ACHIEVING EUROPE'S ENERGY TRANSITION

FULL REPORT

ENGIE's Decarbonization Pathway for Europe

November 2024

ACHIEVING EUROPE'S ENERGY TRANSITION

MESSAGE FROM THE CEO

Catherine MacGregor
CEO – ENGIE

The unprecedented and devastating floods that struck Spain October 2024 are yet another tragic reminder that the climate emergency is a reality today. At the same time, nations around the world now understand that low-carbon technologies constitute a critical competitive advantage, and they are seizing the opportunity. For these reasons, now more than ever, Europe must accelerate its efforts to tackle climate change and embrace the energy transition challenges with confidence, ambition, and pragmatism.

Our updated assessment of the optimal pathway for the decarbonization of Europe highlights that though many challenges remain, Europe's 2030 Fit-for-55 objective is within reach. The bigger challenge, however, is reaching the Net Zero by 2050 objective. For this, the entire energy system will need to be transformed. We have made progress in the electrification of buildings, transport, and industry, and renewables now represent close to half of European power consumption. However, electrification alone will not fully solve the Net Zero challenge. Hard-to-abate sectors in transport and industry, as well as some parts of the building stock, will fall behind if we don't scale the deployment of affordable decarbonized gases.

The energy transition requires considerable investments, but at around 2% of GDP they are within reach of our economy. They will also be gradually offset by savings on fossil fuels. And let's not forget the cost of inaction: climate change has a negative impact not only on our living conditions but also on the overall economy which far outweighs the costs of mitigation.

Our focus should therefore decisively be on continuing to accelerate the more mature decarbonization levers and scale up the less mature solutions that we know are needed to meet our 2050 ambitions. Without these industrial developments, we will lose both the battle of climate and that of Europe's competitiveness, all while putting Europe's sovereignty at risk.

Everyone must do their part. ENGIE is active across most energy transition levers and operates in many countries across Europe. We are ready to do our part and accelerate our efforts. However, we need, at national and European level pragmatic leadership focused on creating the conditions for the emergence of competitive decarbonized industry.

This report provides solutions and concrete proposals which we hope contribute to the debate and lead to meaningful action.

ACHIEVING EUROPE'S ENERGY TRANSITION

All levers are needed to achieve Europe's decarbonization objectives

DEMAND REDUCTION

-30%

Decoupling of energy demand and economic growth (GDP : + 1.3%/y)

ENERGY DEPENDENCY

-65%

Energy imports reduction (fossil fuels and e-molecules)

RENEWABLE POWER

x5.5

Wind & Solar production

FLEXIBILITY

x4.5

Total flexible capacity, including three quarters coming from demand

LOW CARBON GASES

x15

Production & imports for a decreasing demand by -45% in 2050

HYDROGEN

x7

Hydrogen & e-fuels demand, which is fully decarbonized by 2050

COST OF DECARBONIZATION

<2%

of GDP from today to 2050

POWER SYSTEM COST

~

Total cost per MWh to remain stable

All Indicators are 2023 vs 2050 except when indicated otherwise

Methodology to define Europe's optimized decarbonization pathway

A European vision...

- Modelling of **15 European countries**[1] with strongly interconnected energy systems, representing more than 85% of Europe's[2] total energy consumption

… based on realistic techno-economic choices...

- Considering **only low-carbon technologies which have been proven industrially** (i.e., excluding technologies at R&D stage)
- Constrained by **existing near-term policies** (e.g., NECP), **industrial feasibility**, and **societal factors** (e.g. social acceptability)
- Using **external studies and benchmarks** for issues outside our area of expertise, e.g. agriculture, forestry (European Commission, ADEME, etc.)

… that optimizes decarbonization across all energy vectors...

- Seeking an economic optimum on the mid- to long-term (2030 and beyond) to achieve Europe's decarbonization objectives (-55% in 2030 vs. 1990, Net Zero by 2050)
- Capturing interactions between **electricity, methane, hydrogen, e-molecules and heat**
- Modelled with **hourly granularity** to capture energy system reliability and resilience

... to minimize overall energy transition costs.

- Based on a **comparison with a 'steady state' scenario** assuming no further decarbonization beyond 2023
- Assessing **total costs** (capex and opex) of decarbonization of **industry, transport, residential, and energy sectors**

[1] Austria, Belgium, Czech Republic, France, Germany, Hungary, Ireland, Italy, Slovakia, Spain, Switzerland, Poland, Portugal, The Netherlands, The United Kingdom
[2] Europe = European Union (27) + UK + Switzerland

Methodology deep dive: A steady state scenario is used to estimate decarbonization cost

- The **steady state scenario** is used as a counterfactual scenario to assess the additional costs generated by achieving Europe's decarbonization ambitions in **the Net Zero Pathway**
- This incorporates the same **socio-economic & demographic trends** (population, GDP, inflation, number of households, number of cars etc) as **the Net Zero Pathway**

- The steady state scenario considers **no further decarbonization efforts beyond 2023**

Energy production	• No evolution of generation mix except for coal phase out (switching to gas, as this path is already acted) • No new investment in renewables & low-carbon gases (biomethane, electrolyzers, e-fuels, carbon capture, etc.)
Industry	• No more efforts to transform industrial processes to reduce emissions, no further electrification • No significant efficiency gains
Transport	• No further electrification and decarbonization efforts • No further behavioral changes (e.g., carpooling, modal switch)
Buildings	• Stable renovation rates in residential & tertiary sectors • No further behavioral changes (heating/cooling setpoint temp. lowered/increased)

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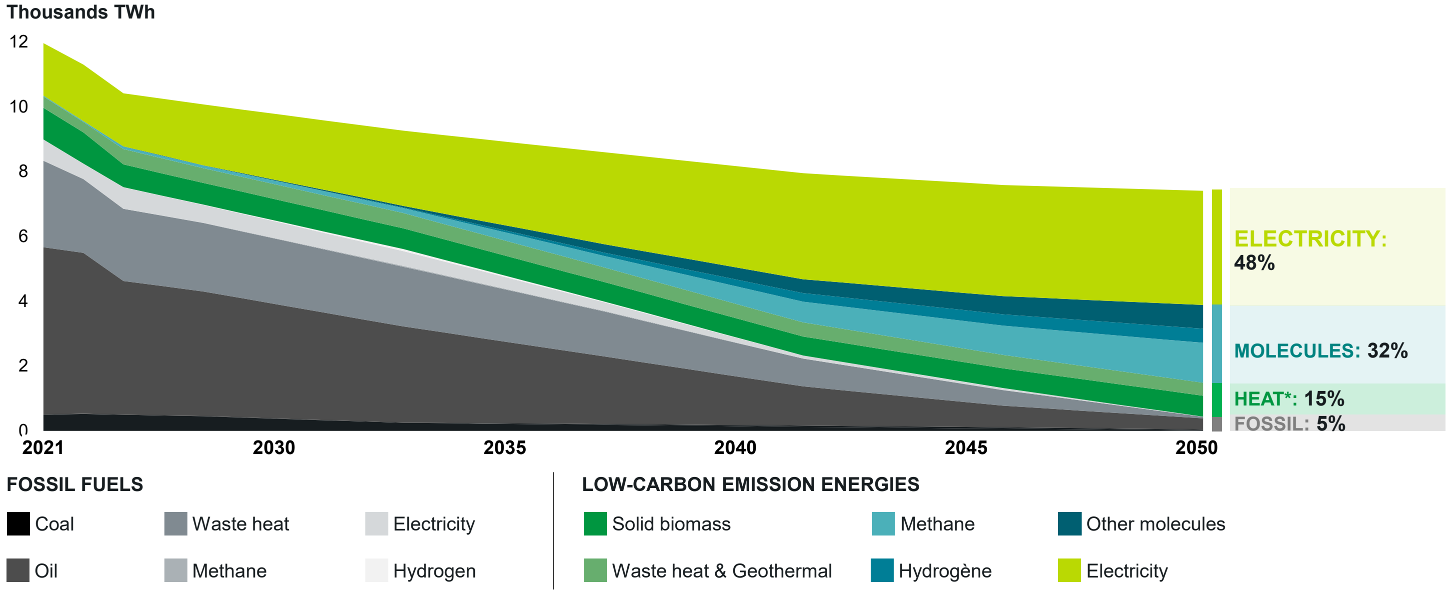
Final energy demand reduces significantly, with strong electrification complemented by decarbonized gases and heat

Optimized Final energy mix | Europe-15



* **Heat**: Biomass, Waste Heat and Geothermal. Electricity and Molecules includes energy to produce heat consumed via DHC
Methodology review vs 2023 exercise, excluding Non energy uses from energy mix
Low carbon methane accounts for biomethane, NG + CCS & e-methane, while other molecules correspond to ammonia, e-methanol & kerosene

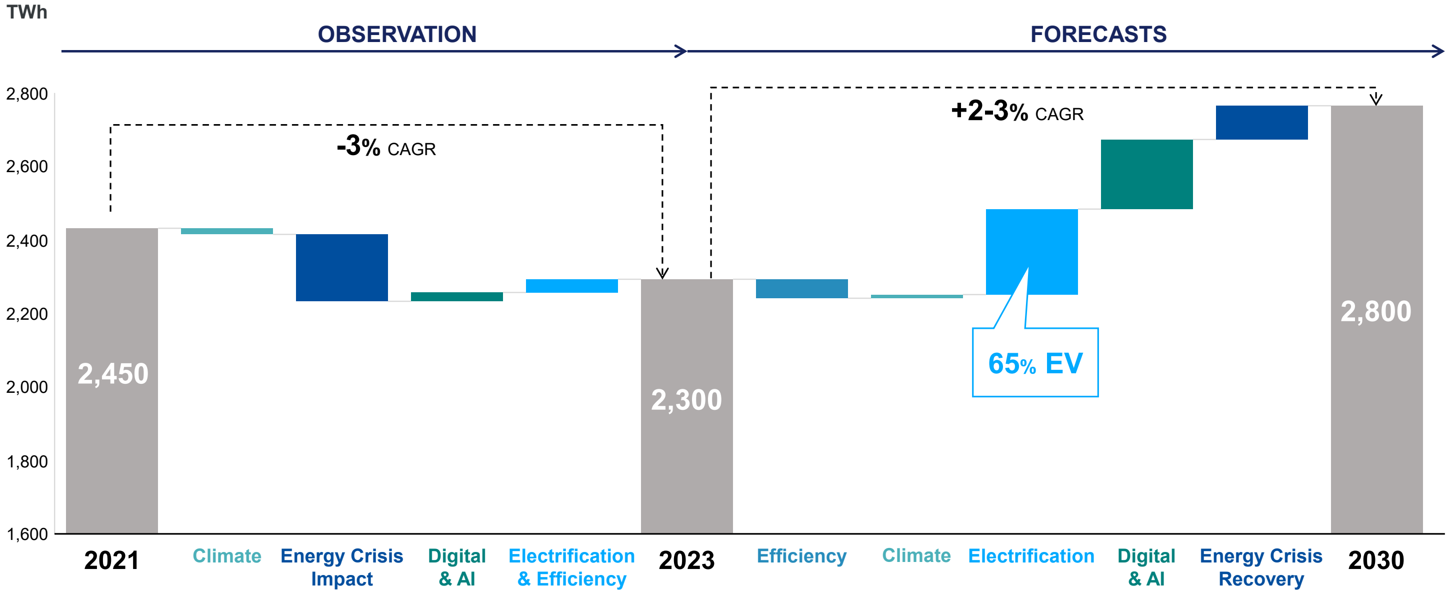
HIGHLIGHTS | Final Energy Mix

All decarbonization levers are needed to reach net zero, demand will reduce by 30% despite GDP growth, share of electricity in final demand will double, molecules represent 32% of the final demand mix.

- **Overall trend:**
  Achieving Net Zero across Europe by 2050 implies a dual transformation of final energy demand. First, an overall reduction in absolute terms of 30% compared to 2023, despite anticipated GDP growth of 1.3% year-on-year and a stable population over the same timeframe. Second, an almost complete decarbonization of the underlying fuel mix. The share of fossil fuels reduces from more than 75% in 2021 to 5% in 2050, primarily limited to some remaining fossil fuels in international aviation and maritime.
- **Energy efficiency:**
  Renovations improve building envelopes and reduce, on average, heat demand by 40% on average across European countries. This is complemented by the replacement of less efficient assets such as retrofitting heating equipment in buildings, retrofitting industrial utilities, or changing vehicles. The evolution of individuals towards more frugal behaviors (e.g., carpooling, heating temperature) complement these technological benefits.
- **Electrification:**
  Electrification almost doubles its share of the energy mix, representing close to half of total final demand in 2050. It is a critical vector of Europe's decarbonization, though with penetration rates varying across sectors and countries.
- **Low carbon molecules:**
  Renewable and low-carbon methane, hydrogen, and other e-molecules are the only viable and economical solution for a variety of applications across heavy transport, heavy industry, and some applications in buildings. They are essential to achieve Europe's full decarbonization at optimal costs and represent close to 1/3 of the 2050 fuel mix.
- **Heating and cooling:**
  Representing 15% of the fuel mix in 2050, heating and cooling solutions are an important part of the decarbonizations levers for Europe.

