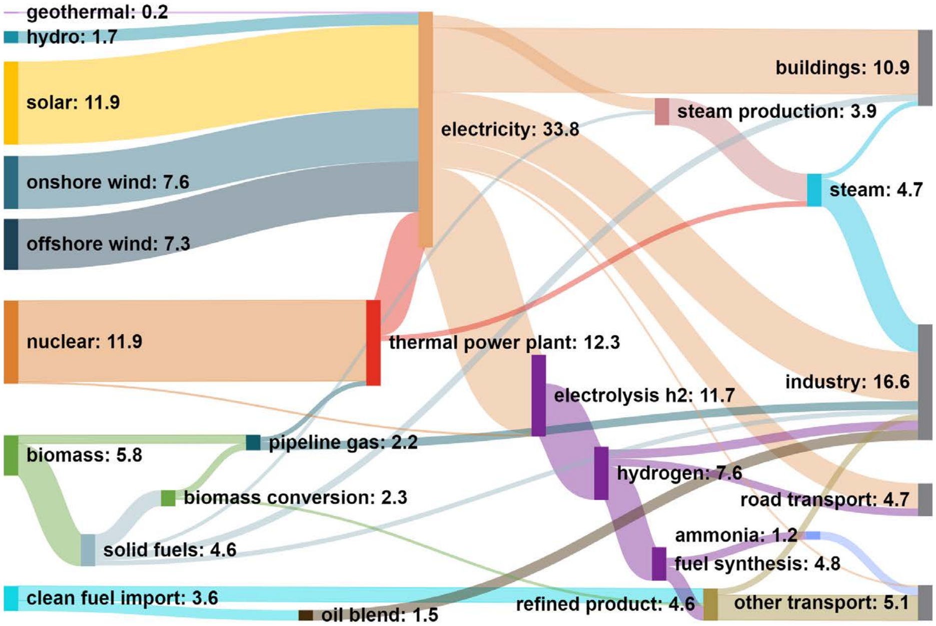
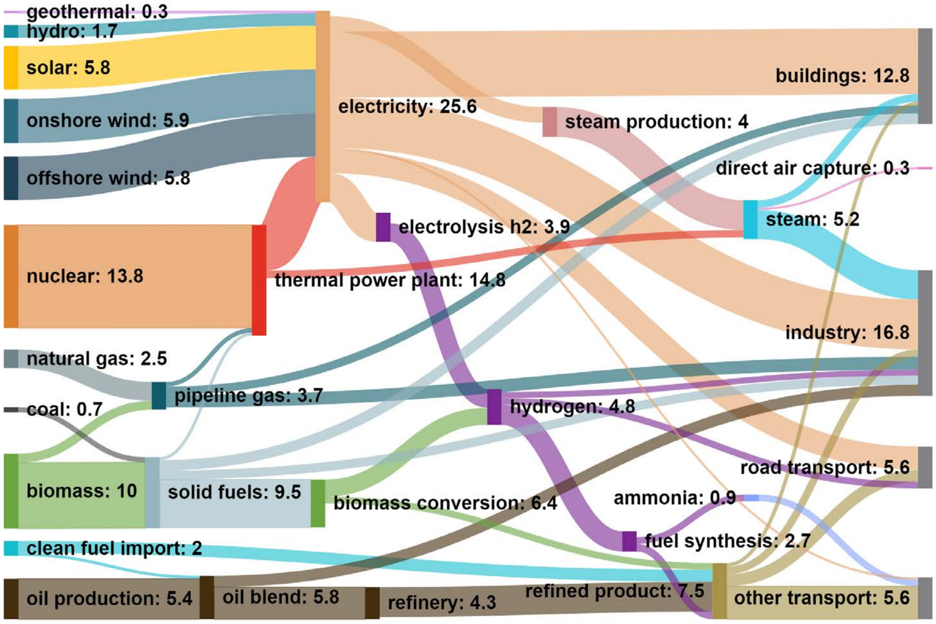


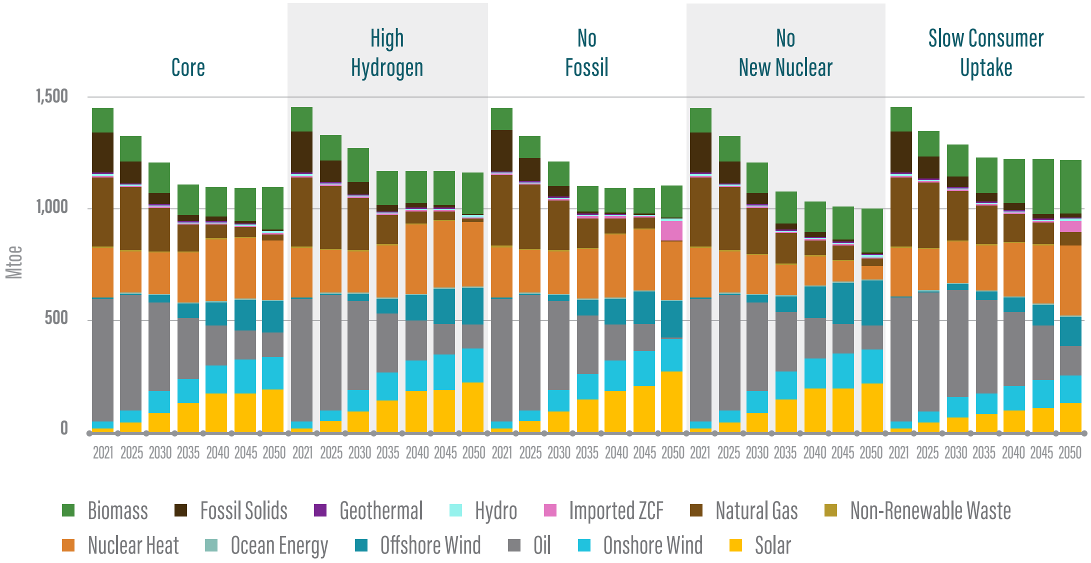
FIGURE 12. Sankey diagram for slow consumer uptake 2050



PRIMARY ENERGY

This reflects all energy use in both the EU and UK, including energy used as chemical feedstocks and in bunkering fuels (which are oftentimes outside traditional accounting of primary energy targets). Where possible, we reflect the original energy source (i.e. onshore wind coming from outside the EU and UK would still be reflected as onshore wind). The decarbonization of primary energy is best seen in the decrease in the fossil fuel share from fossil solids (coal), oil, and natural gas. Coal exists the system first, principally due to a reduction in coal-fired electricity generation. This is replaced with a deployment of renewables (solar, onshore wind, offshore wind) in the near-term. In the long-term, further displacement of fossil fuels depends on progress on electrification — **slow consumer uptake** requires fuels from biomass or other imported sources (zero-carbon fuels from outside the model footprint); requirements to displace all fossil generation — **no fossil** requires zero-carbon fuel imports as well as additional production of e-fuels and biofuels to displace all residual fossil; and competition between other electricity sources — **no new nuclear** means additional renewable electricity generation; and **slow consumer uptake** sees limited growth in electrification and therefore slows renewables deployment, specifically of solar, which allows nuclear to become cost-competitive in the long-term.

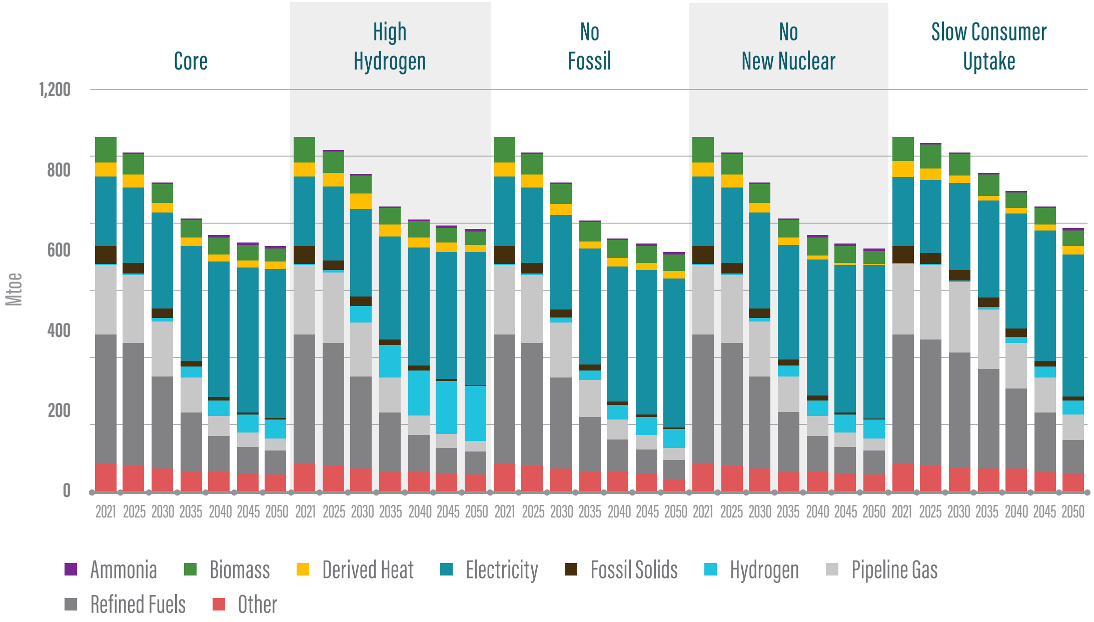
FIGURE 13. Primary Energy



FINAL ENERGY

Final energy consumption declines rapidly in all scenarios with the deployment of energy efficiency as well as the efficiency that accompanies electrification of space heating and transport. The **slow consumer uptake** scenario represents the biggest outlier in terms of final energy demand, with the maintenance of fuel end-uses significantly past their economic replacement. This results in more final energy demand and a higher share of final energy that remains refined fuels, which are difficult and expensive to displace. The **high hydrogen** scenario assumes a world where hydrogen 'wins' the competition for industrial heating applications and freight transport over electrification options and other zero-carbon fuels. A higher share of final energy is therefore consumed directly as hydrogen.

FIGURE 14. Final Energy Demand by Type



CARBON MANAGEMENT

Carbon management refers to the capture of CO_2 and its utilization (as a feedstock to create synthetic fuels or other products) or sequestration (in geologic storage). The amount of carbon sequestered or utilized is highly dependent on levels of electrification; stringency of emissions targets; and other policy objectives. For example, sequestration is often used to offset residual fossil emissions, but isn't required if fossil is banned (**no fossil**). In this scenario, carbon is instead utilized to create synthetic fuels as fossil substitutes. The source of captured carbon is also dependent on input parameter like technology costs (i.e. DAC) or biomass availability (captured biogenic carbon is a significant source of negative emissions by 2050).

A significant share of remaining fossil fuel consumption in net-zero systems is used for chemical feedstocks, with some of the fossil carbon being sequestered in durable products. Generally, however, the greater the share of fossil fuel in the primary energy supply, the more geological carbon sequestration is required to reach net-zero. In the **core** scenario, 390 Mt/y of CO_2 is sequestered; this level of sequestration is consistent across cases except the **no fossil** scenario, which doesn't have any geologic sequestration. Even in that scenario, while no carbon is sequestered, it is nonetheless recycled, being captured and utilized in fuel and feedstock production for reasons of economy and carbon budget.

FIGURE 15. Carbon Capture Application

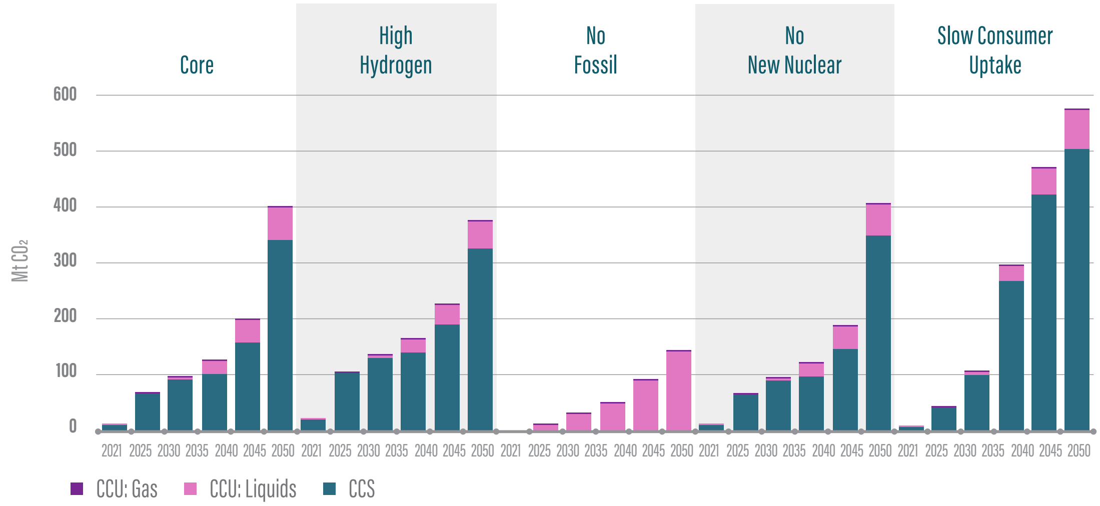
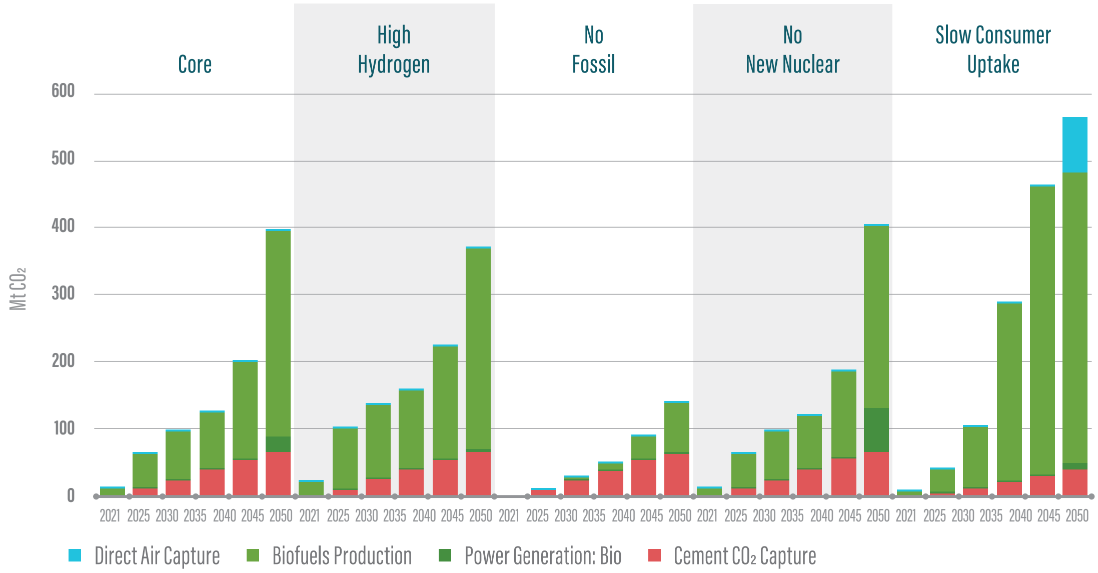


