ENGIE'S DECARBONIZATION PATHWAY FOR EUROPE & FRANCE

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MESSAGE FROM THE CEO

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CEO – ENGIE

ENGIE is proud to share its first-ever European-scale energy transition pathway and contribute to the ongoing public debate concerning the best way to achieve Europe's decarbonization objectives.

Drawing from our extensive experience as a leading energy player committed to an ambitious decarbonization trajectory, our decarbonization pathway for Europe is built upon three crucial principles.

First, we prioritize cost optimization for the wider community. Given the massive investments required for the energy transition, we need to ensure the competitiveness of our economy and industry by making decarbonized energy affordable.

Second, we aim to ensure the robustness of the energy system in the face of potential new dependencies. The vulnerabilities exposed by events such as the Covid pandemic and the war in Ukraine have highlighted the fragility of the system. In this new energy order, it is imperative that the collective choices we make do not jeopardize its stability.

Third, we emphasize alignment with European climate ambitions. As energy strategies become more regionalized, we believe in the power of a united Europe – a Europe of energy – with a shared vision of our decarbonization trajectory, supported by an adapted regulatory framework.

Failure to consider these imperatives will hinder the progress of the energy transition. By evaluating every possible solution against these three principles, our pathway capitalizes on the most effective decarbonization levers and the alliance of renewable electrons and molecules.

To address the climate emergency, we must go beyond ideological posturing and adopt a pragmatic approach to make every effort count. Private companies, hand in hand with public authorities, must play a key role in accelerating the energy transition. In such uncertain times, ENGIE aims to be Net Zero by 2045 and a catalyst for the energy transition of the broader economy.

FIVE CORE BELIEFS

1 All levers must be activated to reach decarbonization objectives.

Achieving Europe's decarbonization ambition of a 55% emissions reduction by 2030 and Net Zero by 2050 (compared to 1990) implies a 4% annual reduction in emissions between 2020 and 2050. In contrast, the average emissions reduction observed between 1990 and 2020 was 1% annually. Quadrupling the rate of emissions reduction will require the utmost pragmatism and the activation of all possible decarbonization levers to their full potential.

2 Energy efficiency is compatible with economic growth and must be fully leveraged.

We foresee a 34% reduction in final energy demand in Europe-15[1] between 2023 and 2050, while the population remains stable (+2%) and GDP grows by1.3% per year. Decoupling energy consumption from economic output is possible and necessary to achieve Europe's decarbonization ambition.

3 Accelerating renewable power deployment across all geographies is a prerequisite for decarbonization success.

The reduction in the cost of solar and wind technologies observed over the past decades make these technologies among the cheapest sources of power generation. They are essential to Europe's efforts to cost-effectively decarbonize the energy system and contribute to reducing fossil-fuel imports. We foresee an 80% increase in power demand in Europe by 2050 accompanied by a sixfold increase in renewable energy production.

4 Flexible technologies must be deployed hand in hand with renewables.

The growth of intermittent renewables means a less predictable energy system requiring flexible power technologies (batteries, green thermal, electric vehicles, hybrid heat pumps, etc.) to complement them when the sun is not shining, or the wind is not blowing. We anticipate close to a fourfold increase in the installed capacity of these technologies. The bulk will target hourly flexibility, yet some capacity will be needed to address longer-term variability, including seasonal.

5 Green molecules are a necessary complement to green electrons.

Green molecules will play a fundamental role in achieving carbon neutrality, as they complement green electrons. They are storable, transferable, and can leverage an existing infrastructure network. By 2050, we anticipate Europe's gas demand to be transformed. Volumes will remain roughly stable and be completely decarbonized through green hydrogen and e-molecules – which will represent half of the total green gas demand – and low carbon methane, whether in the form of biomethane, e-methane, or carbon capture and storage (CCS).

[1] 13 European countries (Austria, Belgium, Czech Republic, France, Germany, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Slovakia, Spain), Switzerland and the United Kingdom

INTRODUCTION AND APPROACH

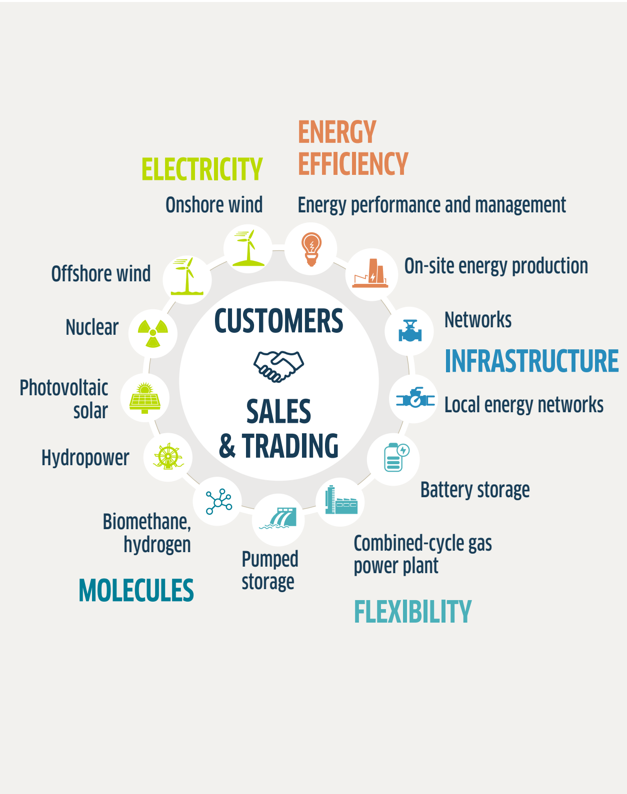
ENGIE's decarbonization pathway investigates the challenges to achieving a Net Zero Europe by 2050. After providing an overview of our approach (Section 3), we first describe the results in terms of emission reduction trajectory (Section 4), before presenting how different decarbonization levers are activated in different sectors of the economy (Section 5). We then zoom in on several key topics:

- the challenges associated with mass electrification (Section 6)
- the role of low-carbon molecules as a complement to green electrons (Section 7)
- the costs of decarbonization (Section 8)

SHARING ENGIE'S UNIQUE PERSPECTIVE ON THE ENERGY TRANSITION

ENGIE has unique experience across all energy transition levers, operating wind, solar, nuclear, and thermal power generation. It is the largest gas infrastructure operator, and it owns and operates power transport and distribution infrastructures as well. It offers energy efficiency services to industrial and government actors. It is one of the biggest utilities serving corporate and individual customers across both power and gas. ENGIE is also active in district heating and cooling, as well as mobility infrastructure, onsite decarbonization of large industrial customers, but also energy trading and risk management. ENGIE is active in more than 30 countries across five continents. This experience informs ENGIE's decarbonization pathway.

All levers of decarbonization...



... Across an international footprint

ENGIE's scope of activities and geographical footprint

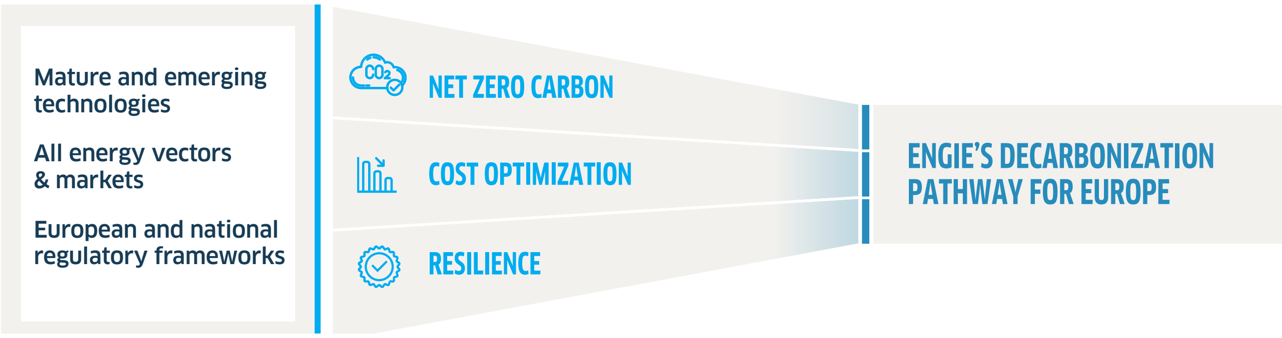
A PRAGMATIC APPROACH TO DECARBONIZATION

ENGIE has been developing energy market projections for more than two decades to inform investment and support business decisions. In addition to our expertise in energy technologies and markets, our pathway captures ENGIE's understanding of the political and societal landscapes. It integrates policy developments and targets at the European and national levels.

ENGIE's decarbonization pathway is designed to meet three essential attributes of the European energy system:

- **Decarbonization**
  it is aligned with Europe's climate ambitions, targeting carbon neutrality by 2050, and with national energy and climate plans for 2030.
- **Cost optimization**
  across decarbonization levers, energy vectors, and the European market
- **Resilience**
  of the energy system, ensuring there is always adequate supply to meet energy demand.

A pragmatic approach to decarbonization
Criteria



A ROBUST METHODOLOGY

Integrating decarbonization levers and energy vectors

The modeling approach integrates interactions across power, methane, hydrogen, e-molecules, and heat, optimizing decarbonization efforts across these energy carriers based on what is most cost-effective. In addition, the model simulates the system on an hourly basis until 2050, ensuring that at any point in time, the energy system is sufficiently resilient to meet all energy needs.

A European vision

The results shown in this report cover 13 European Union (EU) countries (Austria, Belgium, Czech Republic, France, Germany, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Slovakia, Spain), Switzerland, and the United Kingdom (referred to as Europe-15). These countries (excluding the UK and Switzerland) represent 85% of the EU's final energy consumption and 85% of its emissions. These countries also form an area with highly interconnected energy systems. The modeling approach underpinning the decarbonization pathway is therefore based on an interconnected Europe rather than on isolated countries, allowing for cost and resilience benefits.

A realistic approach to techno-economic choices

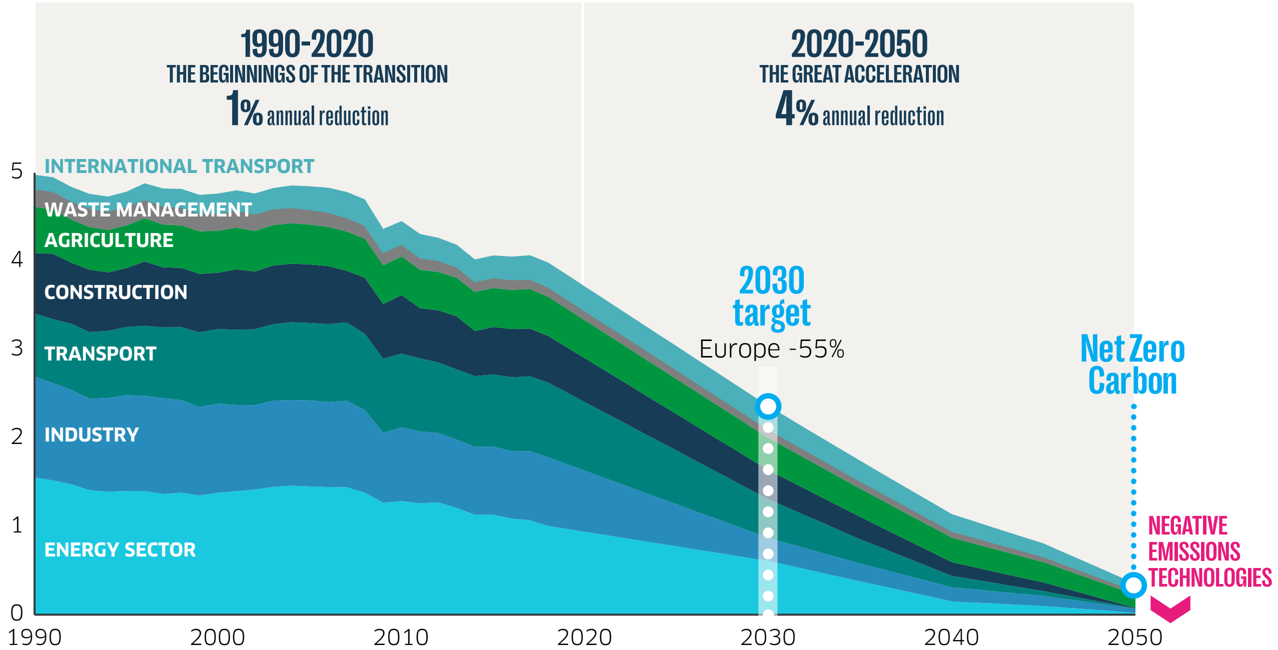
ENGIE's decarbonization pathway relies primarily on mature and proven technologies, but also specific emerging and scalable technologies. We integrate societal constraints. For example, the pathway limits the deployment of carbon capture and storage (CCS) based on known social acceptability challenges. In addition, we also leverage expert benchmarks and third-party studies extensively, particularly on topics that are not part of ENGIE's core expertise (e.g., agriculture, forestry, etc.).

NET ZERO CARBON PATHWAY

VISION FOR EUROPE

Our decarbonization pathway for Europe-15 is designed to achieve the objectives of 55% emissions reduction by 2030 compared to 1990 levels, and Net Zero by 2050 while minimizing total costs and ensuring system resilience.

Green gases emissions | Europe15
CO_2e, Gt/year



From 1990 to 2020, emissions in Europe-15 decreased at an average rate of 1% per year. The power sector contributed greatly to this effort, reducing its emissions by 34%. Europe must now drastically accelerate its efforts to become Net-Zero carbon by 2050: the average yearly emissions reduction across Europe-15 will have to quadruple to 4% per year.

From now until 2030, decarbonization efforts will be steered by the electrification of transport and industry, combined with the continued decarbonization of electricity production. Power sector emissions will decrease by more than 70% by 2030 compared with 1990 levels.

After 2030, the decarbonization of Europe will require greater engagement from all sectors. This stage of decarbonization will be driven by massive electrification, complemented by the emergence of a green molecules economy relying on biomethane, hydrogen, and e-molecules. These green molecules will be necessary mainly for the decarbonization of hard-to-abate sectors such as the cement, steel, and chemical industries, and the heavy transport sectors (trucks, maritime, aviation). Flexible generation will be key to providing power when renewables are not available and demand is high.

