with the scientific contribution of the

Foundation

Final report

Sustainable paths for EU increased climate and energy ambition

23 October 2020

CONTENTS

Executive Summary

Increased ambition in 2030 of up to 55% GHG reduction is achievable, affordable and necessary to achieve net zero in 2050

In line with recent announcements of the "Green Deal" of the European Commission and the climate objectives supported by the EU recovery plan, this study demonstrates that increasing the GHG emission reduction by 2030 to up to 55% is:

- **Achievable** thanks to the combination of:
  - **Recent technological advances** in RES and batteries for electric vehicles enabling faster decarbonisation
  - **Electrification in the transport and building sectors** through electric vehicles and heat pumps
  - **Business initiatives** deploying innovative solutions in particular to develop flexibility and leveraging clean technologies and digital solutions that unlock additional GHG emission reduction potential
  - **New national and local energy policies and regulations** including coal phase-out, ICE bans and tighter emission limits – that support deeper ambition for decarbonisation

- **Affordable** thanks to the **recent cost reductions** for clean technologies and **business models leveraging digitalisation** enabling **the large scale deployment of flexibility on both the supply side and demand side** :
  - Reaching close to 55% GHG reduction in 2030 could be achieved at a slightly lower cost for consumers than the previously agreed 2030 target thanks to the rapid decline in costs of RES as well as flexibility resources
  - Impact on affordability / competitiveness can be reduced via redistributive policies and public support, in particular the Just Transition Mechanism implemented as part of the EU Green Deal and Recovery Plan to support the energy transition by providing economic and social support

- **Necessary to meet 2050 carbon neutral objective** as current scenarios rely on hypothetical acceleration of the effort post 2030 and unproven technologies:
  - In order to achieve net zero ambitions in 2050, electrification of end uses via sector coupling and an increased effort in the transport, industrial and buildings sector are necessary.
  - Nevertheless thanks to recent costs reductions in clean technologies, total cost for consumers is similar to previously anticipated costs with lower ambitions.

Increased ambition in 2030 can be reached with slightly reduced system cost and comparable investment

- **Annual investments in the Reference scenario increase by 65% between 2020 and 2030**.
- Despite the increased ambition in the **Decarbonisation scenario** and greater emission reductions in 2030, **annual investments remain similar thanks to the cost reductions in RES technologies and batteries.**

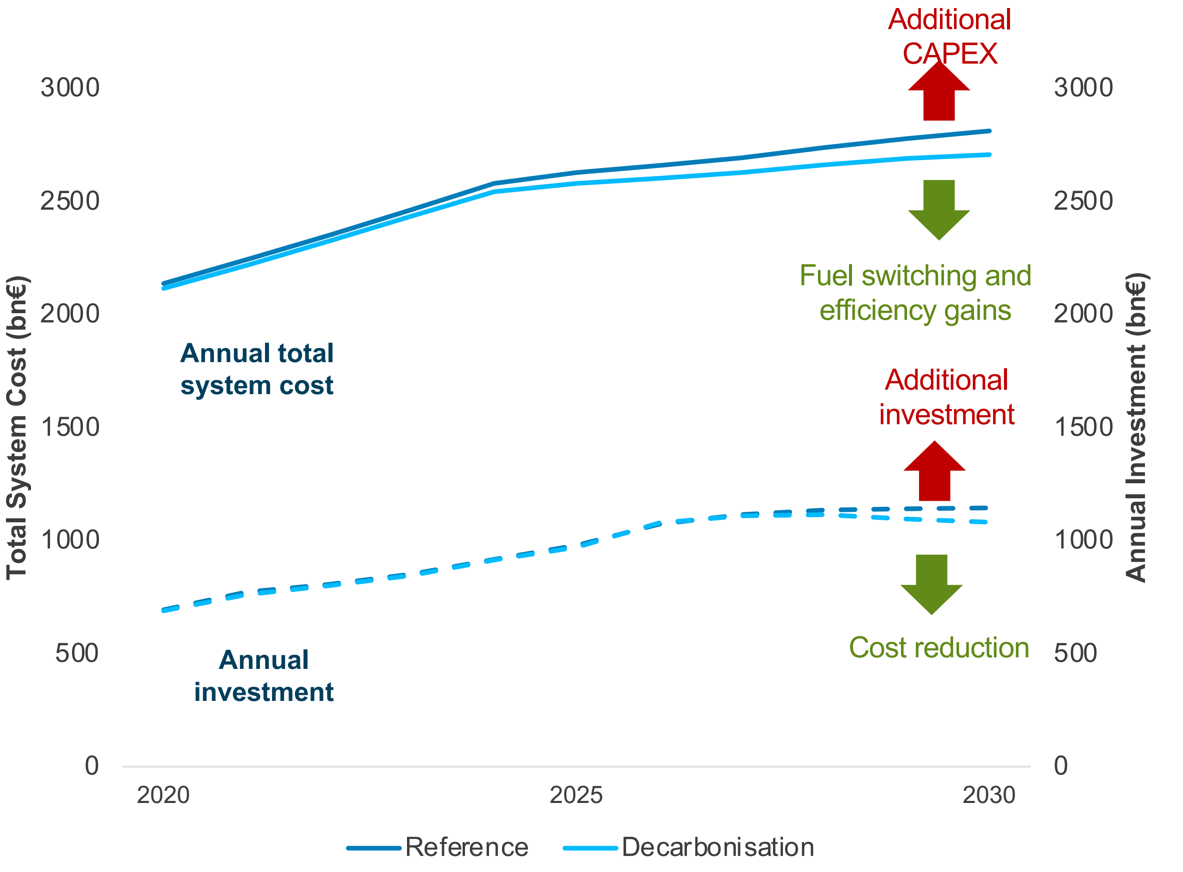
- **Total energy system costs in the Decarbonisation scenario are slightly lower than in the Reference scenario**, thanks to energy efficiency gains and fuel switching.
- The increase in ambition to reach the higher 55% GHG emissions reduction in 2030 targets has thus no impact on consumers, and would be aligned with the objectives of the EU recovery plan to prioritise green investments and steering private and public investments towards green projects.

KPIs, Reference vs. Decarbonisation scenarios in 2030

	CL Reference	CL Decarbonisation
	2030	2030
GHG emissions (vs 1990)*	-46%	-53%
Energy efficiency (2030)	-32%	-35%
RES share in power sector	55%	60%
Direct Electrification share**	29%	31%

* With LULUCF, emissions reduction in the Decarbonisation scenario would be 54% (and 48% in the Reference scenario).
** Excluding non-energy uses in the industry sector

Annual total system costs and annual investments (bn€) in Reference vs Decarbonisation scenarios, 2021-2030



- Annual investments : CAPEX on a yearly basis excluding power network costs
- Annual total system costs : annualised CAPEX + OPEX + fuels costs (including network costs) on a yearly basis
- Capital expenditures are accounted for in the system costs as annuity payments. A discount rate of 5% is applied for all sectors to annualise the capex.

Complete decarbonisation in 2050 requires to sustain investment beyond 2030 but does not increase system costs thanks to the recent clean technologies cost decreases

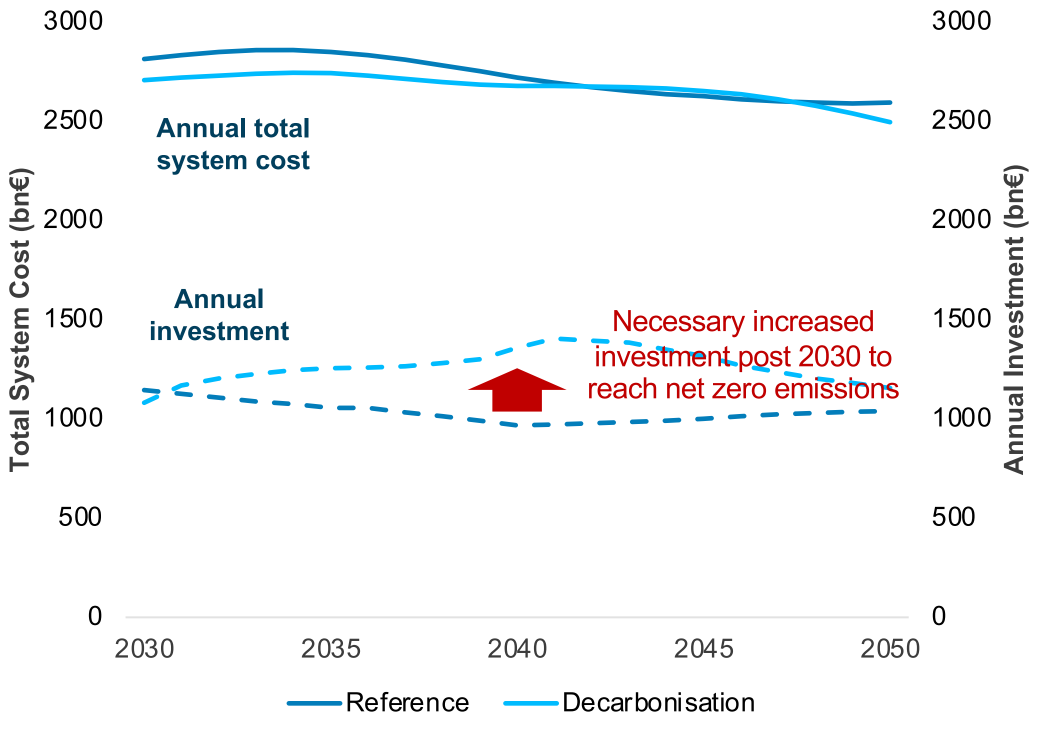
- **Complete decarbonisation by 2050 requires to increasing clean energy investment after 2030 and until 2040 compared to the Reference scenario**, in order to deploy clean technologies. Total investment starts declining in the last decade of the outlook (2040-2050) and eventually reaching similar levels to the Reference scenario beyond 2050.

- **Despite this temporary increase in investment, total energy system costs in the Decarbonisation scenario remain comparable to the Reference scenario throughout the outlook** thanks to the decrease in clean technologies costs, the decrease in flexibility technology costs on the supply side and the increase in embedded demand-side flexibility. Fuel switching to electricity enables end-uses to capture those reductions in costs and to achieve energy efficiency gains unlocked by EVs, HPs, and electrification.