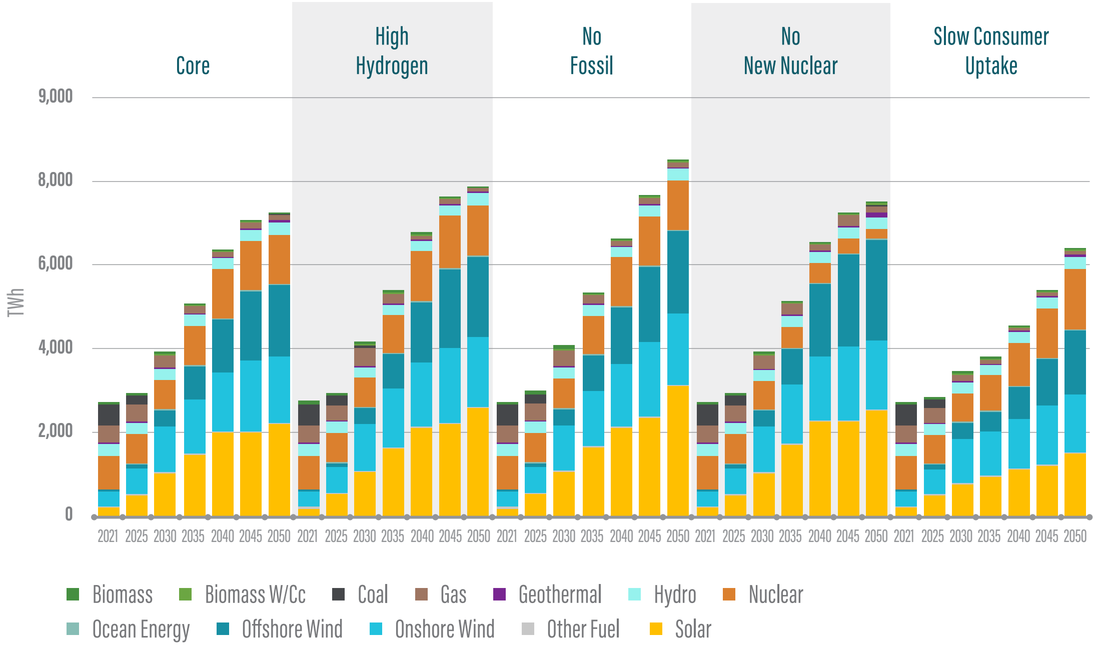
FIGURE 16. Carbon Capture Source



ELECTRICITY GENERATION

Electricity generation comes primarily from solar, onshore wind, and offshore wind in our scenarios. Except when prohibited (**no new nuclear**), nuclear maintains a large share of the generation mix, both replacing plants in countries with retiring generators (France, UK, etc.) as well as expanding capacity in Eastern Europe. The **no fossil** scenario sees the largest expansion of electricity generation in the EU+UK footprint; **slow consumer uptake** limits electrification and overall electricity generation.

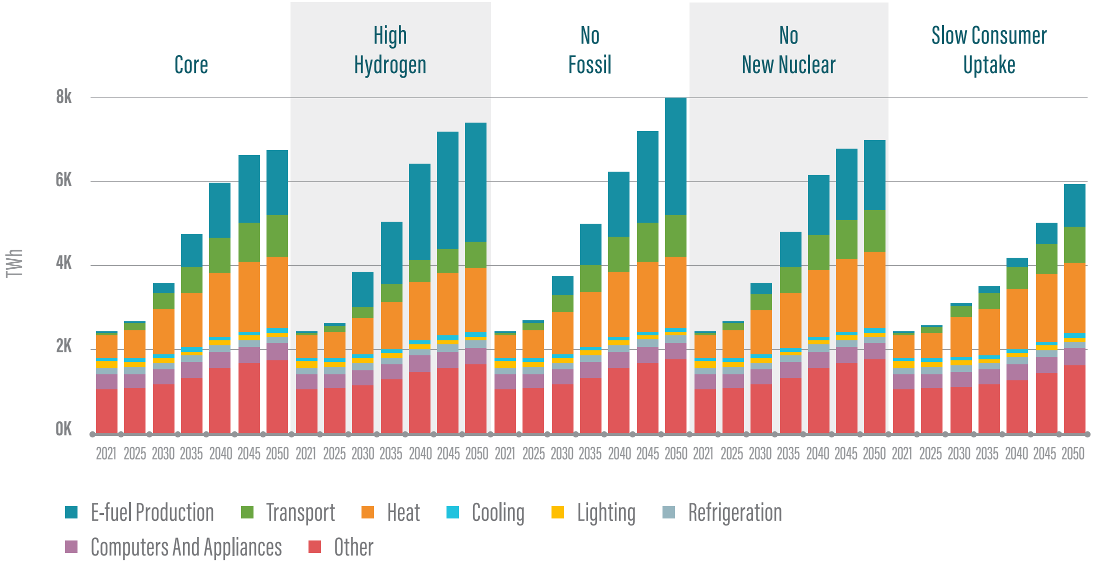
FIGURE 17. Electricity Generation



ELECTRICITY LOAD

There are significant increases in electricity load across all scenarios, with large increases in the amount of electricity going towards heat, transport, and e-fuels production. The largest overall increase is seen in the no fossil scenario due to the largest demand for e-fuels. The slow consumer uptake scenario limits beneficial uptake of electrified heating and transport.

FIGURE 18. Electricity Load



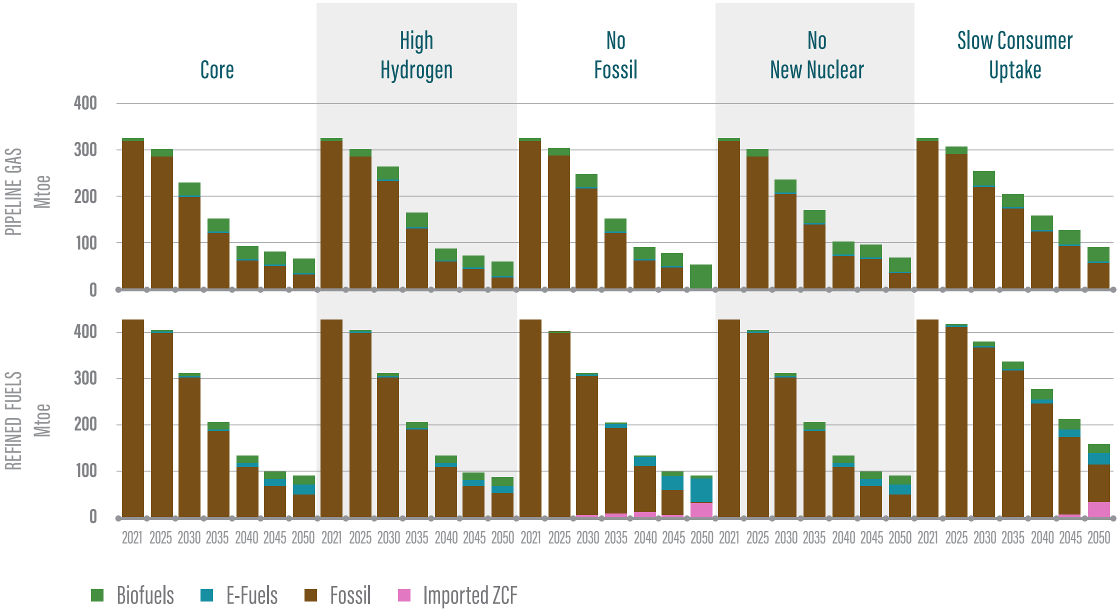
HYDROCARBON FUEL MIX

Switching end-uses from the use of refined fuels and pipeline gas to either electric or hydrogen end uses is a key decarbonization strategy. This fuel switching is responsible for much of the drastic decrease in demand throughout the economy for both types of energy carrier. By 2050, except for the **slow consumer uptake** scenario, Europe demands only 20-25% of its 2021 baseline of both pipeline gas and liquid fuels.

FIGURE 19. Fuel Demand

Along with reducing demand for these energy carriers, the means of production changes. While today's methane and refined fuels are almost entirely fossil, in the long-term, we see a transition to decarbonized supplies. In pipeline gas, this is primarily biofuels (RNG and SNG); for refined fuels, we see a mix of biofuels, e-fuels, and zero-carbon imported fuels. Our low long-term forecasts for fossil fuel prices means some volume of fuel remains fossil, with these emissions offset with negative emissions technologies (biomass with carbon capture and direct air capture).

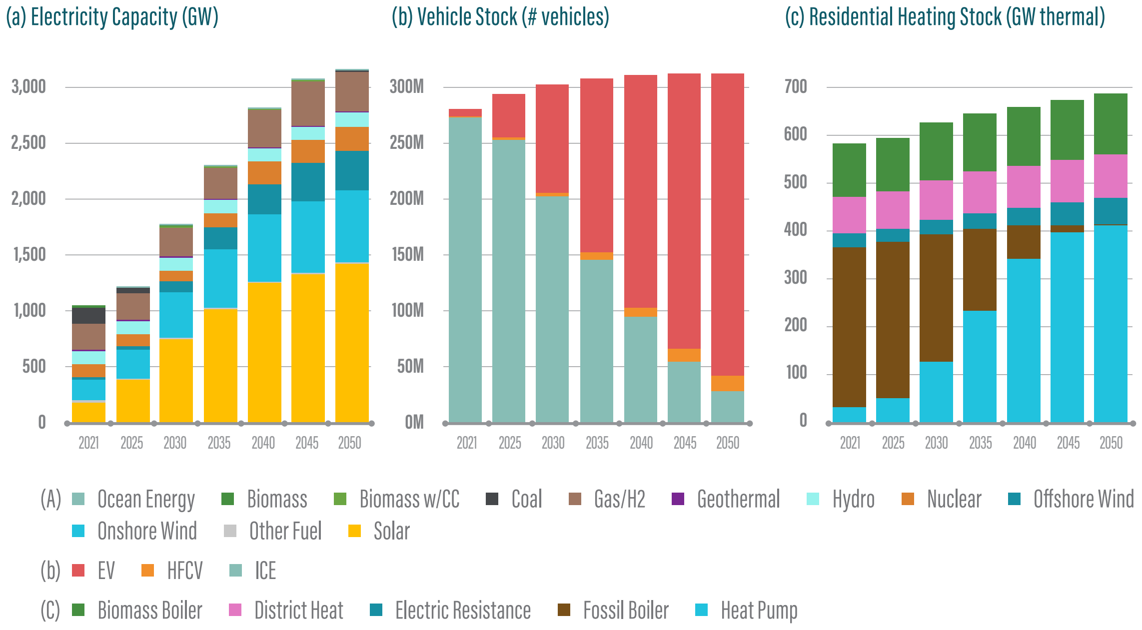
FIGURE 20. Fuel Supply



Energy Infrastructure

To achieve a net-zero energy system, a transition of infrastructure is necessary, in which low-emitting, high-efficiency, and electricity-consuming technologies replace high-emitting, low-efficiency, and fuel-consuming technologies, at a scale and pace required to attain the net-zero target. The transition is exemplified in Figure 21 for three primary sectors: electricity, residential heat, and passenger vehicles. The replacement of existing equipment without early retirement and the addition of completely new capacity typically drives this transition, in almost all cases.

FIGURE 21. Infrastructure transition in core scenario for (a) Electricity Generating Capacity (b) Vehicles, and (c) Buildings.

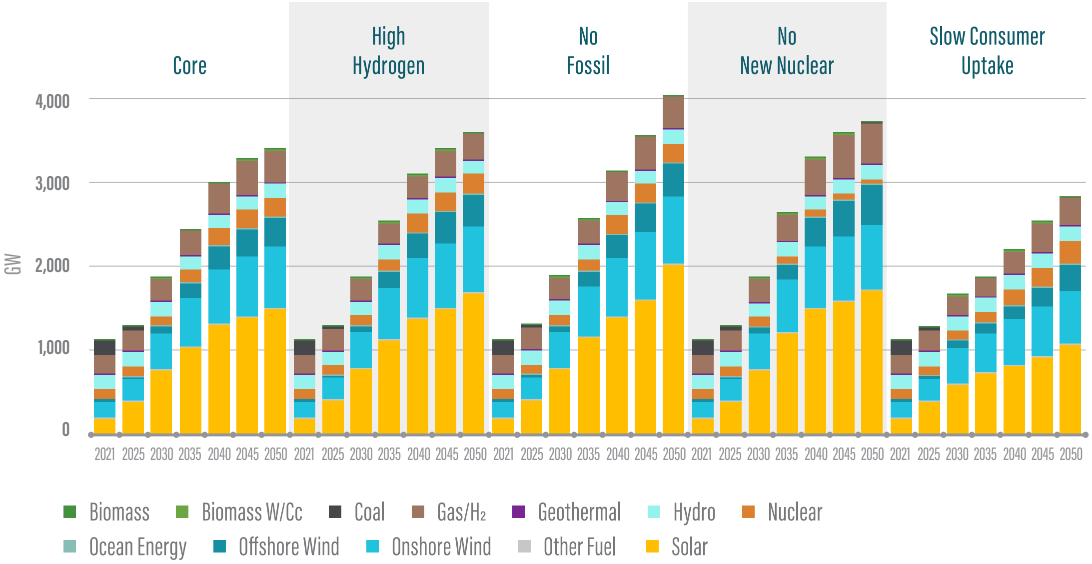


(a) Electricity Capacity (GW) (b) Vehicle Stock (# vehicles) (c) Residential Heating Stock (GW thermal)

ELECTRIC POWER

In the **core** scenario, renewable capacity increases starkly from current levels, with the addition of more than 1 TW of new solar; more than 400 GWs of new onshore wind; and more than 300 GWs of new offshore wind. We also see an increase of overall nuclear generation by the 2040s, with replacement of existing generators as well as expansion into new geographic areas (Figure 21). This nuclear expansion is driven by two phenomena: one, the overall availability of high-quality renewable resources in terms of overall energy potential; and two, the variable nature of renewable generation which results in some share of generation needing to be dispatchable during periods of high load. Across scenarios, total generating capacity ranges from 2500 – 4000 GW by 2050 (2.5 – 4x today's capacity). This is a reflection of the increased need for electricity as well as the lower capacity factor that renewables operate at and the need to have backup generators for periods of low renewable output. The **no fossil** scenario has the highest level of generation capacity due to the need to produce e-fuels to substitute for residual fossil. The **slow consumer uptake** scenario has limited electrification and relies on imported fuels, so capacity growth is more limited.