Following important power demand reduction linked to the energy crisis, demand is expected to grow in the medium term

Power final energy consumption | Europe-15



Sources: Eurostat, Entso-E & ENGIE analysis

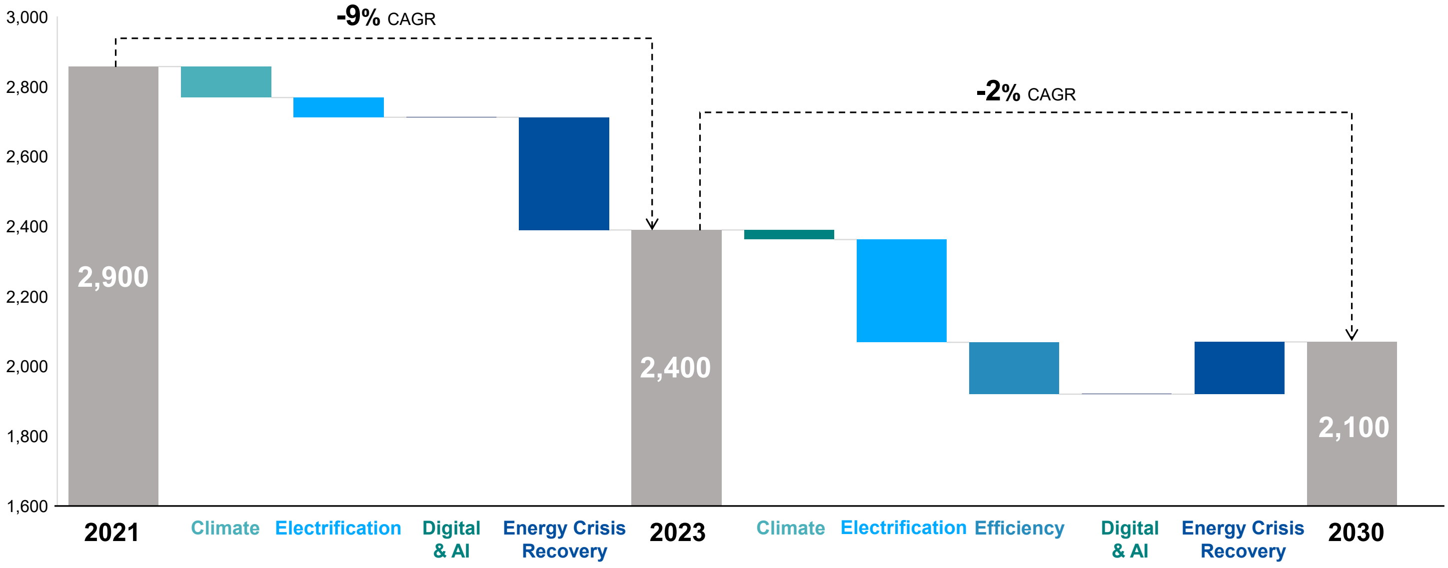
HIGHLIGHTS | Power Demand

Demand should grow between 2 and 3% per year until 2030, driven by the partial recovery of the energy crisis impacts, electrification and the development of data centers.

- **Overall trend:** From 2021 to 2023, we observed a 6% reduction in demand for power. This evolution was largely dominated by the impacts of the energy crisis (e.g., price effect, delocalization). In the near term and up to 2030, the net zero pathway sees a progressive rise in power demand, equivalent to 2-3% year-on-year growth, driven in large part by electrification, anticipated growth in digital and AI needs, as well as energy crisis recovery.
- **Climate**: The record-breaking heat observed in winter 2022-2023 led to a decrease in heating demand in buildings, reducing power demand by 8% in space heating. In contrast, air-conditioning in buildings is expected to increase by over 15% between 2021 and 2030 as a consequence of climate change and diffusion of air conditioners, contributing to an increased power demand.
- **Electrification and efficiency effects**: The increase in demand from electrification of the economy via changes in heating equipment, adoption of EVs and the adaptation of industrial processes is partially offset by energy efficiency gains due to renovations and equipment changes. Taken together these lead to a net increase of +8% in power demand between 2023 to 2030. The penetration of EVs alone account for more than 65% of the increase in electricity demand due to electrification.
- **Digitalization**: By 2030, the surge in AI and continued development of traditional uses of data will require over 90% more power consumption in data centers compared to 2023. AI alone could represent at least 15% of data center power consumption in 2030.
- **Energy crisis and recovery:** The high power prices observed during the crisis led to demand destruction primarily in industry and buildings. For industry, the most affected sectors were the more energy intensive sectors with strong international trade alternatives, such as chemicals, aluminum and steel. Temporary or permanent production outages were observed leading to -12% drop in power demand between 2021 and 2023. 45% of this demand destruction is expected to be long-lasting and as a result industrial demand only partially recovers between 2023 and 2030. In the building sector, changes in space heating behaviors resulting from higher power prices led to a -1% reduction in power consumption between 2021 and 2023.

Methane demand will continue to erode following the energy crisis due to continued electrification and energy efficiency gains

Methane final energy consumption | Europe-15



HIGHLIGHTS | Methane Demand

The decrease in methane demand should be around 2% per year until 2030 driven by electrification and energy efficiency improvements, and only partially compensated by recovery of energy crisis impacts

- **Overall trend:**
  Between 2021-2023 we observed an -17% reduction in gas demand. This decline was largely a consequence of the energy crisis. Our net zero pathway anticipates methane consumption to continue to reduce by 2% year-on-year despite energy crisis recovery, primarily due to electrification trends.

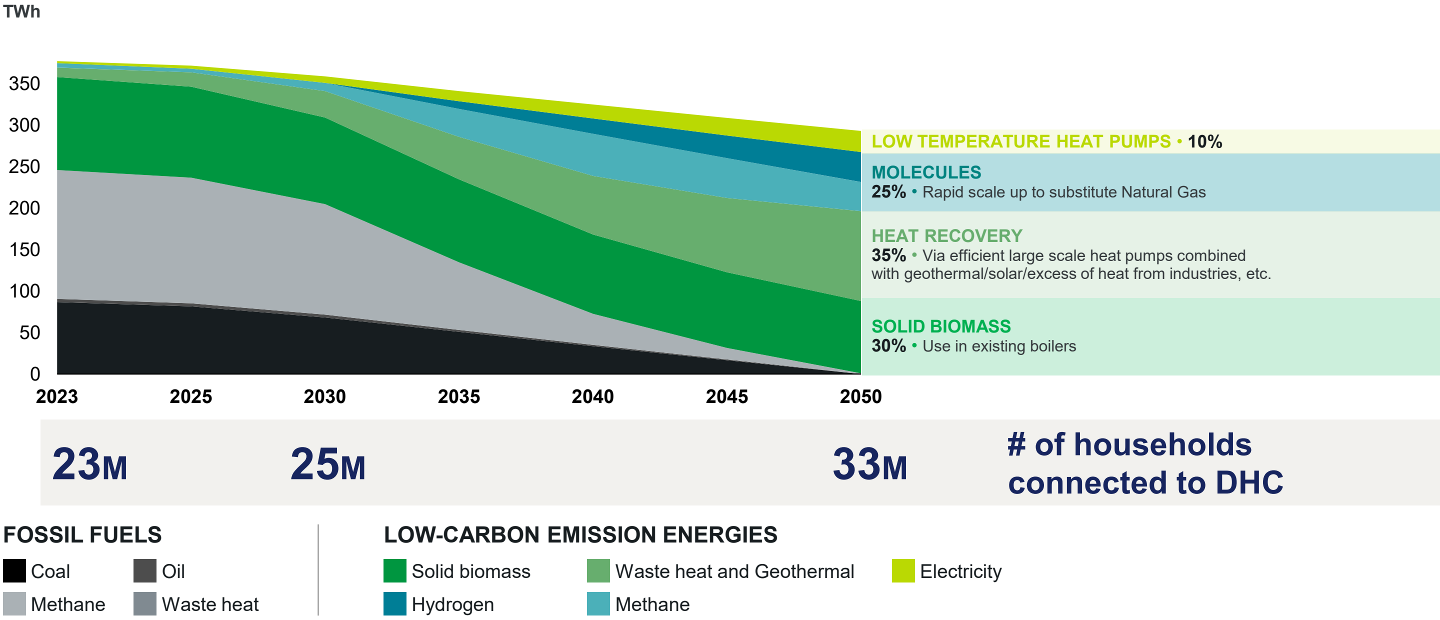
- **Climate:**
  Record heat in the winter 2022-2023 has led to a reduction in heating demand in buildings, reducing methane demand for space heating by -8%. We anticipate climate to continue to have a downward effect moving forward.

- **Electrification and efficiency effects:**
  The electrification of the economy via changes in heating equipment and industrial processes, combined with energy savings from renovations and other energy efficiency measures (e.g., equipment retrofits), reduce methane demand by -12% between 2023 and 2030.

- **Energy crisis and recovery:**
  High prices for methane and sobriety measures had a direct impact on demand. As for power, methane demand destruction has been mainly observed in the industrial and buildings sectors. In industry, the hardest-hit sectors are chemicals, fertilizers, aluminum and steel. Temporary or permanent production outages have been observed, leading to a 23% reduction in methane demand for industry between 2021 and 2023, of which 45% is expected to be long-lasting. From 2023 to 2030, industrial demand is partially recovered, due to an improvement European industry competitivity in a normalized energy price environment. In buildings, changes in households space heating behavior, resulting from high prices led to a -8% reduction in methane demand between 2021 and 2023.

District Heating and Cooling (DHC) can incorporate significant amounts of renewable energy and waste heat and supply cost-effective space heating

District Heating final energy mix serving buildings and industry | Europe-15



* Heat pump also use waste heat; MIL & consumption are expressed for residential only

HIGHLIGHTS | District Heating and Cooling (DHC)

The number of households connected to DHC should increase by 50% by 2050 while overall energy required reduces thanks to efficiency gains and DHCs progressively decarbonize through renewables and waste heat.

- **Overall trend:**
  District heating and cooling (DHC) represents the only option to recover heat from industries at scale.
  Without their large-scale development, recovering heat from data centers would notably be impossible.
  Today, 30% of DHC energy supply comes from renewables or waste energy. By 2050, DHC should be fully decarbonized.

- **Expansion:**
  DHC penetration could increase through the extension of existing networks and the development of new ones.
  A 50% increase in the number of households connected to DHC networks in Europe is expected by 2050.

- **Efficiency:**
  The foreseen expansion in DHC networks combined with a 30% efficiency gain linked to geothermal energy, heat pumps, waste heat recovery, and improved DHC technologies lead to a 25% reduction in energy consumption per household in our net zero pathway. In particular, the new installations are based on lower water temperature (70°C vs 90°C in existing DHC networks) and distribution losses are expected to fall from 14% to 5% over the 2050 horizon.

RECOMMENDATIONS | **Demand**

TACKLING THE DECARBONIZATION OF BUILDINGS AS A PARAMOUNT PRIORITY

1. To minimize total costs, support mechanisms and funding must cover the full range of decarbonization solutions available to the building sector (heat pumps, district heating and cooling solutions, renewable gas boilers, and hybrid heat pumps).

2. Given the slow progress being made in building renovation, there is an urgent need to focus renovation efforts and financial resources on the most inefficient buildings and on low-income households.

3. Recognize waste heat recovery as renewable energy across EU regulations and introduce rising renewable target for district heating and cooling network, with waste heat recovery mandatory requirements, and provide appropriate support to achieve targets (e.g., “Fond Chaleur” in France insufficient to deliver expected growth).