KPIs, Reference vs. Decarbonisation scenarios in 2050

	CL Reference	CL Decarbonisation
	2050	2050
GHG emissions (vs 1990)*	-72%	-100%
RES share in power sector	69%	84%
Direct Electrification share	40%	60%

Annual total system cost and annual investment (bn€) in Reference vs Decarbonisation scenarios, 2031-2050



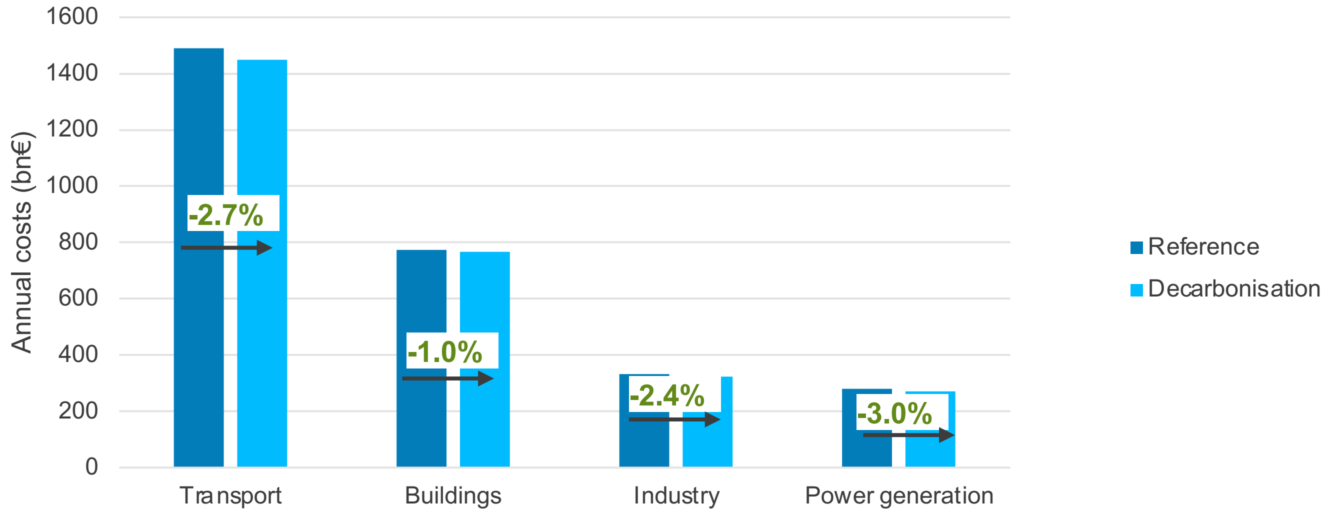
- Annual investments : CAPEX on a yearly basis excluding power network costs
- Annual total system costs : annualised CAPEX + OPEX + fuels costs (including network costs) on a yearly basis
- Capital expenditures are accounted for in the system costs as annuity payments. A discount rate of 5% is applied for all sectors to annualise the capex.

* Including LULUCF

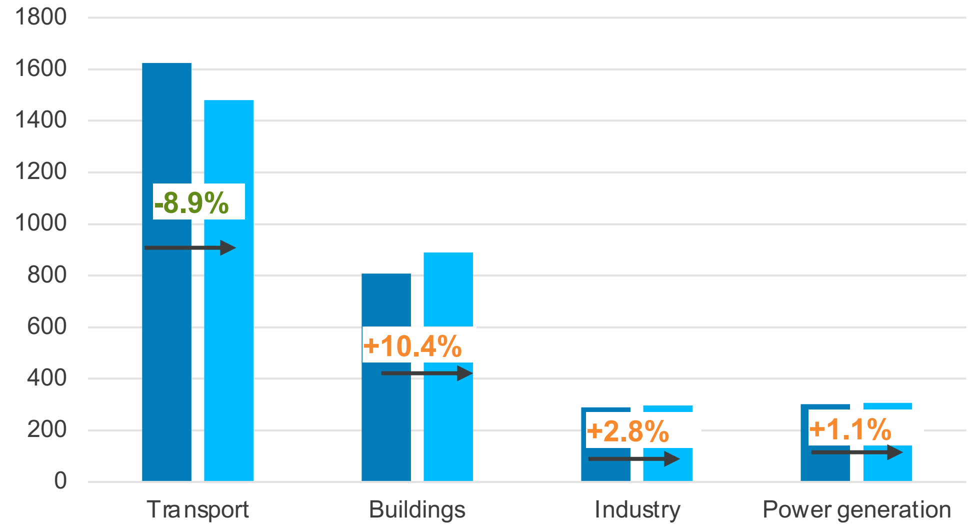
Costs decrease in RES technologies and batteries limit the increase in system costs in the Decarbonisation scenario and result in comparable costs to the Reference scenario

- **In all the sectors considered, the decarbonisation scenario with increased ambitions in 2030 can be achieved at a comparable or lower cost compared to the Reference scenario with lower ambitions**
  - In the power and transport sector, increased ambitions in 2030 result in reduced costs thanks to the costs decrease in RES (mainly onshore wind) and batteries for electric vehicles in transport
  - In the industry and building sectors, increased ambitions in 2030 are reached with comparable costs.
- **Carbon neutrality in 2050 is achieved at comparable cost to the Reference scenario on average although sectors will be affected differently:**
  - To achieve deep decarbonisation in 2050, increased efforts in the industry and buildings must be made resulting in greater costs (+2.8% and +10.4%)
  - The reduction in the transport sector costs (-8.9%) is driven by the reduction of EV costs, increased utilisation rate and efficiency gains

Annual total system costs and power generation costs, Reference vs. Decarbonisation scenarios, 2021-2030



Annual total system costs and power generation costs, Reference vs. Decarbonisation scenarios, 2031-2050



- Annual total energy system cost include industry, buildings and transport costs
- Industry, buildings, and transport system costs include energy capex, opex and fuel costs (including network costs)
- Power generation costs include generation capex, opex and fuel costs

1. Introduction and methodology

Context and objectives of the study

- **Following the Paris Agreement, the European Commission (EC) is considering setting more ambitious decarbonisation targets:**
  - The new von der Leyen Commission announced its **European Green Deal** in December 2019 proposing **more ambitious decarbonisation targets for 2030 (50-55% emissions reduction) and carbon neutrality in 2050**.
  - In the context of the COVID-19 crisis and the resulting economic crisis, the EC proposed in May 2020 an **economic recovery plan** that both repairs the short-term damage of the crisis but also reinforces the green transition strategy of the EU seen as an opportunity to rebound**:**
    - Financial support to Member States **conditional on investments aligned with the Green Deal**
    - Taxes to reimburse mutual debt could include a **carbon border tax**, and more revenues from EU ETS auctions

- **Recent developments make increased decarbonisation ambitions for 2030 both feasible and affordable. Recent years have seen the stars starting to align with regard to:**
  - **Technological progress and cost reductions** in renewables and batteries, and new digital technologies on the supply and demand side providing increased energy efficiency and flexibility potential
  - **National energy policies and regulation** to accelerate decarbonisation: coal phase outs, ICE bans and emissions standards to support the deployment of Electric Vehicles (EVs), actions in favour of a circular economy, etc.
  - **Business initiatives to further support climate action** though digitalisation, deployment of clean technologies and new business models aiming at reducing energy consumption and emissions

In this context, this study offers a fact based analysis to:

i) **assess how more ambitious decarbonisation objectives can be reached in Europe in 2030 and 2050** thanks to cost reduction and recent technological progress both on the supply side and on the demand side,

ii) evaluate the **role of the power sector as a key enabler** of deep decarbonisation and,

iii) estimate the **impact on costs of an increased decarbonisation ambition on an aggregated and sectorial basis.**

The study performs an impact assessment of an EU decarbonisation scenario with a focus on accelerated deployment of clean technologies

- **The study performs an impact assessment of the increased ambition decarbonisation scenario comparing the following scenarios:**
  - **A Reference scenario** aligned with **the current EC climate and energy targets and current costs of clean technologies**
  - **A Decarbonisation scenario** aiming for **increased emissions reduction in 2030 and carbon neutrality in 2050,** and taking into account **recent costs reduction in power generation and EVs**
    - A sensitivity analysis of the Reference scenario was also modelled combining the climate targets of the Reference scenario with costs reductions assumed in the Decarbonisation scenario
- **For each sector of the European economy, the study identifies the key enablers (technology, regulation, and business models)** to unlock deep decarbonisation. **A focus is made on the power sector** given its potential to enable faster decarbonisation in other sectors as electrification of end-uses increases.
- **The impact assessment provides a detailed quantitative assessment based on a set of KPIs** of the increased ambition decarbonisation scenario in comparison to the current EC reference scenario.

Scenario assumptions	Reference scenario	Decarbonisation scenario
Power generation costs	Based on IEA WEO cost curves in line with EU REF 2016	Based on lower range of EC PRIMES 2018
Transport costs	Based on EC PRIMES 2018	Assumed Cost parity between EVs and ICEs in 2025
Building and Industry costs		Based on EC PRIMES 2018
Energy policies	EUCO3232.5 in 2030 + EU REF 2016 in 2050*	50-55% GHG emission reduction by 2030 + Net zero in 2050

KPIs by sector
Energy consumption
Emission reductions
Energy mix
Evaluation of system costs and necessary investments

Power sector indicators
Power demand and generation
Power capacities (including flexible capacities)
Hourly generation profile in winter and summer
Flexibility of demand and supply

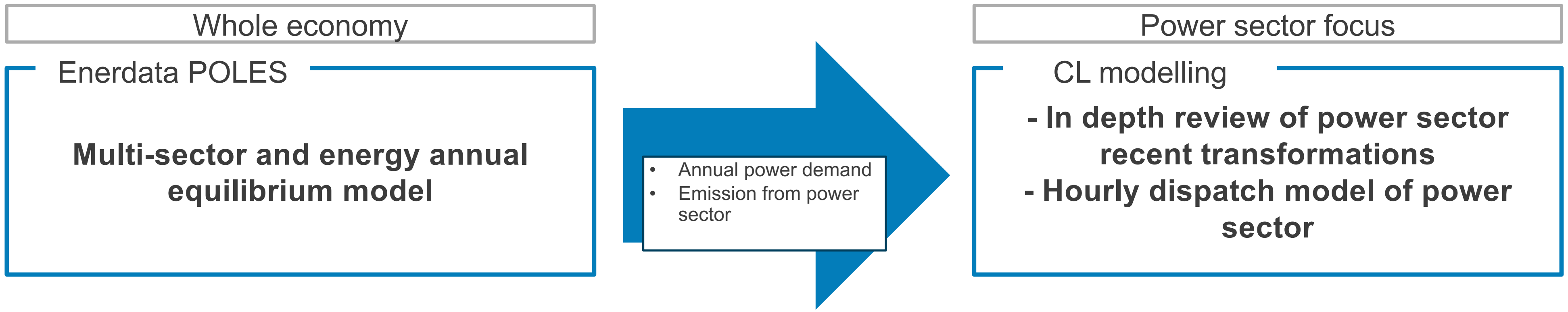
** The 2050 point in the Reference scenario has been recalibrated compared to EU REF 2016 given the 2030 target in the Reference scenario has increased compared to EU REF 2016 and is in line with the EUCO3232.5 scenario*

The study leverages a unique modelling approach combining two models to offer both a full economy and granular power sector representation

- **The study fills a gap with existing studies that are either broad in their sectoral coverage but lack a granular and detailed coverage of the power sector, or solely focussed on the power sector and lacking the cross-sectoral perspective.**

- **In order to capture the potential for decarbonisation across the different sectors, the study uses the POLES energy model which covers the full EU economy**
  - The POLES model is a similar model to the PRIMES model and it is commonly used by the JRC of the European Commission and numerous energy market participants, both public and private organizations.