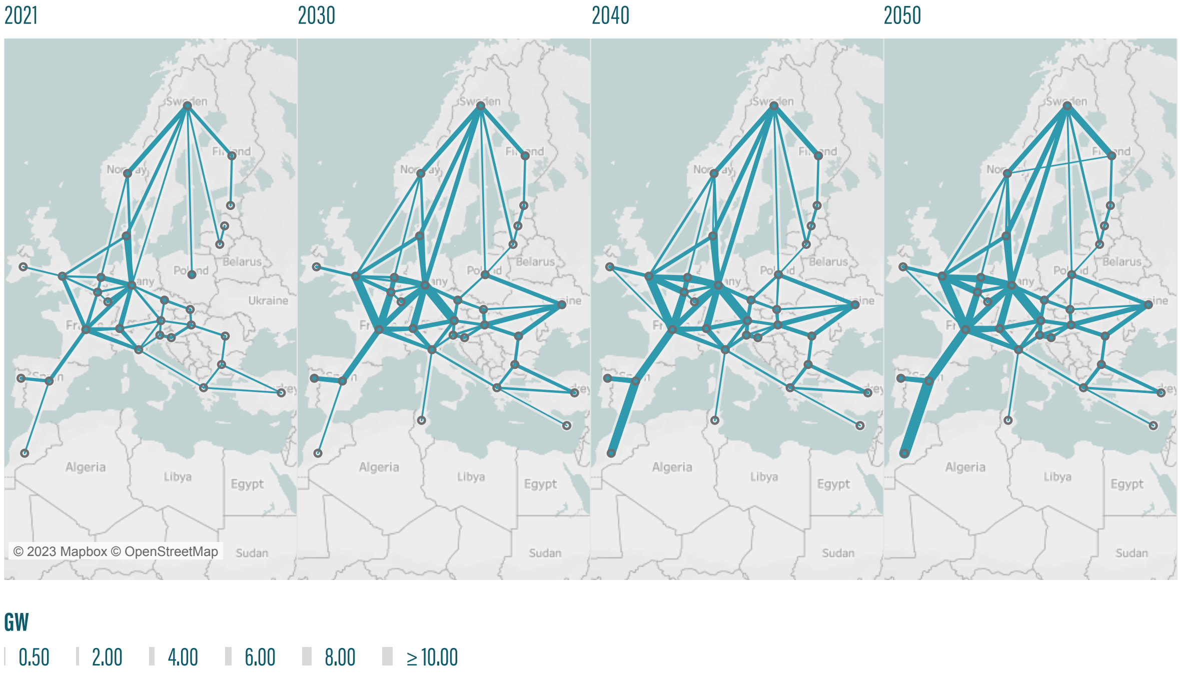
FIGURE 22. Electricity Generation Capacity



Integrating and delivering this scale of new generation requires a significant buildout of new transmission, this includes reinforcement of the existing EU + UK networks as well as, in the long-term accessing new resources from resource-rich areas like Norway, North Africa, Ukraine, and Turkey.


Dennis Schroeder /NREL

FIGURE 23. Electric Transmission Capacity Evolution (core scenario)



VEHICLES

In all high electrification scenarios including the **core** scenario, we achieve 100% zero-emissions vehicles by 2035 (Figure 21b) which fully decarbonizes on-road vehicles by 2050. In the **slow consumer uptake** scenario, this is delayed, and targets for vehicle adoption are not met (this would require a delay in the mandated phaseout of ICEs but it is chosen as a scenario parameter to illustrate the impacts) and vehicles are not fully decarbonized by 2050.

BUILDINGS

Space and water heating constitute the dominant share of fossil fuel uses in existing residential and commercial buildings. In a net-zero transition, fossil boilers and water heaters are replaced by heat pumps. In residential buildings, heat pumps represent over 50% of space heating equipment by 2050 (Figure 21c) with the residual being biomass-based heating equipment or existing district heating (which is also decarbonized with heat pumps).

HYDROGEN

Hydrogen production varies in scale based on policy directives and assumptions about competition in end-uses like heavy-duty vehicles and high-temperature industrial heat. The majority of it is either electrolytic (either low-temperature or utilizing high-temperature nuclear heat) with the residual being supplied by imported hydrogen (from outside the model footprint) or BECCS hydrogen, with the negative emissions benefit of sequestering biogenic carbon enough to ensure its competitiveness against electrolytic hydrogen.

FIGURE 24. Hydrogen Production

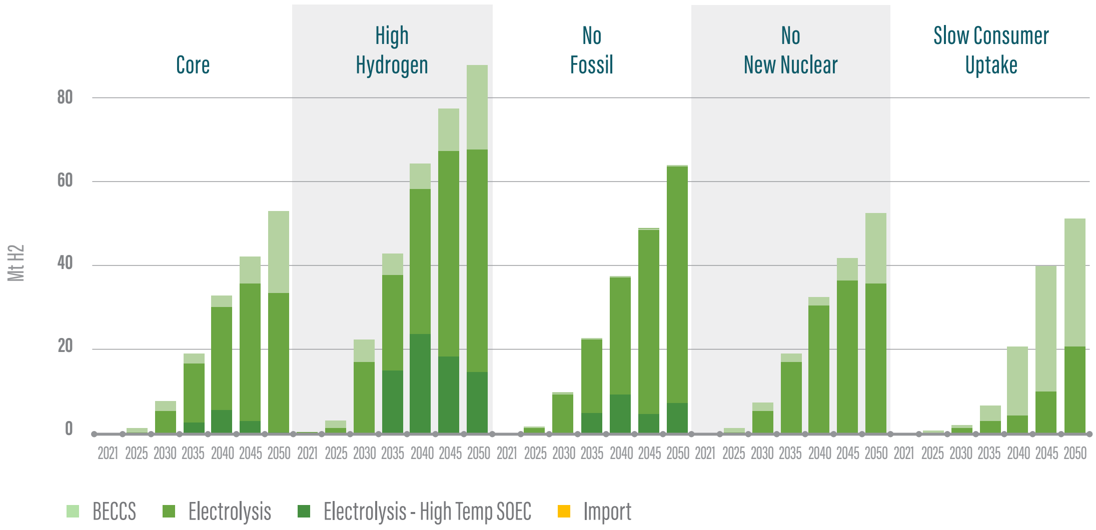
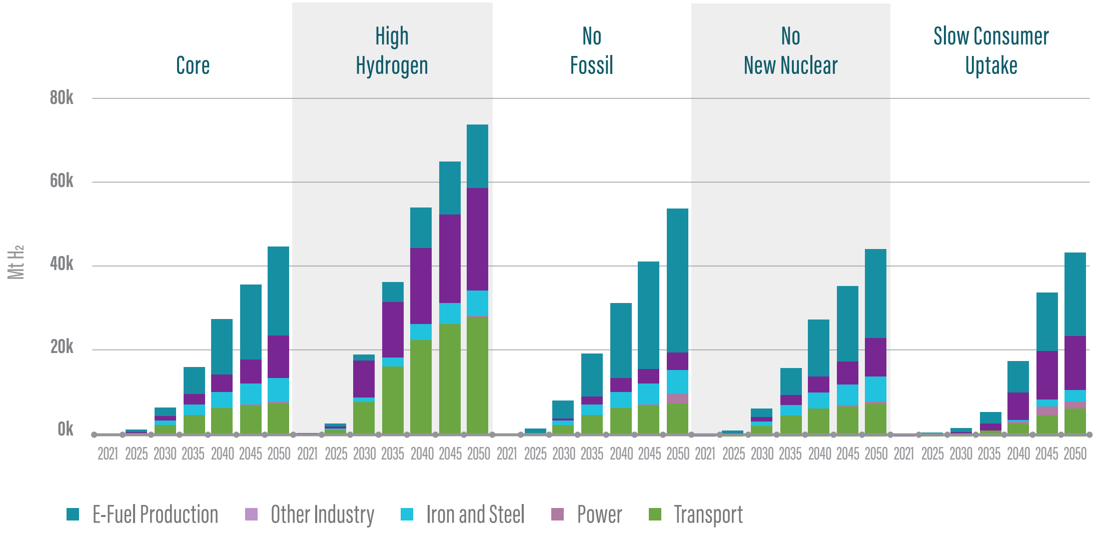
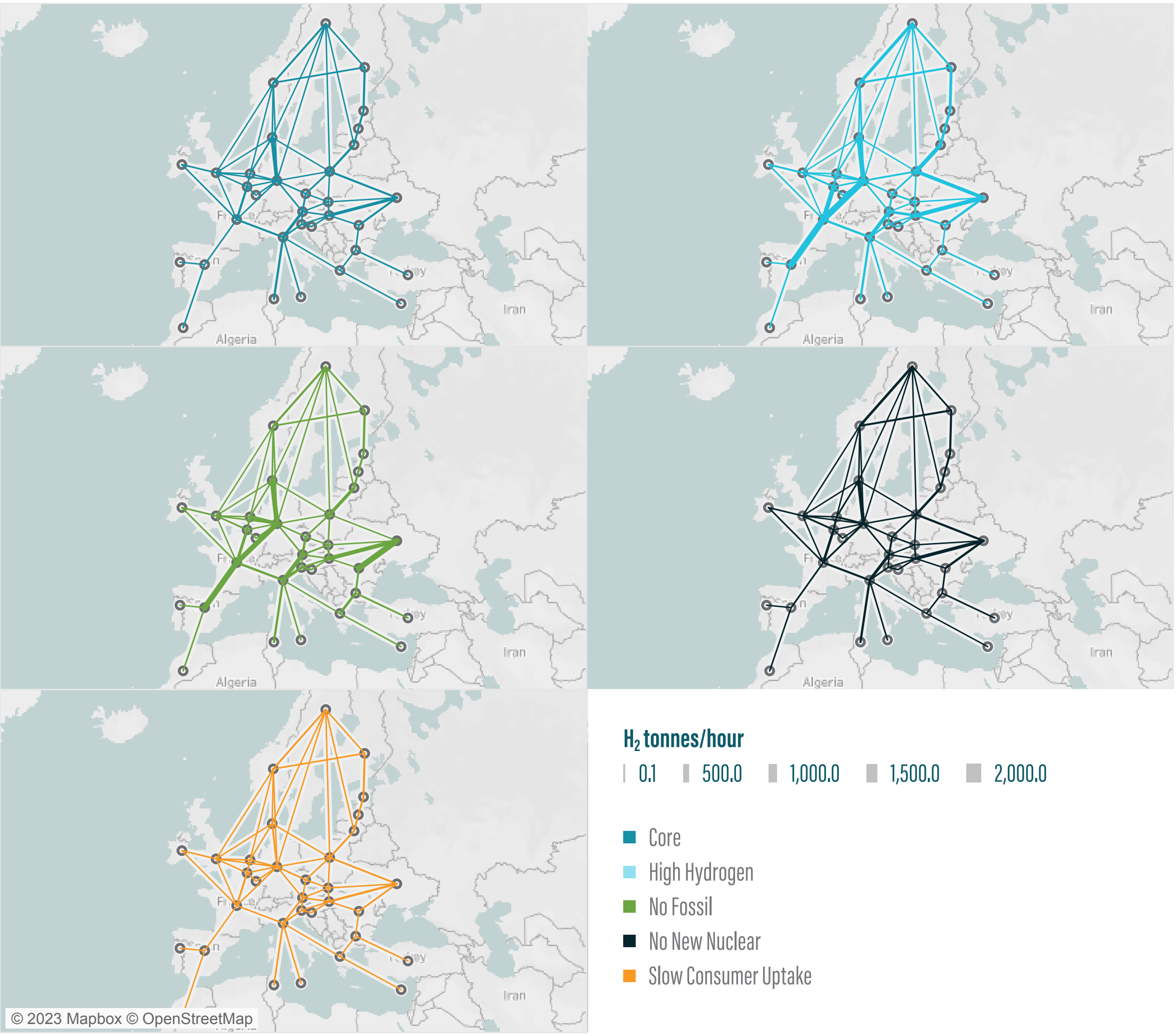


FIGURE 25. Hydrogen Consumption



This increase in the use of hydrogen as an energy carrier necessitates the development of a large-scale hydrogen grid in Europe, with the scale of energy delivered between countries rivalling the scale that is delivered by electricity. In all cases, a significant backbone is required to delivered hydrogen up from the Iberian peninsula and down from the Nordic countries to Germany, which is a significant consumer of hydrogen in the long-term but has limited ability to produce it domestically due to its constrained renewable potential.

FIGURE 26. Hydrogen pipeline comparisons between scenarios



STORAGE

Modeled energy storage increases dramatically (though remains dwarfed by extant gas storage). By 2050, there is almost 200 GW representing almost 3000 GWh of electric storage. This is principally li-ion in the near-term, with long duration storage becoming economic only in the last model period. This deployment of long-duration storage drastically increases the energy capacity by 2050. Thermal energy storage rivals electricity storage in scale by 2050, with greater than 200 GWs of power capacity and 1500 GWh of energy capacity. Hydrogen storage has the largest amount of energy capacity in most scenarios (with more limited power capacity) and is used as the principal mechanism of 'seasonal storage', balancing periods of renewable overproduction by operating electrolyzers seasonally and storing excess production.