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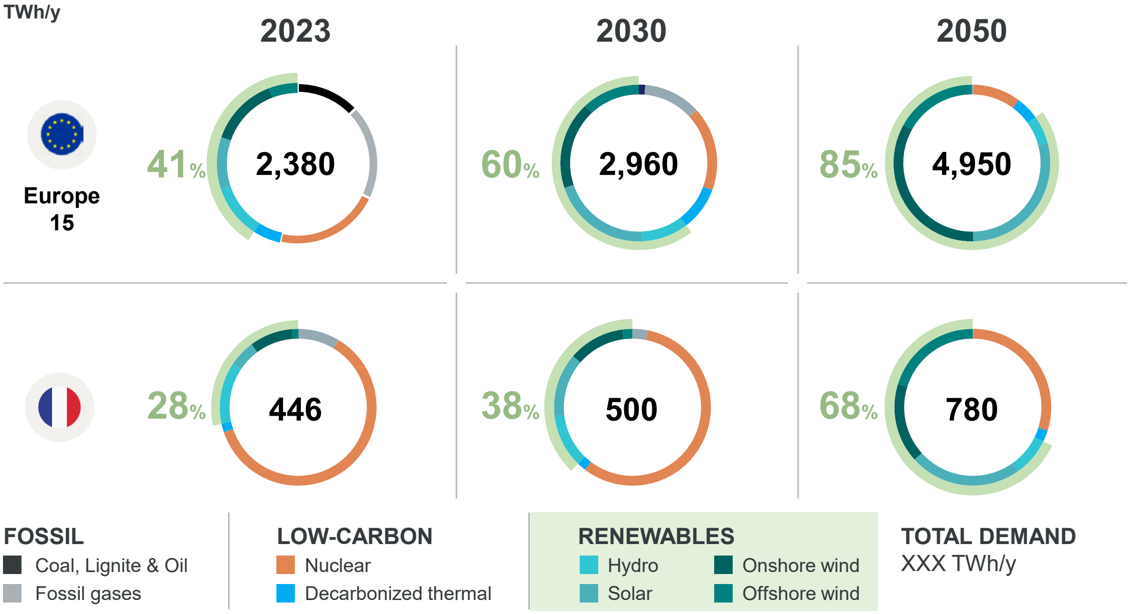
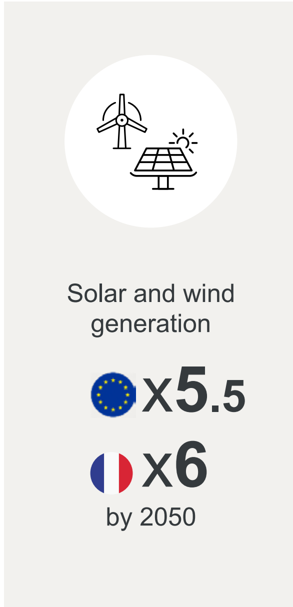
The power generation mix is fully decarbonized by 2050 primarily driven by the rapid growth of renewables, complemented by nuclear and thermal

Power Generation Mix & Total Demand
TWh/y





Sources: Entso-E, RTE & ENGIE Analysis

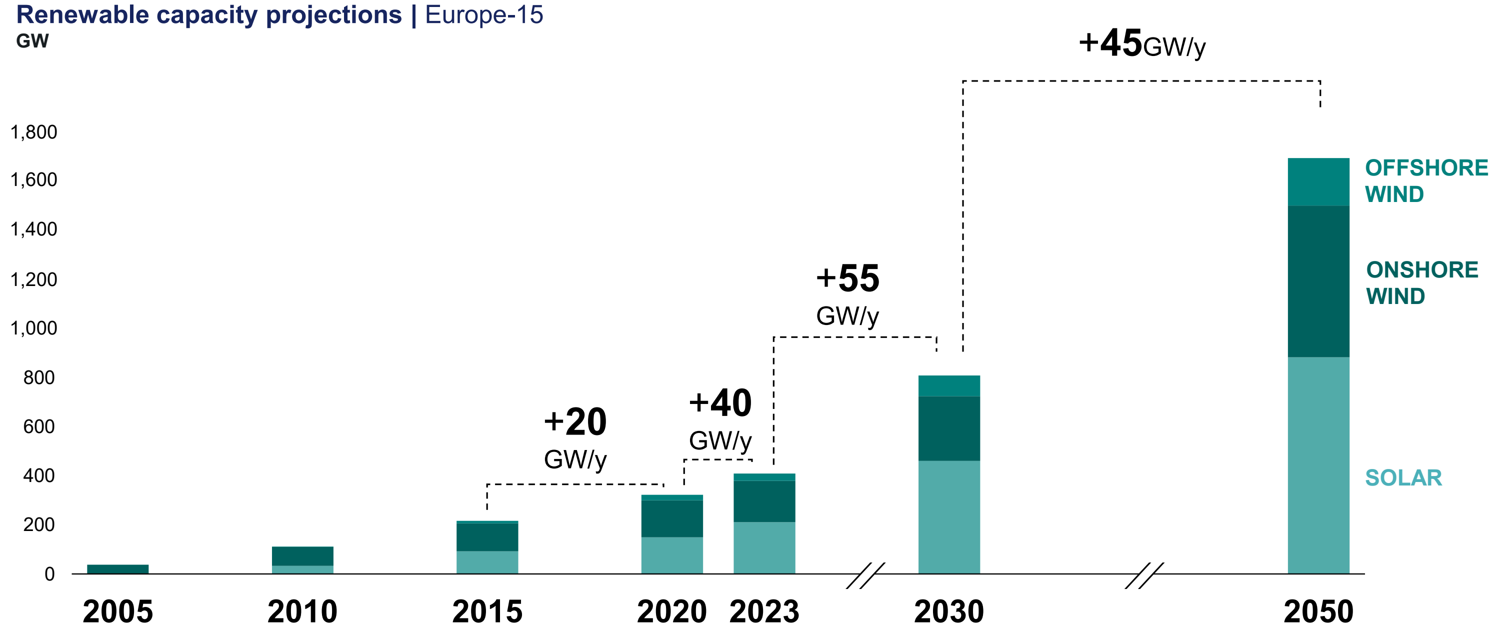
HIGHLIGHTS | Power Mix

Power generated from wind and solar increases over 5-fold in Europe. By 2050, renewables represent 85% of the power mix in Europe-15 and 68% in France. In France nuclear generation will keep a key role representing 30% of the power mix.

- **Overall trend:**
  Power production more than doubles between 2023 by 2050. At the same time, the power mix decarbonizes entirely, albeit from an already strongly decarbonized position in 2023. Indeed, in 2023 fossil fuels represent only one third of total production at Europe-15 scale and 7% in France.
- **Growth:**
  Half of power generation growth can be explained by the electrification of final uses (+60% at Europe-15 level between 2023 and 2050), while the other half comes from the growing power needs for green fuel production, primarily green hydrogen and e-methane. This highlights the importance of competitive renewable production in Europe, as this is vital not only for decarbonizing final power demand but will also be a key price driver of the production of hydrogen and other e-molecules within Europe.
- **Generation mix in 2050:**
  Renewables (Solar, Wind, Hydro) will represent most of the production, reaching ~85% of the electricity mix in Europe compared to 68% in France. Solar and wind production continue their impressive growth, with a 5,5x increase in Europe and a 6x increase in France. Renewables will be complemented by nuclear, which accounts for 10% of the fuel mix in Europe and 30% in France. Decarbonized thermal assets fueled by low-carbon gases, such as biomethane, e-methane, hydrogen, or fossil gas coupled with CCS represent respectively 5% and 2% in Europe and France.

The needed acceleration in renewable power deployment to 2030 seems achievable considering recent developments

Renewable capacity projections | Europe-15

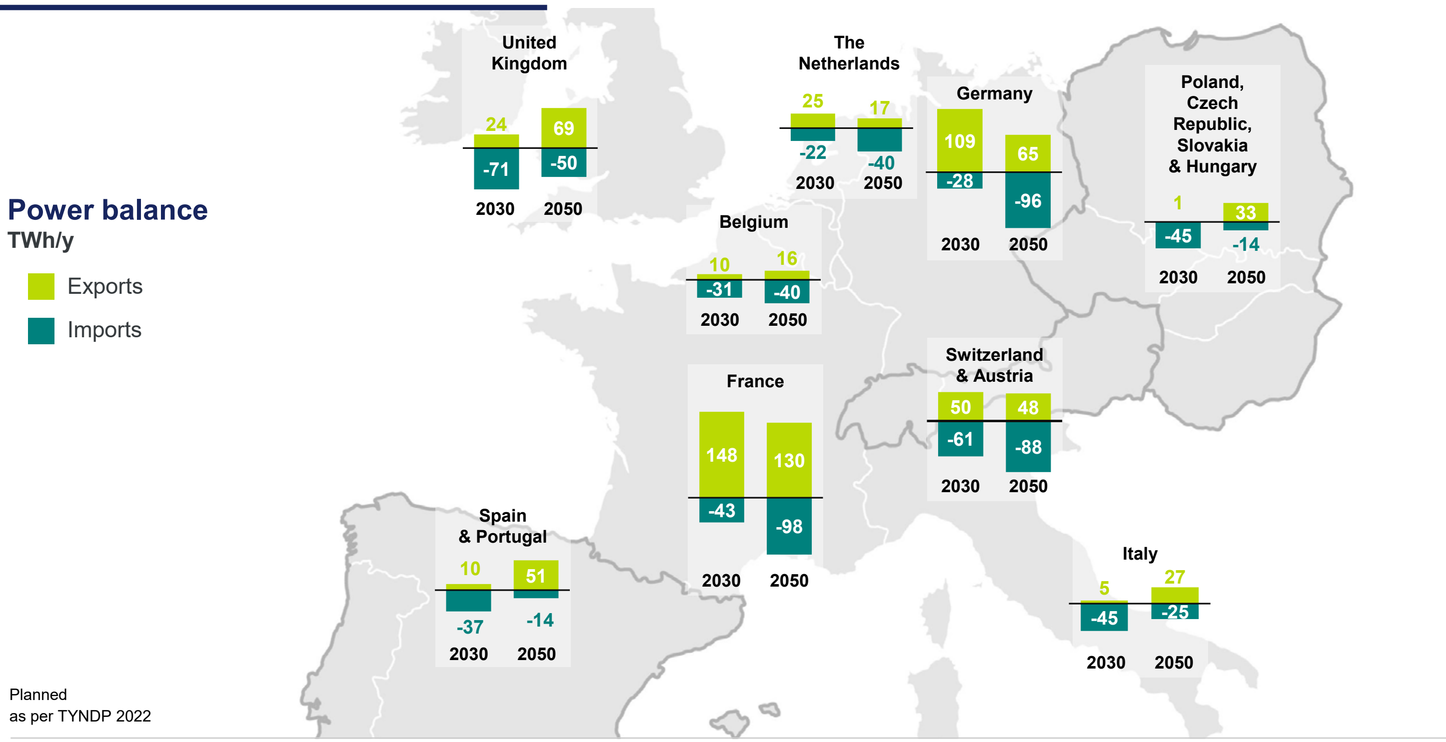


HIGHLIGHTS | Renewable power development

After having recently doubled, the average annual solar and wind power installation rate across Europe-15 must further increase by close to 40% by 2030. This needed deployment should progressively reduce to 2050, at which point the mix will be roughly evenly split between solar and wind.

- **Overall trend:**
  The pace of expansion of renewable energy in Europe, which started over two decades ago, will increase and peak towards the end of the current decade. Strong growth of renewables will continue in the following years. Initially driven by the installation of onshore wind turbines, photovoltaic solutions have recently outpaced the installation of wind power. By 2050 wind and solar capacities should be roughly evenly split, with offshore wind representing 30% of total wind capacity.
- **Recent developments:**
  Europe has showcased its ability to scale up renewable deployments in response to the energy crisis. Despite the challenges posed by COVID, the average yearly installation rate in Europe has doubled between 2020 to 2023 compared to the 2010-2015 period.
- **Acceleration to 2030:**
  To meet the 2030 European emissions reduction target of 55% relative to 1990 levels, Europe will need to further increase its annual capacity installations by around +40% during this decade, reaching 55GW on average over the 2023-2030 period. While a significant increase, this appears within reach given recent evolutions. However, addressing the speed of permitting, the ability to build large projects, and access to the grid for new renewable projects will be critical.
- **Post-2030 growth:**
  The pace of installations should progressively reduce to 2050 to levels closer to those recently observed.

Growth in renewable power production is underpinned by investments in electricity grids that enable to maximize the potential of countries across Europe



HIGHLIGHTS | Power Infrastructures

massive power grid investments are driven by the needs of renewable power capacity connections, grid adaptation to accommodate the electrification of end-uses, and the development of cross border interconnexions.

- **Overall trend:**
  All over Europe, electricity grids will need to keep pace with booming renewable power production and strong electrification. In an optimized energy landscape, power generation assets will be located in such a way as to maximize renewable resources endowment – sun and wind – and deliver competitive power EU-wide to meet national demands.

- **Future interconnections:**
  Europe's map of electricity flows will significantly evolve. Capacity developments will be most significant at the UK's borders with continental Europe, and at the borders of France and Germany to accommodate flows between South-Eastern and Central Europe. From 2030, investments are needed to further strengthen the integration of the Italian peninsula with the rest of Europe.