- **The study then provides a deep dive on the power sector through a detailed European power market model with an hourly definition and a granular geographic coverage**
  - Granular modelling of the power sector decarbonisation (hourly resolution) accounting for deep penetration of RES, batteries, demand response and digitalisation
  - Impact assessment of the Decarbonisation scenario on networks using outputs from the European power market model and a literature review of the incremental network costs due to RES integration, and costs savings associated with demand side flexibility



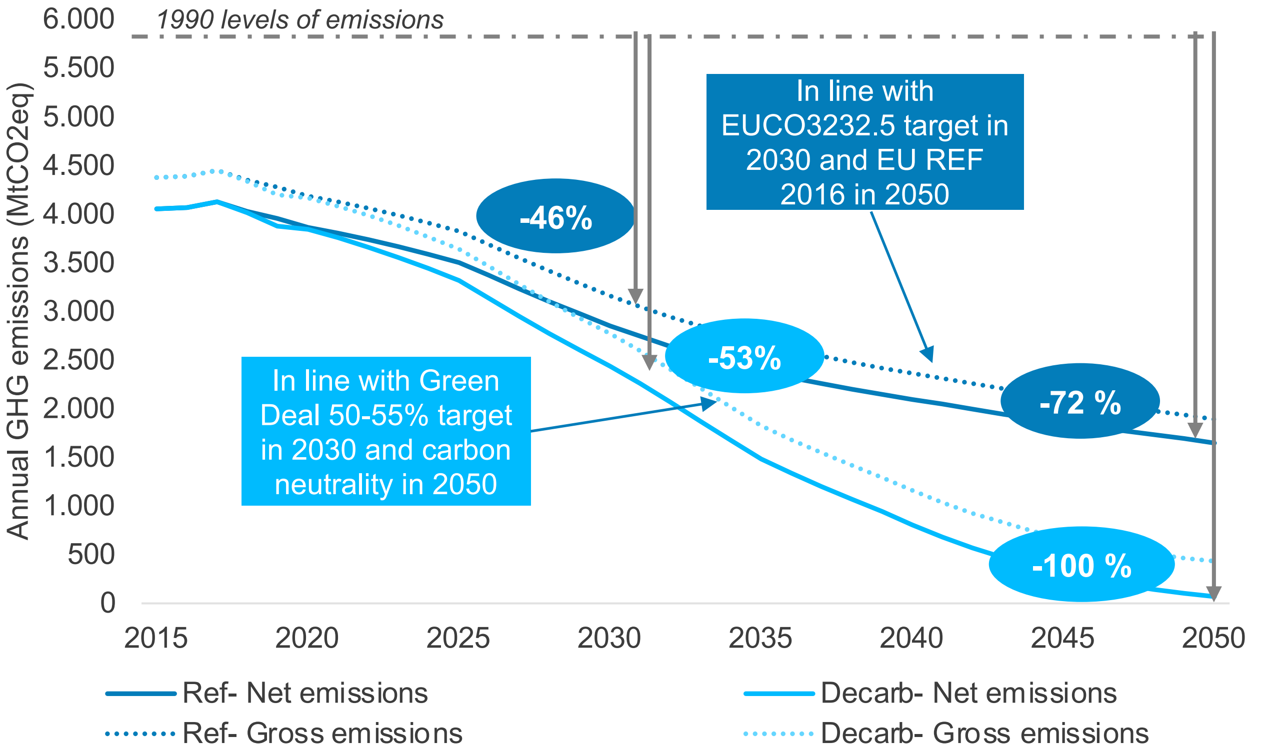
2. Electrification of end uses and energy efficiency are necessary for a full decarbonisation

2.A Increasing the target GHG emission reduction to up to 55% in 2030 is possible thanks to increased electrification of end uses and energy efficiency gains

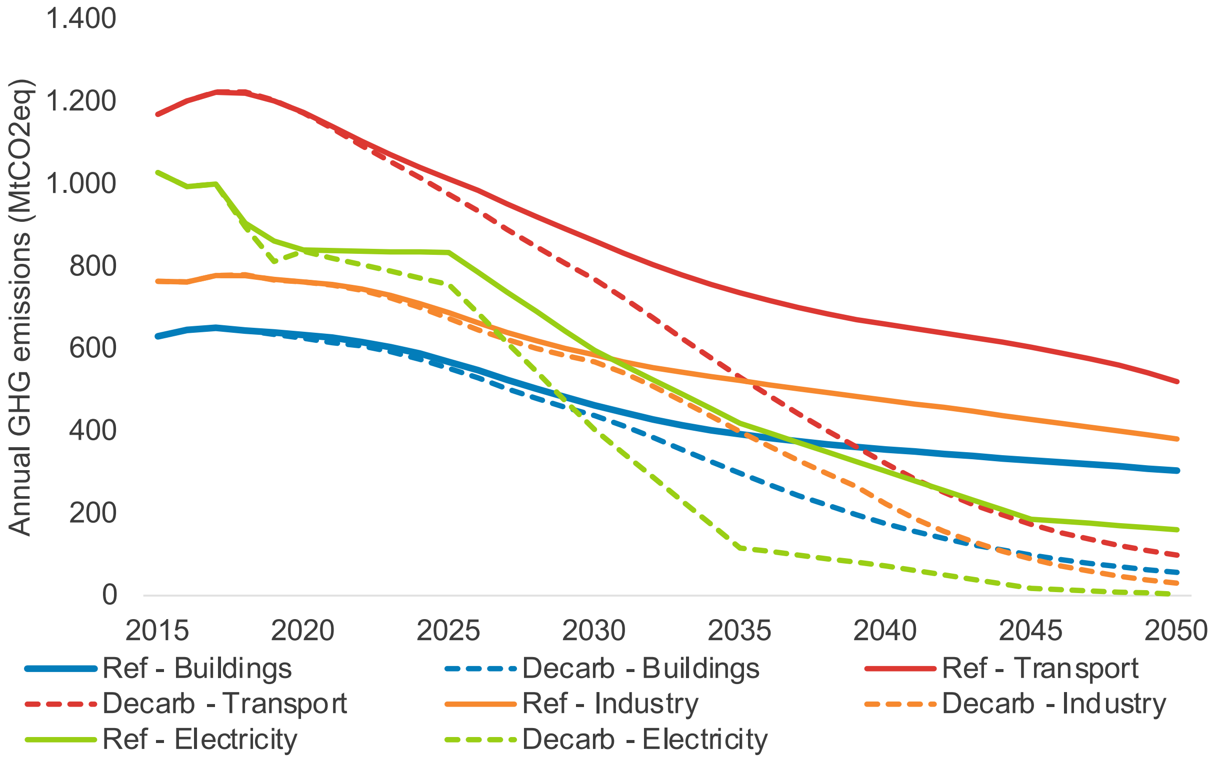
Increasing the target GHG emission reduction close to 55% in 2030 is possible and necessary to achieve net zero emissions in 2050

- **Achieving close to 55% emissions reduction in 2030 is feasible** in the Decarbonisation scenario thanks to the faster decarbonisation already initiated in the transport (-11% in 2030 vs Reference scenario) and electricity (-32% in 2030 vs Reference scenario) sectors in particular.
- Increasing ambitions in 2030 has become **a cost effective approach to achieve net zero in 2050 as the costs of clean technologies have declined** and this allows to reduce the uncertainties associated with the backloading of emission reductions.
- A contribution of all sectors is necessary to achieve carbon neutrality in 2050 and can be achieved through **sector coupling and electrification of end uses**.

Net and gross GHG emissions (MtCO2eq), Reference vs. Decarbonisation scenarios



Gross GHG emissions (MtCO2eq) per sector, Reference vs. Decarbonisation scenarios



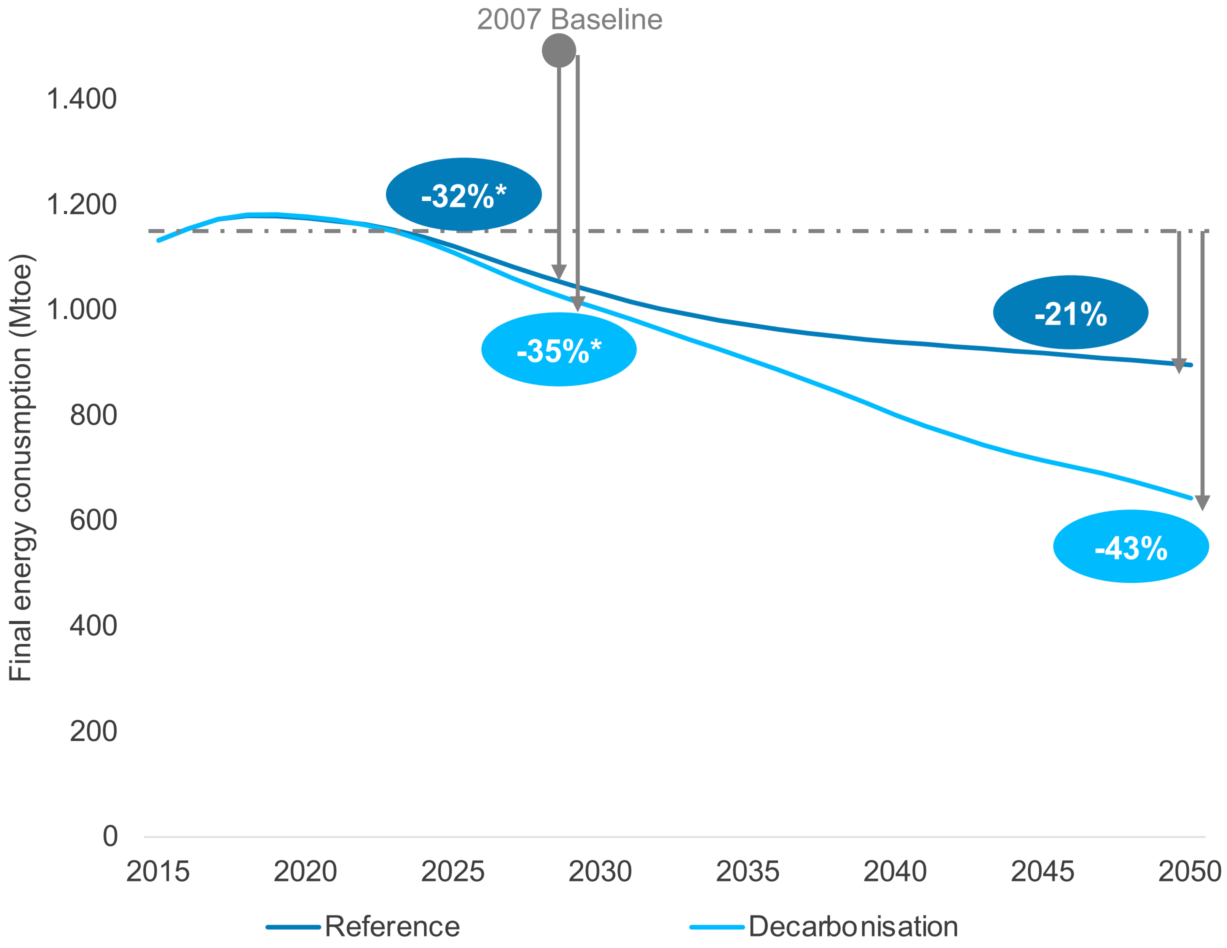
Source: Enerdata and CL

Notes: 1) Difference between gross and net emissions is the Land Use, Land and-use change and forestry (LULUCF) activities 2) 1990 levels of emissions exclude LULUCF (to avoid complexity of accounting) and include international aviation. With LULUCF, emissions reduction in the Decarbonisation scenario would be 54% (and 48% in the Reference scenario).