As of 2040, the power sector will have limited emissions (-93% emissions compared with 1990 levels) and progressively deliver negative emissions by coupling green methane with carbon capture and storage infrastructure. This will allow any remaining emissions, notably from the maritime and aviation sectors, to be offset. Carbon removals will play an important role in the second half of this phase. The circular use of exhausted CO_2 to produce low-carbon fuels will allow the decarbonization of the maritime and aviation sectors or the production of plastic.

FRANCE'S DIFFERENT ROUTES TO REACH FIT-FOR-55 TARGET

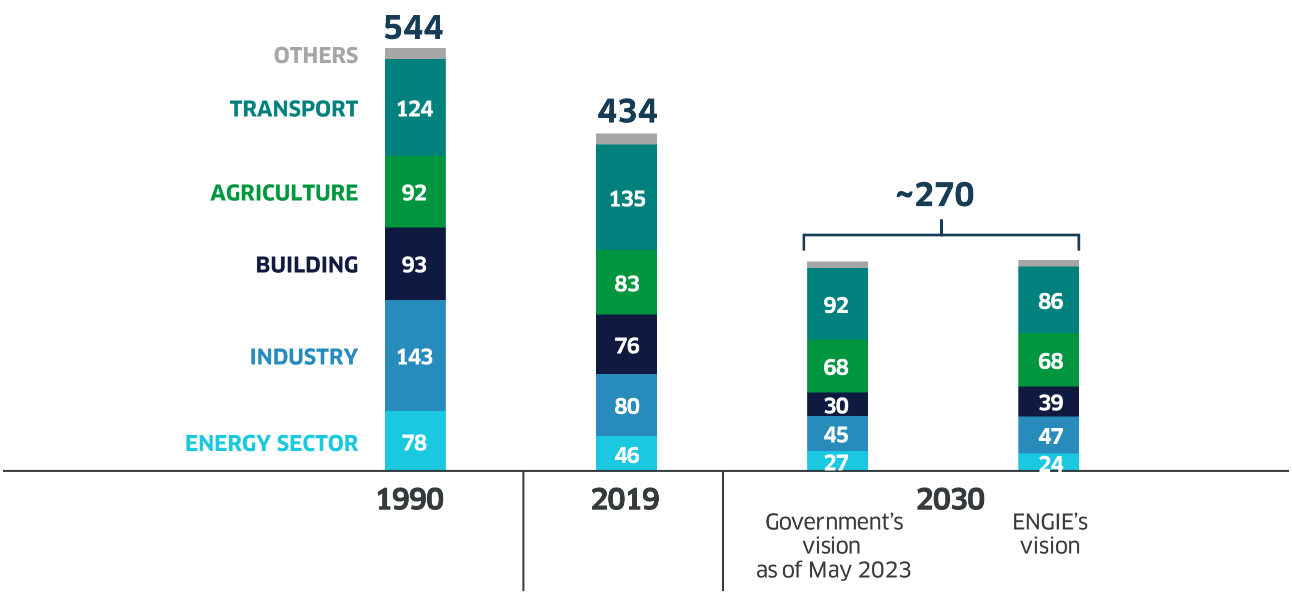
ENGIE's vision for France's decarbonization trajectory is consistent with the government's target. We achieve the same overall level of emissions reduction and leverage the same key sectoral contributors, with transport, buildings and industry covering +70% of the reduction efforts by 2030. The main difference comes from the fact that ENGIE's pathway is more ambitious for the transport sector, whereas the French government is more ambitious for the building sector.

The higher ambition in ENGIE's pathway for the transport sector relies on electric vehicles (EVs) gaining a 90% share of the market for new cars in 2030. ENGIE's view, although it assumes rapid acceleration of EV uptake, is in line with recent announcements by manufacturers about new private car sales in Europe.

ENGIE's pathway minimizes costs and therefore prioritizes sectors associated with lower decarbonization costs. According to our internal assessment, the global average cost of reducing emissions for road transport is approximately 50% less than that of buildings. Prioritizing the measures based on their costs enables the achievement of the decarbonization objective while limiting investments and smoothing the interventions over the entire horizon.

Jean Pisani-Ferry confirms this assessment in his recent report[2] which shows that the additional investment needed to reach 46Mt in emissions reduction for buildings in France is expected to reach €48bn per year in 2030, whereas a €3bn annual investment would be sufficient to reach almost the same reduction (43Mt) for road transport.

Green gases emissions | France
Mt CO_2e, 2030



[2] Pisani-Ferry, J. (2023). *Les incidences économiques de l'action pour le climat.*

DIVERSIFIED FUEL MIX

FINAL ENERGY MIX

Today, fossil fuels represent more than two-thirds of Europe-15's final energy mix. By 2050, they will represent less than 10% and be limited to feedstock uses in industry, international aviation and maritime transport[3], or coupled with carbon capture and storage when remaining in the industrial sectors.

Four complementary decarbonization levers will be activated to achieve a demand outlook compliant with a resilient Net Zero economy.

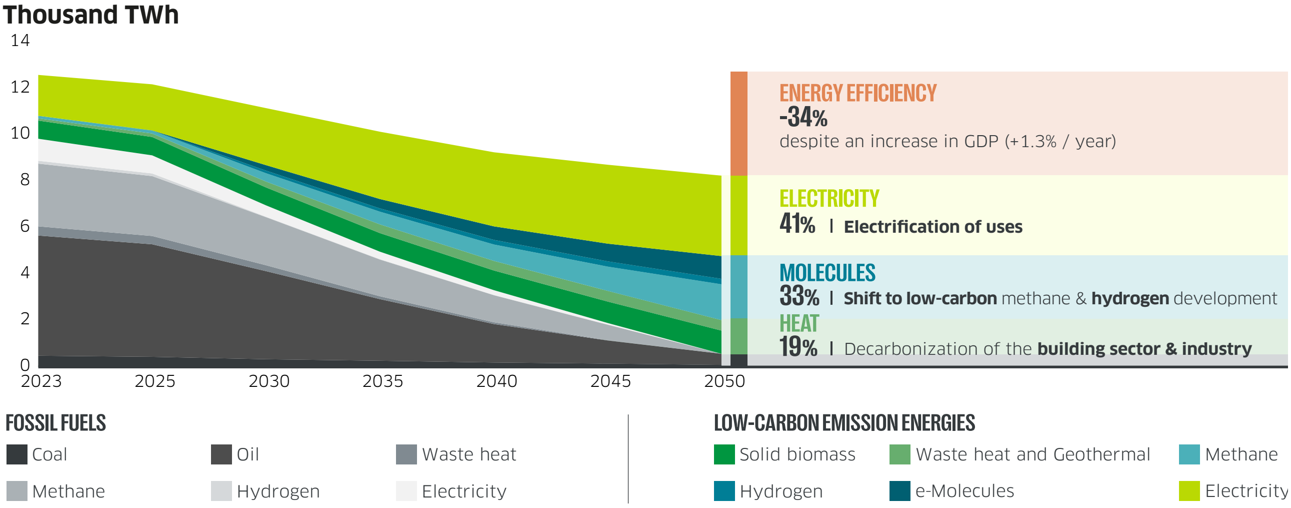
First, **energy efficiency** will contribute to decreasing final energy demand by 34% by 2050, despite moderate population growth (+2%), an increase in the number of households (+12%), and an expected GDP increase (+1.3%/y). This demand change will vary by sector, with road transport (-58%), building (-41%), and industry (-27%) seeing major reductions, while demand in aviation and maritime transportation continues to rise (+24%). The role of electrification in reducing energy demand is particularly noteworthy. For example, the energy efficiency of an electric vehicle is ~3x higher than that of an equivalent vehicle with an internal combustion engine. Similarly, secondary steel production using recycled scrap metal in an electric arc furnace (EAF) divides energy consumption by six compared to today's blast furnaces.

The second lever is the **continued growth of green electrons**, which will account for 41% of the final energy mix in 2050. Two complementary trends will contribute to this growth: the rise of power demand due to the electrification of usages, and the progressive decarbonization of the power mix. When excluding sectors that cannot rely on electrification, such as aviation, maritime, or feedstock consumption, the electrification rate in ENGIE's decarbonization pathway exceeds 50%.

Third, **decarbonized molecules** will represent more than one-third of the final energy mix. Methane demand will be halved and completely decarbonized via green and low-carbon methane by 2050. We foresee 450TWh of renewable and low-carbon methane by 2030, the bulk coming from local production. At the same time, hydrogen demand (including e-molecules) will increase eightfold by 2050, primarily to decarbonize hard-to-abate sectors.

Finally, **decarbonized heat**, including via networks capable of integrating fatal heat, geothermal energy, and biomass, will account for close to a fifth of Europe-15's energy demand mix and play an important role in decarbonizing the building and industrial sectors.

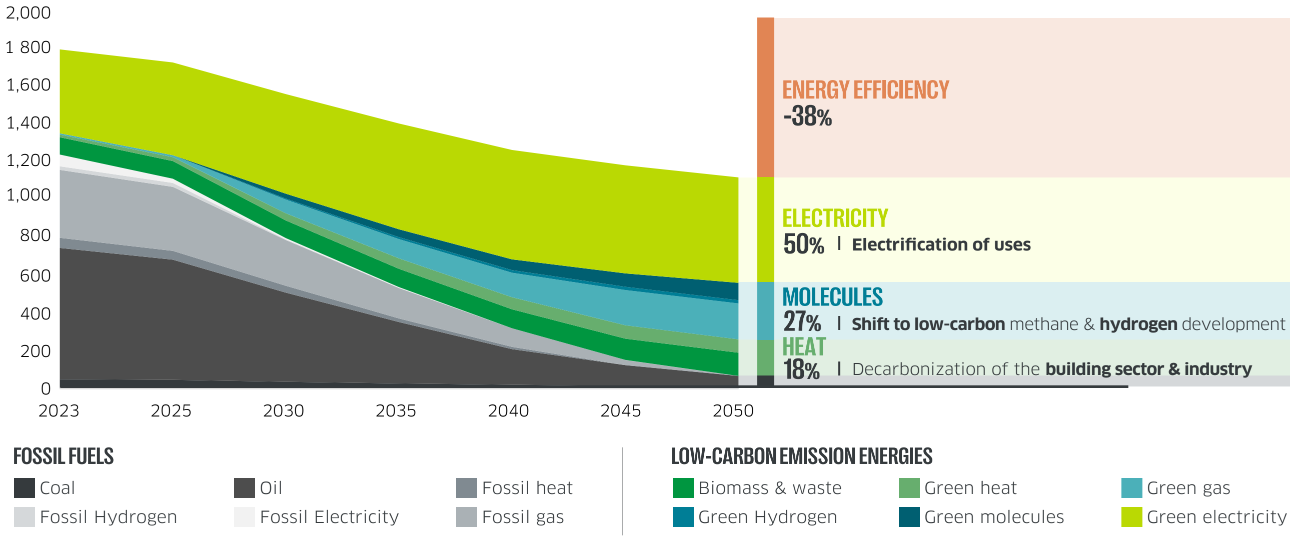
Final energy mix | Europe15



[3] International Aviation and Maritime are decarbonized up to 80% in our pathway. ENGIE supports the full decarbonization of these sectors by leveraging low carbon molecules, but additional political and business engagement and support is needed to achieve carbon neutrality in those specific sectors.

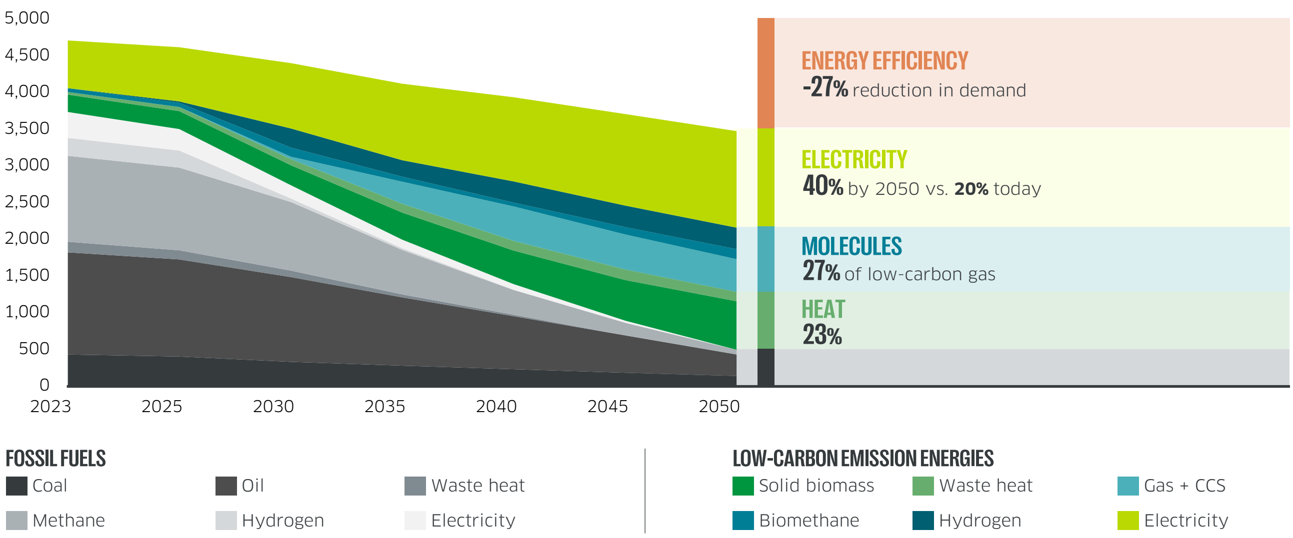
France presents a slightly different outlook due to the important role nuclear power plays in the country, compared to Europe-15. The role of electrons as a decarbonization lever is more pronounced compared to other European countries, covering 50% of the energy mix versus 41% for Europe-15 overall.