RECOMMENDATIONS | **Renewables & Power Networks**

SET THE RIGHT INVESTMENT FRAMEWORKS FOR ADDITIONAL RENEWABLE CAPACITIES AND ENSURE A FAIR DEAL FOR ALL CONSUMERS

1. Address price and volume risks for investors/operators through sound design of two-way CfD and PPAs
2. Implement public guarantees to limit credit risk exposure of long-term renewable PPA off-takers
3. Facilitate trans-European green power PPAs / CfDs through access to long term cross-border transmission rights
4. Enable consumers to protect themselves against short-term price volatility via long-term contracts (e.g., PPAs) or fixed-term fixed-price contracts

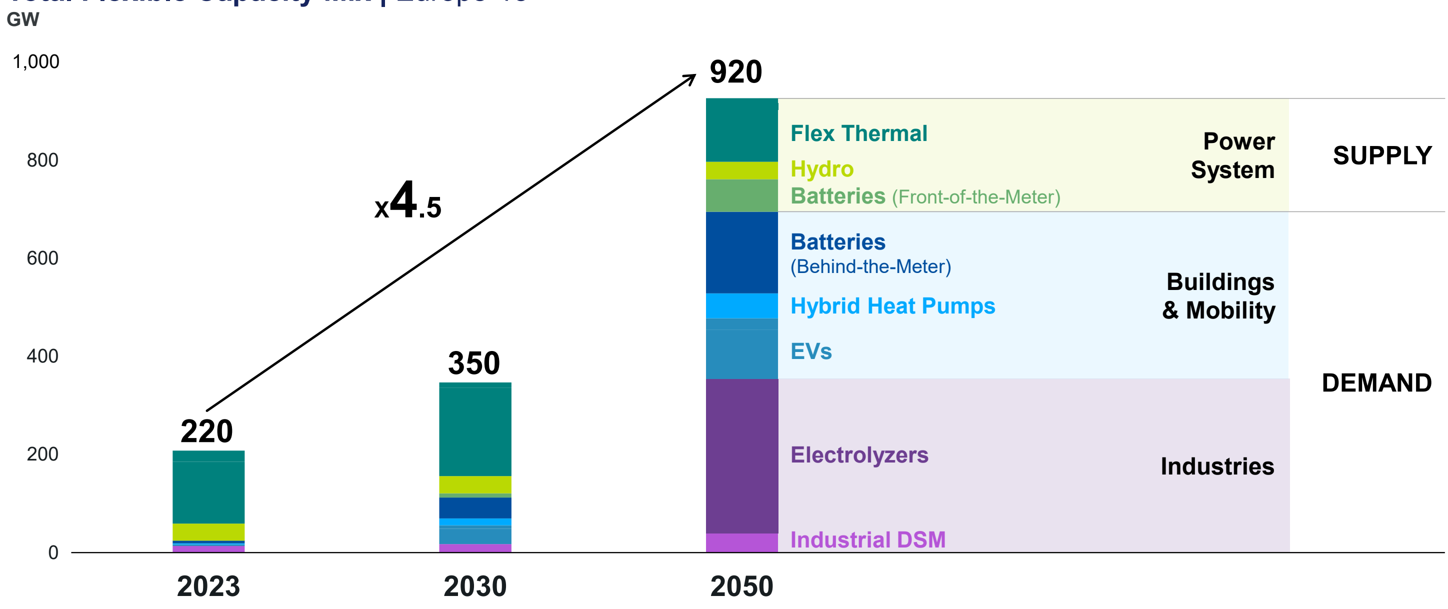
FAST TRACK NETWORK DEVELOPMENTS AHEAD OF RENEWABLES DEPLOYMENT

1. Require infrastructure operators to anticipate grid developments ahead of renewables, Battery Energy Storage System (BESS), as well as H_2 projects.
2. Consider introducing a single entity in charge of coordinating infrastructure development across all energy vectors
3. Facilitate investments of private capital in European energy infrastructures to address investment gap

ACHIEVING EUROPE'S ENERGY TRANSITION

Power system flexibility capacity must be enhanced, in large part through batteries and demand side solutions

Total Flexible Capacity Mix | Europe-15



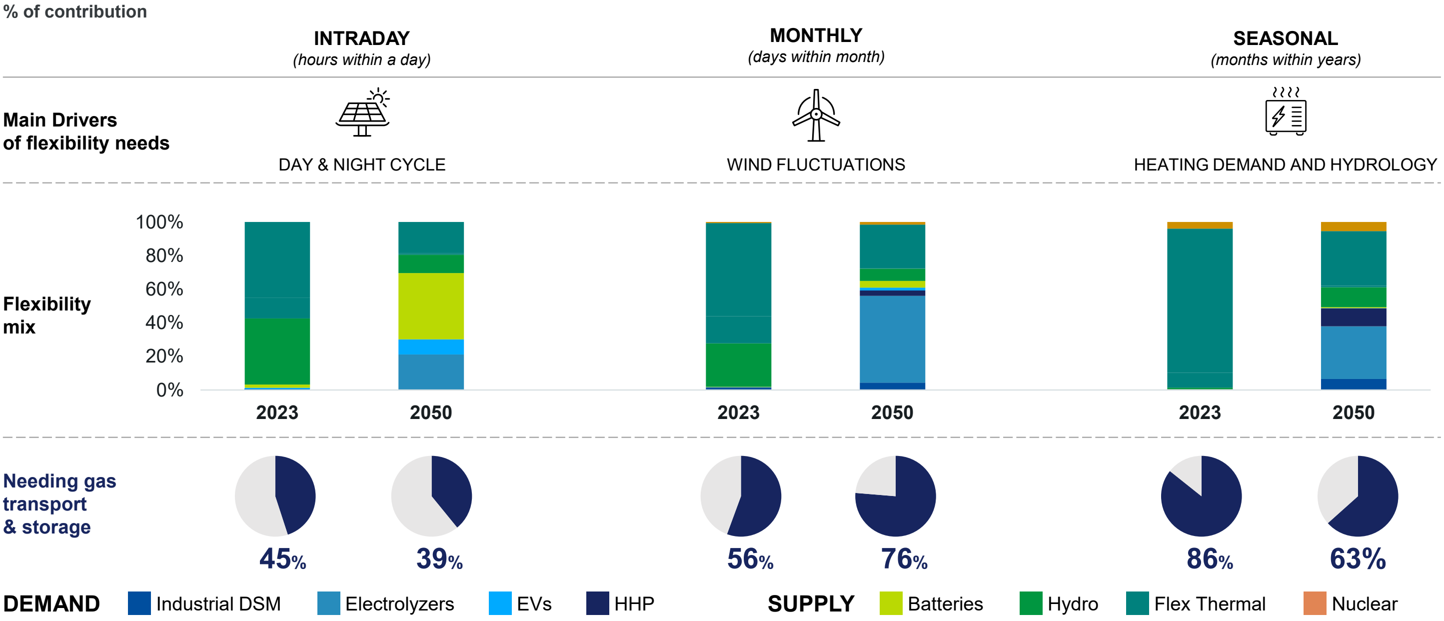
HIGHLIGHTS | Flexibility

Total flexible capacity will need to increase by a factor of 4,5 by 2050, with ¾ of this coming from new sources on the demand side. Flexible electrolysers will play a particularly important role, representing 1/3 of total flexible solutions.

- **Overall trend:** The growing need for flexibility is directly linked to the growth in renewable power generation. In the Net Zero Pathway, total flexible capacity increases by 4.5x and is entirely decarbonized by 2050. While supply side flexibility will continue to play an important role, the most significant increase will be in demand-side flexibility solutions in buildings, mobility and industry. Although playing a limited role today, demand side solutions are anticipated to account for 30% of the flexibility mix in 2030, and 75% in 2050.
- **Industry:** In 2050 the flexible operation of electrolyzers are anticipated to constitute one of the most significant sources of flexibility for the European power system. Electrolyzers will run when power prices are low to optimize their economic profile and will utilize storage infrastructures as well as gas networks to ensure reliable supply to consumers.
- **Buildings and mobility:** Electric vehicles play an important role in flexibility through both smart charging and Vehicle to Grid (V2G) solutions. Hybrid Heat Pumps alone allow to reduce peak capacity needs by 50 GW in 2050. Finally, behind the meter (BtM) batteries are expected to be the dominant types of battery solutions.
- **Power system:** Historically, the dominant provider of flexibility is the power system itself. However, it will represent less than ¼ of total flexibility in 2050. Thermal assets continue to play an important role, particularly for long-term flexibility needs. By 2050, capacity levels are roughly equivalent to today's level and are entirely decarbonized. These are complemented by front-of-the-meter battery solutions.
- **Uncertainties:** While the increasing need for flexibility is clear, the contribution of different solutions is contingent on multiples conditions being met and is therefore intrinsically uncertain. The case of electrolyzers is particularly salient. First, electrolyzers should operate in a flexible manner without significant technical degradation. There is a consensus in the industry that this is possible, however it still needs to be proven at scale and over time. Second, H_2 storage must develop as demand for H_2 will not follow the fluctuation in H_2 flexible production. H_2 can leverage the vast existing natural gas infrastructures, such as salt caverns, but this needs to be demonstrated and operated at scale.

Different flexibility sources are needed over different timeframes

Flexibility activation by time horizon | Europe-15



HIGHLIGHTS | Different flexibility needs

The mix of flexibility solutions will differ depending on the time horizon considered. In 2050, batteries play a dominant role for short duration flexibility, while decarbonized thermal and electrolyzers are the main drivers of weekly and seasonal flexibility. As such, gas storages will continue to be key enabler of power system flexibility.

- **Intraday flexibility:**
  Intraday flexibility needs will increasingly be driven by daily solar cycles. They will increase over time, alongside Solar PV penetration. While intraday flexibility is mainly provided by thermal & hydro assets today, batteries contribution is expected to increase over time and become the main source of intraday flexibility.
- **Monthly flexibility:**
  Weekly or monthly flexibility will increasingly be influenced by the growing penetration of onshore wind. By 2050, the flexible operation of electrolyzers, together with the occasional operation of thermal assets, constitute the main source of monthly flexibility.
- **Seasonal flexibility:**
  The increase in seasonal flexibility needs will be triggered by the electrification of heating solutions, some of which will remain inflexible. These will in large part be met by decarbonized thermal, which is the only supply side flexible solution capable of maintaining a certain level of production level over a lengthy period.
- **Gas storage & infrastructure are an important enabler of power flexibility:**
  Underground gas storages enable the flexible operation of electrolyzers but also the storage of the green gas needed for thermal assets and hybrid heat pump when the power system faces tension. Thanks to their storability, molecules are a critical complement to electrons.

Not developing demand side flexibility levers would have major impact on system viability and costs

HYPOTHESIS

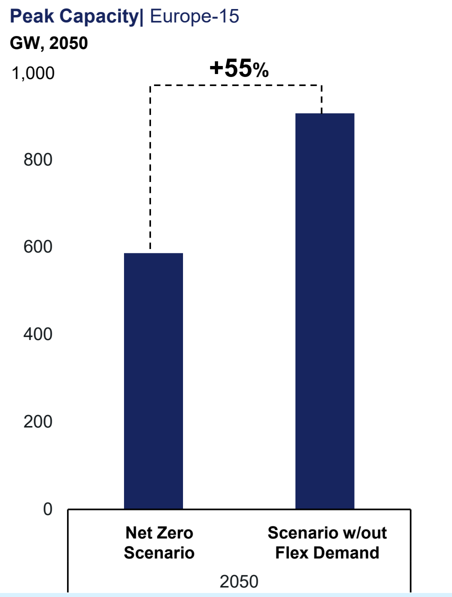
Scenario where only supply side flexibility solutions are developed to complement the growth in renewables (no demand side flexible solutions):

Electric vehicles
Deployed as anticipated, but not contributing to system flex via smart charging or V2G

Hybrid heat pumps
Only Heat Pumps are developed (i.e., no hybrid heat pumps)

Industrial demand side management
Not exploited for system flexibility

Electrolyzers
Limited deployment as per baseload functioning only



KEY IMPLICATIONS

Compared to the Net Zero Pathway

Decarbonization Costs

+70% €150bn/y (avg. 2030-2050)

Average wholesale prices | France

+25% Increase in 2050

*All figures are compared to the Net Zero Pathway Scenario.

HIGHLIGHTS | The role of demand side flexibility

The activation of demand side flexibility has major economic benefits as it reduces peak capacity requirements. It therefore plays an important role in minimizing total system costs.

- **Overall trend:**
  The Net Zero Pathway sees demand-side flexibility represent ¾ of total available flexibility by 2050. However, many sources of uncertainty remain as to the deployment of more distributed, demand-driven sources of flexibility, and especially with respect to electrolyzers or the aggregation and operation of V2G and Behind-the-Meter batteries. To highlight the importance of demand side flexibility we test a scenario where demand side flexibility does not develop and the system is only served by better-known supply-side flexibility solutions, namely batteries and decarbonized thermal solutions.
- **Key implications:**
  Arguably the most important impact of not activating flexible demand is that higher demand levels would require an increase of 55% in peak capacity needs compared to the optimal Net Zero Pathway. Under this scenario, batteries and thermal deployment should increase significantly to compensate for this missing and cost-competitive flexibility. In addition, renewables capacities would have to increase by 55% to contribute to meet peek needs. As such, total system costs would further increase by +70%, (€150bn/y) and, for example, in France, the average wholesale price would be roughly 25% higher.