To achieve the ambition of net zero emissions in 2050, significant gains on energy efficiency are needed

- **Additional energy efficiency gains can be achieved in 2030 in the Decarbonisation scenario** (35% energy efficiency rate vs 32% in the Reference scenario) thanks in particular to the higher uptake of EVs.
- **In order to achieve carbon neutrality in 2050, energy efficiency gains must double** (final energy demand in the Decarbonisation scenario reduces by 43% in 2050 compared to 2015 while only 21% reduction is achieved in the Reference scenario).
- **This effort will be borne by all sectors by 2050 in the Decarbonisation scenario**:
  - **Significant efficiency gains are achieved in the transport sector** (67% reduction in energy consumption between 2015 and 2050) thanks to the large scale deployment of electric vehicles.
  - **In the buildings sector**, 41% energy efficiency gains are achieved in 2050 thanks to **the increased electrification of the sector via Heat Pumps** from renovation of existing buildings and new buildings.
  - **In the industry sector, energy intensity** measured in koe/€ **decreases by 45% between 2015 and 2050** thanks mostly to the reuse and recycle measures, the use of hydrogen as industrial feedstock in the chemical industry, and the electrification of steel processes (electric arc furnaces).

Final energy demand (Mtoe), Reference vs. Decarbonisation scenarios



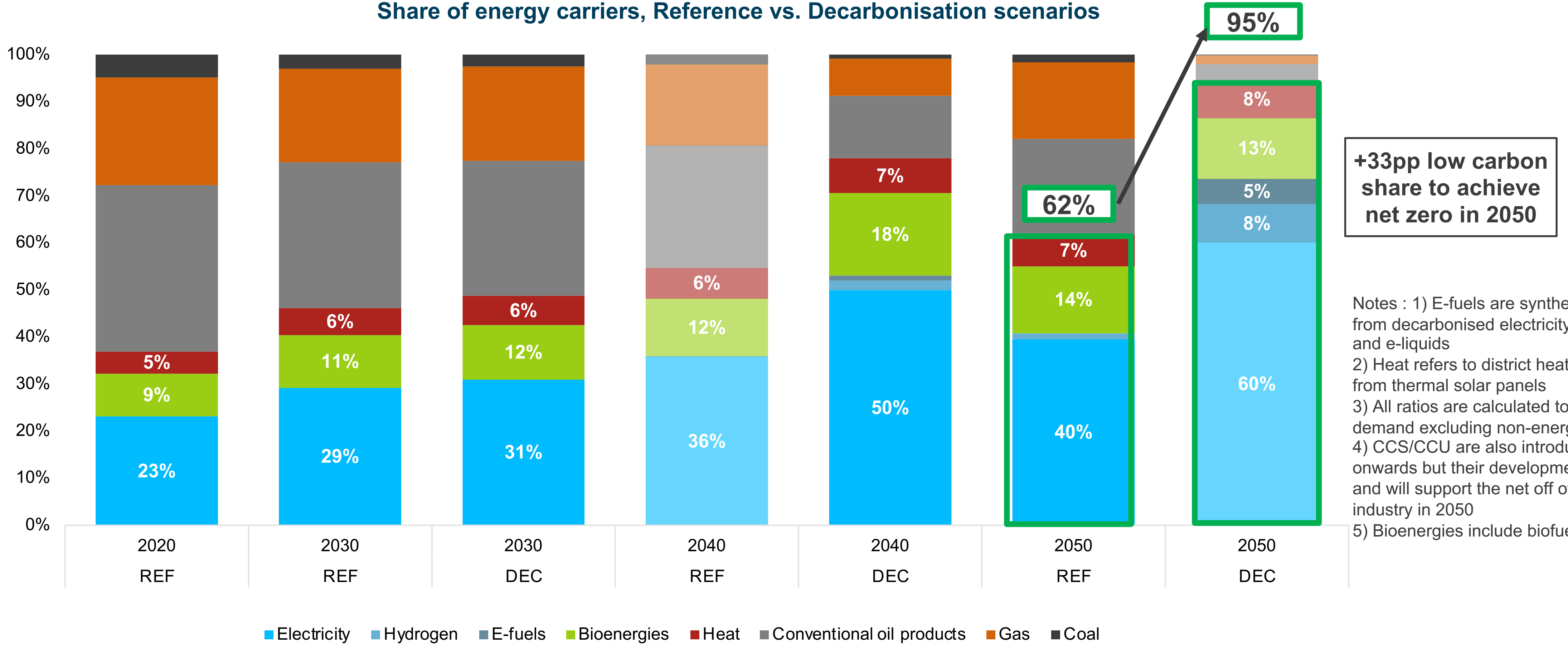
Source: Enerdata and CL

Note: Final energy demand in POLES represented on the figure includes non-energy uses. For the comparison with the 2007 EC Baseline, we add international flights and remove non-energy uses to calculate the energy efficiency targets in 2030 on the same perimeter as the European Commission's.

Electrification of end uses increases significantly in the Decarbonisation scenario to achieve net zero emissions in 2050

- With a significant increase in direct electrification rate from 40% in the Reference scenario in 2050 to **60% electrification in the Decarbonisation scenario**, **electricity emerges as the critical energy vector to achieve net zero ambitions in 2050**.
- The inclusion of **hydrogen** (from electricity, either green from RES or blue from nuclear) **as a new energy vector** (in particular as feedstock for the industry) **along with bioenergies** contributes to a 33pp increase in low carbon share in 2050 in the Decarbonisation scenario compared to the Reference scenario.
- Gas either renewable or non-renewable remains used in the industry sector for heat applications, and in the buildings sector.

Share of energy carriers, Reference vs. Decarbonisation scenarios



Notes : 1) E-fuels are synthetic fuels produced from decarbonised electricity, including e-gas and e-liquids
2) Heat refers to district heating and solar heat from thermal solar panels
3) All ratios are calculated to total industry demand excluding non-energy uses
4) CCS/CCU are also introduced from 2040 onwards but their development remains limited and will support the net off of emissions in the industry in 2050
5) Bioenergies include biofuels and biomass.

Source: Enerdata and CL

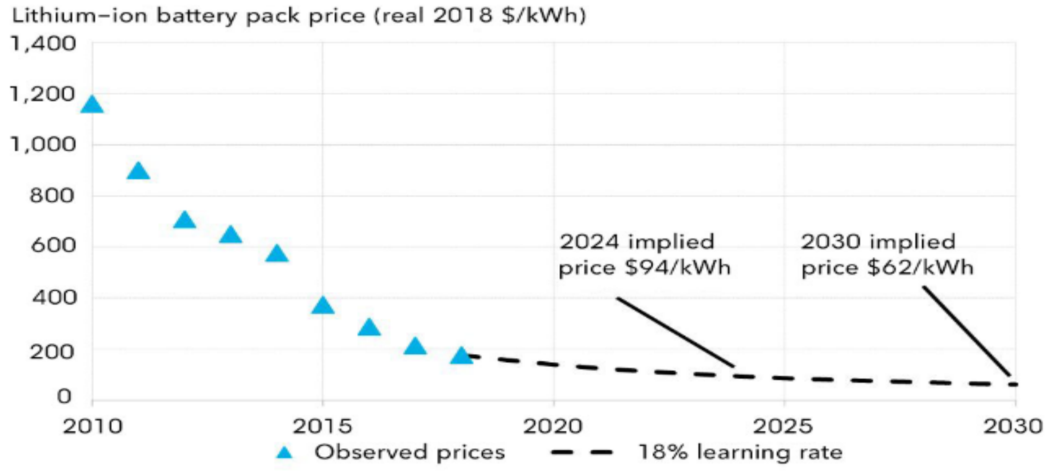
2.B Ambitious electrification of transport is possible thanks to batteries cost reductions, regulatory policies and new business models

Boosted by costs reduction in batteries, EVs will play a key role to decarbonize the transport sector

The recent and expected continued decrease in batteries price will support the growth of EVs:

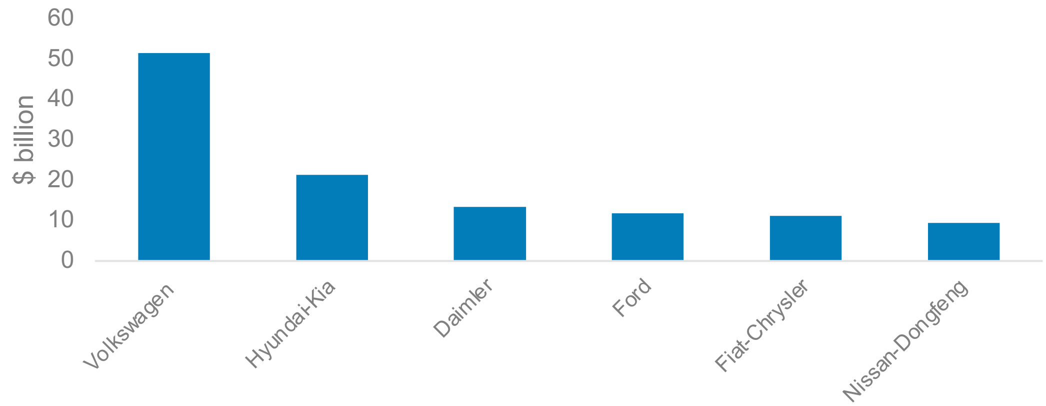
- The volume weighted average battery pack fell **85%** from 2010 to 18 and **cost parity** between EVs and traditional vehicles is expected in **2025.**
- Car manufacturers representing **more than 65% of EU market shares** are ripping up their business models towards EVs:
  - Volkswagen : investments of €33 bn in electromobility before 2025, objective of 40% of EVs in sales by 2030
  - PSA : From 2019, systematic electric or hybrid version for every new car ; 14 new electric-powered vehicles launched by 2021
  - Renault group : as part of new strategic plan “Drive the Future 2017-2022 plan”, expansion of line of electric-powered vehicles with 8 new electric models and 12 electrified models to be released by 2022
  - Hyundai : offer most new models with EV drivetrain by 2030 in major markets; objective to sell 670,000 BEVs and FCEVs annually by 2025, of which 560,000 are BEVs and 110,000 are FCEVs
  - Volvo : Objective of 50% of EVs in sales by 2025
  - FCA: development of 30 electrified models by 2020, of which 4 models are 100% electric; gradual phase out of diesel-engine of Fiat vehicles in Europe.

The observed and expected fall in battery prices until 2030



Sources: BloombergNEF, Battery price survey
McKinsey Energy Insights’ Global Energy Perspective, January 2019

Investments in electric vehicle production capacity



Source: BloombergNEF Electric Vehicle Outlook 2019

As enabler of deep decarbonisation of the transport sector, EVs are supported by a range of European, national, and local policies

EU-wide policies supporting decarbonisation of transport

- Under Regulation (EU) 2019/631 By 2020, the EU fleet-wide average emission target for new cars will be 95 g CO2/km by 2020. From 2025, additional reductions of 15% of the target in 2021 for new passenger car fleet and from 2030, reduction of 37.5%.
- Revised Energy Performance of Buildings Directive (EPBD) including requirements for charging points for residential and commercial buildings.

National policies supporting the electric mobility

- National policies support the electric mobility and are critical to enable a rapid penetration of EVs. A number of EU countries will implement a ban on ICEs sales in 2030 (and beyond).