Final energy mix | France



INDUSTRY

Final energy mix for the industrial sector | Europe15



Industry: all energy transition levers should be activated

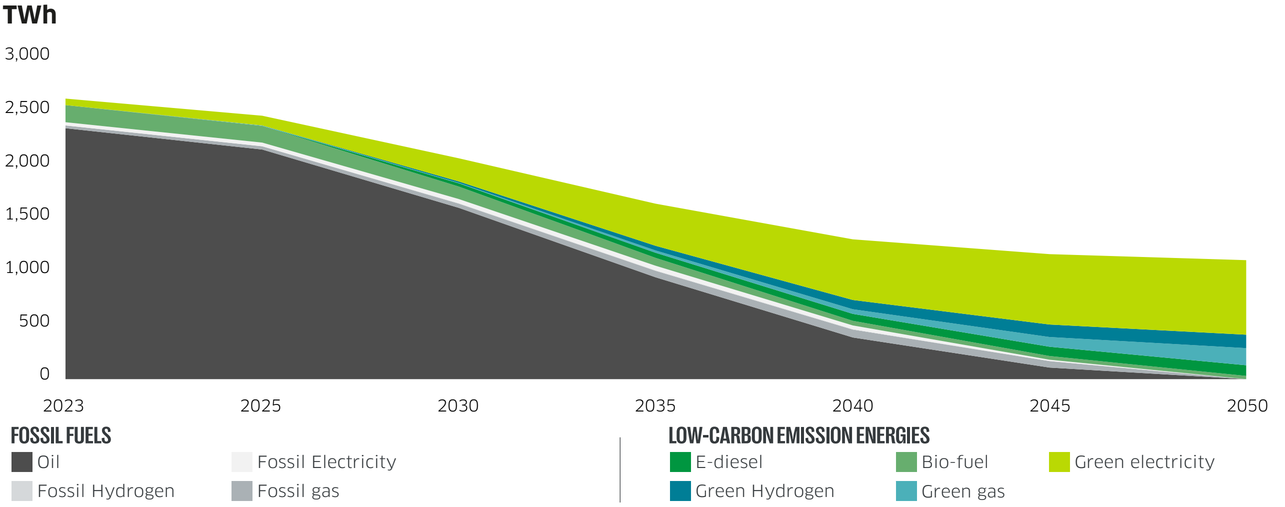
The decarbonization pathway for industry leverages the same four levers: energy efficiency, decarbonized electrons, molecules and heat. Energy demand in the industrial sectors will decrease significantly by 2050 (-27%), primarily driven by the electrification of processes. The share of green power in the industrial fuel mix will increase from 20% today to 40% in 2050. Low-carbon molecules and heat solutions represent 50% of the final energy mix for industrial sectors. They are notably essential for industries that require temperatures between 800-1500°C, such as steel, cement, glass and ceramics, where electrification is not the best solution to achieve carbon neutrality, whether due to technological maturity, physical constraints, or cost competitiveness concerns.

TRANSPORT

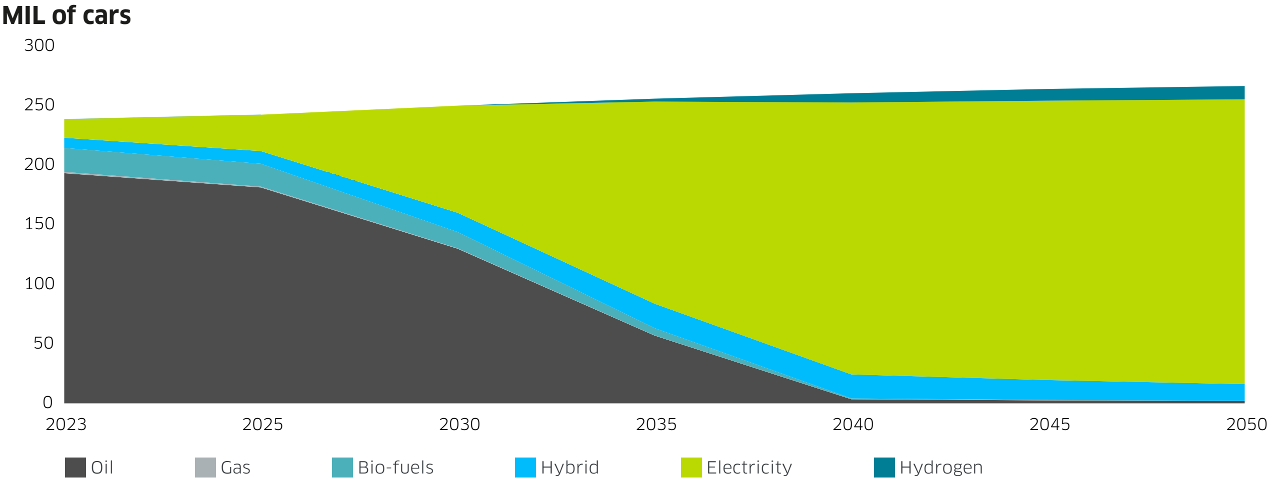
Road Transport (cars and trucks)

Final energy demand in road transport will decline by 58% by 2050, primarily driven by the higher efficiency of EVs compared to existing internal combustion engines. ENGIE anticipates complete electrification of the car segment, which is one of the major levers to reach Europe's 55% emissions reduction target in 2030. This is consistent with the announcements of several European countries targeting 100% EV sales between 2030-2035. The result is a significant increase in the share of EVs in the total fleet, reaching respectively 37% in 2030, 88% in 2040 and 90% in 2050.

Final energy mix for Road Transport (car, light duty, trucks) | Europe15



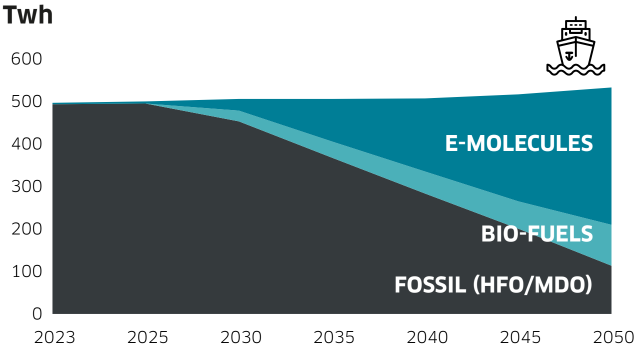
Vehicle stock | Europe15

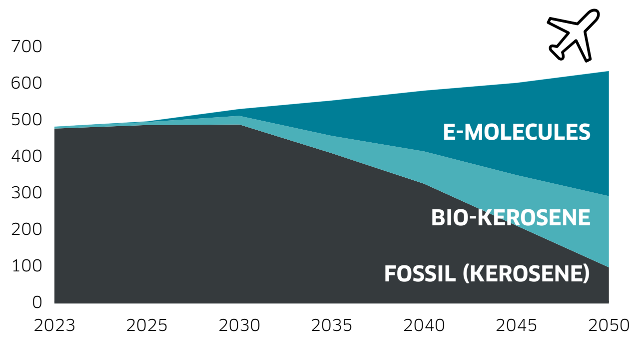


Bio-fuels currently represent the majority of low-carbon solutions in the trucks sector. However, based on a proposal from the European Commission (EC), a 90% emissions reduction target on new, heavy-duty road transport for 2040 could be introduced, spurring the deployment of alternative solutions. This is already impacting the plans of truck manufacturers, with some announcing their ability to produce enough electric, heavy-duty trucks to reach 50% of their sales by 2035. Based on these forecasts, our scenario expects the market to be divided among electric (60%), hydrogen-powered (15%), and methane-powered (20%) trucks by 2050. This will represent 17M electric and 4.1M hydrogen-powered trucks in 2050. The remaining fleet will transition to synthetic fuels such as e-diesel. The growing competitiveness of electric and other solutions in road transport will free up biomass resources for other end uses.

Aviation and Maritime

Final energy mix | Europe15



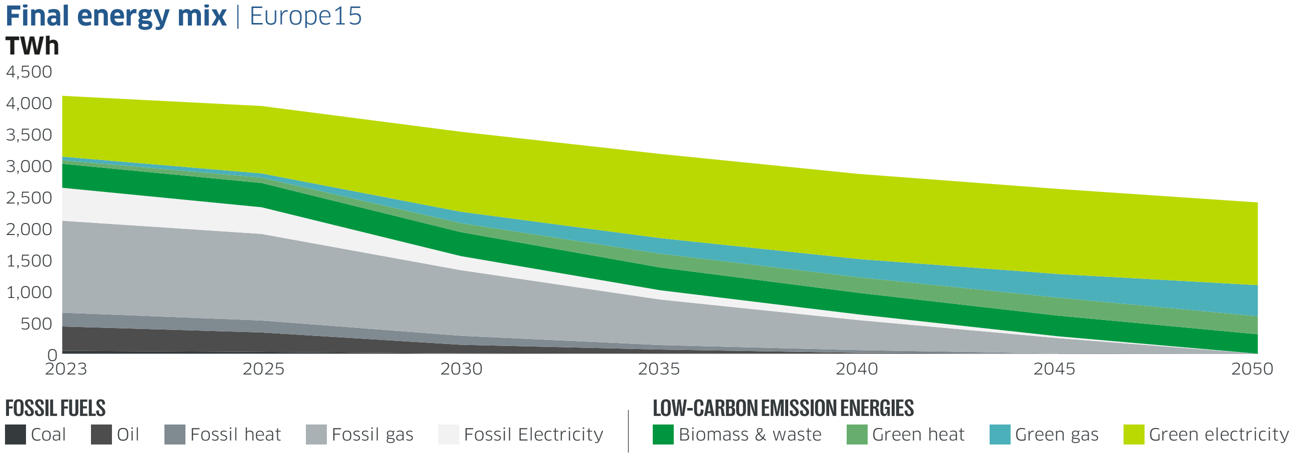


HFO: Heavy Fuel Oil
MDO: Maritime Diesel Oil

Conversely to the road segment, electrification is unrealistic in both the aviation and maritime sectors due to the energy density required for the distances travelled and weights transported. ENGIE's pathway embraces the decision recently taken in Brussels to set a target of reducing greenhouse gas intensity by 80% by 2050. For both maritime and aviation, decarbonization occurs by substituting bio-fuels (bioliquids or biomethane) and synthetic fuels (methanol, ammonia, methane, kerosene) for fossil fuels. The first category corresponds to renewable fuels based on organic biomass materials, while the latter uses processes like electrolysis to produce hydrogen, which is then combined with CO_2 to create liquid fuels with similar properties to fossil fuels.

BUILDINGS

Final energy mix | Europe15



ENGIE's pathway expects a 41% energy demand reduction in buildings by 2050. This reduction can be distributed among renovations of existing buildings (43% of savings), construction of more efficient new buildings (10% of savings), and adoption of alternative heating solutions (47% of savings), such as heat pumps or high-performance gas boilers burning renewable gas.

The scale of renovation efforts in buildings is critical to achieving decarbonization objectives. Unfortunately, EU countries are not on track to reach renovation ambitions that have targeted 3% of the building stock to undergo deep renovations each year as of 2030. For example, the French government aims to reach 700-800k deep renovations per year as of 2030[4] but has only hit 10% of this target to date. In light of the current state of the renovation market, ENGIE's pathway adopts a more conservative outlook, estimating that 1.5% of the building stock will undergo deep renovations[5] by 2050 (from 0.3% today in France and 0.2-0.3% at the EU28 level).

[4] RTE – *Futures Énergétiques* 2050

[5] Renovations leading to at least a 67% energy demand decrease

Electricity will represent 55% of the final energy mix of the buildings sector in 2050. Approximately half of European households will be heated by heat pumps in 2050, contributing to reduced energy demand, given their high-performance standards. Nevertheless, the adoption of heat pumps can represent a threat to energy systems during peak events or cold spells, when their performance is significantly reduced.

To avoid these negative consequences, ENGIE's pathway couples some of these solutions with green-gas backup boilers. These hybrid solutions rely on electricity and switch to their gas functioning mode in the event of high electricity prices or stress on the system. This allows achieving a carbon neutral heating system without compromising system resiliency (see the box below on the role of hybrid heat pumps)

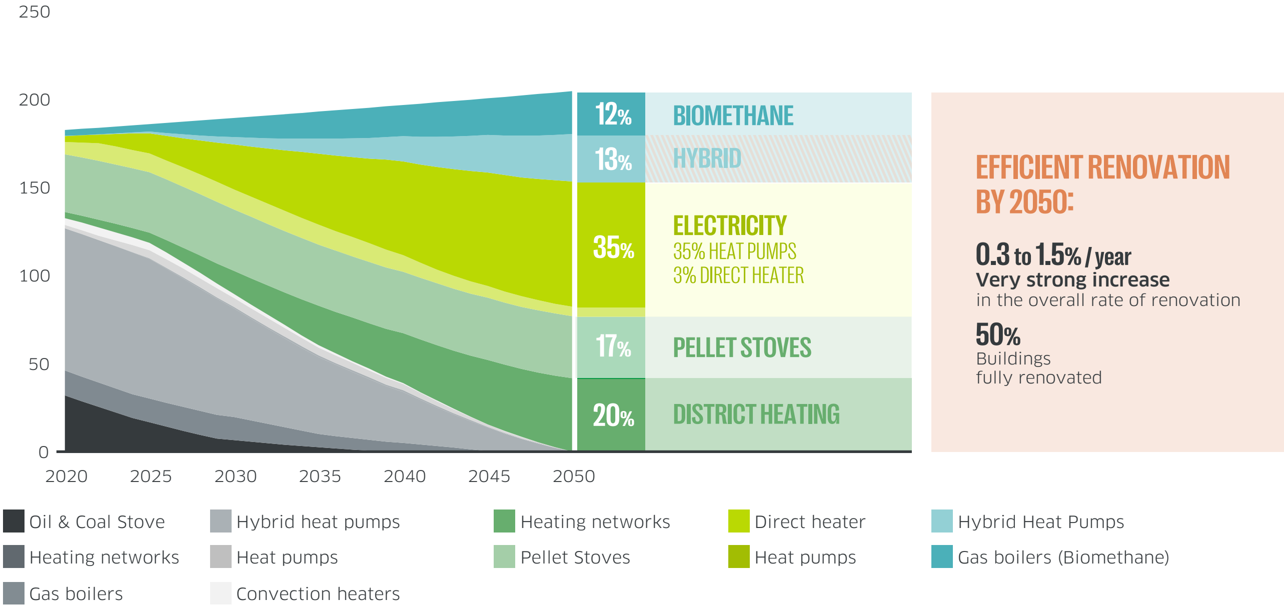
Green molecules will complement electrification and contribute to the decarbonization of buildings. Methane will be fully decarbonized by 2050, though its share in the final fuel mix of buildings will be significantly reduced, representing only 20% of the final energy mix by 2050 compared to more than 37% today.