RECOMMENDATIONS | **Flexibility**

INCENTIVIZE DEVELOPMENT OF BOTH DEMAND AND SUPPLY SIDE FLEXIBILITY SOLUTIONS

Faced with the rapid development of renewables, and in particular to deal with more frequent negative price episodes in Europe:

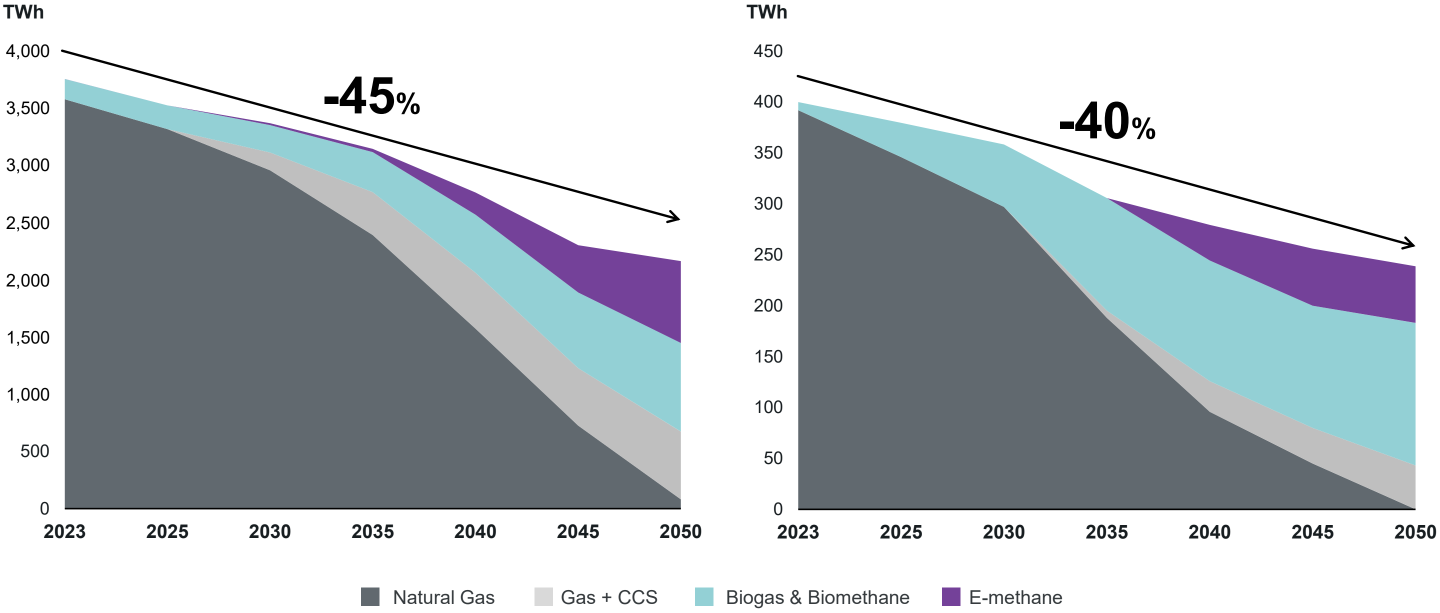
1. **Demand-side flexibility solutions**
   Introduce specific incentives to fully valorize the system-level flexibility attributes of demand side solutions, such as Behind-the-Meter batteries, Hybrid Heat Pumps, EV charging, electrolyzers, and industrial demand management

2. **Supply-side flexibility solutions**
   Develop instruments - such as capacity mechanisms - to incentivize all necessary flexibility solutions both on short duration (e.g., batteries, renewables) and long duration (e.g., decarbonized thermal assets), align them as much as possible at European level to create a common level playing field and accelerate their approval by the European Commission.

ACHIEVING EUROPE'S ENERGY TRANSITION

Methane demand is reduced massively and is entirely decarbonized by 2050

Methane demand | Europe-15 | **Methane demand |** France



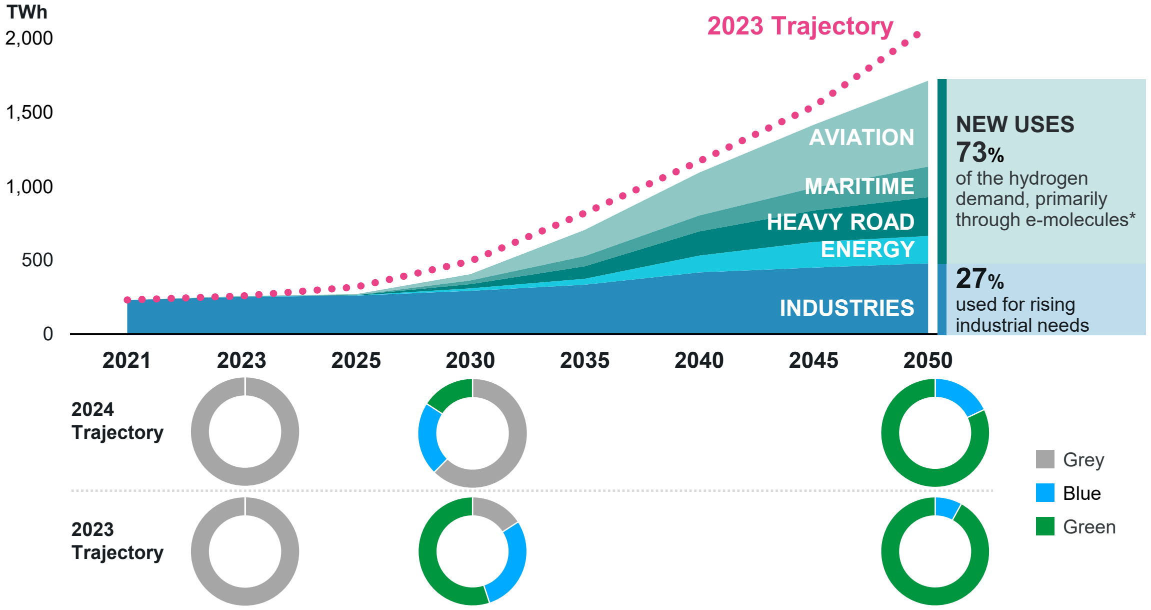
HIGHLIGHTS | Methane Demand

Methane demand will decrease by 45% by 2050. It will be fully decarbonized through biomethane, e-methane, and natural gas with carbon capture and storage (CCS).

- **Overall trend:**
  Methane demand is set to reduce by 45% by 2050 at Europe-15 scale, and 40% in France. At the same time methane supply will be progressively decarbonized. By 2050 the European methane supply mix will be split roughly evenly between biomethane/biogas, e-methane, and natural gas with CCS. Biomethane in France will represent closer to 60% of the decarbonized methane supply mix in 2050 given the higher biomethane potential.
- **Industry maturity:**
  All three low-carbon sources of methane require industrialization efforts. Biomethane/biogas account for a small share of methane demand today (<5% at European scale) and its production will need to be multiplied by 1.5x by 2030 and 5x by 2050. CCS and e-methane are still at early stages today and are anticipated to breakthrough only towards the middle of this and next decade respectively.
- **Local production vs imports:**
  Europe-15 import dependence of natural gas today stands roughly at 85%. By 2050 we estimate methane dependency to reduce to 55%, primarily driven by European biomethane production. The remaining imports will be associated to e-methane, which we assume the vast majority to be imported, and natural gas (assumed to be imported in the same proportion as today) with CCS.

Low-carbon hydrogen deployment is delayed and reduced compared to what was anticipated in the 2023 Net Zero Pathway for Europe.

Hydrogen demand | Europe-15



x7 total demand increase vs 2023

70% produced in Europe-15

Extra Europe-15 imports primarily via e-molecules

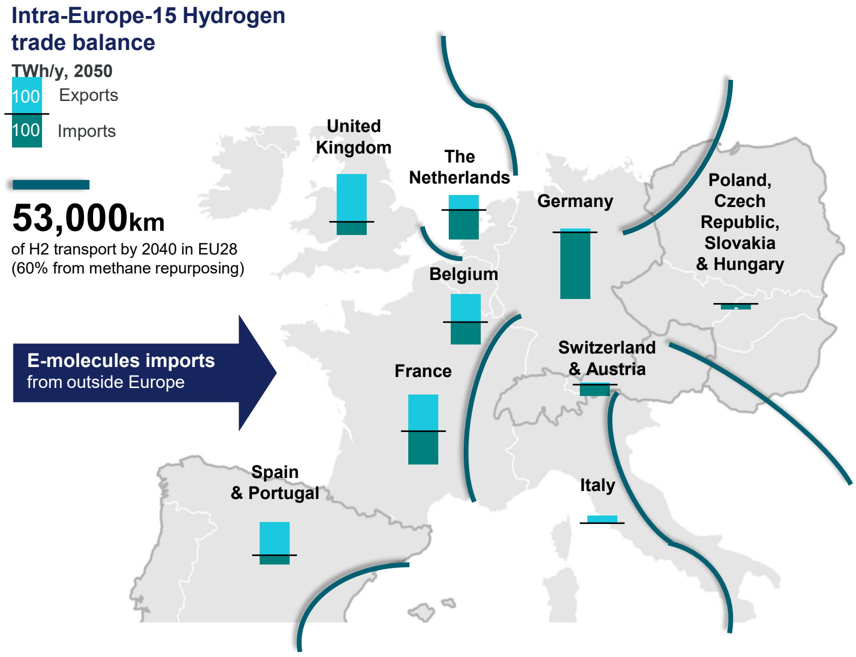
* e-ammonia, e-methanol, e-kerosene, e-diesel

HIGHLIGHTS | Hydrogen and e-fuel demand

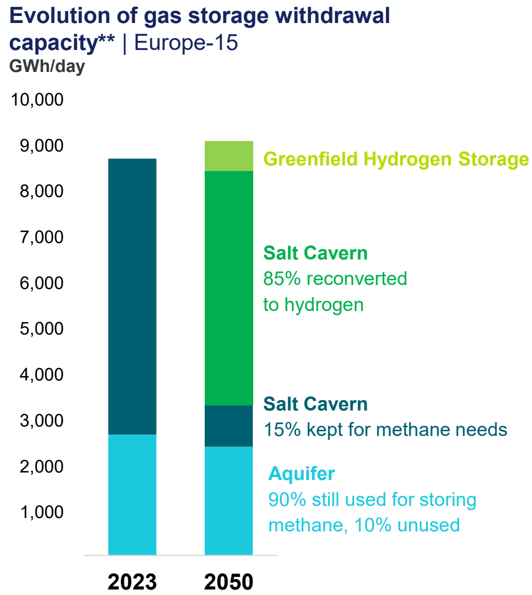
7-fold increase in hydrogen demand by 2050, with new uses outside industry accounting for close to ¾ of total demand by 2050. Despite delays in adoption, hydrogen will be entirely decarbonized by 2050, primarily via green hydrogen, though blue hydrogen will play a more significant role than previously anticipated.

- **Overall trend:**
  Demand for hydrogen & other hydrogen derived molecules, such as ammonia and e-fuels, will grow seven-fold between 2023 and 2050. These fuels will play a critical role in the decarbonization of sectors that cannot be electrified, such as maritime (alongside biogas), aviation (alongside biofuels), or steelmaking (alongside natural gas with CCS). By 2040, we anticipate hydrogen production to be fully decarbonized, primarily via green hydrogen, which will be complemented with blue hydrogen.
- **Local production vs imports:**
  We anticipate 70% of hydrogen and e-fuels demand to be produced within Europe, with the remainder being imported primarily in the form of e-fuels. By 2050, only one third of Europe's e-fuels demand can be competitively produced within Europe, the remaining two thirds should come from extra EU imports. Import of e-molecules will be necessary to minimize decarbonization costs as it enables access to remote, cheap, green electricity while leveraging existing import infrastructures.
- **Main changes vs 2023:**
  Compared to the previous edition of ENGIE's Decarbonization Pathway for Europe, forecasts of long-term hydrogen supply have been revised downwards by 20%. This is primarily driven by recently published EU requirements for the decarbonization for aviation and maritime sectors. We estimate emissions reduction from these sectors to reach -75% vs 1990, as opposed to the full decarbonization assumed in the 2023 edition of our Net Zero Pathway. In addition, our updated Net Zero Pathway also considers a 5-year delay in the deployment of electrolyzers to reflect some of the challenges the industry has been facing in recent years.

A European hydrogen transport and storage system which leverages existing methane infrastructure to reduce total system costs



Planned as per Hydrogen Backbone Initiative



*Aquifer are part of porous reservoir storage capacity (mainly located in France)
**Conversion of Depleted fields to H_2 storage not investigated, but a possible long-term option.

HIGHLIGHTS | Hydrogen & Methane Infrastructure

Thanks to the development of an H_2 backbone mainly based on retro-fitted natural gas infrastructures as well as repurposed gas storage assets, the South and West of Europe, which concentrate better H_2 producing locations, will be connected to the North and East of Europe where important demand clusters are based.