Country	Combustion engine vehicle sales phase out
Denmark	2030
France	2040
Germany	2030
Ireland	2030
Netherlands	2030
Portugal	2040
Spain	2040
Sweden	2030
UK	2040

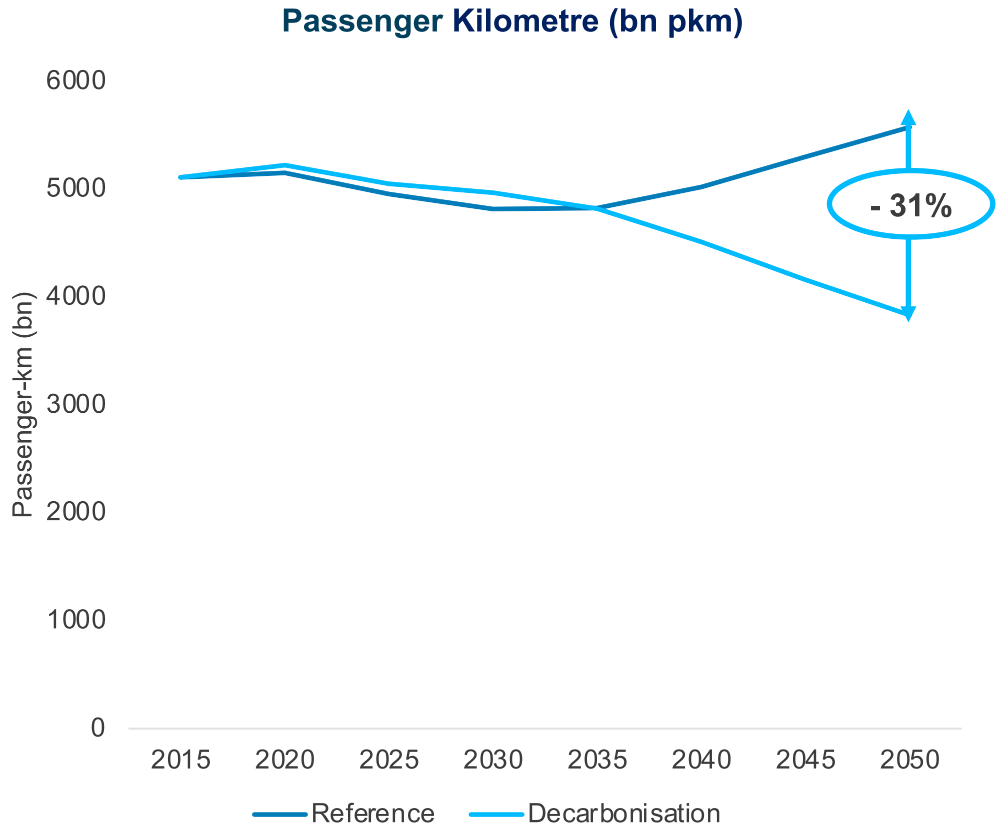
City initiatives to bring decarbonisation further

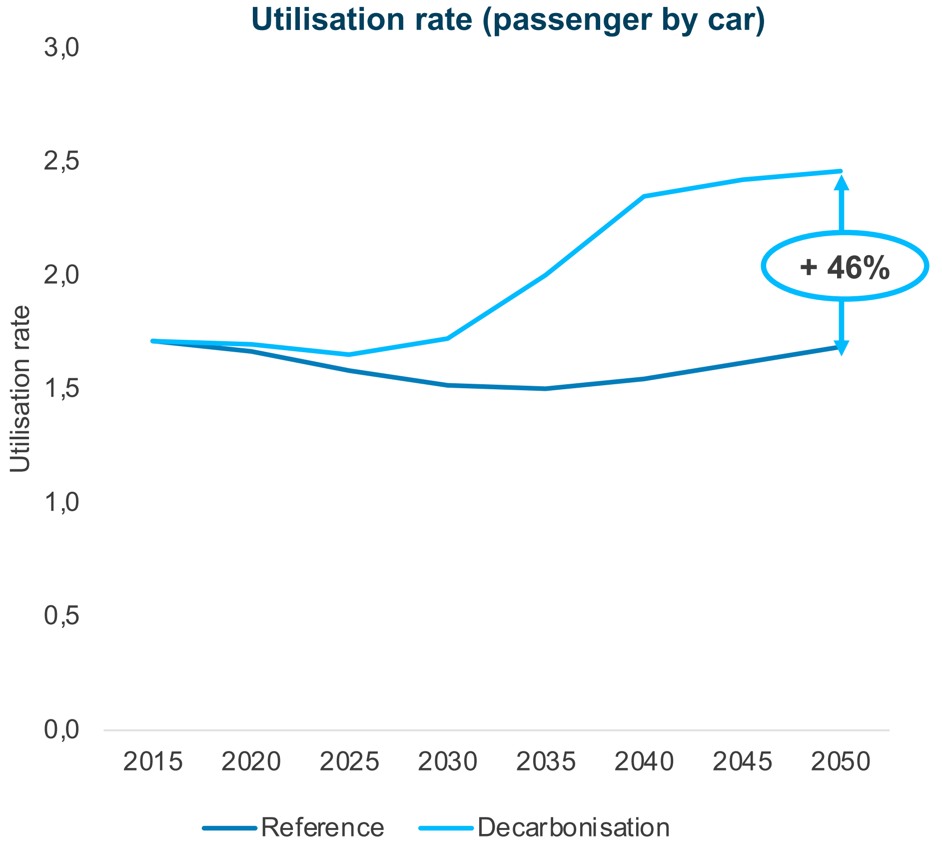
- Urban authorities are best placed to implement local measures benefiting citizen’s health and well-being and the environment, including for instance long-term air quality plans.
- Therefore, cities may set more advanced targets for vehicles on their territory, enabling better air quality.

City	Policy examples
Brussels capital region	- Phase-out of sales of new diesel cars in 2030 and of new petrol cars between 2030 and 2040 - 100% of public transport registered after 2025 to be zero-emission
Paris	Ban on diesel vehicles from city centres by 2025
Madrid	From 2020, older diesel and gas-powered cars are banned Ban on diesel vehicles from city centres by 2025
Athens	Ban on diesel vehicles from city centres by 2025
London	Introduction of Ultra Low Emission Zone to restrict access for older vehicles (or will have to pay charges) in 2019
Milan	Diesel free by 2030

New business models contribute to the reduction of emissions in transport in the Decarbonisation scenario

- Thanks to new business models including involving car pooling and multi modal transport, passenger-km drops by 25% between 2015 and 2050 in the Decarbonisation scenario (compared to a 9% increase in the Reference scenario) , representing a reduction of 31% compared to the Reference scenario in 2050. This reduction contributes to the reduction of energy consumption and emissions and of the investment expenditure in the Decarbonisation scenario.
- In addition new business models through autonomous connected vehicles lead to increased utilisation rate of private vehicles in the Decarbonisation scenario (+46% in 2050 vs Reference).





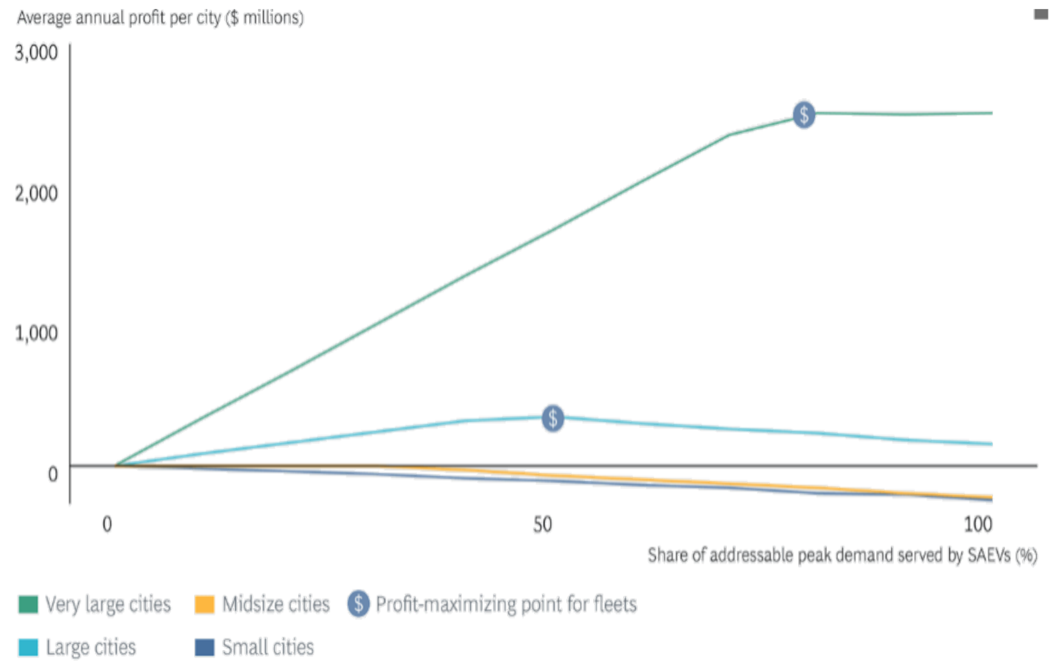
Notes: 1) Passenger kilometre represents the transport of one passenger over one kilometre using road (passenger cars here). It is calculated as total passengers carried x total distance covered in km.
2) Utilisation rate is calculated as : passenger km/(number of vehicles average distance covered by a vehicle) and represents the occupancy rate of a private vehicle (i.e. number of passengers by car).*

Zoom on autonomous and connected vehicles: The robot-taxi model reduces transport emissions

Robot-taxi model

- **Not owned by households** because of their high cost.
- Used on a **regular and shared basis in the form of "robot taxis":** the absence of a driver makes the use of these taxis much more affordable for the user, and part of the population can then switch permanently to this type of mobility for everyday journeys.
- The spread of the shared autonomous vehicle leads many households to **no longer own their own vehicle** in order to use mobility services provided by shared autonomous vehicles, coupled with the increased use of public transport.
- On average, **one robot-taxi replaces seven private cars**.
- Autonomous electric vehicles are **charged during periods of lower mobility needs** (mainly at night but also during the day, outside peak mobility periods). During these periods, charging is **controlled dynamically** using the vehicles' advanced functionalities. Vehicles could spend the night at suburban charging centres, consistently with transport needs of commuters.