We estimate that the number of homes connected to district heating networks could increase fourfold by 2050 across Europe-15 and represent more than 12% of the final energy mix for buildings. Population density, availability of excess heat, and geothermal potential are key criteria for the development of new district heating networks.

Decarbonizing buildings in Europe

Given the high penetration of electricity use in French households, ENGIE expects green electricity to play a more prominent role in France than in the rest of Europe. Nevertheless, approximately 50% of European households will be equipped with an electrical solution (35% heat pumps, 3% direct heaters, 13% hybrid heat pumps). The 13% of households with hybrid systems that couple heat pumps with gas boilers running on methane will play a critical role in alleviating energy system impacts in case of extreme events (see the box below for details).

European households | Heating solutions
Millions



Green molecules remain important, with 12% of the heating demand supplied by switching from natural gas to green gas in dwellings where heat pumps are not efficient. 20% of households rely on district heating, which enables further local renewables penetration (geothermal, biomethane, fatal industrial heat). Finally, 17% of the heating needs will be supplied via pellet stoves.

STRESS TEST

THE ROLE OF HYBRID HEAT PUMPS (HHPS) ON ENERGY SYSTEM RESILIENCE

CONTEXT

As shown in the previous section, electrification will be the cornerstone of the building sector decarbonization. This exposes the energy system to resilience risks and higher investments should extreme events occur where no flexible solutions are available. For this reason, ENGIE's pathway assumes that four million heat pumps coupled with backup gas boilers fired with green methane will be deployed by 2050 across households and tertiary sectors. These hybrid solutions enable better sizing of heat pumps and reduce investment costs. More importantly, by switching to their gas functioning mode in the event of higher electricity prices or cold spells, hybrid heat pumps limit the investments needed for flexibility solutions and grid reinforcements and allow households to react to price spikes in times of volatile prices.

STRESS TEST HYPOTHESIS

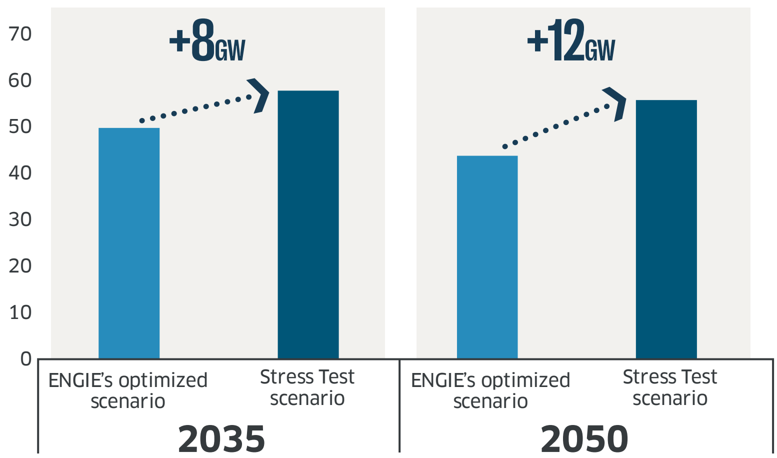
Hybrid heat pumps are not deployed and replaced by conventional heat pumps (80%) and direct heaters (20%).

RESULTS

The chart below shows the impact on the French power system if hybrid solutions are not developed. We estimate that failing to install 4M hybrid heat pumps in France will increase peak demand by up to 8GW in 2035 and 12GW in 2050 (+27% of space-heating power peak). In Europe, failing to develop hybrid solutions will increase peak demand by up to 39GW in 2035 and 53GW in 2050.

The increase in peak demand in France requires additional investments (grid, peaking units) leading to higher system costs of €2.7bn/y.

Contribution of heating to the electric peak | France
GW

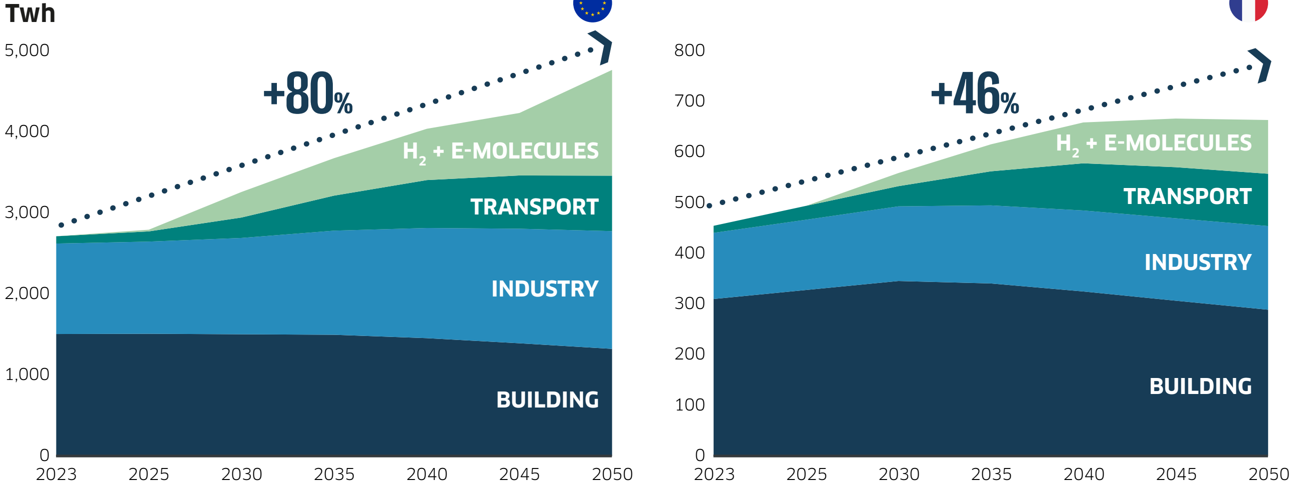


CHALLENGES OF MASSIVE ELECTRIFICATION

POWER DEMAND

In Europe-15, power demand will increase by 80% by 2050, driven by the adoption of electrified solutions in all sectors. Electrification will enable the decarbonization of the heating and road sectors, while becoming the basis for producing green hydrogen and associated e-molecules used to decarbonize hard-to-abate sectors like aviation and maritime. This increase in power demand will be even higher if energy efficiency measures are not implemented in the industry or buildings sectors.

Power demand | Europe15 & France



France is a special case in Europe: electricity has historically played a predominant role in the energy mix, which is reflected in a lower relative increase in power demand (+46%) by 2050. Building demand for power is expected to rise further in France in the first decade until 2030, due to the increased use of electrical solutions. However, it will eventually fall by the end of the horizon, owing to efficiency gains achieved both by replacing convectors with heat pumps and by speeding up renovations.

GENERATION MIX

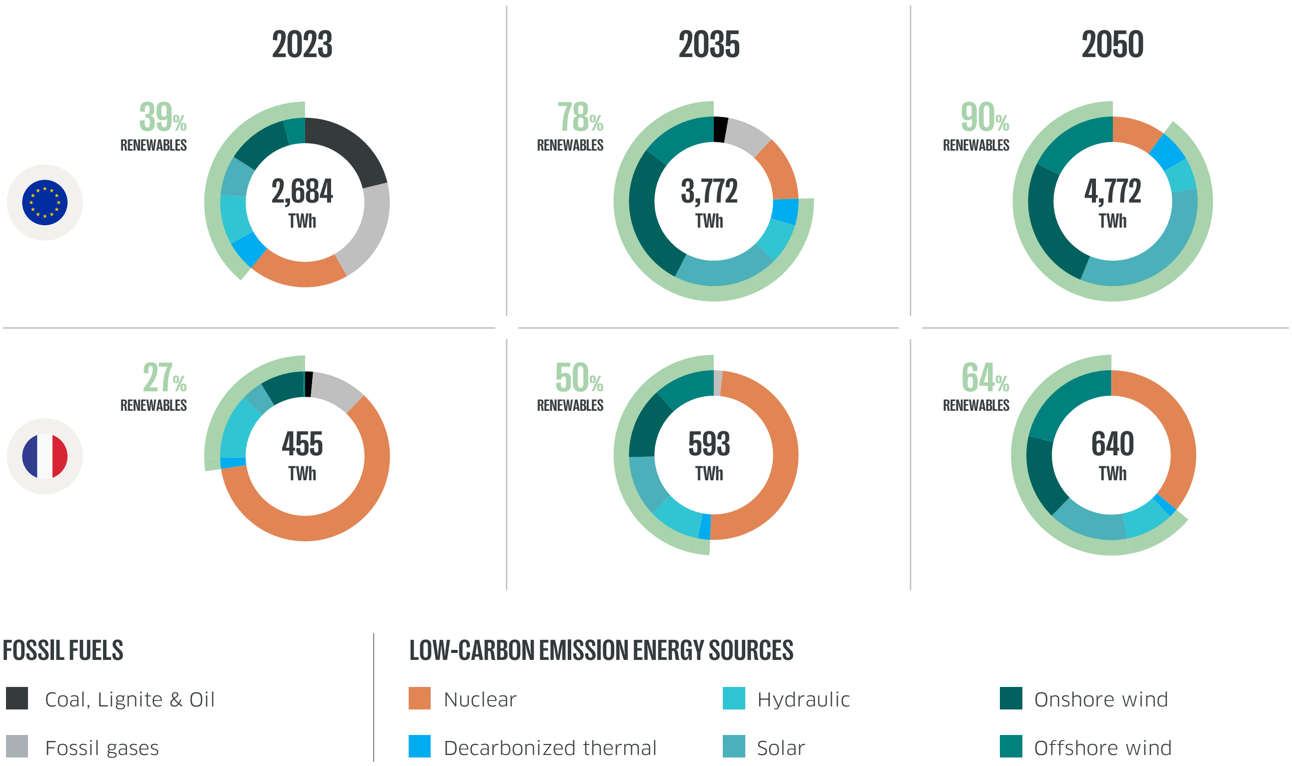
The European power generation mix will drastically evolve to meet this growing demand and achieve carbon neutrality. At the Europe-15 level, wind and solar production will more than triple by 2035 and will increase sixfold by 2050. Their additional 3,000TWh between 2023 and 2050 will cover the increase in electricity consumption (+2,100TWh in 2050), while offsetting the decline of fossil fuel-based generation (-1,100TWh).

PV capacity will increase eightfold by 2050, accounting for 33% of electricity production in Europe. Onshore wind will be pivotal in achieving 2030 emissions reduction targets as it is already mature, competitive, and can be deployed across Europe. Offshore wind will experience strong momentum as its flatter and more stable generation profile will help limit total system costs. By 2035, onshore capacity will more than double to reach ~375GW, while more than 100GW of offshore capacity will be developed.

The importance of nuclear power in the production mix will decrease. Its relative share in the Europe-15 production mix will decline from 20% today to 10% in 2050. In France, nuclear power has historically played an important role in the fuel mix, representing as much as 75% of the production mix. However, this share has fallen to around 60% in 2022, mainly due to reactor corrosion requiring unforeseen maintenance of several plants. We assume in the pathway that the availability of the existing fleet in France will recover to historical standards for its remaining life.

ENGIE's decarbonization pathway also assumes the new ambition in nuclear development in France is met (14 new reactors[6]). However, this new nuclear capacity will not entirely replace the existing nuclear fleet, which is expected to be decommissioned before 2050 according to the lifetime of the assets. The share of nuclear in France will further decline to 36% of the power supply by 2050. Accordingly, wind and solar generation will represent a smaller share in France compared to the Europe-15 configuration, accounting for 37% of the production mix by 2035, and 53% by 2050. Still, wind and solar capacity in France will increase threefold by 2035. By 2050, the pathway anticipates that more than 40GW of offshore capacity (bottom-fixed and floating technologies) will be installed in France.

Power outlook: supply & demand | Europe15 & France
Twh



Power production from gas will decline considerably across Europe over the next decade. Its role will change from being a mid-merit supplier (2500-3500 running hours per year) to a peak provider (250-600 hours), which ensures power system adequacy by firing low-carbon gases (biomethane, hydrogen, natural gas with carbon capture and storage).

The impact of natural gas prices on electricity prices will therefore be reduced, and investment in new decarbonized thermal assets will emerge by 2035. Additionally, industrial combined heat and power plants (CHPs), progressively fueled by low-carbon molecules (gas and hydrogen), will continue to play a role in the electricity mix.

By the next decade, coal and lignite will essentially be phased out. Their contribution to the energy mix will be reduced by 75% in 2030, and will become marginal in the second phase of the trajectory, playing primarily a backup role in case of supply security concerns.

[6] According to RTE N2 Scenario, adding more than 20GW of new nuclear capacity online.

STRESS TEST

FAILURE TO REMOVE BARRIERS AROUND RENEWABLE POTENTIALS

CONTEXT

The growth of renewables in ENGIE's pathway is very ambitious and exceeds all historically observed annual deployments, as well as the Fit-for-55 targets. However, it falls short of the RePowerEU targets for 2030 due to persisting delays in grid development, long queues for connecting new projects, and lengthy permitting processes. Accelerating renewables development and removing underlying bottlenecks is critical to meet European climate goals and keep costs down.

STRESS TEST HYPOTHESIS

We estimate the impact of missing by five years the renewable energy target set by European national governments in their current energy and climate plans[7], and falling behind by five years in the evolution of the electricity grid as anticipated by Entso-E[8].