- **Overall trend:**
  European countries are endowed with different renewable potentials which only a connected market via transport, distribution, and storage infrastructures can correctly exploit and maximize. Low carbon molecules can largely use existing methane infrastructures to rapidly and cost effectively adapt to a net zero energy system.
- **The evolution of methane infrastructure:**
  While methane demand is anticipated to reduce significantly, gas infrastructures will continue to play an important role in an increasingly decarbonized energy system. They will be used to collect and distribute green gases, enable the flexible use of electrolyzers as well as the combination of natural gas with CCS. LNG terminals will be used by the end of the next decade to also import e-molecules and to export CO_2.
- **Hydrogen Backbone:**
  Adapting the gas network will be pivotal to enable hydrogen flows across Europe. France will play a transit role 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.
- **Hydrogen and Methane Storage:**
  The energy system will continue to use existing gas storages as a means of flexibility. 85% of existing salt caverns will be converted to H_2 storages, significantly limiting costs and accelerating speed of deployment. We estimate only a limited need for new H_2 storage capacities. In addition, the bulk of existing aquifer gas storages will continue to be used for methane seasonal flexibility.

RECOMMENDATIONS | **Low-carbon gases**

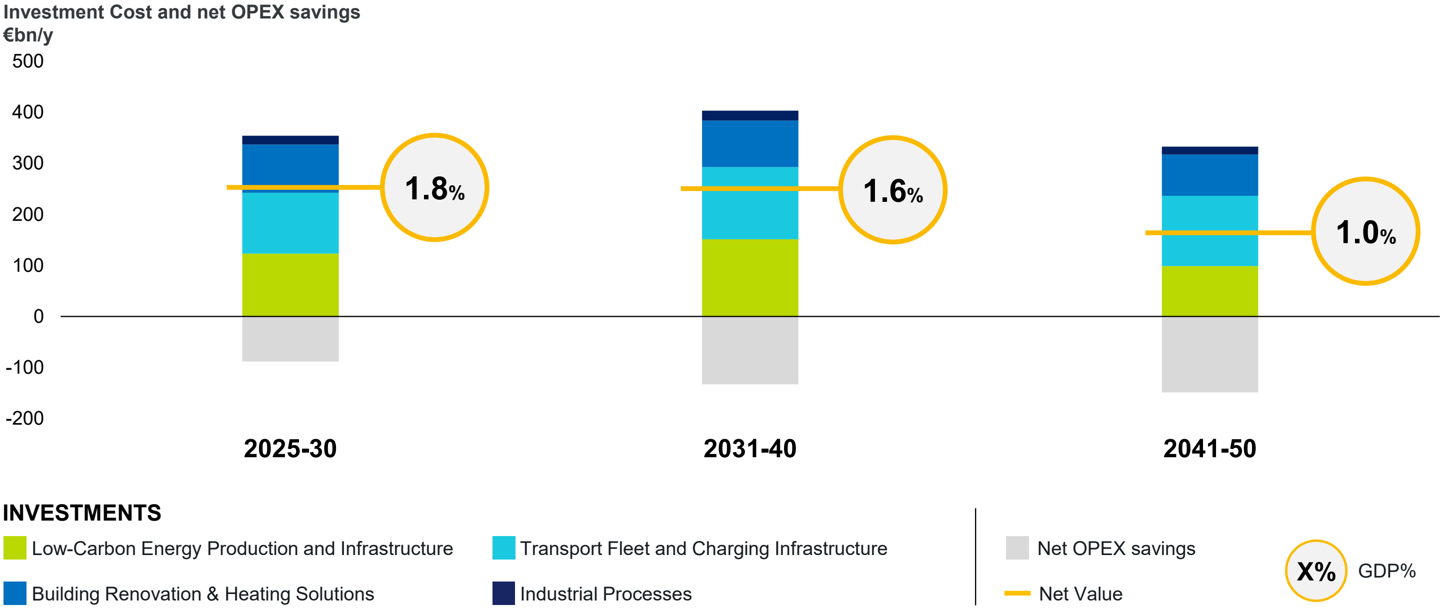
LEVERAGE ALL LOW-CARBON AND RENEWABLE GASES FOR A COST-EFFICIENT TRANSITION

1. Articulate low-carbon gases objectives based on carbon content and rely on solid certification and traceability.
2. Boost large scale demand for renewable and low carbon gases in hard-to-abate sectors through public subsidies – targeting hydrogen (H_2), e-fuels, CCS (carbon capture and storage), and biomethane

ACHIEVING EUROPE'S ENERGY TRANSITION

Investments necessary for the decarbonization of Europe are gradually partially offset by savings in fossil fuel

Decarbonization Costs & Savings | Europe-15



Costs excludes taxes & CO_2 prices

HIGHLIGHTS | Decarbonization Costs

When incorporating net OPEX savings, total decarbonization costs progressively reduce from 1,8% to 1% of GDP. Energy and transport represent the bulk of investments.

- **Overall trend:** Decarbonization costs are assessed for energy, transport, buildings and industry. These costs include both investments and operational expenses (OPEX). Investments increase slightly over the coming decade to peak at ~400bn/y for the Europe-15 region. At the same time, net OPEX savings will increase steadily, primarily driven by savings in fossil fuels resulting from investments in decarbonized solutions. Taken together the net cost should peak this decade, reaching ~1.8% of GDP, and reduce over time to reach ~1% of GDP on average for the 2041-2050 period.

- **Energy production and infrastructure investments**: account for roughly 35% of total investments across the 2025-2050 period. Energy related investments include all low-carbon production and fuel expenses across the economy (e.g., wind & solar assets, biomethane, hydrogen & e-fuels, etc.), as well as power and gas infrastructures.

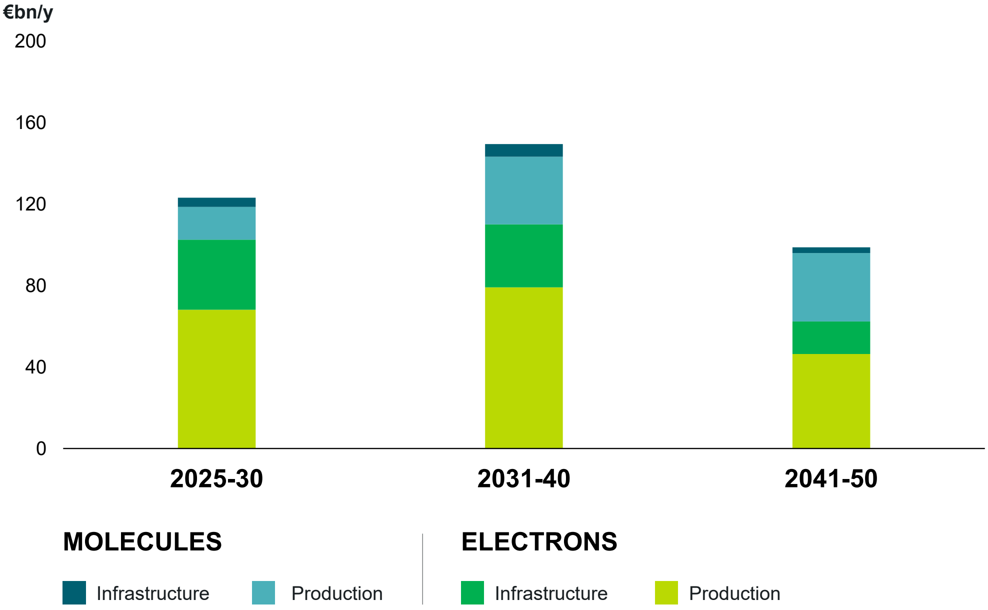
- **Transportation investments**: Also account for roughly 35% of the total investments, they cover the evolution of fleets and investments in charging infrastructures. EVs reach cost parity with internal combustion engine (ICE) vehicles before 2035 without government support, and therefore contribute to reduce expenditures. Still, important investments remain in charging infrastructure, light- and heavy-duty trucks, as well as aviation and maritime.

- **Building sector investments:** These consist of renovations and changes in heating equipment and are the third most important driver of decarbonization investments, accounting for 25% of total investments on average.

- **Industry investments**: The decarbonization of industrial processes account for 5% of total investments on average. The bulk of industry decarbonization comes from energy expenses (accounted for in the energy sector). For example, primary steel, produced in blast furnaces, will be decarbonized via H_2 and methane via direct reduced iron (DRI) processes.

Power generation and networks account for the majority of investments needed to decarbonize the energy sector

Investments in low-carbon energy production and infrastructure by energy carrier | Europe-15



Costs excludes taxes & CO_2 prices (tax recycling)

6x

Investments in electricity vs gas infrastructure

HIGHLIGHTS | Energy Investment

The majority of energy investments will go to the power system, although the share of gas will increase to reach 40% by 2050. The investments in power infrastructures are 6 times higher than those in gas infrastructures.

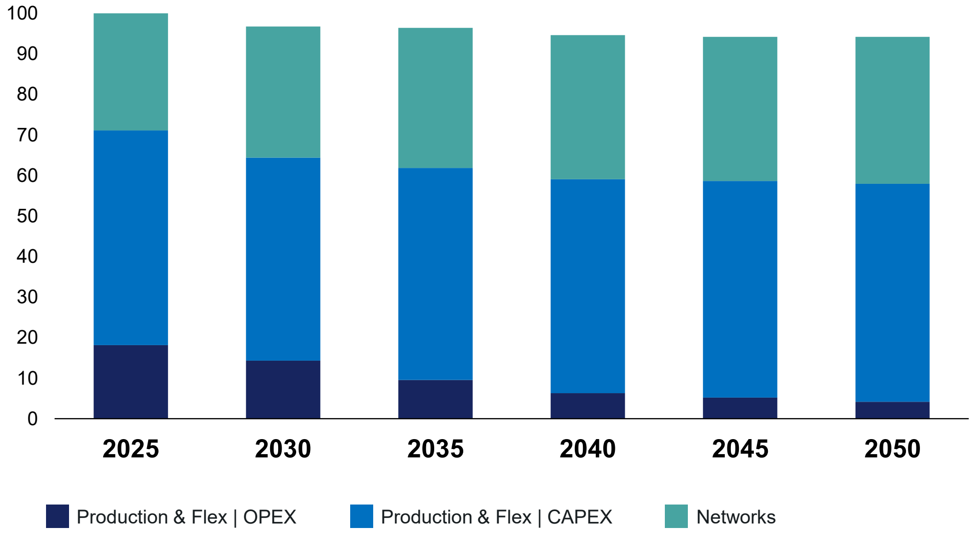
- **Overall trend:**
  Driven by the electrification of the European energy mix, decarbonization investments in power largely dominate overall decarbonization investment in the energy sector. These account for over 80% of the total annual investments between 2025-2030 and progressively reduce to slightly above 60% by 2041-2050. In contrast, investments in the decarbonization of molecules gain importance over time as investments for hard to abate uses progressively accelerate, notably to decarbonize heavy industries and transport, these account for less than 40% of average total annual investments at their peak over the 2041-2050 decade.

- **Infrastructure:**
  Power and gas network investments account for 20-30% of total energy sector investments over the entire 2025-2050 timeframe, with power networks requiring on average 6 times more investments than gas. This is explained by the fact low carbon gases are expected to largely be based on the use of existing natural gas infrastructure (transport, distribution, storage, and terminals), but require limited greenfield investments compared to power.

Despite important investments, total power system costs per unit of energy produced are expected to remain stable

Total Power System Cost | Europe-15

Annualized €/MWh, Index 2025 = 100



Costs excludes taxes, subsidies & CO_2 prices (tax recycling)

-10%

Estimated average wholesale prices France, 2050
Net Zero Pathway
vs average actual 2023-24

HIGHLIGHTS | Total Power System Cost

Total power system costs per MWh produced should remain roughly stable, while wholesale prices could reduce slightly.

- **Overall trends**:
  Total power system costs include generation and flexibility CAPEX and OPEX as well as transmission & distribution network costs. Despite the growth in demand, on a unit cost basis, total costs follow a slight downward trend between 2023 and 2050. This is driven by the relative reduction in production fuel costs per electricity produced, which is partially compensated by the increase in network costs. This trend is explained by the importance of wind and solar investments as their adoption translates in a cost base transitioning from fuels (natural gas or coal) to essentially CAPEX.
- **Wholesale prices evolution**:
  Though there is much uncertainty in how prices will evolve over the long term, a simplified price model of this optimized scenario indicates that, for example in France, wholesale prices would decrease by roughly 10% compared to observed average prices over the 2023-2024 (year-to-date) period and 2050. This price trajectory is linked to key underlying assumptions:
  i. the existing market design where prices are set by the marginal technology is maintained,
  ii. a “perfect foresight” optimization where demand evolution and fuel prices are fully anticipated on the entire horizon to build an optimal power mix,
  iii. the deployment of efficient demand side flexibility solution (as described in the flexibility section) without which wholesale prices could increase.