FIGURE 27. Total modeled power capacity (GW) and energy capacity (GWh) of storage for all scenarios. *Note that the scale of the y-axis changes between storage types.*

Investment

Figure 28 shows the scale of investments made to satisfy Europe's net-zero commitments by 2050. Overall investment is dominated by renewables in all scenarios, along with additional electricity technologies like battery storage, nuclear, and backup thermal generation (gas/h2 turbines). Investment for fuels pathways is also critical as well as delivery infrastructure to move energy (electricity, hydrogen) and CO_2.

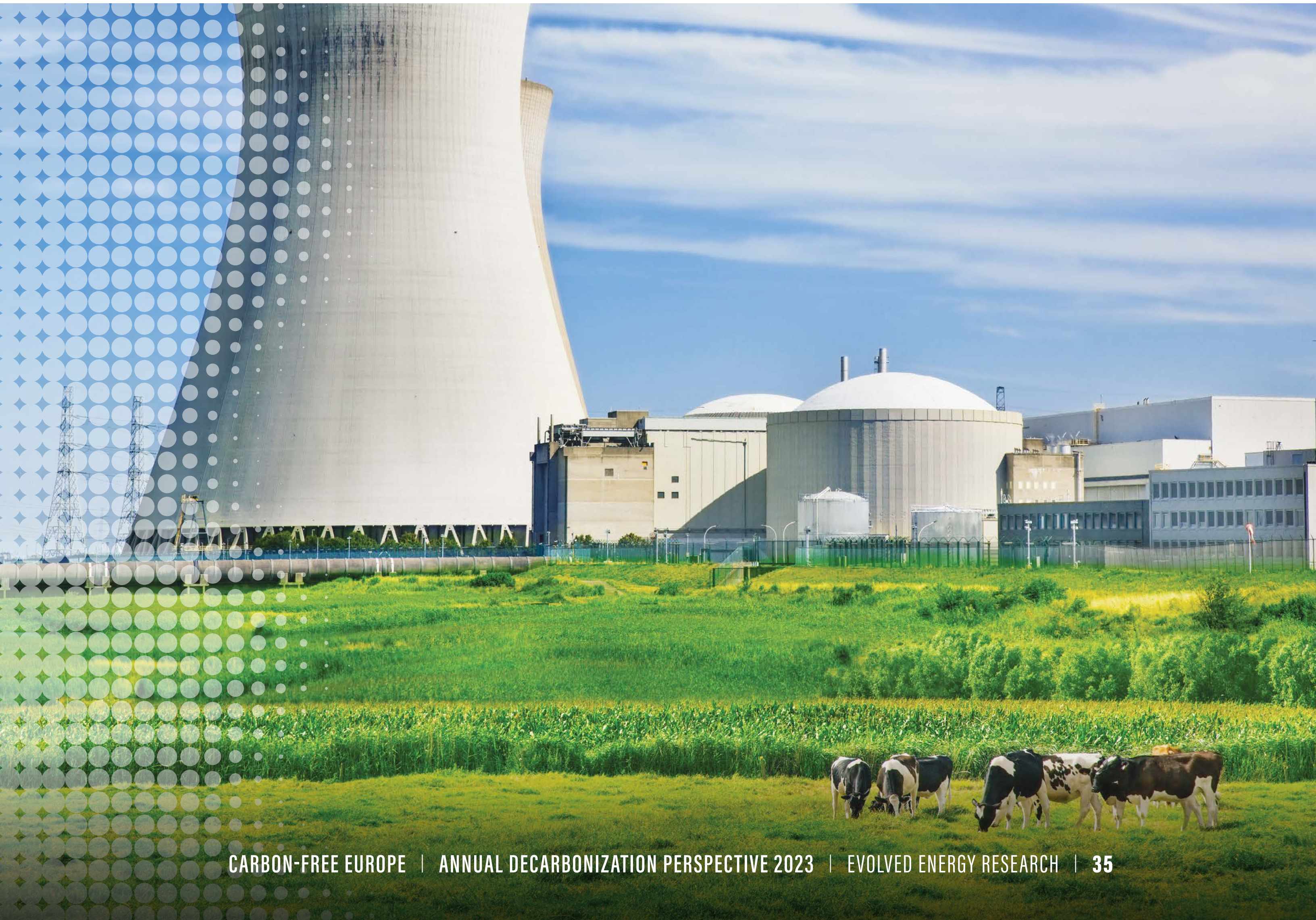
KEY TECHNOLOGY INVESTMENT

FIGURE 28. Capital investment (2023-2050) by scenario and key technology

	Core	High Hydrogen	No Fossil	No New Nuclear	Slow Consumer Uptake
Offshore Wind	1,206B €	1,349B €	1,363B €	1,648B €	1,020B €
Solar	1,221B €	1,359B €	1,602B €	1,400B €	840B €
Onshore Wind	958B €	1,059B €	1,084B €	1,038B €	759B €
Nuclear	894B €	997B €	906B €	0B €	1,034B €
Other Thermal Power	489B €	384B €	491B €	648B €	428B €
Biofuels	511B €	519B €	185B €	472B €	735B €
Electrolysis	355B €	803B €	574B €	359B €	110B €
Electricity Storage	286B €	203B €	291B €	380B €	211B €
Decarbonized Steam	177B €	123B €	175B €	186B €	190B €
E-Fuels Synthesis	96B €	80B €	173B €	96B €	90B €
Inter-Regional Electricity Transmission	65B €	50B €	66B €	76B €	66B €
Backbone Hydrogen Pipelines	24B €	68B €	58B €	30B €	10B €
Advanced Geothermal	28B €	19B €	30B €	60B €	43B €
Biomass Power	38B €	9B €	2B €	99B €	22B €
Backbone CO_2 Pipelines	23B €	19B €	0B €	23B €	35B €

V SCENARIO RESULTS

The highlights of each scenario are compared qualitatively below and in Table 3 and supporting quantitative values can be referenced in Table 2. The take-home message is that from a technological standpoint there are multiple feasible pathways to net-zero by 2050, at affordable cost, even in cases when some key technologies or resources are limited. However, meeting net-zero under these constraints requires compensating changes in other areas, typically resulting in higher cost and greater use of other technologies or unconstrained resources.



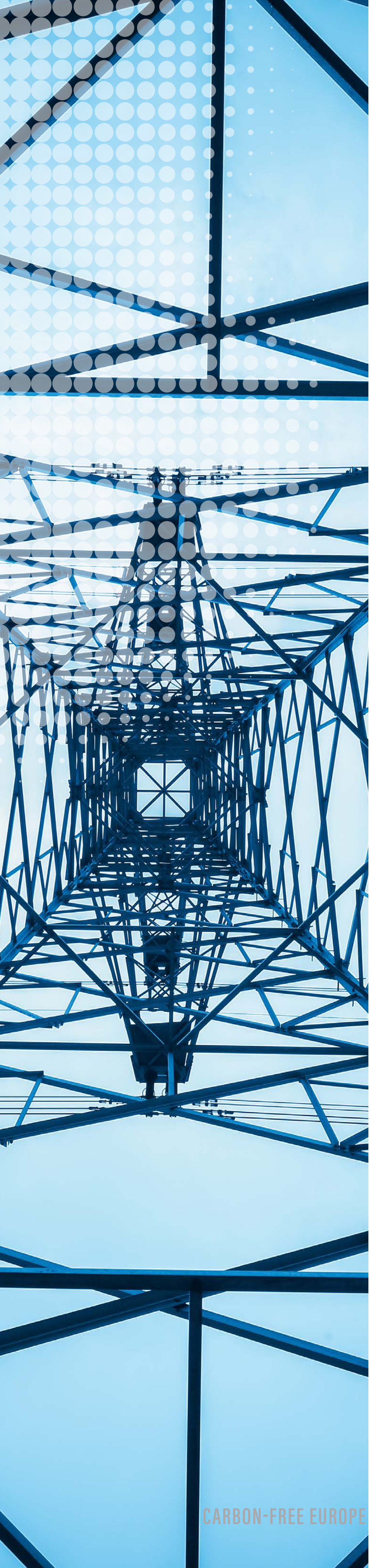
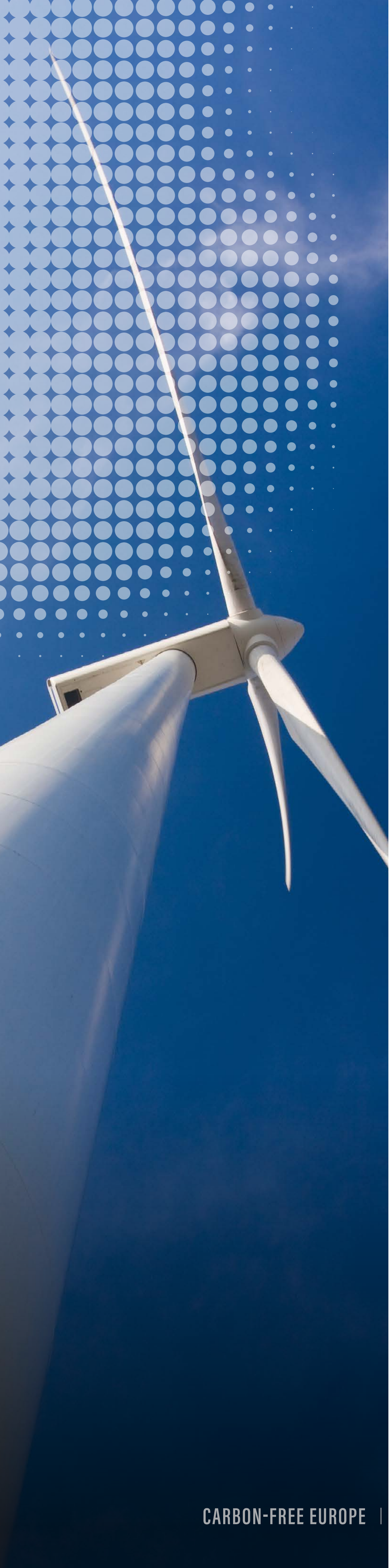


TABLE 3. Main decarbonization scenario results compared to core scenario

	Core	High Hydrogen	No Fossil	No New Nuclear	Slow Consumer Uptake
Cumulative CO_2 (2021-2050)	CO_2	CO_2	CO_2	CO_2	CO_2
2050 FINAL ENERGY					
Total Final Energy	e	e	e	e	e
Electricity	⚡	⚡	⚡	⚡	⚡
Hydrogen	H_2	H_2	H_2	H_2	H_2
Other Fuels	⛽	⛽	⛽	⛽	⛽
2050 PRIMARY ENERGY					
Total Primary Energy	E	E	E	E	E
Imported Primary Energy	→	→	→	→	→
Biomass	🌱	🌱	🌱	🌱	🌱
Natural Gas	🔥	🔥		🔥	🔥
Offshore Wind	🌬	🌬	🌬	🌬	🌬
Oil	💧	💧		💧	💧
Onshore Wind	🌬	🌬	🌬	🌬	🌬
Solar	☀	☀	☀	☀	☀
Nuclear	⚛	⚛	⚛	⚛	⚛
2050 CARBON MANAGEMENT					
Total CO_2 Capture	🏭	🏭	🏭	🏭	🏭
CO_2 Sequestration	🏭 CO_2	🏭 CO_2		🏭 CO_2	🏭 CO_2
CO_2 Utilization	CO_2	CO_2	CO_2	CO_2	CO_2



Core

The **core** scenario is the least constrained and therefore lowest cost net-zero scenario. This scenario represents a best laid plan with limited friction in terms of consumer adoption, acceptance of renewable electricity development and social license for significant increases of nuclear technologies. It dramatically transforms both the supply and demand side of the energy system currently dominated by fossil fuels. It is characterized by a heavy reliance on the pillars of decarbonized electricity and electrification. The model relies on the most economic solutions it can find across electricity, fuels, and carbon management.

High Hydrogen

This scenario models increased competitiveness of direct hydrogen end-uses in sectors where they are potentially competitive against direct electrification approaches — specifically, high-temperature industrial process heating and on-road transport (principally heavy-duty transport). This results in a higher share of energy delivered to end-users as hydrogen (as opposed to direct electricity or a fuel that uses hydrogen as a feedstock). This has implications for the location of renewables-driven electrolysis production and hydrogen pipelines as well as the scale of necessary hydrogen storage.

No Fossil

Because this case has no fossil fuels, choices for producing fuels and chemical feedstocks are limited to biomass and electricity. This case requires the highest level of generation capacity, electricity generation, electric fuel production, and electrolysis capacity. It doesn't see any geologic sequestration but does have the highest level of carbon utilization. It doesn't utilize BECCS hydrogen (because it doesn't need to offset fossil use), and so doesn't see as much biomass usage as other cases, instead relying on zero-carbon imports to ensure the system is zero-fossil by 2050. Geologic sequestration is not needed, but a relatively large amount of carbon capture is still required to supply the carbon needed for fuel and feedstock production.

No New Nuclear

No new nuclear requires a significant increase in the deployment of renewables compared to the **core** scenario including more expensive floating offshore wind resources and lower quality solar. It also increases the need for transmission to deliver these resources to load. The largest impacts are felt in the most resource-constrained areas of Eastern and Central Europe.