RESULTS

If no additional action is taken to compensate for wind and solar delays, the power system will rely heavily on gas- and coal-fired power generation to compensate for the shortfall. Relying on these energy sources for the resulting additional generation would increase cumulative power sector emissions by 3Gt of CO_2. In other words, the estimated carbon budget for the power sector will increase by 50% if renewables are not supported accordingly.

As renewables are now among the cheapest source of electricity production, failure to remove barriers to their deployment will also increase by €4bn/y until 2050 the costs of the power system.

[7] NECPs final version of 2019, not considering updated draft of 2023

[8] System Needs 2022

STRESS TEST

FAILURE TO ANTICIPATE DELAYS IN THE CONSTRUCTION OF NEW NUCLEAR REACTORS AND THE LOW AVAILABILITY OF EXISTING ASSETS

CONTEXT

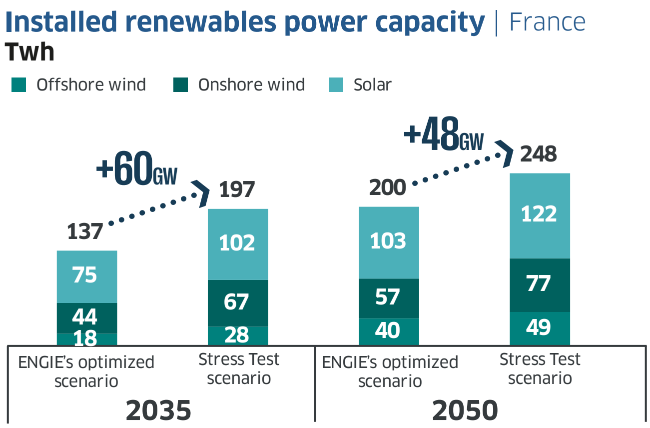
In 2022, a significant share of the French nuclear fleet was shut down for maintenance and repair work, following the discovery of stress corrosion cracking in several reactors. This localized event impacted the entire European generation mix, triggering an increase in the contribution of coal and gas-fired assets and thus raising the carbon intensity of electricity production. At the same time, the development of new nuclear projects in Europe has been delayed, falling behind the planned deadlines.

STRESS TEST HYPOTHESIS

We assess the impact of lower availability of the existing nuclear fleet, similar to those observed during the 2021-22 events. We also evaluate the impact of a delay in the delivery of new nuclear assets in France, and assume that only 10 EPRs will be available by 2050 (compared with 14 EPRs in the pathway).

RESULTS

Lower nuclear production due to lower availability and delays leads to a need for greater deployment of renewables to produce the same amount of electricity without worsening the carbon budget and hedge against outage risks (importing power from neighboring countries will not always be possible during peak events).



DETAILED RESULTS

The power system requires 33GW of additional wind and 27GW of additional solar capacities by 2035, meaning that the pace of renewables deployment should increase by 5GW each year until 2035.

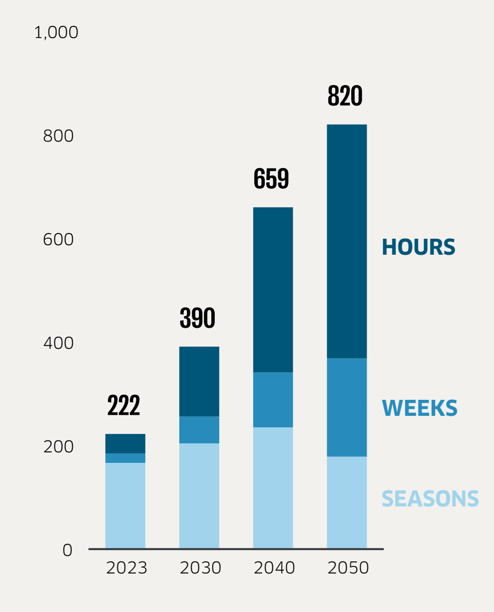
The additional renewables capacity acts as an insurance policy for the energy system, costing +€2bn/y. It also creates additional benefits if delays in new nuclear plants do not materialize, or reduced availability is observed. The additional green electrons will increase emissions reductions by 320MtCO_2e by 2050, further reducing emissions in the power sector. These additional renewable investments will therefore ease the burden of reducing emissions in hard-to-abate sectors. The additional green electrons will also be valorized by the energy system. They will be exported to neighboring countries, supporting their decarbonization, and the production of e-molecules will increase, reducing the imports balance.

FLEXIBLE SOLUTIONS

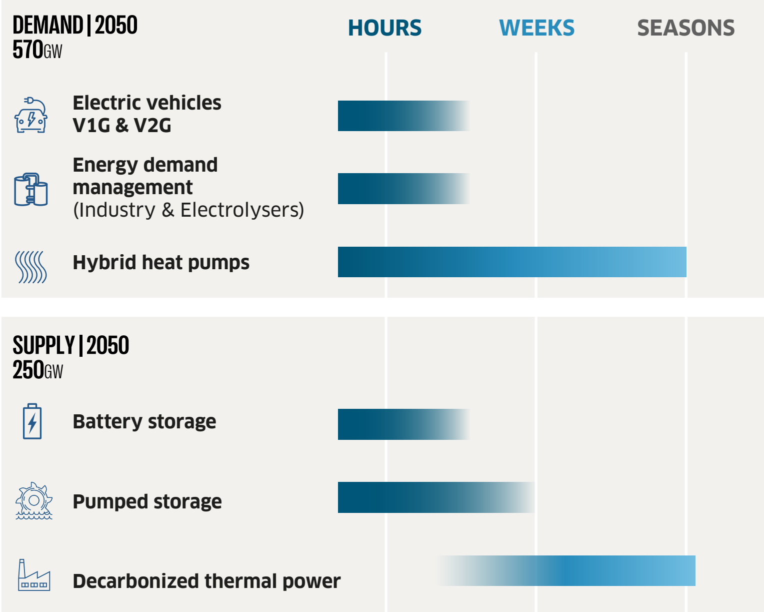
A diversified portfolio of flexible solutions will be fundamental to easing the integration of an increasingly large share of renewable power within the mix while ensuring that demand is always met. We estimate that flexible capacity will have to increase by nearly 600GW by 2050 to complement the foreseen growth in renewables at the European level.

Various flexibility solutions are needed to accommodate variations in supply and demand over different time horizons, from hourly to seasonal variations. Some flexibility options are driven by market evolutions and cost reductions, while others will require policy intervention to foster adoption and correctly plan the corresponding infrastructure.

Flexible capacity outlook | Europe15
GW



Flexibility technologies
Various technologies for meeting specific needs



Supply-side flexibility solutions

Supply-side solutions will represent 250GW of flexible capacity by 2050 and their growth will be largely driven by batteries and decarbonized thermal assets. Batteries will play a significant role in the energy transition as a solution to hourly and daily flexibility needs, notably triggered by PV deployment. Furthermore, batteries are well suited to providing additional services to the grid, such as frequency stability. The pathway assumes +80GW of utility-scale batteries is developed in Europe-15 by 2050, especially in southern countries and Germany, where a high penetration of solar PV is anticipated.

Pump storage already provides a similar service but the potential to expand or build new pump storage units is very limited.

Dispatchable and decarbonized thermal power plants are necessary to achieve carbon neutrality while ensuring security of supply. Indeed, thermal units can provide all kinds of flexibility, from real-time and intra-day balancing, daily/weekly load firming, to inter-seasonal or even interannual modulation.

Storing large amounts of energy in methane or hydrogen form is significantly cheaper than storing electricity in batteries. These low-carbon energy sources can then be fired in decarbonized thermal plants to cope with extended periods of low renewable production or high load (peak) periods in winter months.

We anticipate a need for approximately 105 additional GW of decarbonized thermal solutions, with an evolving role throughout the transition. In 2030, biomethane and hydrogen-fueled plants, as well as natural gas power plants cofired with hydrogen, will be needed to meet Fit-for-55 ambitions. In our pathway, they jointly provide 50TWh of decarbonized power in 2030. In 2050, decarbonized thermal plants will mainly be used as peaking units, running less than 600 hours a year. These assets will act as a back-up in an energy mix largely dominated by variable renewable assets. They will provide seasonal flexibility, helping to cover winter consumption peaks and periods of low availability of renewables.

Power plants coupled with carbon capture and storage play a transitional role. By 2035, half of the production of flexible thermal assets could be coupled with CCS. When biogenic molecules emerge, using CCS in biomethane or e-methane-fueled power generation will lead to negative emissions. We estimate that by 2050, one third of gas consumption will be met by bioenergy with carbon capture, allowing compensation for the remaining emissions associated with the aviation and maritime sectors.

Demand-side flexibility solutions

The supply-side flexible solutions described above will represent less than a third of the total estimated flexible capacity installed in 2050. The rest will come from demand-side solutions. Many energy-consuming usages will become more flexible, due to behavioral changes, regulatory changes, and the adoption of digital technologies. Demand-side flexibility will also unlock significant economic benefits, facilitating the consumption of electricity when it is abundant (and cheap), hence avoiding the development of additional storage units or more expensive dispatchable and decarbonized power plants.

In reaction to energy prices or capacity system needs, industries have been participating in demand-side management programs as flexibility providers for many years. Given the increasing penetration of electricity in the industry, we estimate this role can be accentuated. Its capacity is expected to double to more than 30GW by 2050.

The development of dynamic signals already present in the industrial sector must be extended to residential customers to enable the growth of other sources of flexibility by leveraging the real time capabilities of smart meters. For example, smart heating solutions in the building sector, such as hybrid heat pumps, allow a system to switch between power and methane in case of high electricity prices or extremely cold spells. By 2050, they will deliver 70GW of flexible capacity in Europe (12GW in France), reducing the investment need in peaking units. Their methane-fired back-up boiler can support a system under stress for longer periods than batteries or industrial demand-side response. Hybrid heat pumps are a profitable investment for policymakers (e.g., via an installation premium), since the whole energy system benefits from the attenuation of power demand peaks that they enable and the investments in further peak capacity that they help to avoid.

Similarly, EV batteries can support power system flexibility in two ways. First, they enable its charge pattern to be adapted to react to price fluctuations (reflecting the system's constraints) by load shedding and shifting (also called V1G). Charging events are distributed across the day at different times, or the power required from the grid is reduced to smooth peak events.

Second, EVs can also inject power from their batteries back into the grid (also called V2G). We estimate that V1G can deliver +145GW of effective flexibility to the power grid, while V2G can complement it with +30GW.

Finally, the development of green hydrogen will also provide flexibility to the system in complementary ways. Electrolyzers, connected to large hydrogen storage units via a European backbone, allow hydrogen production to be shifted at times when power is abundant and cheap. Decarbonizing efficiently the economy via green hydrogen will lead to the deployment of +270GWe of electrolyzers by 2050, most of them being connected to a new European infrastructure where more than 20TWh of hydrogen storage is developed.

STRESS TEST

LIMITING THE DEPLOYMENT OF DECARBONIZED THERMAL POWER PLANTS

CONTEXT

The massive deployment of renewables will only be manageable if it is supported by the deployment of flexible assets, capable of shifting the overproduction of green electricity and providing both short-term and seasonal flexibility.

Renouncing the development of decarbonized thermal power to address the need for long-term flexibility (either via a ban on thermal generation or through a lack of support mechanisms) would require using assets not suited for such long term flexibility and result in needing to 'oversize' the energy systems.

STRESS TEST HYPOTHESIS

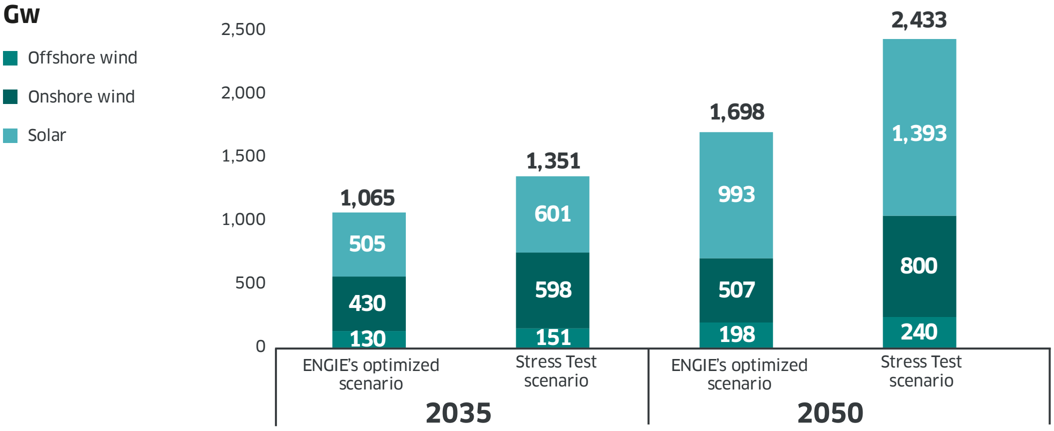
We test the impact of not developing the 105GW of green thermal solutions by 2050 identified in the pathway.

RESULTS

As batteries cannot serve the same long-term flexibility as decarbonized thermal power, the system needs to be oversupplied by renewables to substitute the missing decarbonized thermal flexible assets and to mitigate system reliability risks. We estimate that not developing the identified 105GW of green thermal capacity will necessitate 200GW of additional battery capacity coupled with an additional 400GW of Solar PV and 335GW of Wind power by 2050 (+43% compared to the pathway case).

The resulting development in batteries is expected to increase threefold compared to estimates in the pathway with decarbonized thermal power: batteries deployment will reach +270GW by 2050. Despite the massive development of storage capacities, renewables curtailment will increase to 175TWh in 2050. In other words, the equivalent of the production of 85GW of wind technologies would be lost, which also corresponds to wasting twice Belgium's annual electricity consumption.