Fleet investments in different sizes of cities

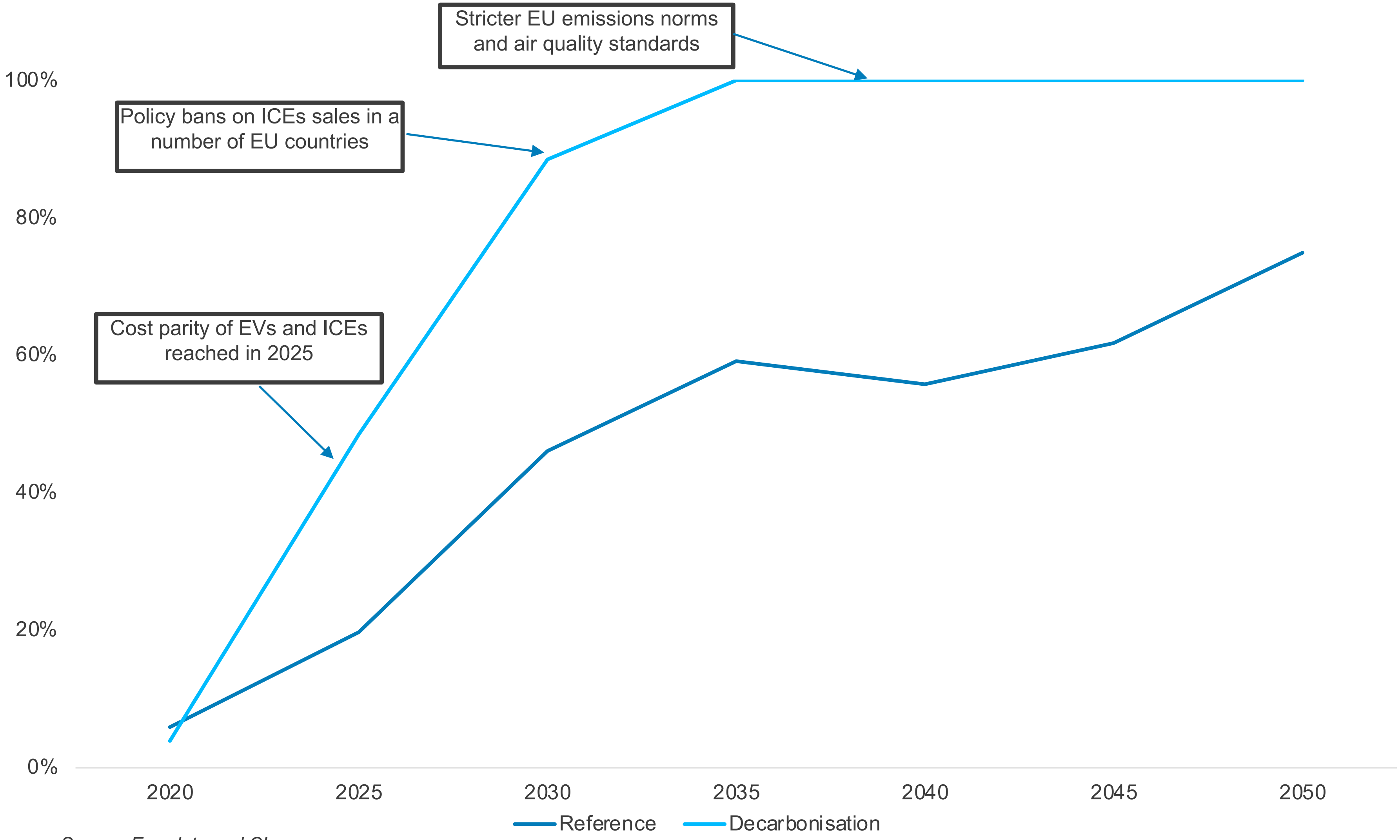


Source: BCG (2017)

- **Shared Autonomous Electric Vehicles (SAEV) investments will pay off in large and very large cities** where SAEV fleet would respectively serve 50% and 80% of peak demand.

LEVs share in new sales reaches 88% by 2030 in the Decarbonisation Scenario thanks to cost parity with ICEs and policy bans on ICEs sales

Private Low Emission Vehicles (LEVs) penetration rate in new sales, Reference vs. Decarbonisation scenarios



Source: Enerdata and CL

Share in private new sales in 2050	Electric	Hybrid	Hydrogen
Reference	49%	18%	7%
Decarbonisation	88%	5%	7%

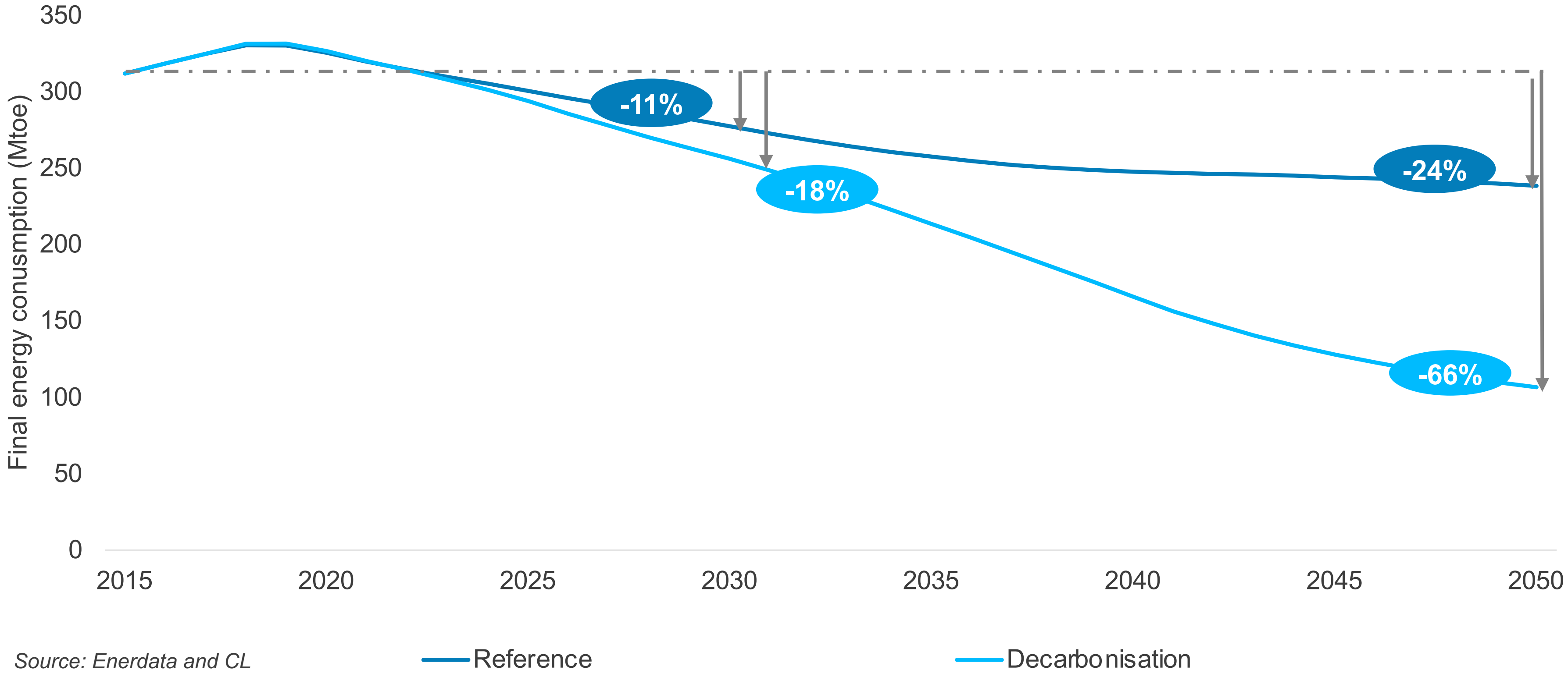
Notes:
- Cost parity assumed in the Decarbonisation scenario relates to the capital cost of the vehicle.
- We assume a cost parity of EVs and ICEs by 2025 for cars with a range below 350 km, by 2026 with a range of 400 km and by 2029 with a range of 500km.

Note: LEVs (Low Emission Vehicles) include hybrid, electric, and hydrogen vehicles

E-mobility will drive energy demand reduction in the Decarbonisation scenario and support the decoupling of consumption and transport emissions

- The faster deployment of clean and more efficient vehicles (EVs, hydrogen, etc.) and changes in transportation modes and usages in the Decarbonisation Scenario lead to significant energy demand reductions, particularly after 2030:
  - By 2030: reduction in final energy demand of 11% and 18 % in the Reference and Decarbonisation scenarios compared to 2015.
  - By 2050: amplification of the effort in the Decarbonisation Scenario (66% cut in demand in 2050 vs a mere 24% cut in the Reference scenario compared to 2015).

Final energy demand (Mtoe), Reference vs. Decarbonisation scenarios

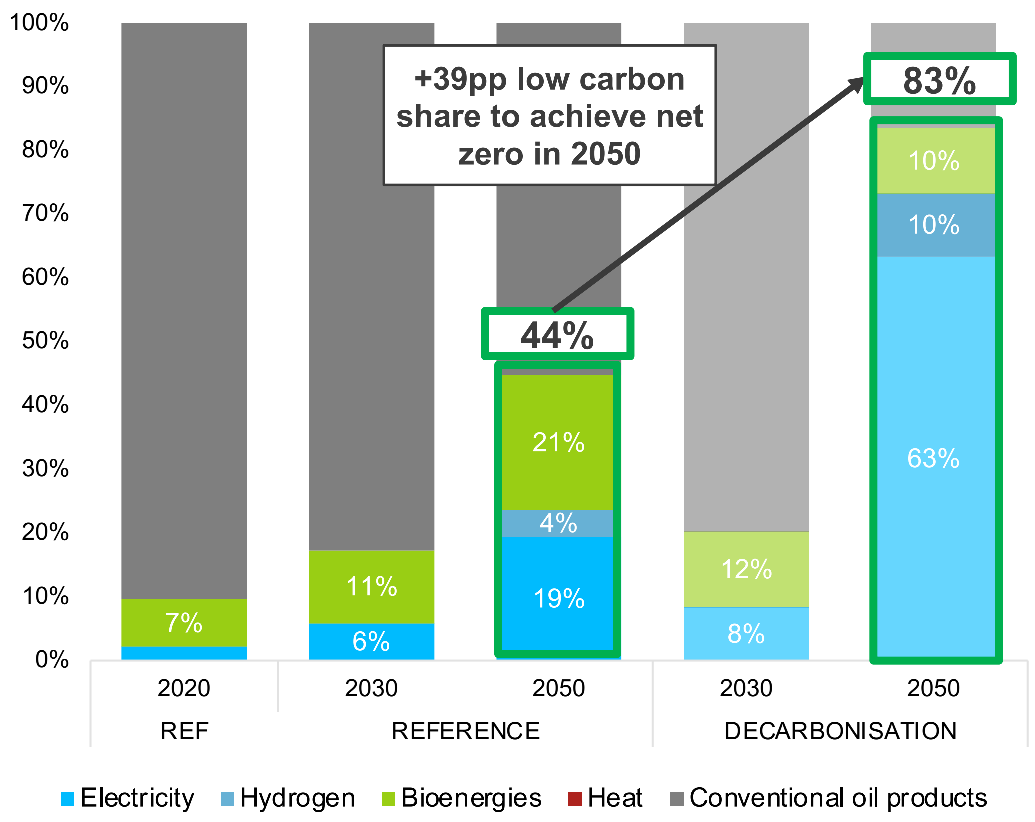


Source: Enerdata and CL

Supported by policies and batteries costs reduction, EVs deployment contribute to the electrification of transport

- The transport sector progressively sees a **growing role for electrification, mainly driven by the electrification of the passenger vehicle fleet through EVs:**
  - **63% electrification rate in the sector in 2050 in the Decarbonisation scenario** (19% in the Reference scenario).
  - The small level of electrification in 2030 in the Decarbonisation scenario is due to the low level of replacement of the fleet which will take a decade to materialise.
  - EVs represent 67% of new private vehicles sales in 2030 but only 24% of the passenger fleet**. In 2050, almost 80% of private vehicles are EVs** (hybrid vehicles represent an additional 9%).
  - To support the penetration of EVs, infrastructure for e-mobility through private and public charging stations needs to rapidly increase by 2030.
  - The bans on ICEs sales in 2030 in a number of EU countries will support the rapid penetration of EVs.
- **To decarbonise heavy duty transport in 2050, electrification is key with 76% of EVs, as well as the use of biofuels and hydrogen** (although the consumption of fossil fuels still represents 18% in 2050). The use of hydrogen vehicles has been assumed for greater range vehicles and for fleets (buses, trucks and ships), although battery vehicles could also play a prominent role as shown by emerging projects.
- **Decarbonisation of maritime and aviation sectors will require technological progress** to develop affordable and technologically feasible solutions (biofuels and synthetic fuels) as well as infrastructure development for ports (e.g. cold ironing systems).