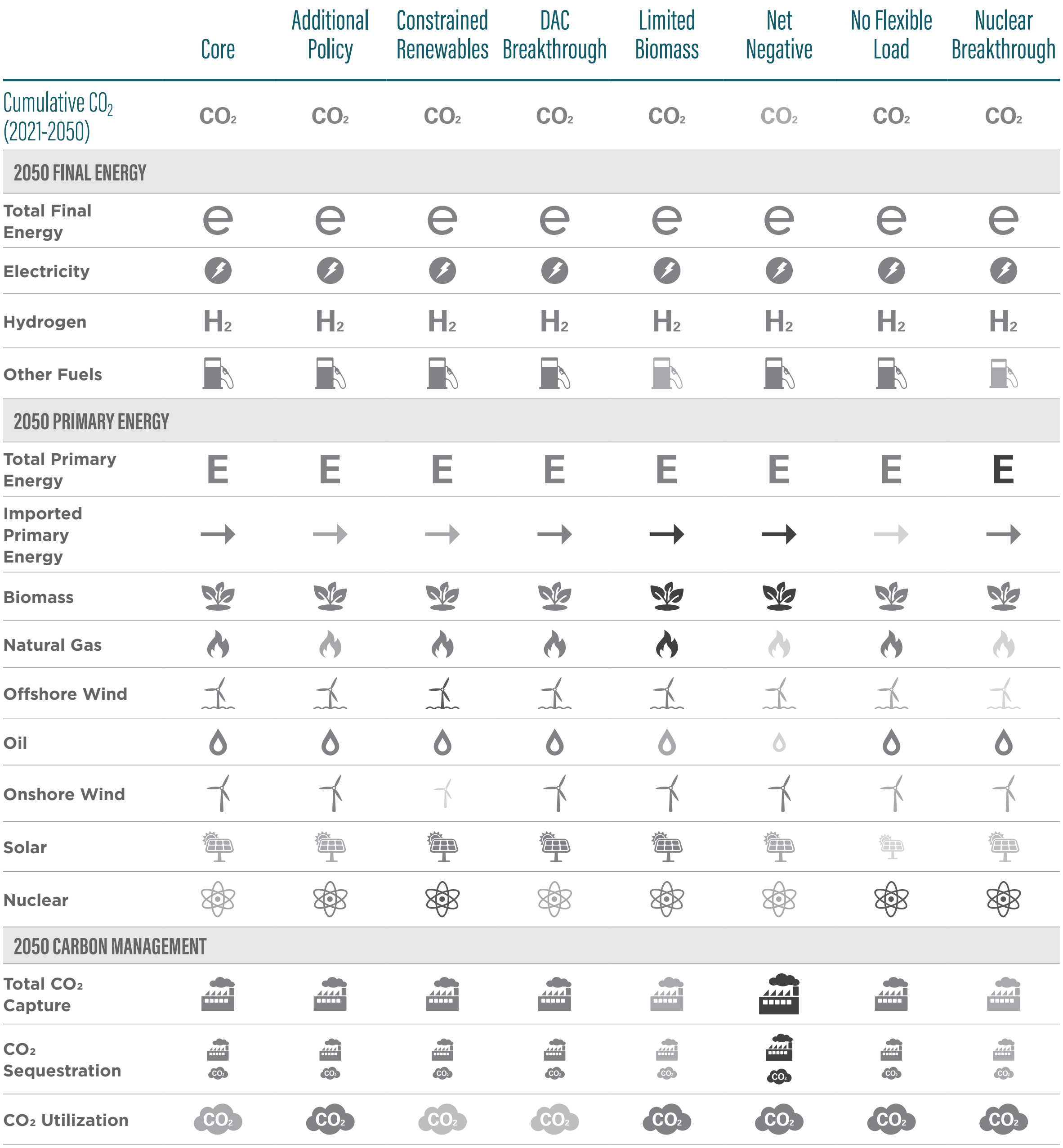
Slow Consumer Uptake

Delaying consumer adoption of electrified and direct hydrogen end-use technologies results in the highest share of residual hydrocarbons, which either need to be produced or imported as zero-carbon alternatives. Unsurprisingly, this has the lowest deployment of electricity infrastructure but the largest share of imported fuels.

VI SENSITIVITY RESULTS

The sensitivity analyses in this study are grouped into two categories. The first explores the effects of changes in key technology costs or deployments (**nuclear breakthrough; DAC breakthrough**), constraints on resources (**constrained renewables**; **limited biomass**), or policy failures (**no flexible load**) or changes (**additional policy; net negative**) relative to the values in the **core** scenario. The directional impacts on key metrics are shown in Table 4, and the key results for each sensitivity are described below.

TABLE 4. Sensitivities comparison to Core scenariox



	Core	Additional Policy	Constrained Renewables	DAC Breakthrough	Limited Biomass	Net Negative	No Flexible Load	Nuclear Breakthrough
Cumulative CO_2 (2021-2050)	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
2050 FINAL ENERGY								
Total Final Energy	e	e	e	e	e	e	e	e
Electricity	⚡	⚡	⚡	⚡	⚡	⚡	⚡	⚡
Hydrogen	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2
Other Fuels	⛽	⛽	⛽	⛽	⛽	⛽	⛽	⛽
2050 PRIMARY ENERGY								
Total Primary Energy	E	E	E	E	E	E	E	E
Imported Primary Energy	→	→	→	→	→	→	→	→
Biomass	🌱	🌱	🌱	🌱	🌱	🌱	🌱	🌱
Natural Gas	🔥	🔥	🔥	🔥	🔥	🔥	🔥	🔥
Offshore Wind	🌬	🌬	🌬	🌬	🌬	🌬	🌬	🌬
Oil	💧	💧	💧	💧	💧	💧	💧	💧
Onshore Wind	🌬	🌬	🌬	🌬	🌬	🌬	🌬	🌬
Solar	☀	☀	☀	☀	☀	☀	☀	☀
Nuclear	⚛	⚛	⚛	⚛	⚛	⚛	⚛	⚛
2050 CARBON MANAGEMENT								
Total CO_2 Capture	🏭	🏭	🏭	🏭	🏭	🏭	🏭	🏭
CO_2 Sequestration	🏭 CO_2	🏭 CO_2	🏭 CO_2	🏭 CO_2	🏭 CO_2	🏭 CO_2	🏭 CO_2	🏭 CO_2
CO_2 Utilization	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2

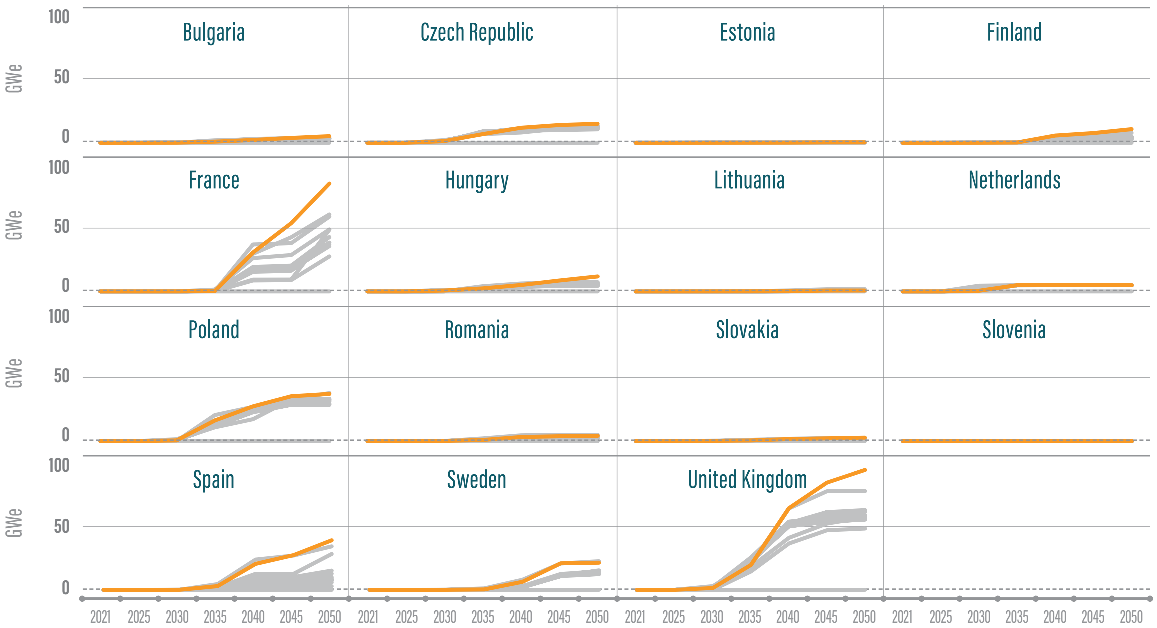
Nuclear Breakthrough

The **nuclear breakthrough** explored in this sensitivity imagines rapid cost declines in reactor technologies for both the high-temperature gas reactors and light-water reactors modeled.

FIGURE 29. LCOE Comparison – Nuclear Breakthrough vs. Other cases

The impact of these different cost trajectories are shown below in Figure 30. Sensitivity to these costs is not uniform across modeled countries. For some countries with renewable alternatives, cost is extremely important to the ultimate deployment. In France, Spain, Finland, and the U.K, a technological breakthrough significantly increases economic deployment as it principally displaces more expensive offshore wind. For others, like Czech Republic and Romania, deployment is insensitive to this breakthrough, reflecting clean electricity resource constraints even at more conservative cost forecasts.

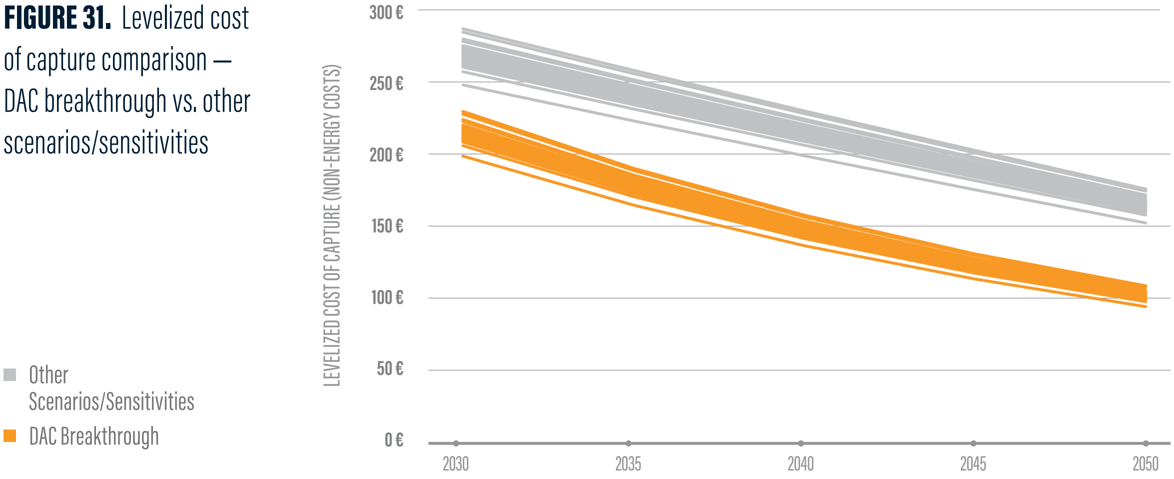
FIGURE 30. Nuclear power deployment



DAC breakthrough

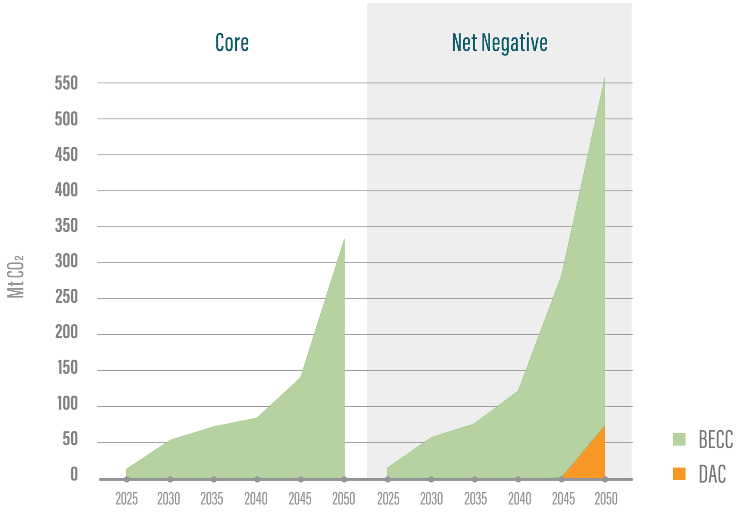
Assuming a more optimistic trajectory of costs for direct air capture encourages its deployment, increasing its competitiveness against other preferred negative emissions technologies deployed in the **core** scenario, which consists of BECCS deployed to produce electricity, refined fuels, and hydrogen.

FIGURE 31. Levelized cost of capture comparison — DAC breakthrough vs. other scenarios/sensitivities



These lower cost trajectories increase the contribution from DAC relative to bio-energy with carbon capture (BECC) which contribute most of the carbon capture in the **core** scenario. Increasing emissions ambition (**net negative**) and limiting available biomass resources (**limited biomass)** have a similar scale of effect on DAC deployment.

FIGURE 32. CO_2 capture from negative emissions technologies (NETS)



No Flexible Loads

Increasing the flexibility of customer end-use loads such as EV charging and HVAC can have a positive impact on the cost of the core scenario, particularly in the distribution system. By enhancing load management, it enables the economic deployment of distributed solar PV and reduces the need for grid-scale electricity storage and electric distribution system peaks. However, since shifting customer loads is generally a short-term capacity resource, it provides fewer benefits to the bulk power system compared to sector-coupled industrial flexible loads like electrolysis. Removing dynamic coupling between the electricity and fuel-supply sectors means that industrial scale loads such as electrolyzers and boilers operate as conventional non-responsive industrial loads, reducing load flexibility. As a result, there is an increase in curtailment, which makes electric fuels less economical and hinders the economics of renewable generation against nuclear. This leads to a decrease in wind and solar primary energy and electricity generation, while biomass use and nuclear generation increases. Sector coupling is crucial to the economics of energy systems based on high penetrations of renewable energy.