Renewables capacity | Europe15



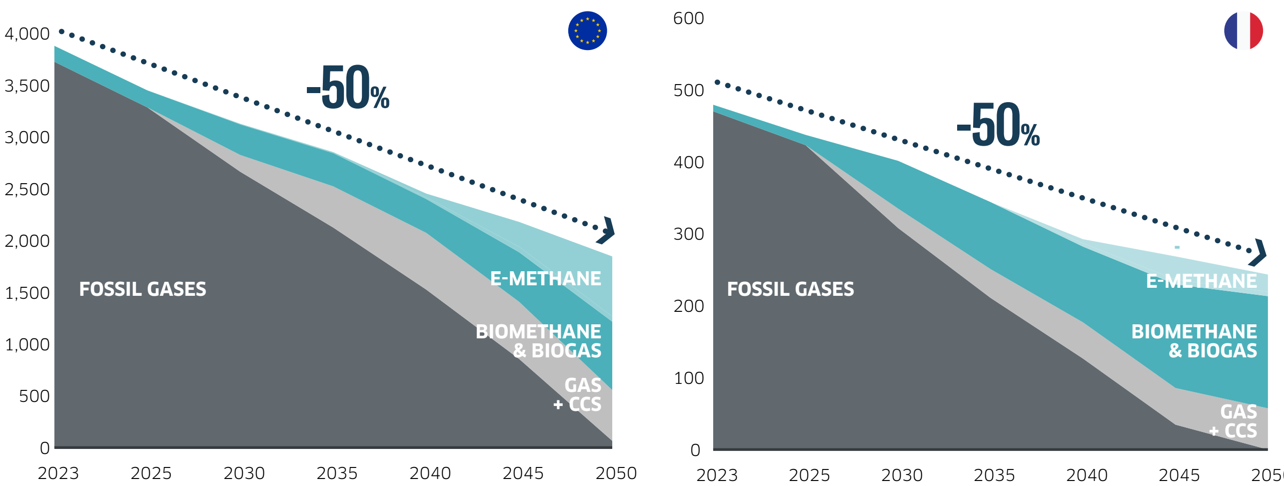
KEY ROLE OF DECARBONIZED GASES

Energy efficiency and electrification must be complemented by low-carbon gases, which will play an important role in both the medium and long term. By developing low-carbon methane, hydrogen, and associated e-molecules, and by leveraging existing infrastructure and end-use equipment, the gas sector will contribute to the reduction of the costs of the energy transition and ensure the resilience of the whole energy system.

DECARBONIZING METHANE

Methane demand is expected to be halved across European and French markets by 2050. As of 2030, biomethane will represent close to 10% of all methane consumption in Europe15, while natural gas with CCS is 5% of the consumption. In contrast, biomethane will represent close to 15% of methane demand in France in 2030, which is equivalent to Russian gas imports before the conflict in Ukraine, and natural gas with CCS will represent ~6% of methane demand by 2030. By 2050, methane supply will be completely decarbonized and split between biomethane, natural gas with CCS and e-methane (a green H_2-derived methane molecule). The split is roughly even among these three low-carbon methane solutions in Europe-15. In contrast, in France, biomethane dominates the decarbonized methane mix given the country's relatively rich biomass potential.

Methane demand | Europe15 & France
Twh

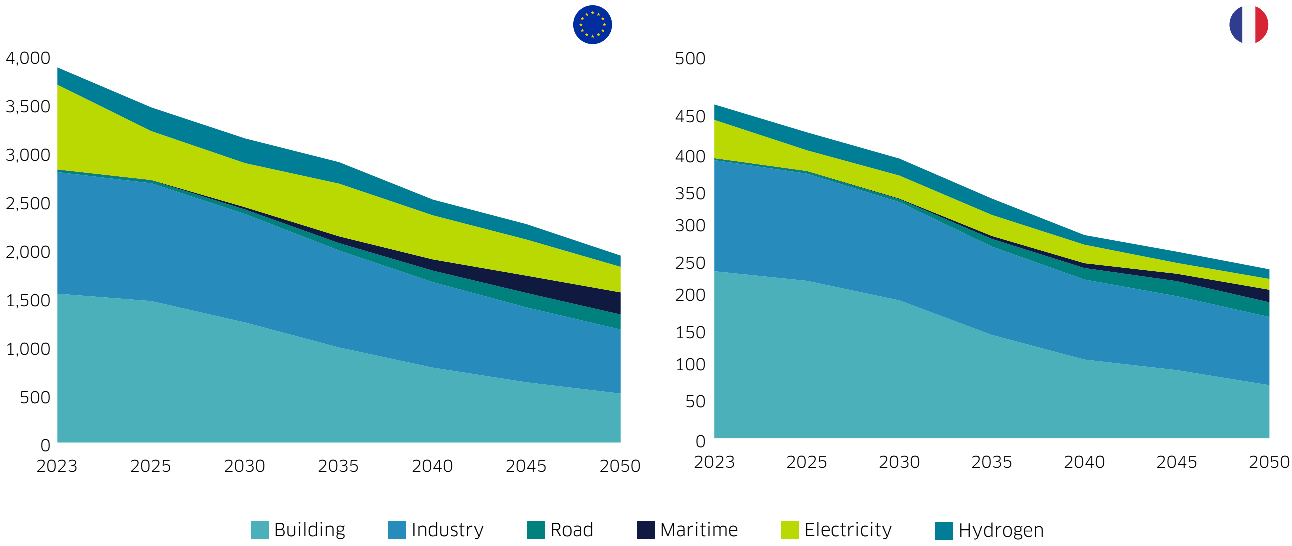


Biomethane is produced by purifying biogas generated from anaerobic digesters (first generation) or gasification processes (second generation). This methane purification process also releases biogenic CO_2, which when combined with green hydrogen can produce e-molecules, such as e-methane, e-methanol, and e-crude derivatives. E-methane has the same chemical properties as fossil methane and therefore can be used in all existing natural gas infrastructures. Finally, some natural gas may still be used in 2050 when coupled with carbon capture and storage (CCS).

Today, the maturity of the biomethane industry in Europe varies widely across member states. In some European countries (like the Netherlands or the United Kingdom), the biomethane industry has already developed. In France, biomethane was one of the few technologies to meet the target of the latest multi-annual energy policy (PPE).

The graph below shows the evolution of methane demand by sector. The volume and structure of demand changes drastically by 2050. Demand in building, industry, and power generation is divided by three; transport is emerging but limited to 20-25% of global demand by 2050.

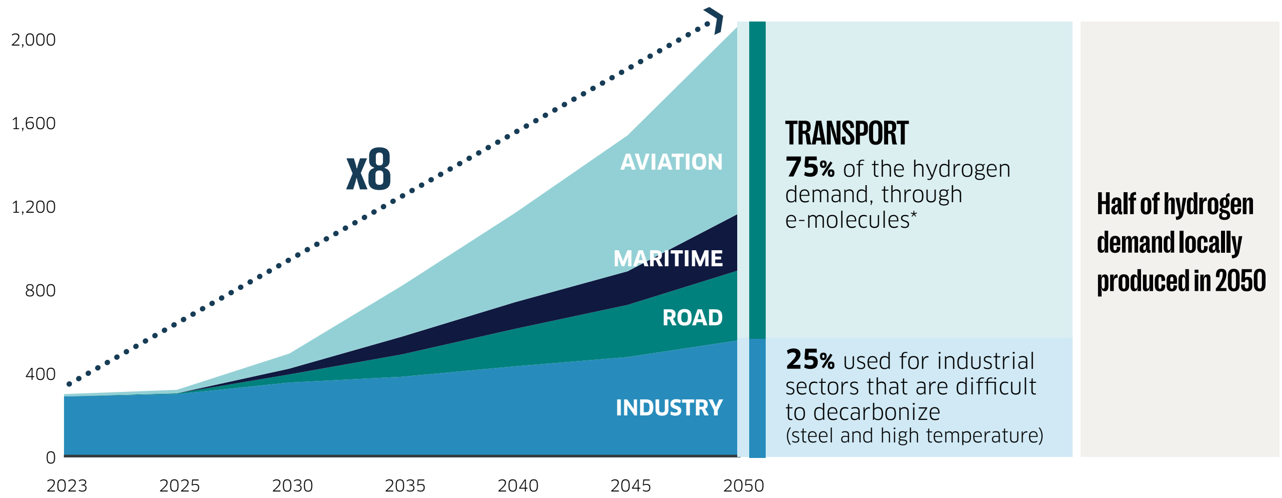
Methane demand by sector | Europe15 & France
Twh

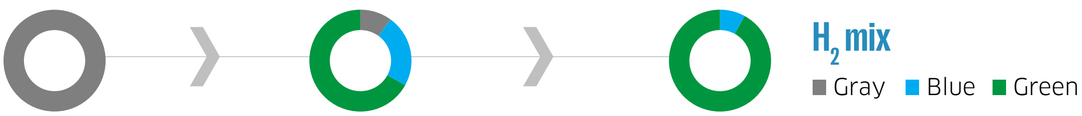


THE GROWTH OF GREEN HYDROGEN

Today, hydrogen consumption is primarily fossil-based 'gray' hydrogren linked to key industrial sectors, where it is used as a feedstock to produce other molecules.

Sectors of the hydrogen economy | Europe15
Twh





* e-ammonia, e-methane, e-methanol, e-kerosene, e-diesel

We expect global hydrogen demand (including for the production of e-molecules) to increase eightfold from now until 2050, driven by demand for green hydrogen, produced via electrolysis sourcing renewable power.

Transport and in particular heavy transport will represent 75% of this demand by 2050. Transport will rely on e-molecules (e-methane, e-ammonia, e-methanol, e-diesel, e-kerosene) that are derived from green hydrogen but possess higher energy density.

Half of the European hydrogen demand will be served by local sources with the other half imported in the form of e-molecules from geographies benefiting from abundant and cheap green electricity. During the ramp-up of the green hydrogen industry, we expect the 23% share of 'blue' hydrogen in 2030 to fall to 8% in 2050. Blue hydrogen corresponds to different production processes involving steam methane or autothermal reforming, combined with the capture and storage of the emissions associated with methane combustion, leading to low-carbon hydrogen production.

BIOMASS POTENTIAL & UTILIZATION

Biomass comes in the form of solid, wet or dedicated crops. Solid biomass (forest wood, out-of-forest wood, wood waste, green waste and solid recuperation fuels), can be used directly to produce heat and electricity for district heating or industry, or to produce biomethane by pyro-gasification. This last process involves the thermo-chemical processing of many different sources, such as wood waste, residues from waste management, and mostly organic waste to produce biomethane.

In order to estimate biomass resource for forest wood, ENGIE considers a scenario of forest evolution by the European Forest Institute, which integrates the impact of climate change on forests. The forest increment is shared between carbon sink and wood uses: lumber, industry and energy. The amount of wood needed for lumber and industry is estimated from prospective scenarios of the construction sector from FCBA (the French reference technological institute on the use of wood for construction and furniture). Residues from harvest, lumber and industry are then allocated to energy.

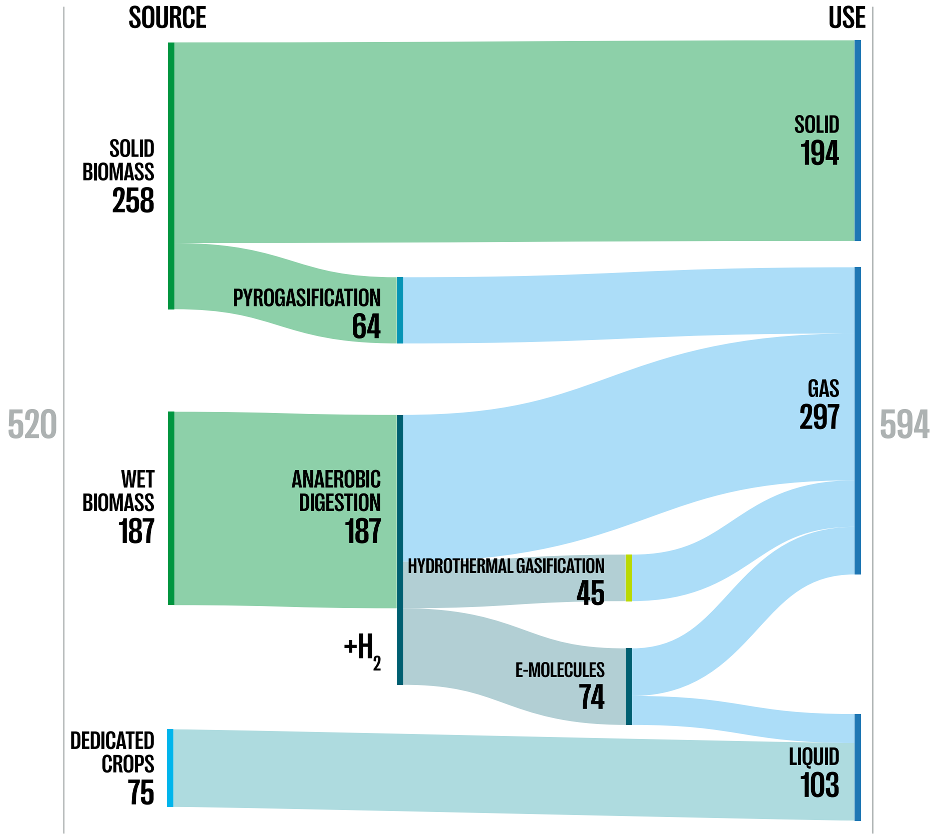
Wet biomass (livestock manure, sequential crops, agricultural residues and biowaste from households or agri-food industry) will be used to produce biomethane primarily by anaerobic digestion due to the positive externalities they provide. The assessment of the European potential of wet biomass feedstock also integrates the effect of climate change (e.g., on crop yields) and the societal response (e.g., decrease of meat consumption) using data from IPCC scenarios. Non-energetic uses (e.g., need for straw for livestock bedding or soil cover) are also considered and are prioritized over energy.

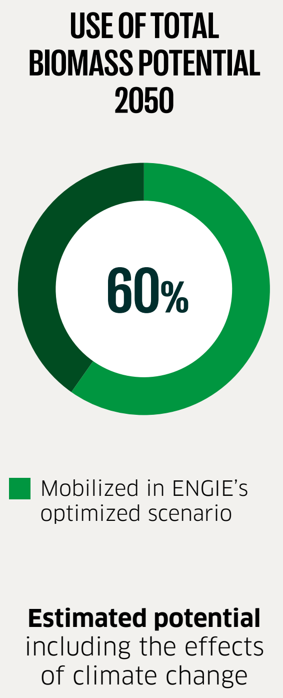
Finally, advanced bio-fuels could either be produced using dedicated crops (lignocellulosic crops such as switchgrass or miscanthus, or short rotation coppice) on available surfaces not suitable for agriculture, as in the European Commission scenarios, or imported. Dedicated crops are only used to produce liquid bio-fuels.