RECOMMENDATIONS | **Decarbonization Costs**

ENSURE MORE EFFECTIVE FUNDINGS FOR THE ENERGY TRANSITION

1. Financial support allocated to the decarbonization of the different sectors should be coherent with total decarbonization costs of each sector
2. Access to financial support should be simplified via a one-stop-shop for all EU funds and granted funds must be disbursed quickly.
3. Simple mechanisms to compensate funding gaps, like the European Hydrogen Bank providing a fixed premium for renewable hydrogen, are favorable but must consider realistic market conditions.
4. The announced new ‘EU Competitiveness Fund’ must efficiently support competitive industrial projects and deliver the much-needed simplification of the IPCEI process.

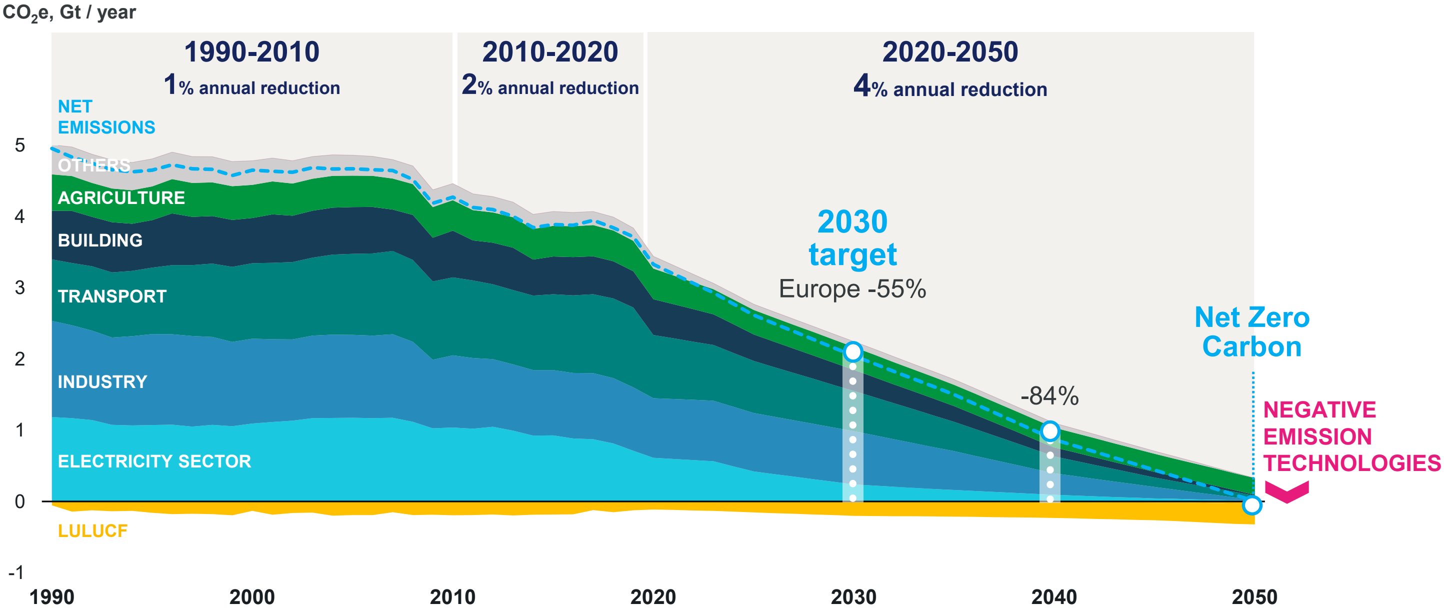
ENERGY TRANSITION AS A LEVER FOR REINDUSTRIALIZATION IN EUROPE

1. Focus support on energy transition technologies which have the highest strategic and competitiveness value to Europe, such as wind turbines and electrolyzers, and concentrate financial, commercial (e.g., “Made in Europe” label) and regulatory efforts on these value chains.
2. Swiftly implement technology-specific non-price criteria (NZIA) for renewable auctions that are harmonized across Europe and reach a level playing field that facilitates investments by manufacturers and avoids competition between European Member States.

ACHIEVING EUROPE'S ENERGY TRANSITION

Emissions reductions must accelerate across all economic sectors to achieve Europe's Net Zero target

Greenhouse gas emissions | Europe-15



LULUCF: Land use, land use-change and forestry

HIGHLIGHTS | Emissions by sectors

Emissions reductions must continue their acceleration to reach the 2050 objective, from 1% to 2% historically, and to 4% per year to 2050. All sectors will need to contribute to Europe's emissions reductions.

- **Overall trend:**
  Europe has progressively accelerated its rate of decarbonization over the last decades, from 1% annual reductions between 1990 and 2010, to 2% between 2010 and 2020. However, reaching Europe's 2030 and 2050 decarbonization objectives will require a further acceleration of emissions reductions to reach 4% per year.
- **Sectoral dynamics to 2030:**
  During the last thirty years, power and industry sectors have substantially contributed to Europe-15 decarbonization, accounting for more than 60% of the observed reduction in emissions. From now until 2030, decarbonization efforts will be driven by the electrification of transport and industry, combined with the continued decarbonization of electricity generation. Power sector emissions will fall by more than 80% by 2030 compared with 1990 levels.
- **Sectoral dynamics post 2030:**
  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 low-carbon molecules (biomethane, hydrogen, e-molecules) needed primarily to decarbonize hard-to-abate sectors such as the cement, steel, and chemical industries, as well as heavy transport (trucks, maritime, aviation).
- **Negative emissions:**
  The development of land and forestry based negative emissions (LULUCF) is needed to offset remaining emissions, notably from Agriculture[1].

* European Commission: Impact Assessment on a 2040 Climate Target, 2024

RECOMMENDATIONS | **Emissions**

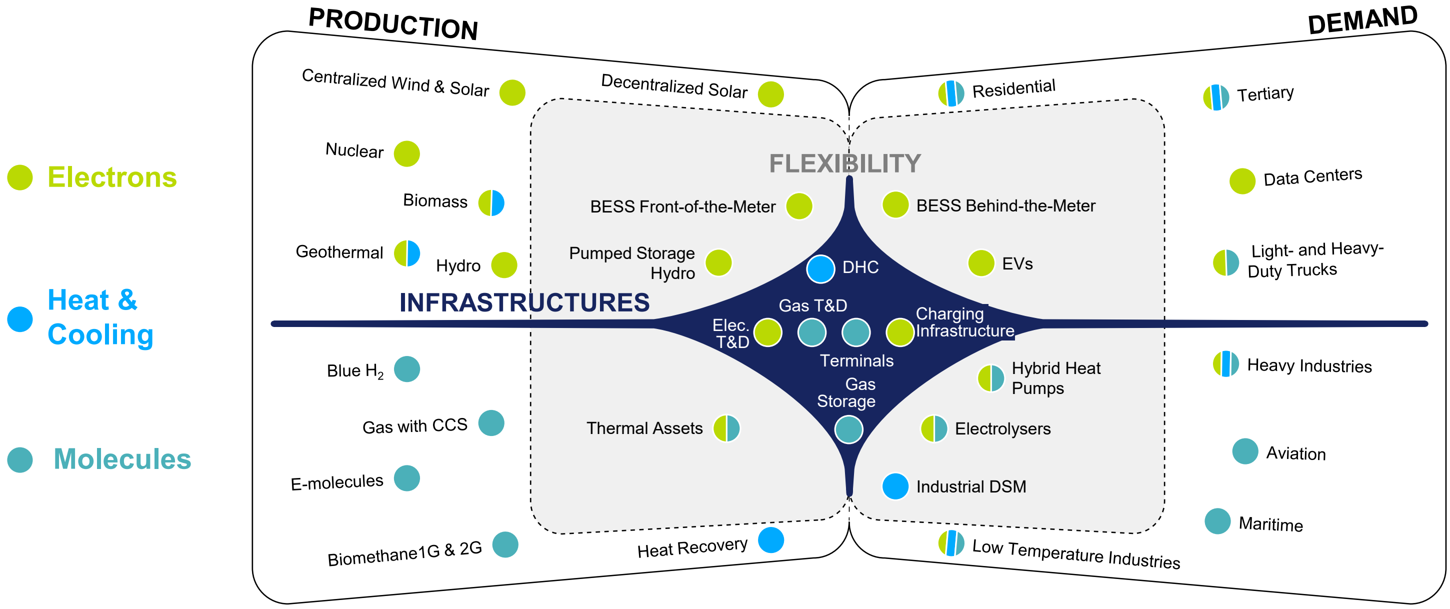
RAMP UP THE CO_2 ECONOMY

1. Introduce a minimum carbon price in Europe
2. Establish an EU Action Plan for CCS and CCU, with realistic deadlines (e.g. phasing out of industrial CO_2 by 2041)
3. Integrate high quality carbon removals, of which bio-energy carbon capture and storage technologies, into the EU-ETS, and simplify the management of carbon schemes at European level. For instance, consider a European CO_2 entity to centrally govern CO_2 instruments (ETS 1 / ETS 2, removals, aviation, etc.)
4. Encourage the utilization of biogenic CO_2 in synthetic fuels, while extending the use of CO_2 from other sources

ACHIEVING EUROPE'S ENERGY TRANSITION

The energy transition requires the transformation of the entire energy system

Components of Europe's 2050 net zero energy system

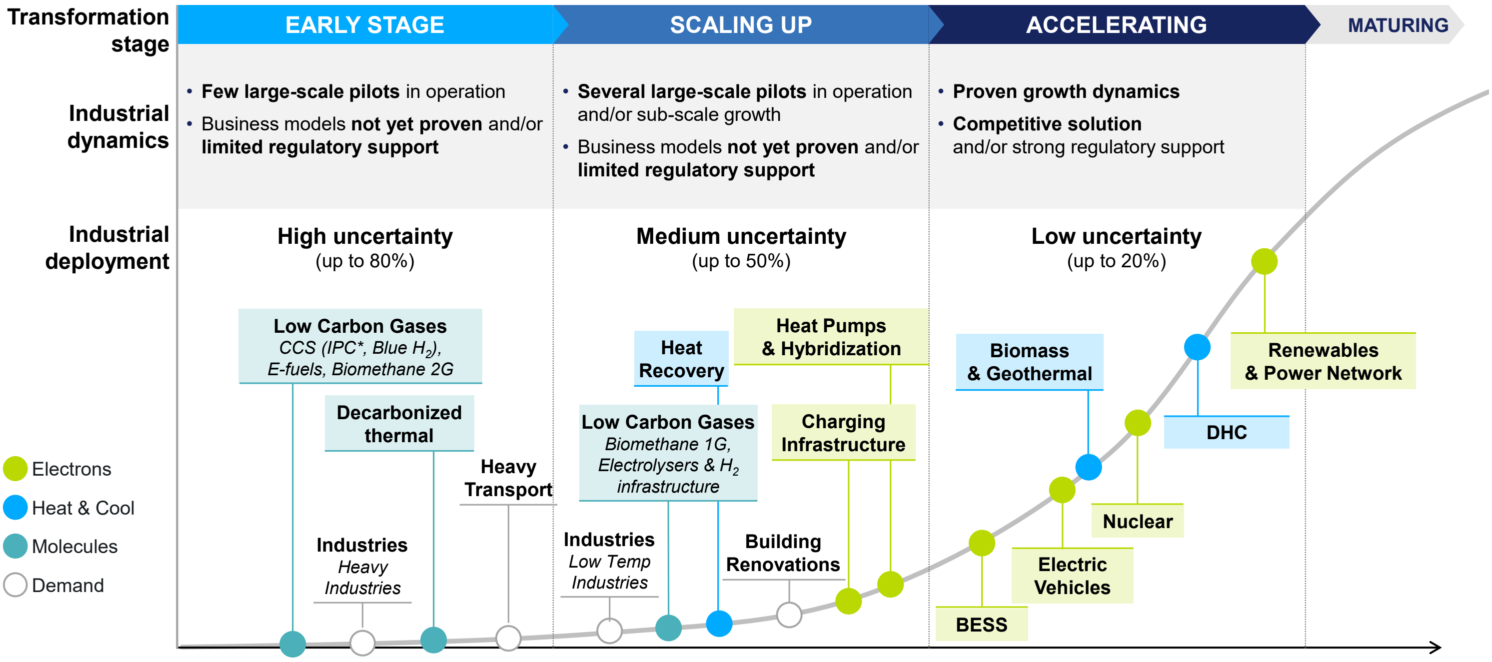


HIGHLIGHTS | Components of Europe's 2050 Net zero energy system

The energy transition requires the transformation of the entire energy system from supply to demand, infrastructure to flexibility, and covering electrons, molecules, as well as heating and cooling.