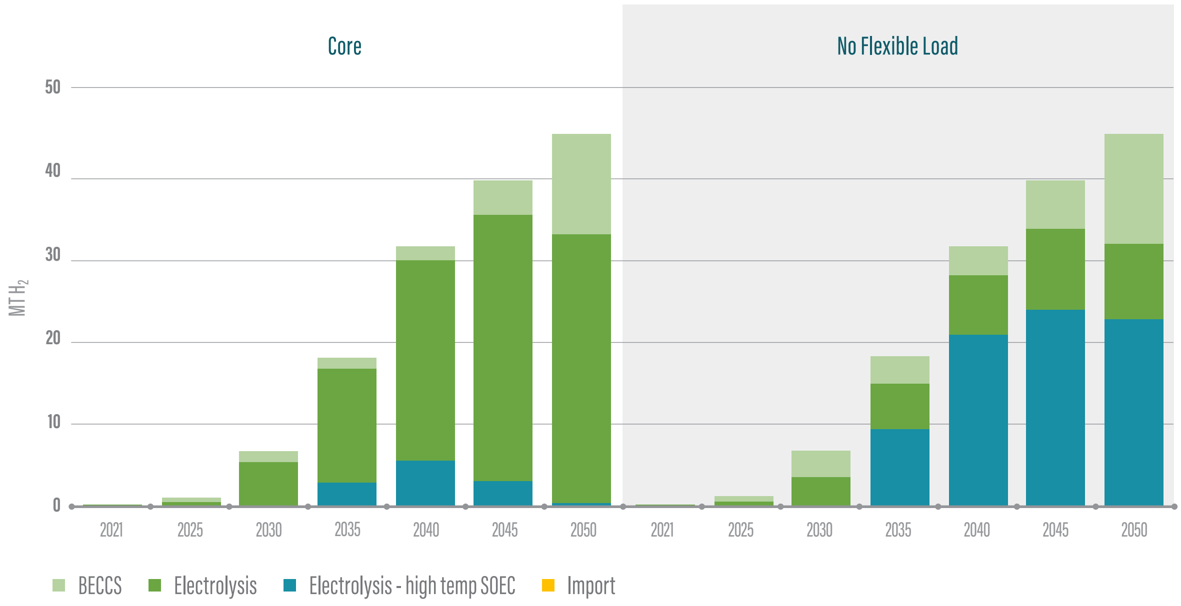
Enhanced load management has significant effects on the type of generation resources that are economic as well as the need to build electricity storage as supporting flexibility resources. Without flexible load, solar is significantly less economic (flexible loads can't soak up production in the middle of the day), and more storage is required for a less renewable system.

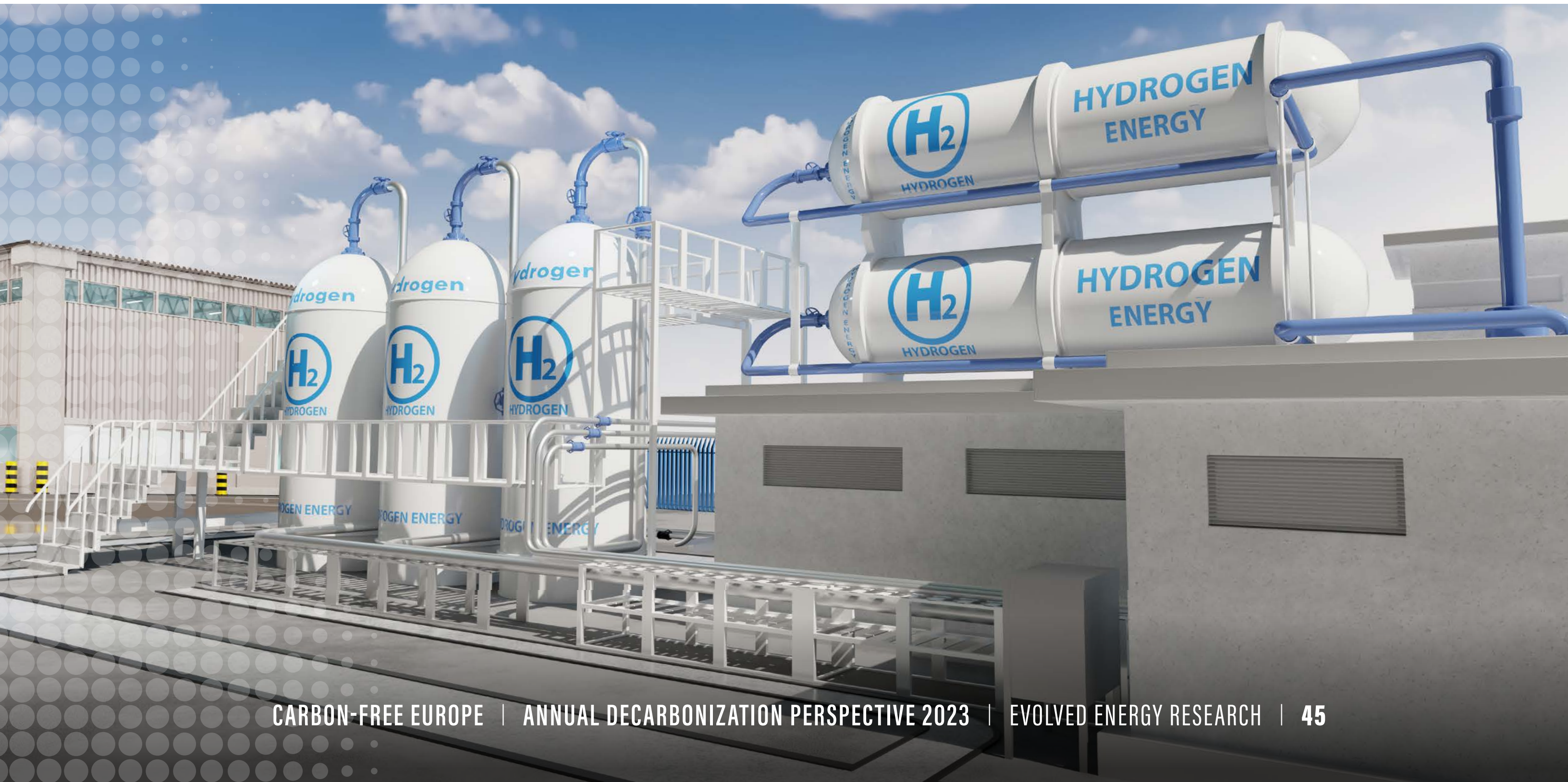
Because the shifting of customer loads is typically a short-duration capacity resource, it provides smaller benefits to the bulk power system than sector-coupled industrial flexible loads such as electrolysis. The effect of eliminating dynamic coupling between the electricity and fuel-supply sectors is that industrial scale loads such as electrolyzers and boilers do not respond flexibly to electricity system conditions as they do in the **core** scenario but instead operate as conventional non-responsive industrial loads. The lack of coupling increases curtailment (Figure 32, makes electric fuels much less economics, and hurts the economics of renewable generation against nuclear as the electricity system needs the dispatchability of nuclear (with integrated thermal energy storage). In addition, opportunities to decarbonize industrial heat with zero carbon electricity are wasted. The systemic result is that wind and solar primary energy and electricity generation decrease, while biomass use and nuclear generation increases. This case illustrates why sector coupling is critical to the economics of energy systems that are based on high penetrations of renewable energy. In light of the discussion surrounding the EU electricity market design reform, the imperative to develop rules that encourage this load flexibility (through market payments, rates, etc.) is critical.

FIGURE 33. Annual renewable curtailment percentage across all scenarios and sensitivities

The economics of hydrogen production are affected when low-temperature electrolysis can't operate flexibly to match renewable production. Instead of the majority of H_2 being produced through this process, the economics shift towards nuclear high-temperature electrolysis and BECCS.

FIGURE 34. Hydrogen Production Comparison, Core vs. No Flexible Load

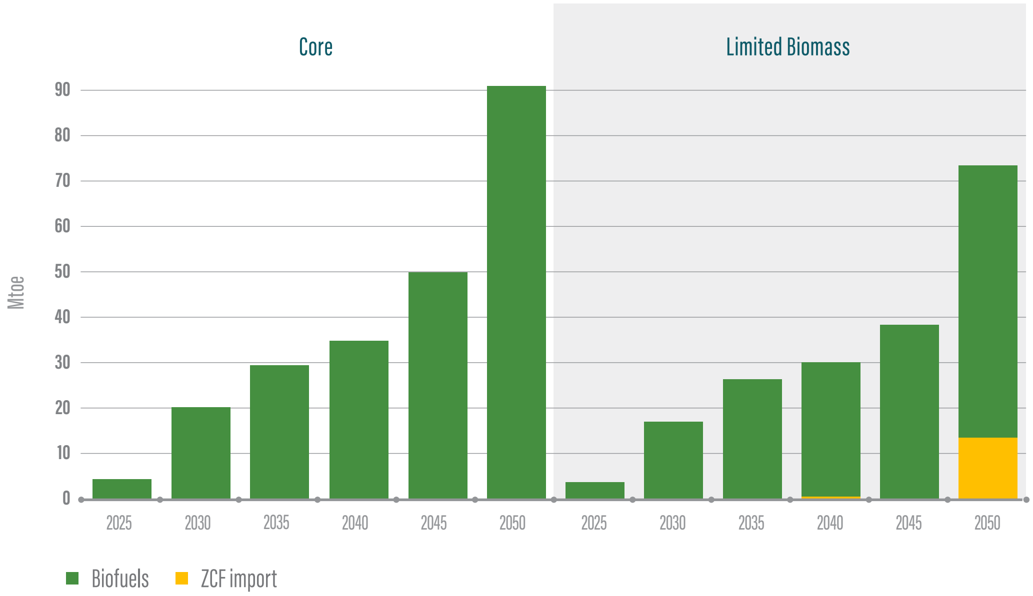




Limited Biomass

Restricting available biomass supplies increases the share of fuels that are imported from outside the model footprint. It also reduces the overall amount of zero-carbon fuels, with a larger share of emissions offset through direct air capture with sequestration as opposed to BECC processes.

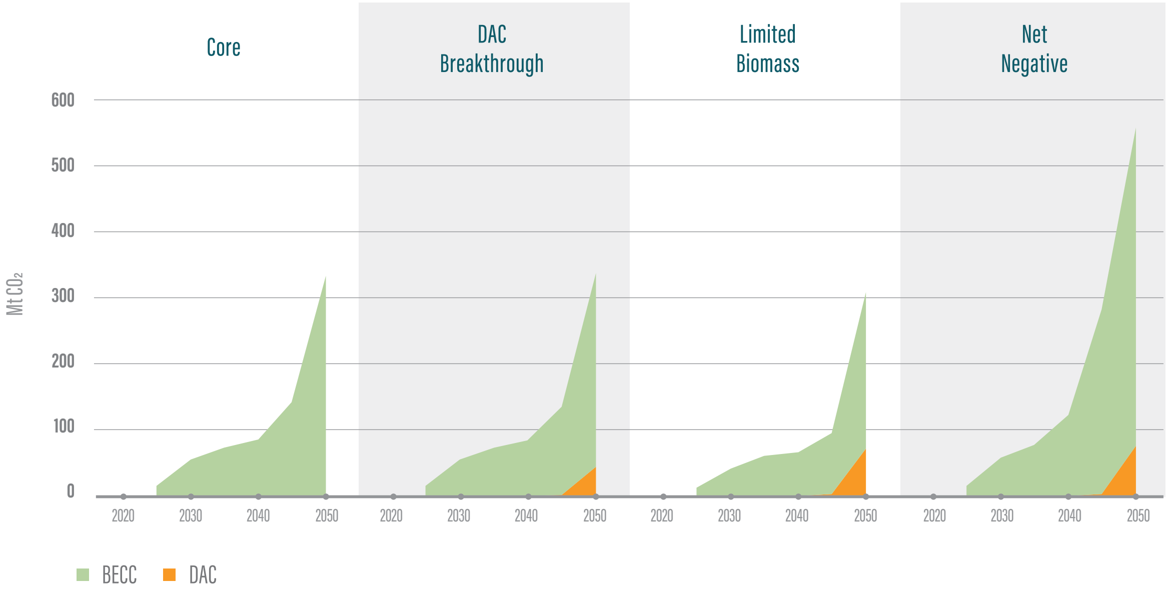
FIGURE 35. Zero-carbon biofuels and imports; core vs. limited biomass



Net Negative

The **net negative** sensitivity reaches net GHG emissions of -500 Mt CO_2e in 2050, representing a stylized scenario of accelerated ambition towards unwinding atmospheric concentrations. This requires reducing residual fossil use that remains in the **core** scenario (small amounts of natural gas remain in electricity and heat production and oil remains in refined fuels) and increasing contributions from negative emissions technologies like direct air capture. This additional scale of technology deployment and resource use should be understood when policymakers are considering additional targets or mechanisms for achieving negative emissions.

FIGURE 36. Carbon capture form NETS; Core vs. Net Negative

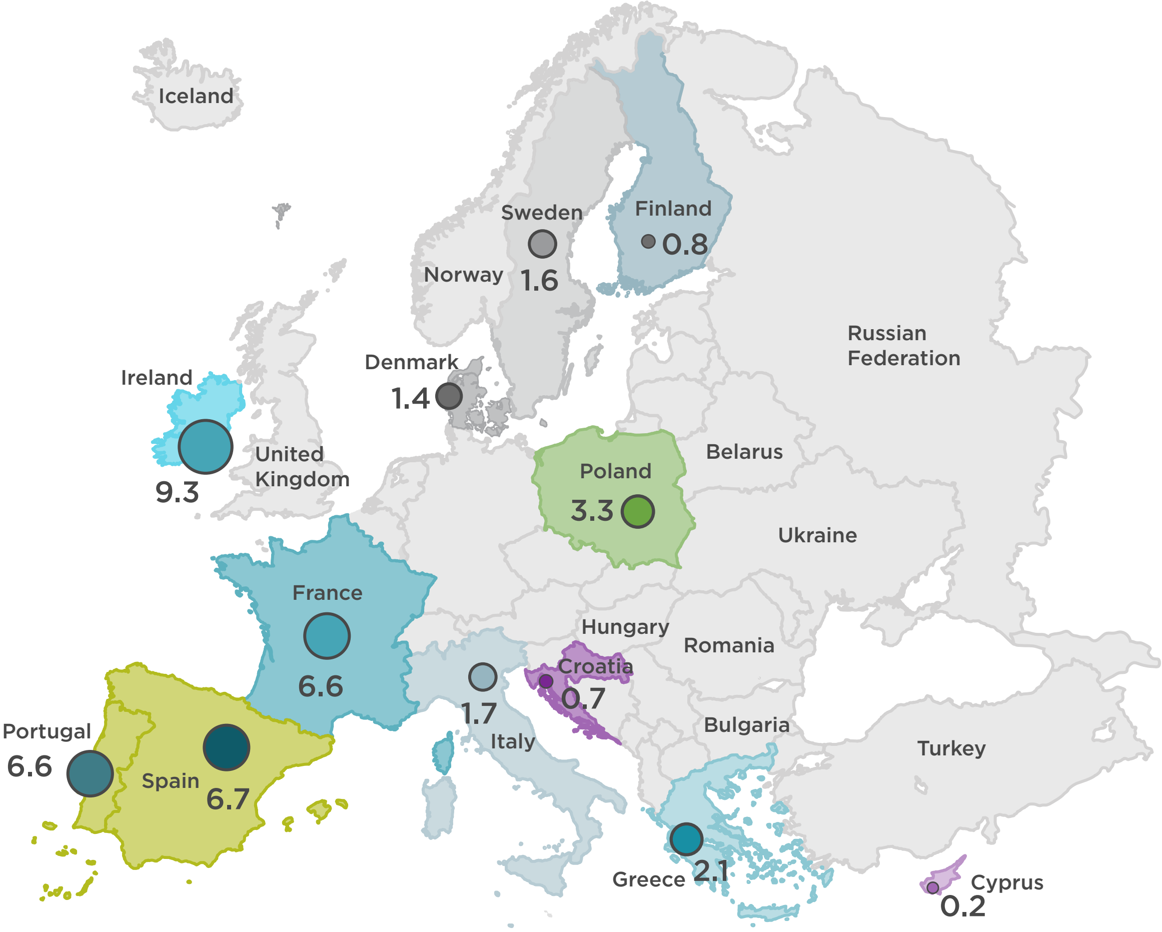


Additional Policy

Our **core** scenario aligns very closely with existing EU policy prescriptions. The only significant differences in the **additional policy** sensitivity are in the hydrogen sector and the electricity sector (with the addition of significant ocean energy deployment). The EU targets of 20 Mt of domestic production and imports by 2030 are faster than the optimal trajectory favored by the model in the **core** scenario. The model finds that the best use of the available renewable deployment through the 2030 period is displacing existing thermal generation or supplying new heat pump and electric vehicle loads. In the long-term, hydrogen is valuable as a sector coupling resource to address long-term supply and demand imbalances in a highly renewable electricity system, but this benefit shows up only at higher renewable penetrations than forecast through 2030. One cvet to this results is that we do not have a high level of visibility into existing hydrogen uses (refineries, bulk chemicals, etc.). In our modeling, those are consuming pipeline gas (even though the ultimate demand is for hydrogen). This decomposition will be a focus for future work.