France has the highest potential of biomass for energy production in the EU. The assessment of the potential of different biomass sources (solid, wet, dedicated) shown in the graphic below is currently highly debated. ENGIE bases its analysis entirely on external publications available at the time of writing, and in particular from INRAE and ADEME[9]. As new research and publications become available, ENGIE will adapt the hypothesis on biomass potentials in this scenario.

[9] INRAE: *Institut national de recherche pour l'agriculture, l'alimentation et l'environnement*,
ADEME: *Agence de l'Environnement et de la Maîtrise de l'Energie*,
IPCC : Intergovernmental Panel on Climate Change

Potential | France
TWh





Sources: ADEME, IGN and INRAE, IPCC & France Agrimer

Solid & wet biomass potentials in France in 2050 by vector (TWh HHV)

ENGIE identifies a total potential of ca. 520TWh HHV[10] of bioenergy produced from the available biomass. The approach described consists of systematic recycling of waste from one process as an input for the production of bioenergy in another process. It allows one to maximize total bio-fuel production to reach 594TWh by adding hydrogen to produce e-molecules[11]. In the ENGIE pathway, only 60% of this biomass potential is used to satisfy demand.

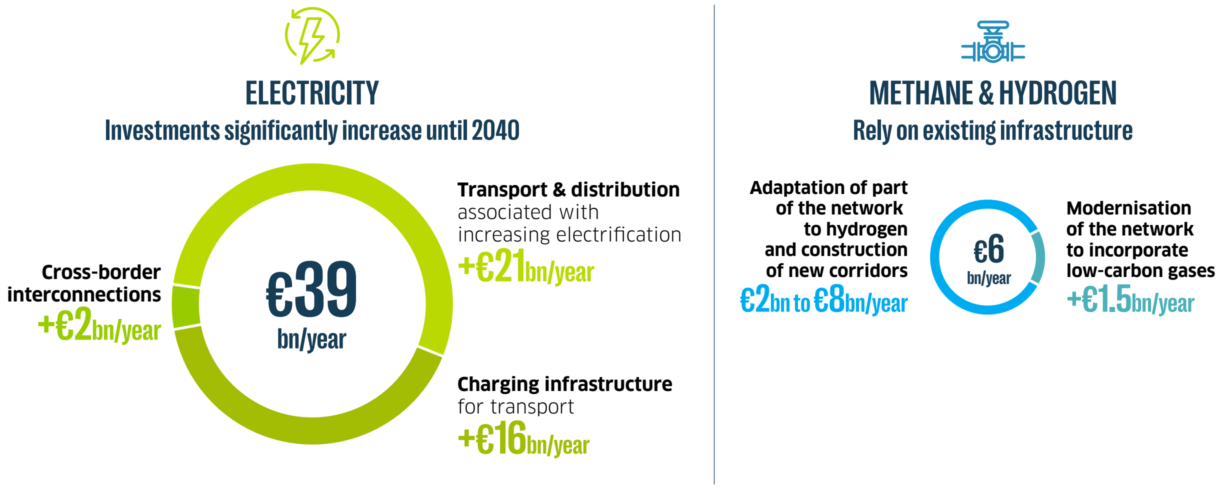
10 The unit chosen for most studies is TWh LHV, for consistency reasons the unit chosen in the present document is systematically TWh HHV.

11 Although not used in the ENGIE pathway, hydrothermal gasification is added on this chart as a potential breakthrough technology which could boost the potential of biomethane production using liquid biomass feedstock (including digestate in excess).

INVESTING IN INFRASTRUCTURE

Enabling this green production will require significant investment in power grid development. About €39bn/y will be needed to integrate renewables and to cope with the necessary reinforcement of the grid at the distribution level. Combined with the charging infrastructure for transport, electricity infrastructures require by far the largest investment share.

Biomass potential & utilization | Europe15
€bn/y



The electricity infrastructure allows the deployment of renewable energies

The gas infrastructure plays a crucial role in meeting demand peaks and making the energy system more flexible

Gas infrastructures, be it for methane or hydrogen, should only mobilize €6bn/y. These investments will mainly be needed to adapt existing infrastructures to renewable gases.

By 2040, we anticipate all hydrogen production to be fully decarbonized via green hydrogen complemented with limited deployment of blue hydrogen. The bulk of hydrogen production will be in countries with the greater renewables' potential (such as the Iberian Peninsula) and a hydrogen transportation backbone will be essential to meet Northern Europe demand at a competitive cost. France will be at the crossroad of this network. Adapting the network remains pivotal to achieve the transition. Although flows are expected to change drastically[12], France will remain a transit country due to its central location. Sections of natural gas transport pipelines are already planned to be converted to hydrogen, mainly in the case where double pipelines exist.

LNG terminals, developed today to ensure European supply during the energy crisis, will be used by the end of the next decade to also import e-molecules necessary to minimize decarbonization costs, thanks to access to remote, cheap green electricity.

Even in a very low-demand context (half of today's demand for methane), gas infrastructures will remain necessary to provide flexibility, collect, and distribute green gases. These assets will be largely amortized and the investments necessary to adapt to renewable gases are an order of magnitude much lower than those necessary for the power grid.

[12] While East-West and North-South natural gas transit is expected to decrease at faster pace, West-East transit for LNG (then e-LNG) is already a reality, while South-North transit will increasingly connect the Iberian region (and beyond Maghreb) with France and Northern Europe for both H_2 and e-CH_4. The hydrogen backbone will be gradual starting 2030 with conversions and adjunctions until 2050.

WAY FORWARD

Like most macro scenario exercises, ENGIE's decarbonization pathway is based on several fundamental principles:

- Price signals for operations and investments by market players,
- Timely generation capacity development,
- Timely upscaling of power grids, both at the transmission and distribution levels,
- Sector coupling when economically efficient,
- Development of efficient supply chains,
- Deployment of energy efficiency technologies and best practices,
- Technological learning and cost reductions.

These attributes are crucial to achieve a cost-effective, resilient, carbon-neutral energy system and ENGIE's decarbonization pathway strongly encourages policy makers to adapt the regulatory and economic environment and to increase their efforts accordingly. Without this, Europe will probably miss its decarbonization targets and the growth opportunities that the Green Deal could offer if well designed and implemented.

Specifically, five areas of policy actions appear to be most critical to ensure the acceleration of climate mitigation action outlined in this document:

1. **Reducing demand while not jeopardizing economic activity**
Energy efficiency remains a large and economically efficient decarbonization lever today. Policy makers must make this an absolute priority and, beyond the current legislative framework, make it an area of active sharing and experimentation across Member States.

2. **Promoting a European vision of energy security and system reliability**
Member states must take full advantage of the integrated European energy market by promoting cross-border exchanges as a means to reduce decarbonization costs, increase Europe's resilience and promote even more European solidarity between Member States, which is at the core of the European project. In addition, cost-efficient system adequacy and reliability requires exploiting synergies between energy vectors to their maximum potential.

3. **Accelerating the deployment of renewables for the benefit of all consumers**
While now reaching technological maturity, wind and solar technologies need a stable investment framework offering long-term price signals (eg via PPAs, or CfDs), the fast-tracking of grid connections and permitting, and specific support to the European value chain when facing unfair competition.

4. **Promoting flexibility on the demand side**
Flexibility technologies are as important as the renewable power they complement. They must be supported with the right remuneration models adapted to the different sources of flexibility, whether supply side, demand side, short or long duration. Policy makers must urgently ensure the economic viability of the business models for flexibility.

5. **Developing renewable and low carbon molecules**
Europe should send a clear signal on the need to develop all decarbonization levers and set a bold target for biomethane deployment (eg 35bcm/year by 2030). It should also swiftly adopt swiftly a cost-efficient H_2 regulatory framework capable of competing with other global regions in terms of support level and process simplicity, by adapting if needed the framework recently drawn.

APPENDIX

BENCHMARKS

Sources that have been selected

The scenarios used in this comparison share the objective of achieving a Net Zero-emission Europe by 2050.

The Announced Pledges Scenario, computed by the International Energy Agency (IEA, supranational organization, part of OECD), models a scenario where all national commitments are met.

ENTSO-s scenarios present two different approaches in the Ten Year Development Plan (TYNDP) produced jointly by European power and gas TSOs (namely ENTSOE and ENTSOG both based in Brussels). In the Distributed Energy scenario, the focus is on local decarbonization efforts. In the Global Ambition scenario, the global energy trade is leveraged to accelerate decarbonization.

IHS (now part of Standard and Poors) is a leading consultancy for energy markets. The Accelerated Carbon Capture and Sequestration scenario envisions widespread use of CCS technology to offset emissions from energy and hard-to-abate industrial sectors. In contrast, the Multitech Mitigation scenario relies less on CCS and emphasizes diversification of the energy supply and extensive electrification across all sectors, relying on renewable energy sources.

Specific scenarios from French institutions have been used when looking in particular to France. S3 Scenario from ADEME (Energy Transition Agency) and the N2 Scenario from RTE, the Transmission Network Operator have been compared to our outlook.

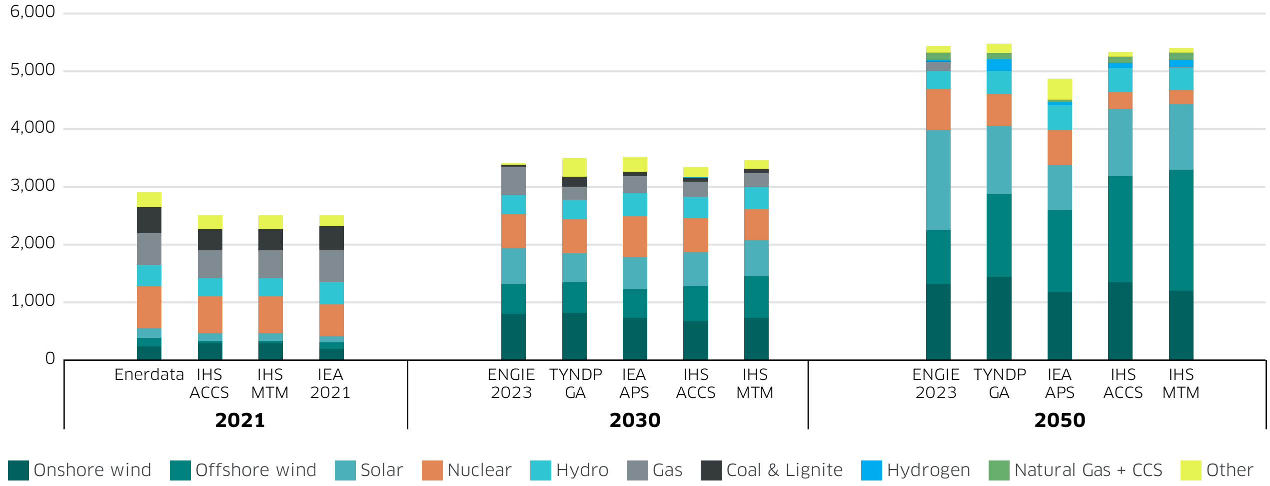
List of sources

ENGIE 2023
ADEME S3 Scenario (Transition(s) 2050)
RTE N2 Scenario (*Futurs Energétiques* 2050)
TYNDP Global Ambition
TYNDP Distributed Energy
IEA APS 2022
IHS ACCS
IHS MTM