- **Overall trend:** Achieving the energy transition will require a complete transformation of the energy system. This includes transforming production and supply levers, as well as energy demand levers, such as residential and tertiary buildings, transportation, and industry. This also entails transforming how the power system remains in balance and secure via decarbonized flexibility levers across both supply and demand. Finally, this also requires the transformation of how energy is transported, distributed, and stored via energy infrastructure. This complete transformation must take place across power, gases, heating and cooling. The interconnectedness of energy transition levers is such that any delay in the transformation of one lever will likely have knock-on impacts on the ability of others to transform.
- **Production:** To successfully reach Net Zero, the production mix will need to rely on both centralized and decentralized renewable power sources such as wind and solar, as well as nuclear power. Biomass, waste-heat and geothermal will provide renewable heat to DHC networks and low temperature & heavy industries. Green molecules such as biomethane, green hydrogen and e-molecules will support decarbonization in hard to abate sectors, such as heavy industry or maritime. other supply side solutions, such as hydro, batteries and thermal assets will also provide flexibility to the power system.
- **Infrastructure:** Infrastructure development is critical to enable rising electrification, the valorization of heat on a large scale, and the integration of green molecules. Additionally, they enable sector coupling across the different energy vectors. Despite this, infrastructure is a critical bottleneck for the development of decarbonized value chains. For instance, wind and solar connection to the grid takes on average twice the time of project development.
- **Demand:** Residential and tertiary buildings as well as low-temperature industries, and light transportation will increasingly adopt renewable electricity produced from wind, solar and nuclear power. When electrification is no longer feasible or economical, green molecules will support the decarbonization process. Demand-side management, smart charging, vehicle-to-grid, and the use of hybrid heat-pumps will support system flexibility.

The components of Europe's net zero energy system are today at different stages of transformation



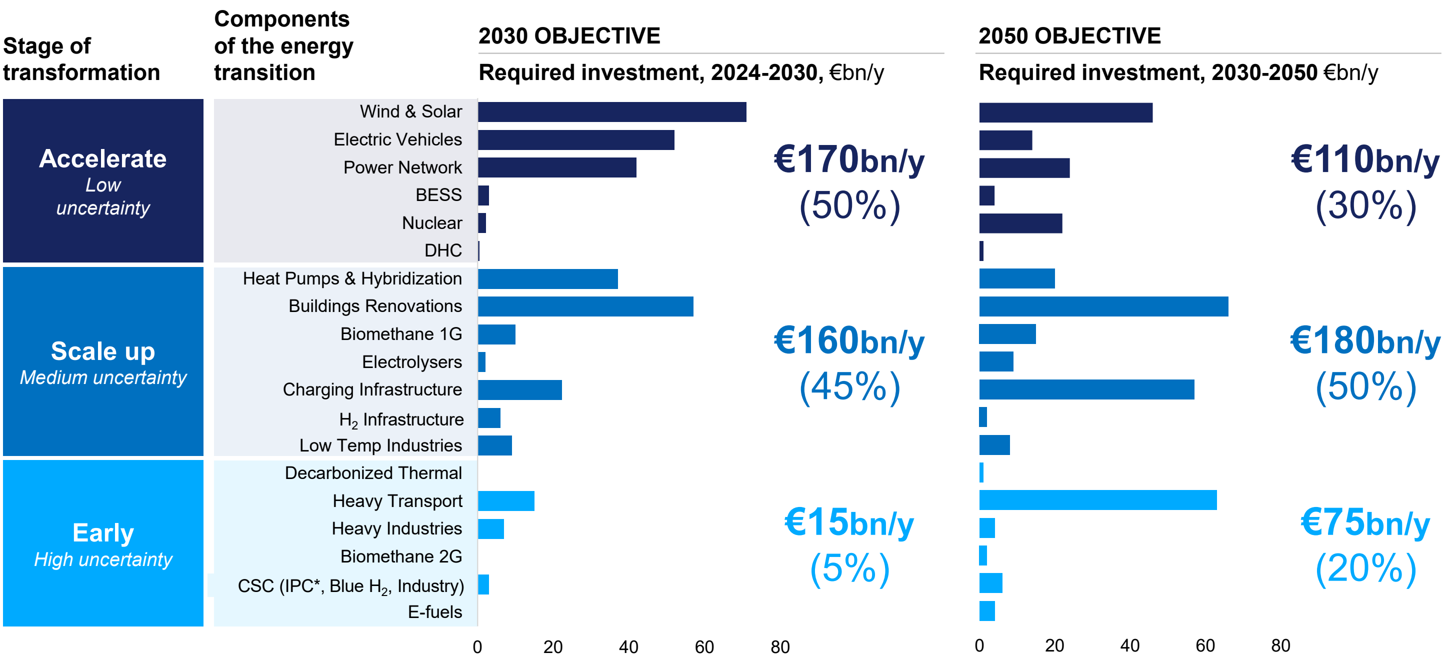
*IPC: Industrial Point Source Capture

HIGHLIGHTS | Energy transition levers maturity

The components of Europe's Net Zero energy system are at different stages of transformation. These are driven by the stage of industrial development (few pilots to proven growth), the maturity of the underlying business model and/or of the regulatory support. The earlier the transformation stage, the higher the uncertainty in industrial deployment and the risks of lagging behind compared to the identified Net Zero Pathway.

- **Overall trend:**
  Three main stages of transformation can be distinguished. A more mature "accelerating" phase, where solutions have proven growth dynamics and demonstrated their competitiveness with clear regulatory support; a "scaling up" phase, where growth is picking up through several large-scale pilots, though business model and regulatory support still needs to be proven; and finally an "early stage" where only few industrial pilots exist globally and the business model remains far from proven.
- **Accelerating category:**
  These solutions have limited deployment uncertainty, estimated to be ~20% of the total need to reach the Net Zero Pathway. The more established green technologies are in this category - in particular the ones associated to electrons, such as wind & solar, BESS, power grids, electric vehicles, and Nuclear.
- **Scaling up category:**
  These solutions are associated to a higher deployment uncertainty, estimated to be ~50% of the total identified needs to reach the Net Zero Pathway. Electrolyzers and building renovations are examples of critical levers falling into this category. While building renovations highlight less of a technological challenge, their implementation is hindered by fragmentation and a difficult business model with excessively long payback periods.
- **Early-stage category:**
  These solutions are associated to a high deployment uncertainty, estimated up to ~80% of the total identified needs to reach the Net Zero Pathway. Included within this category are CCS and e-fuel chains, as well as aviation and maritime decarbonization.

Achieving Europe's decarbonization objectives implies shifting investments towards portfolios of solutions at earlier stages of transformation



***IPC**: Industrial Point Source Capture

HIGHLIGHTS | Required Investment

The investments required to successfully meet Europe's 2030 targets and Net Zero by 2050 differ in terms of their balance across the different stages of transformation.

- **Overall trend:**
  The 2030 target requires a higher proportion of more mature solutions, in particular renewables, EVs, and power networks, and fewer investments in solutions at earlier stages of transformation. In contrast, meeting the 2050 Net Zero objective will require a higher proportion of investments in solutions at earlier stages of transformation (e.g., heavy transport and charging infrastructure). Importantly, building renovations and associated electrification via heat pumps and hybridization play a major role throughout the full time-horizon.

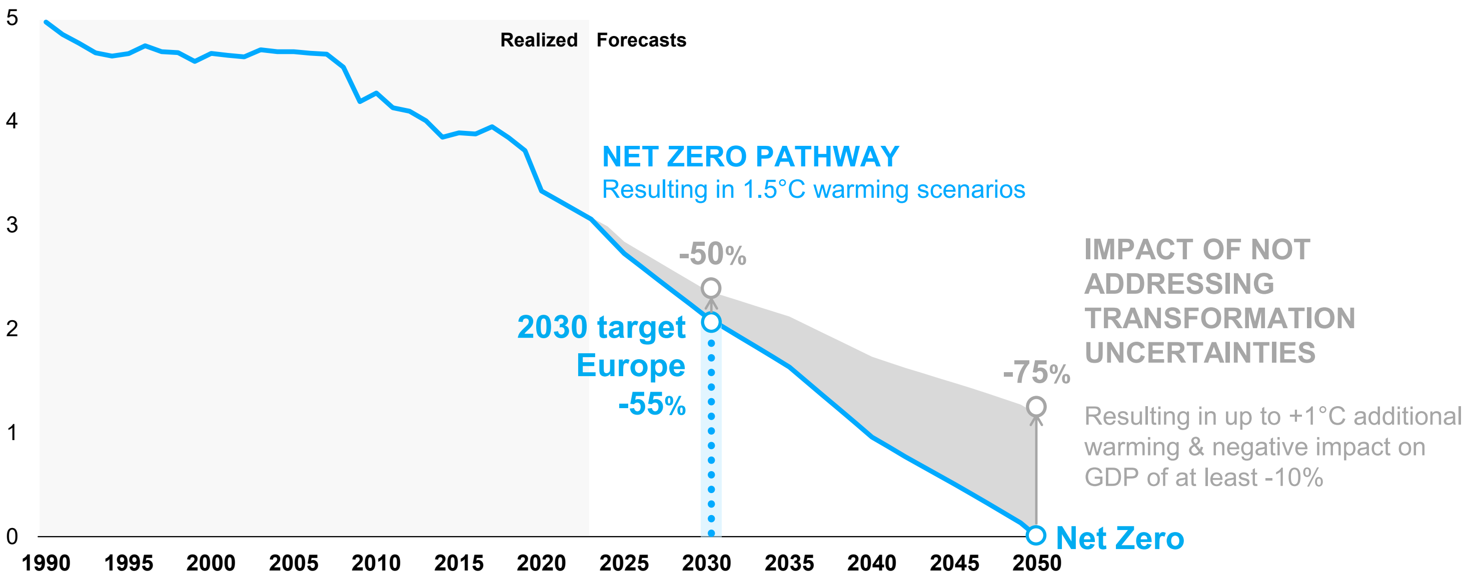
- **Reaching Europe 2030 objectives pathway:**
  50% of the investments needed to reach the 2030 objectives are within the most mature "accelerating" category. More than 95% of investments are covered within "accelerating" and "scaling up", while only 5% are associated to the levers in the "early" stage. The most significant investments are around wind and solar, electric vehicles, and power networks, as well as building renovations and heating systems.

- **Reaching 2050 objectives pathway:**
  In contrast to 2030 objectives, only 30% of 2030-2050 investments fall within the more mature "accelerating" phase. A larger part of investment will be needed in solutions at earlier stages of transformation – including early-stage levers. The lion share of the investments in this latter category comes from heavy transport, and in particular the development of electrical trucks, hydrogen and low carbon gas trucks or tri-fuel ships.

These transformation uncertainties imply that Europe could miss its targets if actions are not taken to ensure the timely development of all necessary solutions

Net Greenhouse gas emissions | Europe-15

CO_2e, Gt / year



Sources: ENGIE Analysis CO_2, GDP: Kotz et al. (2024), Bilal & Kanzing (2024)

HIGHLIGHTS | Emissions trajectory with deployment risks

The net zero pathway trajectory is at risk. Risks exist by 2030 but should be limited to 5% of total 1990 emissions. By 2050 the extent to which the objective could be missed increases to 25% of total emissions. This emission gap could trigger significant GDP losses (up to 10% per year).

- **Overall trend:**
  The energy transition deployment uncertainties create a risk that Europe may miss its decarbonization objectives.
  The risk is even more significant for Europe's 2050 objective given the greater role of energy transition solutions at earlier stages of transformation.
- **Risks to 2030 objectives:**
  We estimate the uncertainty range to be limited, with Europe most likely to reduce emissions by between 50 and 55% vs. 1990 levels, the latter being the objective set by Europe's Fit for 55 program. This is primarily due to the more mature levers needed to achieve 2030 objective but also to the more limited time horizon remaining. Nevertheless, the target remains at risk and notably requires the continued penetration of electric vehicle sales, the fast-tracking of power infrastructure investments, and the scale up of building renovation.
- **Risks to 2050 objectives:**
  In contrast to the 2030 objectives, we estimate that the identified deployment uncertainties lead to a much broader range of possible emissions by 2050, from -75% emissions reductions to -100%, the latter corresponding to net zero.
  The worst-case scenario corresponds to a +1°C of additional global warming, which based on latest climate economics research is estimated to have a negative impact on GDP of ~10% per year.

ACHIEVING EUROPE'S ENERGY TRANSITION

10 bold measures to achieve Europe's objectives

TRANSVERSAL	1	Introduce a carbon price floor increasing over time
	2	Optimize the energy system at European scale
SUPPLY	3	Remove regulatory bottlenecks for renewable power deployment and facilitate trans-European green power PPAs / CfDs* through access to long term cross-border transmission right
	4	Articulate low-carbon gases objectives based on carbon content alone
DEMAND	5	Boost large scale demand for renewable and low carbon gases in hard-to-abate sectors
	6	Capture the full potential of heat recovery
	7	Target renovation efforts on most inefficient buildings and low-income households
FLEXIBILITY	8	Valorize both demand-side flexibility and supply-side flexibility
TRANSVERSAL	9	Require infrastructure operators to anticipate grid developments ahead of Renewables, Battery Energy Storage System (BESS), as well as H_2 projects
	10	Facilitate investments of private capital in European energy infrastructures to address investment gap

* Power Purchase Agreement / Contract for Difference