Share of energy carriers in the transport sector, Reference vs. Decarbonisation scenarios



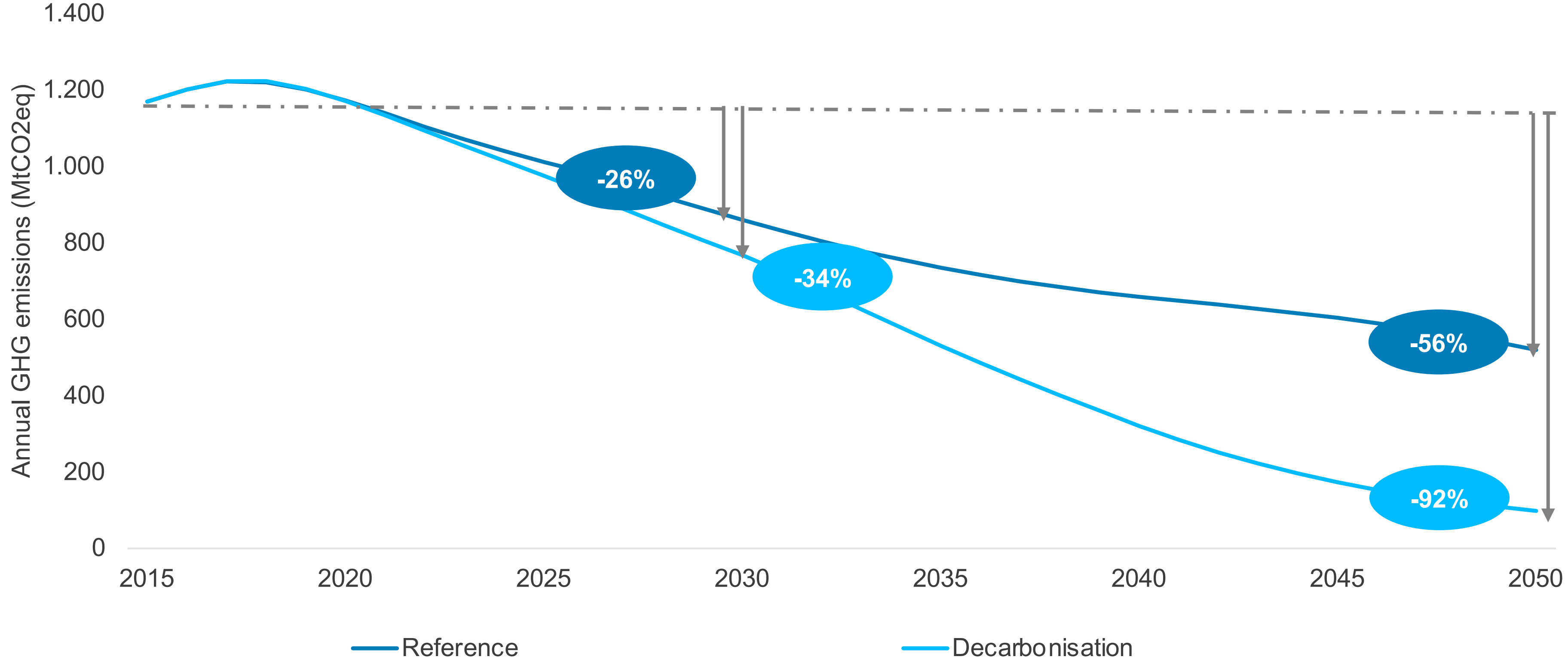
Source: Enerdata and CL

Note: Bioenergies include biofuels and biomass.

To achieve net zero ambitions in 2050, the transport sector needs to cut its emissions by 90% in 2050

- The **decarbonisation effort needs to be well advanced by 2030 to achieve a 90% reduction of emissions in the transport sector in 2050** (compared to 2015 levels):
  - By 2030: 34% reduction of emissions in the Decarbonisation Scenario (vs. 26% in the Reference Scenario), decreasing from 861 MtCO2eq to 769 MtCO2eq
  - By 2050: 92% reduction of emissions in the Decarbonisation Scenario (vs. 56% in the Reference Scenario), decreasing from 520 MtCO2eq to 98 MtCO2eq
- **Transport sector CO2 emission reduction represents almost 30% of CO2 emission reduction** between Reference and Decarbonisation scenario

Gross GHG emissions (MtCO2eq), Reference vs. Decarbonisation scenarios



Source: Enerdata and CL

The increasing development of EVs raises new challenges for the power sector and a need to optimize dynamic charging to leverage EV's flexibility potential

- **The increasing penetration of EVs raises challenges for the security of supply of the power sector that can be addressed with smart charging solutions:**
  - **National** level challenge:
    - **Peak demand** could be too high during winter evenings without simple control solutions (such as control via time-of-use signal) due to charging time of all vehicles between 7pm and 9pm
    - **Renewable curtailment** can be reduced with smart charging: smart charging would make it possible to **reshape the load curve**, on a daily and weekly scale, **to follow variations in solar and wind production**
    - Smart charging of EVs allows charging to take place in periods when **production costs are lowest**
  - **Local level challenge:**
    - Cities with high EV density need to **match charging needs with charging capability**
    - **Urban planning** should integrate charging points (especially for people who can't charge from home)
    - A study has demonstrated that 32% of UK low voltage circuits would require **reinforcing** if 40% – 70% of customers had EVs with 3.5 kW. That was estimated as a present-day cost of around £2.5bn. But much of that reinforcement cost can be **avoided by managing charging** when local grid capacity starts to be strained.

- **Optimising EVs charging can mitigate the impact on the grid and can also provide the required flexibility to the electricity system when EVs can act as storage:**
  - **One-way** function / simple recharging : The battery charge can be time-modulated but the battery cannot feed electricity back into the external grid.
  - **Bi-directional** function / reversible charging: The battery can draw from the grid but can also feed back into the grid (domestic and/or public electricity network). This function requires an AC/DC converter at the vehicle or charging station. **Developments are required in battery chemistry/management technologies** to enable a longer cycle life. V2G also requires active two ways **communication** between the grid and the vehicle.

Different charging approaches and incentives can help leverage the flexibility embedded in EVs for the electricity system and minimize grid reinforcement

Recharge monitoring

- Recharge monitoring for electric vehicles allows **recharges to be placed during periods when production costs are lowest** (high wind or solar production)

Simple tariff control

- Recharging is triggered in defined **tariff bands** (e.g. current off-peak times or other tariff signals). This can be achieved by means of tariff control (as with hot water cylinders) and is thus transparent to the user.

Dynamic control based on electricity price signals

- The times at which recharging (and possibly grid feed-in) is triggered **are controlled dynamically**, **depending on the hourly electricity prices on the wholesale market** and the user's future mobility requirements.
- In a heavily monitored context, controlled vehicles (simple or dynamic) would represent **80%** of the EVs.

Vehicle to grid (V2G)

- **Monitoring with participation in real-time balancing of the power system = Vehicle to grid**: The charging (and possibly discharging) of the batteries is modulated according to the balancing needs of the power system, for example by means of a frequency signal control. In a heavily monitored context, V2G vehicles would represent **20%** of the EVs.

Vehicle to home

- **Coupling with photovoltaic self-consumption = Vehicle to home**: The charge (and possibly discharge) is placed so as to make the best use of locally produced energy with photovoltaic panels. Vehicle to home can also cover home consumption (no need to produce)

Source: RTE Enjeux du développement de l'électromobilité pour le système électrique

A deployment and charging approach of EVs that contribute to the electricity system flexibility will require a supporting regulatory framework

- **Need to prevent "double charging" on the energy extracted and re-injected into the grid.**
  - In France, the interest of vehicle-to-grid for trade-offs in energy markets is now reduced for consumers: whereas the energy extracted is valued at the energy tariff including tax, the energy injected is only valued at the market price. Thus, **each storage-dispatching cycle "pays" taxes**.
  - In the UK, the current regulation would make the customers pay taxes for both extracting energy and re-injecting energy into the grid.
- **Regulations to impose night charging** don't seem to be implemented, but commercial offers have already been developed to encourage night charging.
- **For the practical valuation of flexibility to match the theoretical potential, it is necessary to ensure that market mechanisms are well open and do not contain barriers to entry for these new offers.** Two levels of complementary responses could be envisaged:
  - Ensuring that all markets (primary and secondary reserves, adjustment, capacity mechanism) are open to the provision of such services by aggregators.
  - Implementing simplified procedures in order to support the development of the new business models.

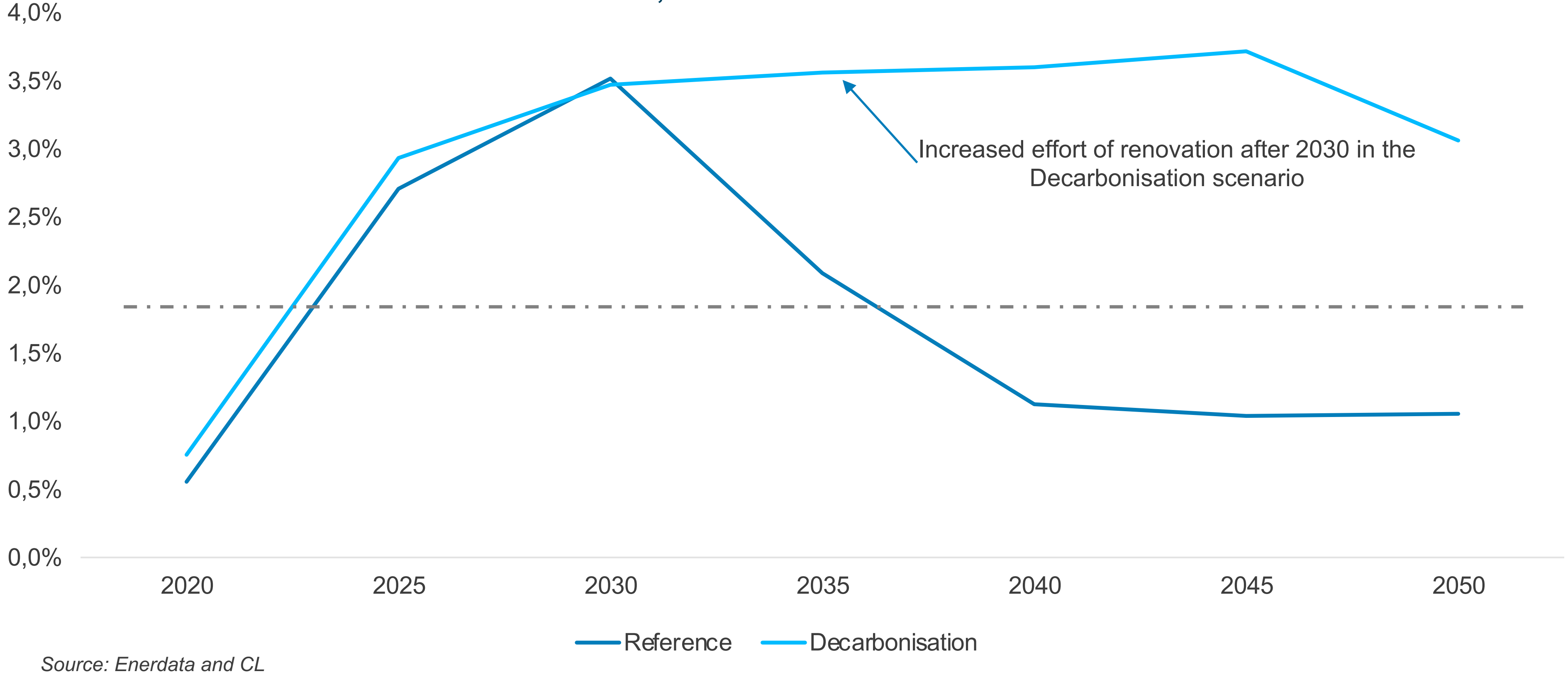
In the Reference scenario, we assume that only Time of Use charging (mainly overnight charging) is used. In a Decarbonisation scenario, an uptake of dynamic charging and V2G charging would unlock the flexibility potential of EVs and mitigate the impact of EVs electricity demand on the grid.