Power mix

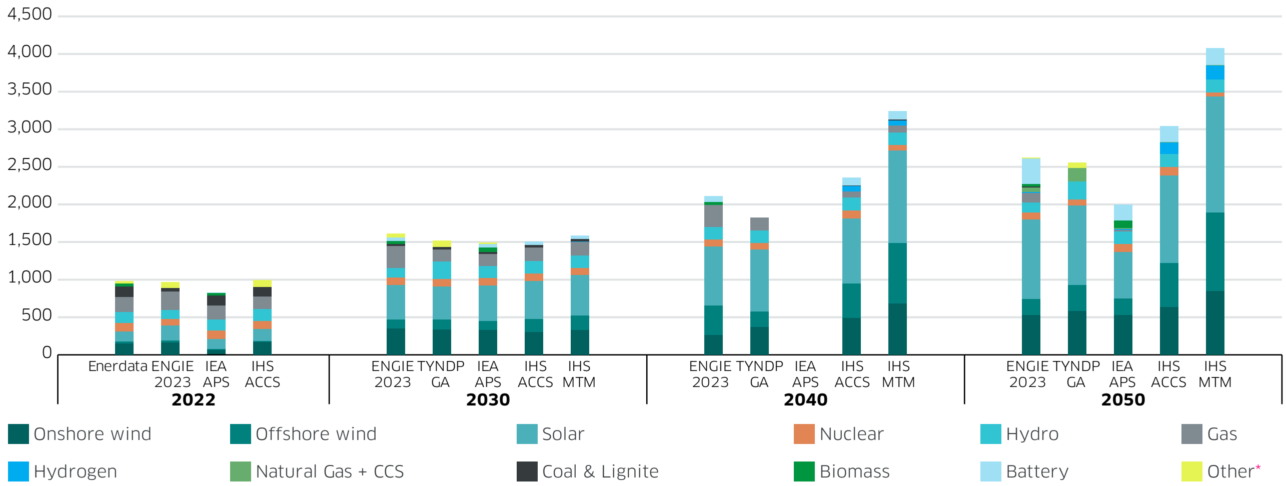
Power generation | EU27

TWh



Power capacity | EU27

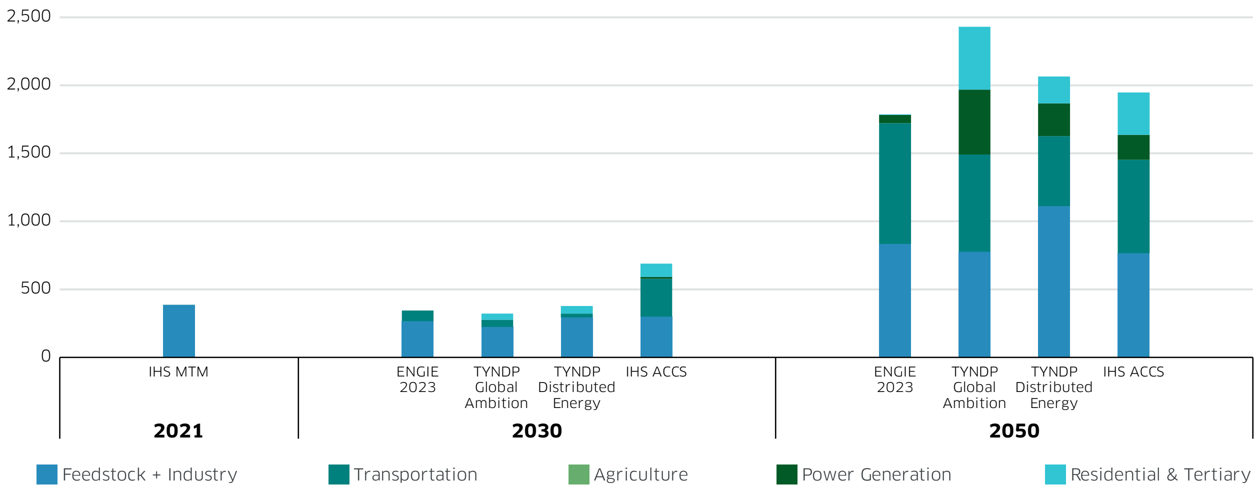
GW



Hydrogen demand

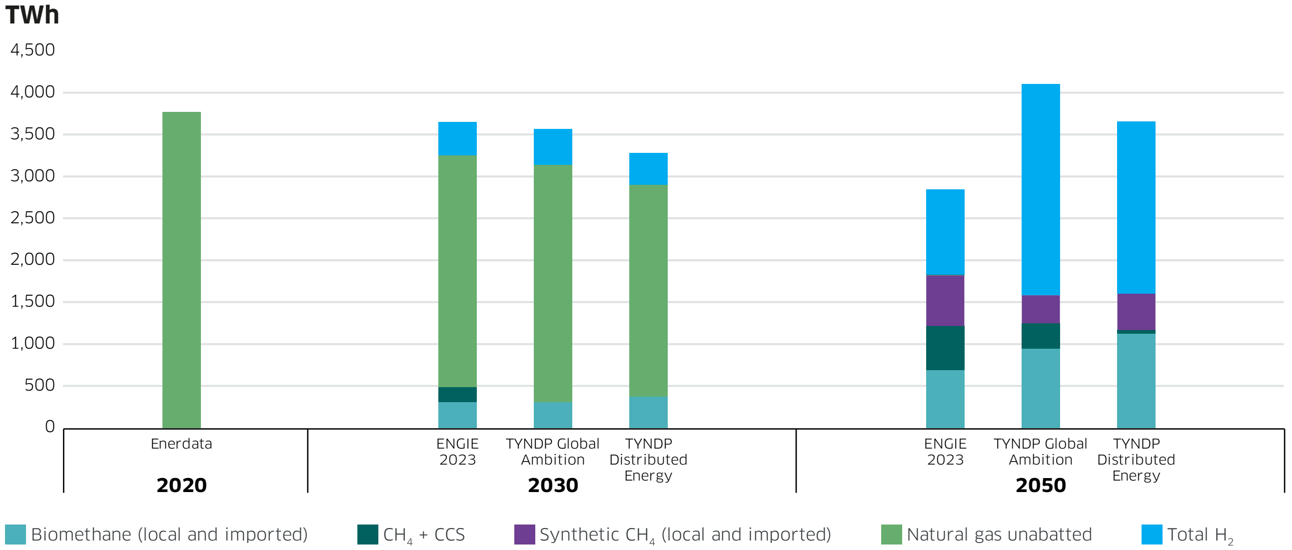
Hydrogen demand by sector | EU27

TWh



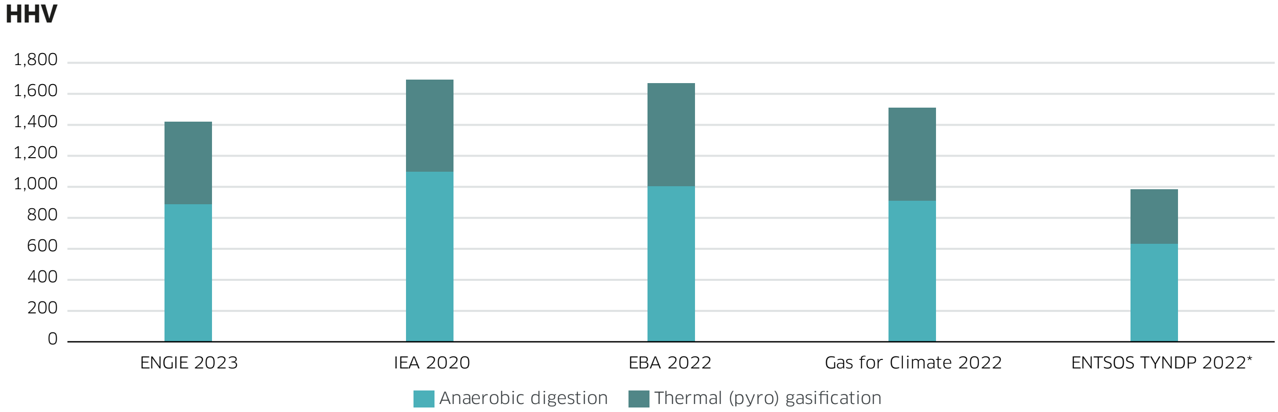
Methane supply

Gas supply | EU27



European biomethane potential

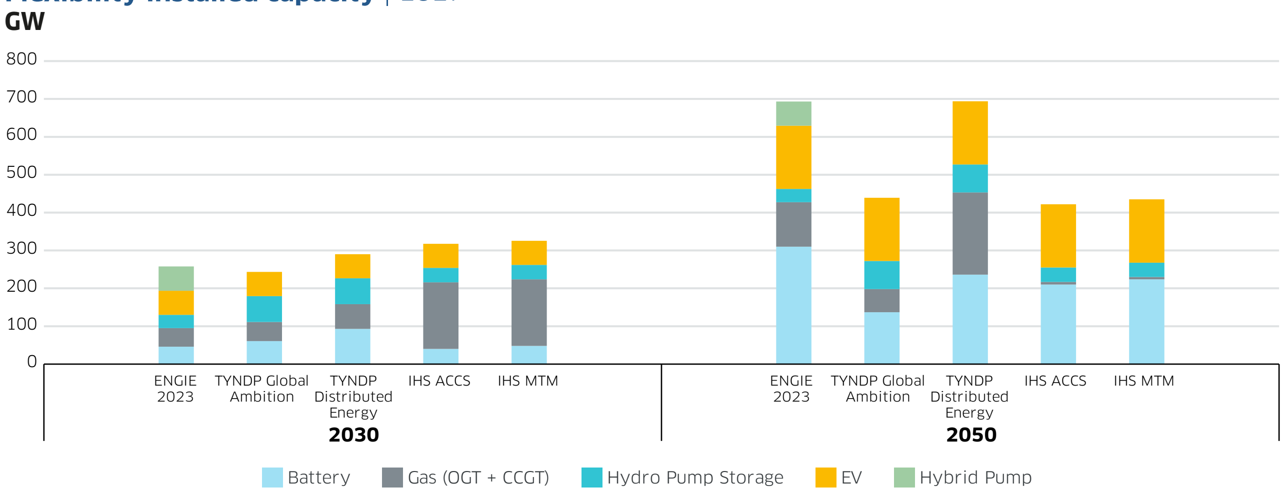
Biomethane potential by 2050 | EU27



* For ENTSO scenarios, actual injected volumes. Indicates a lower boundary for potential assumption.
European Biogas Association gathers biogas/biomethane producers. Gas for climate study is supported by European TSOs.

Flexibility capacity for the power system

Flexibility installed capacity | EU27

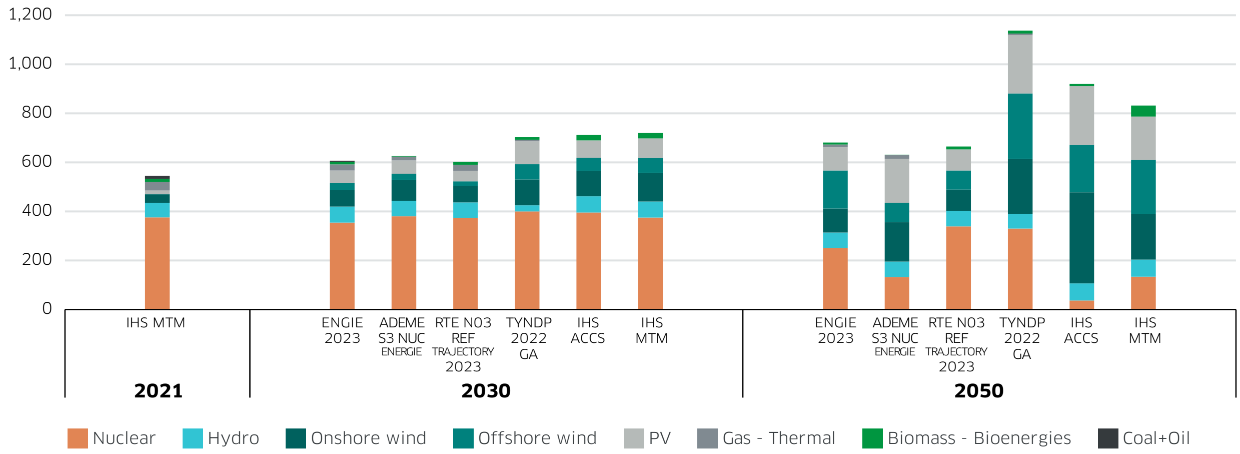


PROJECTIONS FOR FRANCE

Power mix

Power generation | France

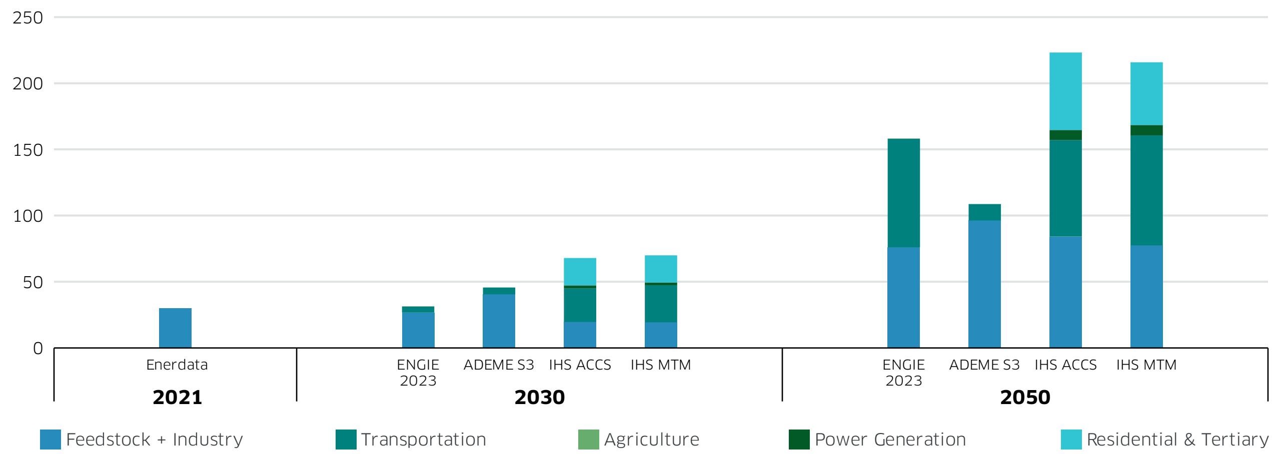
TWh



Hydrogen demand

Hydrogen demand by sector | France

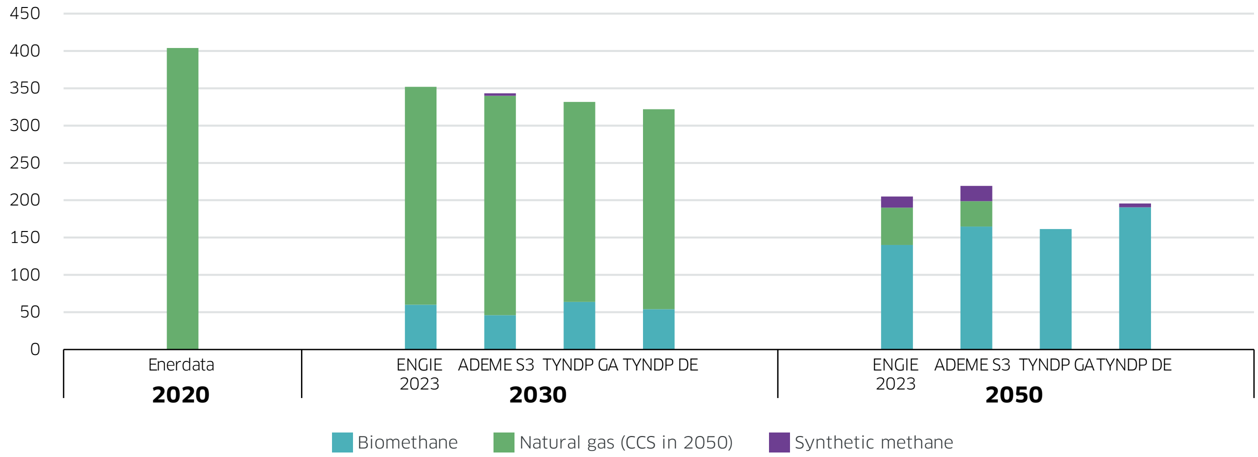
TWh LHV



Gas supply

Gas supply | France

TWh LHV



engie.com

Layout/production: As One