The ocean energy targets result in a significant deployment of wave or tidal resources, with the larget deployments in Ireland, Spain, France, and Portugal.

FIGURE 37. Ocean energy deployment by 2050 (GW)



VII DISCUSSION

Key Findings

(1) Meeting Europe's policy objectives by 2030 is attainable through the swift implementation of various measures such as expanding the use of renewable energy sources, adopting rigorous measures in the building sector to minimize gas consumption and facilitate the transition to heat pumps, and carrying out the plans to prohibit internal combustion engines in passenger transport. These crucial measures will significantly reduce the final energy demand by 2030, lessen Europe's dependence on imported natural gas, and contribute to a sustainable, net-zero energy future.

(2) Building new clean energy infrastructure at an unparalleled pace is essential to achieve a net-zero status by mid-century. Despite setting ambitious energy efficiency goals, industrial-scale infrastructure is needed to decarbonize, and Europe must construct a new low-carbon infrastructure in the next thirty years to meet this challenge.

(3) The active involvement of consumers in the decarbonization process can significantly impact the outcomes. The choices consumers make when purchasing technologies like electric vehicles and heat pumps instead of conventional alternatives, as well as their operational behavior, such as enabling flexible load management, are crucial for cost containment in decarbonization. These actions can help limit the necessity of upgrades to the electricity distribution systems, and the need to purchase flexibility and reliability services from thermal generators and electricity storage.

(4) There is broad agreement on the path to 2030, but scenarios diverge considerably by mid-century due to their distinct assumptions and limitations. The economics of early decarbonization are clear: speedy electrification together with the rapid implementation of renewable energy. To achieve a net-zero trajectory, policymakers must concentrate on near-term policies that prioritize this approach while supporting technology development for the future. The challenges faced in the near to medium-term (known as the "pace" challenge of decarbonization) differ significantly from the long-term "scale" challenges, where resource limitations will be a significant issue. It is vital to comprehend land-based natural resource availability and constraints when deciding which decarbonization technologies to pursue. It is challenging to determine whether a technology, such as advanced nuclear or DAC or electric fuels, is feasible or necessary until the ability to use biomass, site renewables and transmission, and sequester CO_2 is understood.

(5) These questions of resource availability may determine what share of decarbonization is satisfied by decarbonized fuels and electricity produced within Europe vs. the share imported from global markets (in the case of fuel) and neighboring regions (in the case of electricity). Europe needs a comprehensive and intentional fuel strategy as it will determine the necessary scale of energy infrastructure in the long-term. It may be economic to import zero-carbon fuels from other regions, which limits necessary production infrastructure (low-carbon generation, electrolyzers, e-fuels synthesis) but this creates a situation where a large residual of Europe's energy consumption remains exposed to global markets.

(6) Electricity supply in the long-term is dictated as much by resource availability as relative economics. Foreclosing technological options like nuclear, advanced geothermal, or biomass power given their lack of competitiveness against current renewable price is shortsighted.

In summary, the challenges faced in the near to medium-term differ significantly from the long-term "scale" challenges of decarbonizing the economy. The criticality of technologies through 2030 is not necessarily reflective of their role in the long-term. Appreciation of this uncertainty should lead policymakers to develop flexible frameworks that acknowledge both risks and opportunities in the long-term. The section below illustrates where some key uncertainties lie and where there are areas of potential competition that may dictate the direction of Europe's decarbonization pathway.

Competing Mitigation Options

The broad set of scenarios and sensitivities modeled in this study lend themselves to some general observations on technology and resource mitigation options that compete, sometimes in ways that are not obvious. The section below highlights some of these competitions and discusses circumstances that would tend to favor one option over another. Awareness of these competitions may help to inform policy, investment decisions, and R&D priorities.

- **Electricity transmission vs. fuel pipelines.** In a net-zero economy, the movement of energy from regions with abundant renewable resources to regions with high energy demand is critical. Transmission lines and fuel pipelines are both options for transporting energy, but the choice between the two depends on several factors, including the distance over which energy needs to be transported, the type of energy, and the desired final form of energy. For example, when the final energy form desired is electricity, transmission lines are typically the best option because they can transmit electricity over long distances with minimal energy loss. However, when it comes to transporting fuels like hydrogen, pipelines are often the more cost-effective option because they have higher throughput rates and lower costs per mile compared to electric transmission lines. The decision between producing the hydrogen close to the renewable source and shipping it by pipeline versus transmitting the electricity over a long distance then using it to produce hydrogen locally depends on several factors, such as the availability of renewable resources, the cost of producing hydrogen at the source, and the cost of building and operating pipelines. Overall, the choice between transmission lines and fuel pipelines depends on a variety of factors, and the optimal solution will depend on the unique circumstances of each energy system.

- **Direct air capture vs. biomass.** In our modeling, for example in the DAC breakthrough and limited biomass sensitivities, DAC capacity and biomass consumption move in opposite directions. This is because DAC and biomass, both of which remove CO_2 from the atmosphere, compete economically to supply zero-carbon CO_2, either for sequestration to create a source of negative emissions, or for utilization in making carbon-neutral hydrocarbon fuels. Biomass competitiveness hinges on feedstock availability and cost. DAC competitiveness depends on technology progress in energy intensity and capital cost, climactic conditions which affect capture efficiency, and the availability of low-cost electricity (even after the rest of the economy has electrified).
- **Electrification vs. fuels.** The economic benefits of electrification using decarbonized electricity over conventional technologies using decarbonized fuel are evident in some applications such as light-duty vehicles. Additionally, electrification reduces land use concerns, making it a favorable choice for reducing the amount of land needed for e-fuel and biofuel production. However, there are technical challenges with electrification in applications such as aviation and chemical feedstocks, making fuels the only practical choice in the foreseeable future. For applications like industrial steam production, either electricity or fuels could be used, and fuel competitiveness depends on lower resource costs, breakthroughs in production technology or DAC, and institutional factors such as poorly planned electricity distribution system upgrades or ineffective gas decommissioning.
- **Nuclear power vs. offshore wind.** As seen in the nuclear breakthrough sensitivity, with significant cost reductions and wide social acceptance, nuclear power would grow rapidly in a net-zero economy. Nuclear, even with the aggressive costs forecasted in our nuclear breakthrough sensitiviity, is not competitive with high-quality renewables. However, in areas with lower quality solar and limited near-shore offshore wind, nuclear is competitive even against baseline cost estimates.
- **Batteries vs. flexible load.** Battery storage competes with flexible customer load such as EV charging for addressing electricity supply-demand imbalance, especially on distribution systems. Flexible load is more competitive if customer participation comes at low cost, can be effectively aggregated, and includes control technologies that minimize customer impacts. Put differently, the challenge for flexible load is to be seen by utilities as equivalent to a battery at a substation. Batteries are more competitive with lower costs and with applications that require a longer-duration time shifting of energy, since many flexible loads are of limited duration. This is where sector coupling loads (electrolysis, thermal energy storage etc. discussed below) need to be employed.

- **Sequestration vs. utilization.** Whether to sequester CO_2 or to utilize it to make fuels comes down to the cost of producing decarbonized hydrogen and assumptions about prevailing fossil fuel costs. Hydrogen plays a key role in all scenarios even though it is used in relatively limited volumes compared to the fuels of today, due to its cost. Some end uses are more high value and some are more marginally competitive against alternatives, but hydrogen's role as an intermediate energy carrier whose production helps to balance high-renewables electricity systems is critical.
- **Industrial steam decarbonization.** Providing decarbonized steam to industrial processes is a three-way competition between heat pumps, thermal energy storage, and dual-fuel boilers. Heat pump competitiveness hinges on achieving low capital costs. Dual-fuel (electric and combustion fuel) boilers are more competitive when there are irregular renewable curtailment patterns in the electricity system, for example with high penetrations of wind generation, making storage operate at low capacity factors. Thermal storage competitiveness revolves around low capital cost, high reliability, and co-location with PV. It also hinges on changing current utility rate designs to reflect the utility's ability to avoid distribution upgrades through customer use of thermal storage. More broadly, the economic decarbonization of industrial heat is reliant on sector coupling and taking advantage of cheaper opportunities for energy storage.

VIII SUPPLEMENTAL RESULTS

FIGURE 38. Primary Energy; All Sensitivities

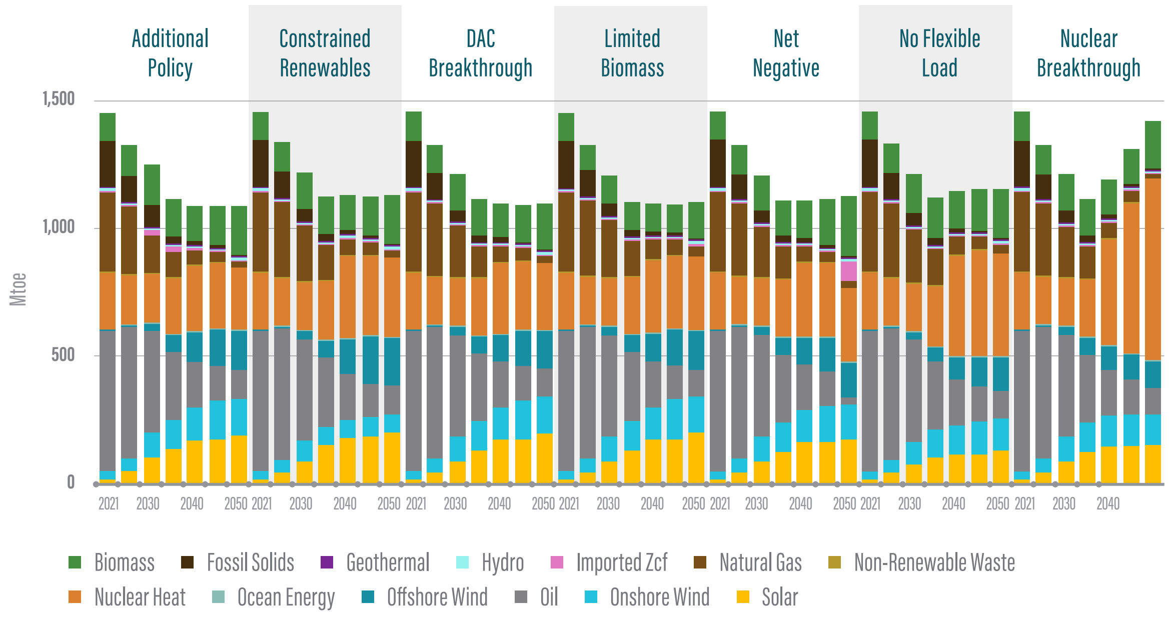


FIGURE 39. Final Energy; All Sensitivities

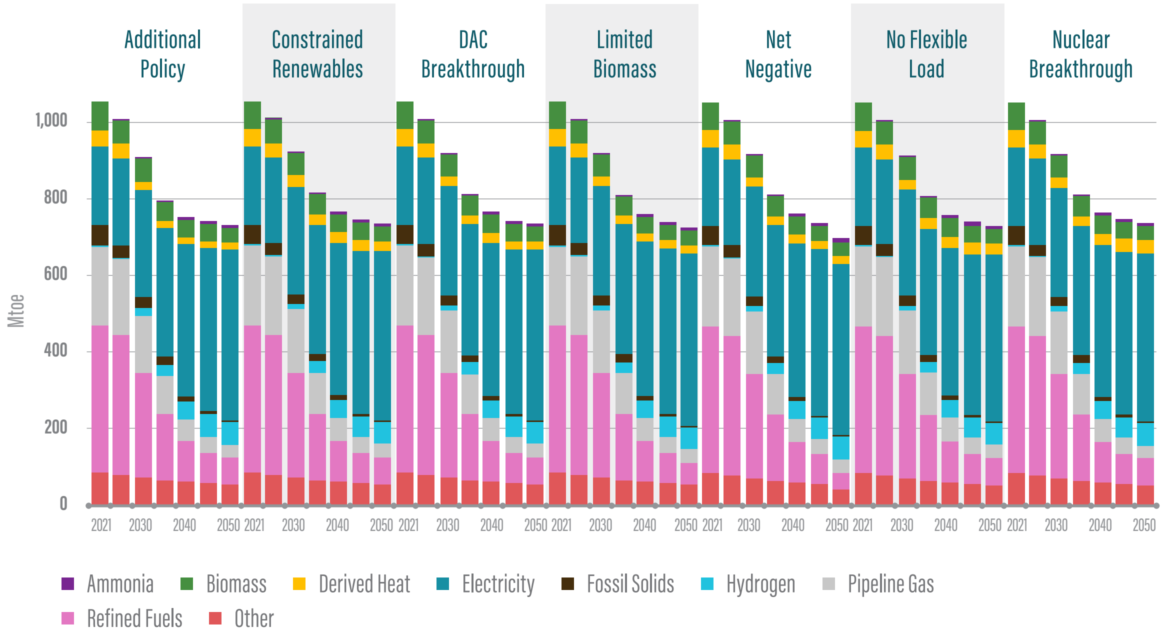


FIGURE 40. Captured CO_2 Uses; All Sensitivities

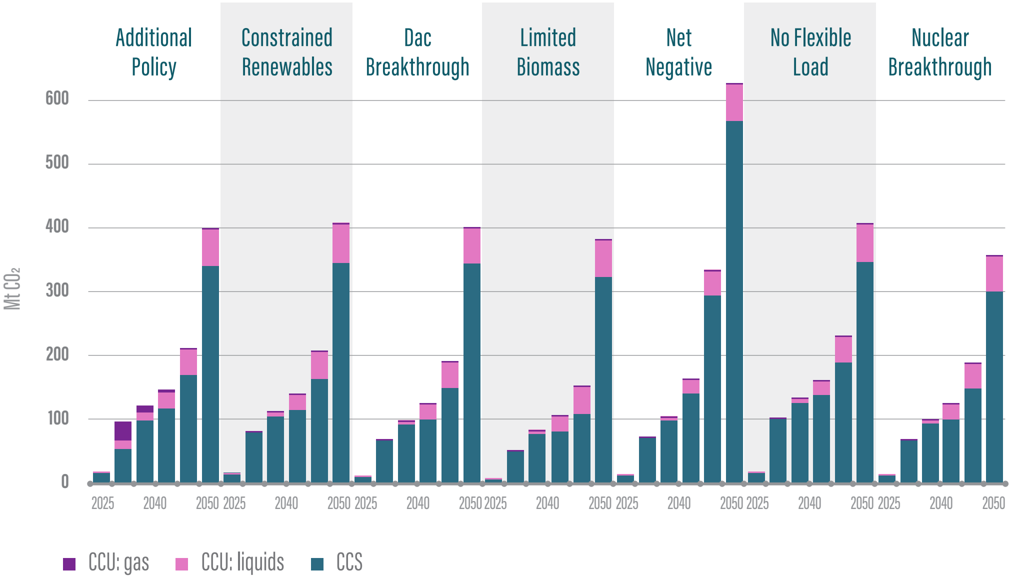


FIGURE 41. Captured CO_2 sources; all sensitivities

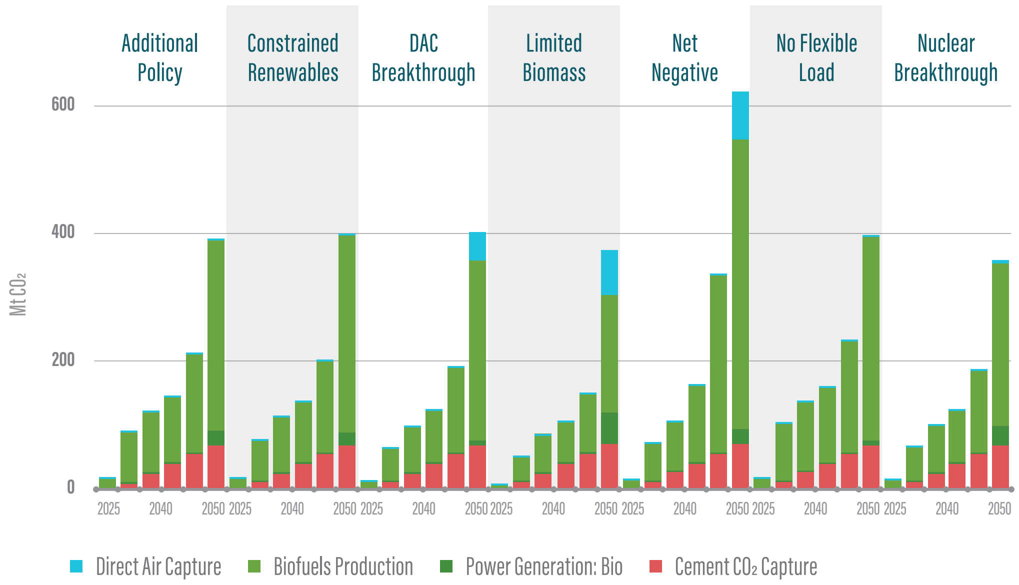


FIGURE 42. Electricity Generation; All Sensitivites

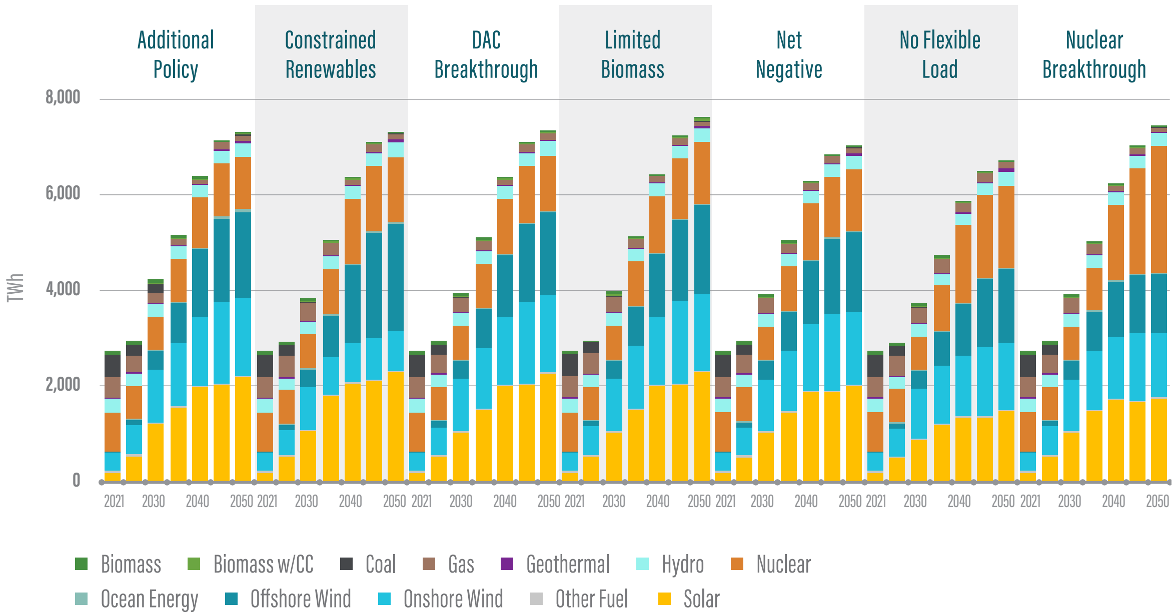


FIGURE 43. Electricity Load; All Sensitivities

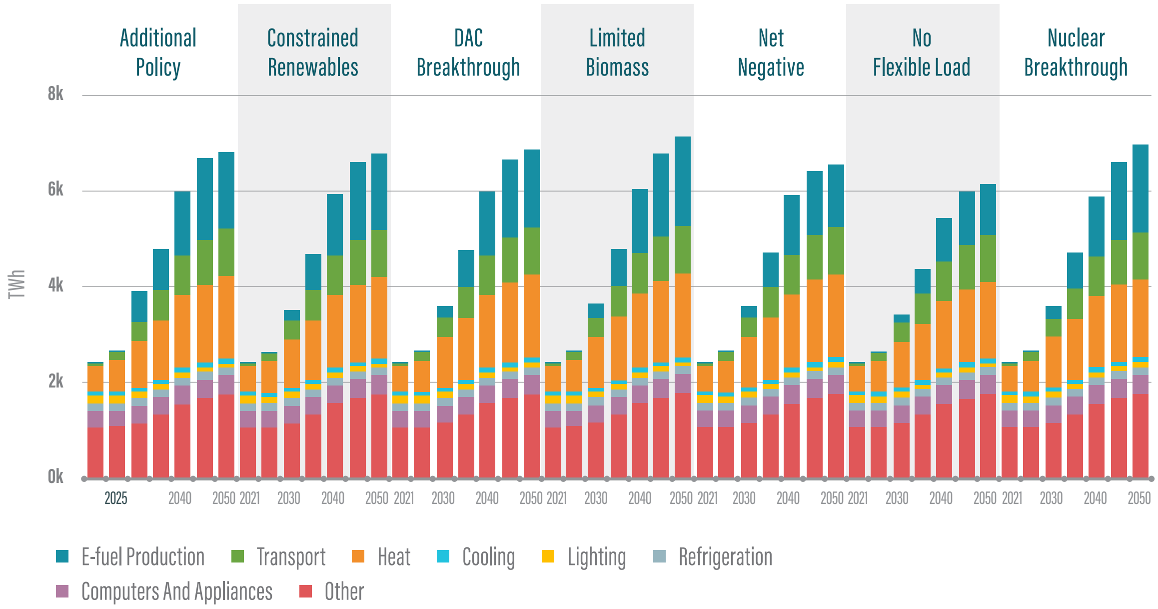


FIGURE 44. Fuel Demand; All Sensitivities

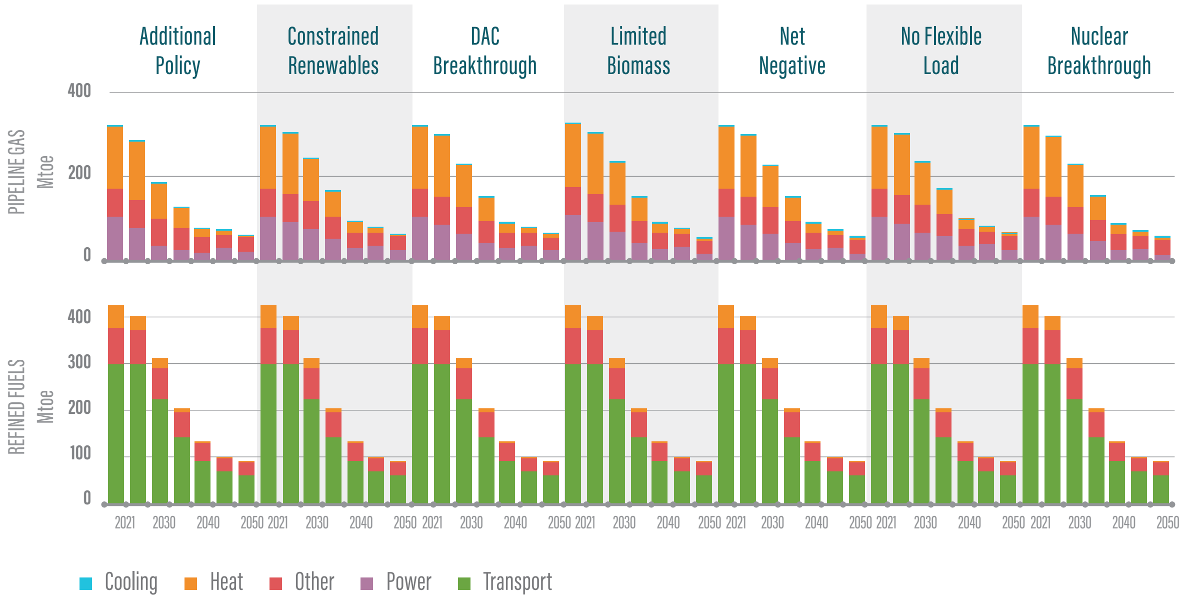
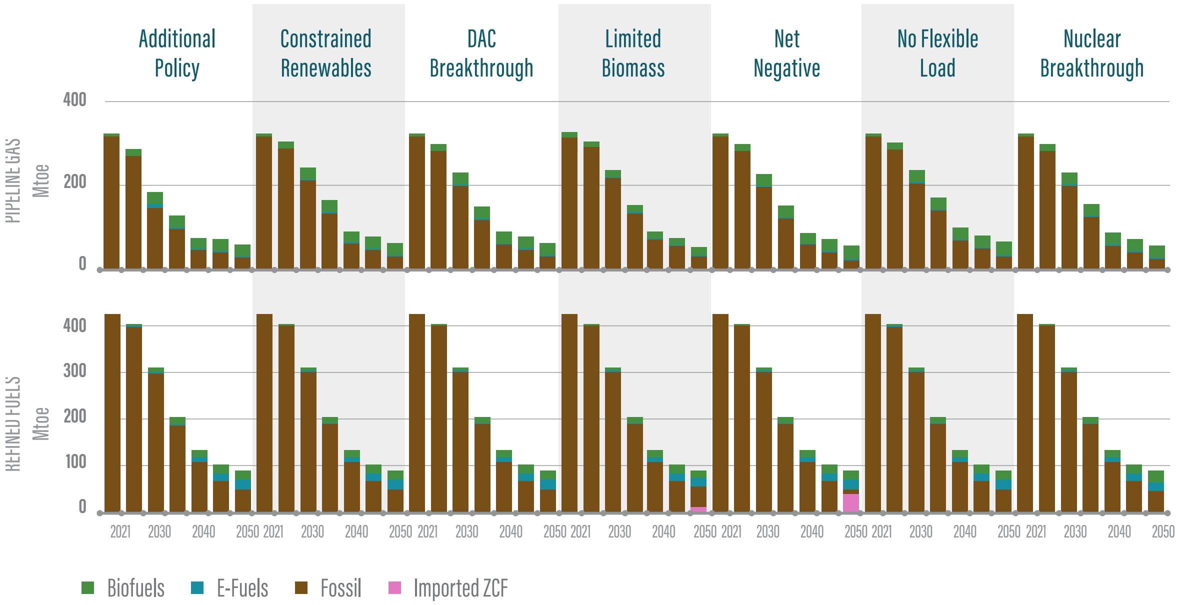


FIGURE 45. Fuel Supply; All Sensitivities



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