2.C Decarbonisation of buildings relies on greater electrification through the deployment of heat pumps

Renovation rate needs to be at least 3% per annum to achieve the decarbonisation of the buildings sector

- In the Decarbonisation scenario, the pace of renovation rate increases significantly with a sustained effort over 3% between 2030 and 2045 (compared to a drop in renovation rate after 2030 in the Reference scenario) driven by EU and national policies:
  - EU regulation of 3% target for public buildings renovation
  - Renovation Wave initiative is a priority under the Green Deal and the EU recovery plan: “Today the annual renovation rate of the building stock varies from 0.4 to 1.2% in the Member States. This rate will need at least to double to reach the 2030 EU’s energy efficiency and climate objectives.”
  - Other institutes such as the Renovate-Europe of Buildings Performance Institute Europe support the vision for a 3% renovation rate to achieve the minimum Paris climate targets

Renovation rate, Reference vs. Decarbonisation scenarios



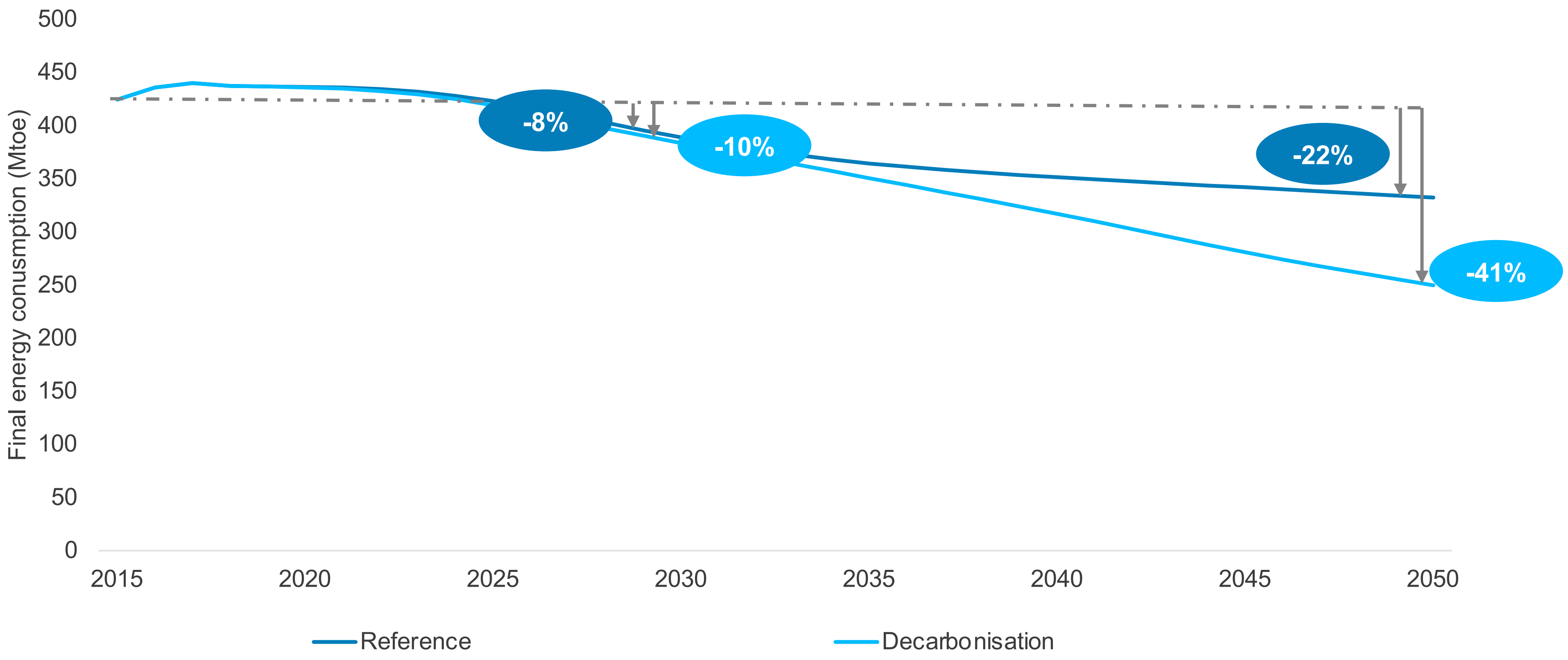
Source: Enerdata and CL

Note: Renovation rate is the average renovation rate of the dwelling stock and includes both insulation as well as efficiency gains of heating solutions

Energy efficiency gains in buildings step up in the Decarbonisation scenario through supporting policies, faster technologies deployment and gradual phase-out of fossils

- The reduction in final energy demand in the Reference scenario in 2030 is relatively small compared to 2015 (from 425 to 389 Mtoe), and is expected to reach only 22% by 2050 (reaching 332 Mtoe in 2050).
- In the Decarbonisation scenario, the reduction in final energy demand doubles in 2050 compared to the Reference scenario, to reach a 41% cut compared to 2015 levels (from 425 Mtoe to 250 Mtoe in 2050).
- The final energy demand savings in the Decarbonisation scenario are mainly driven by the switch from gas boilers to heat pumps with a small contribution from district heating.

Final energy demand (Mtoe), Reference vs. Decarbonisation scenarios



Source: Enerdata and CL

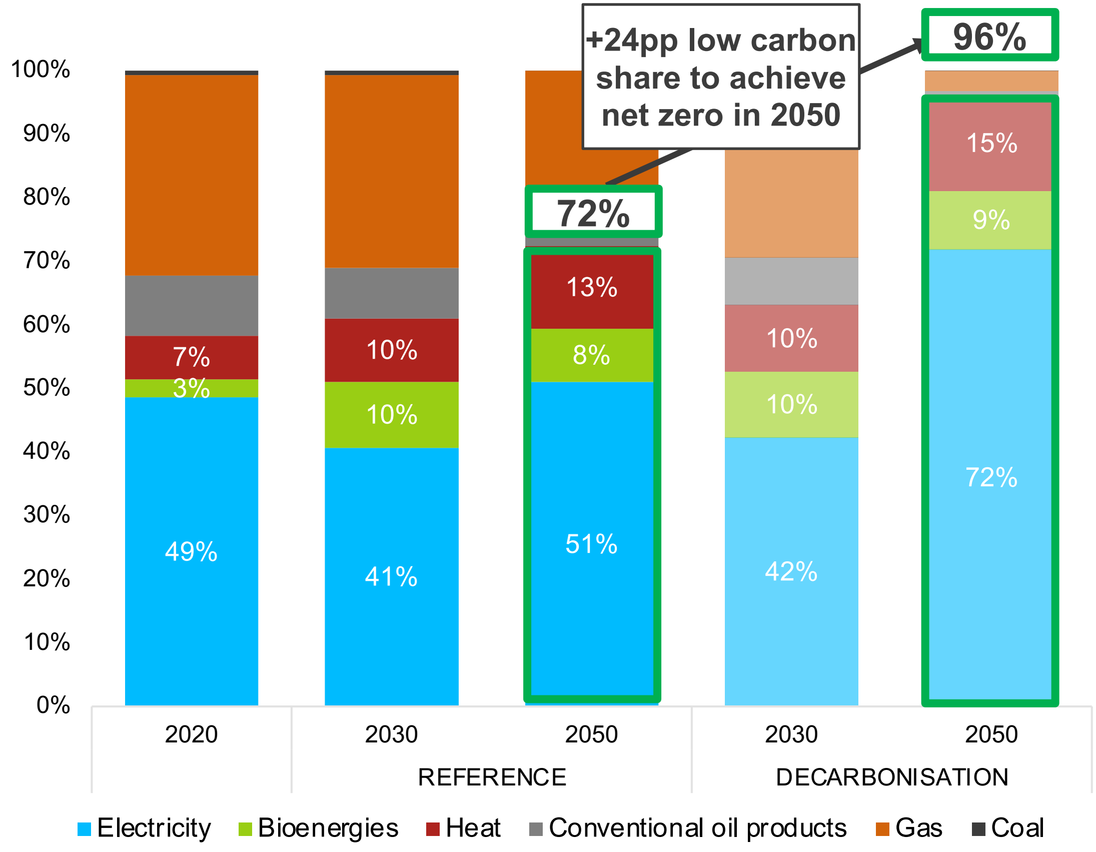
Decarbonisation of buildings relies on greater electrification through the deployment of heat pumps

- In both scenarios, **the electrification of buildings through the deployment of Heat Pumps allowing for the electrification of heating & cooling increases**:
  – In the Reference scenario, the share of electricity increases to 51% with still a remaining share of 22% for gas energy
  – **In the Decarbonisation scenario, the share of electricity increases up to 72%** of final energy demand by 2050, thereby replacing gas energy by electricity for heating purposes

- **Between 2020 and 2030, the rate of renovation of existing buildings will rapidly increase from 1% to 3.5%.** This acceleration of the annual renovation rate is in line with the objective of the EU Recovery plan that will provide funding and financing support (through the Recovery and Resilience Facility and the InvestEU scheme) to at least double the annual renovation rate.

- In the Decarbonisation scenario, **the pace of renovations is sustained after 2030 compared to the Reference scenario and stays at 3-4%** until at least 2045, in line with the rate of renovations targeted by the EC in its Green Deal. While the rate of renovation doubles between the Reference and Decarbonisation scenarios, the decarbonisation of the buildings sector is also achieved thanks to the deeper renovations incorporating electric and smart technologies (heat pumps and smart electric appliances unlocking decarbonisation potential) .

Share of energy carriers in the building sector, Reference vs. Decarbonisation scenarios



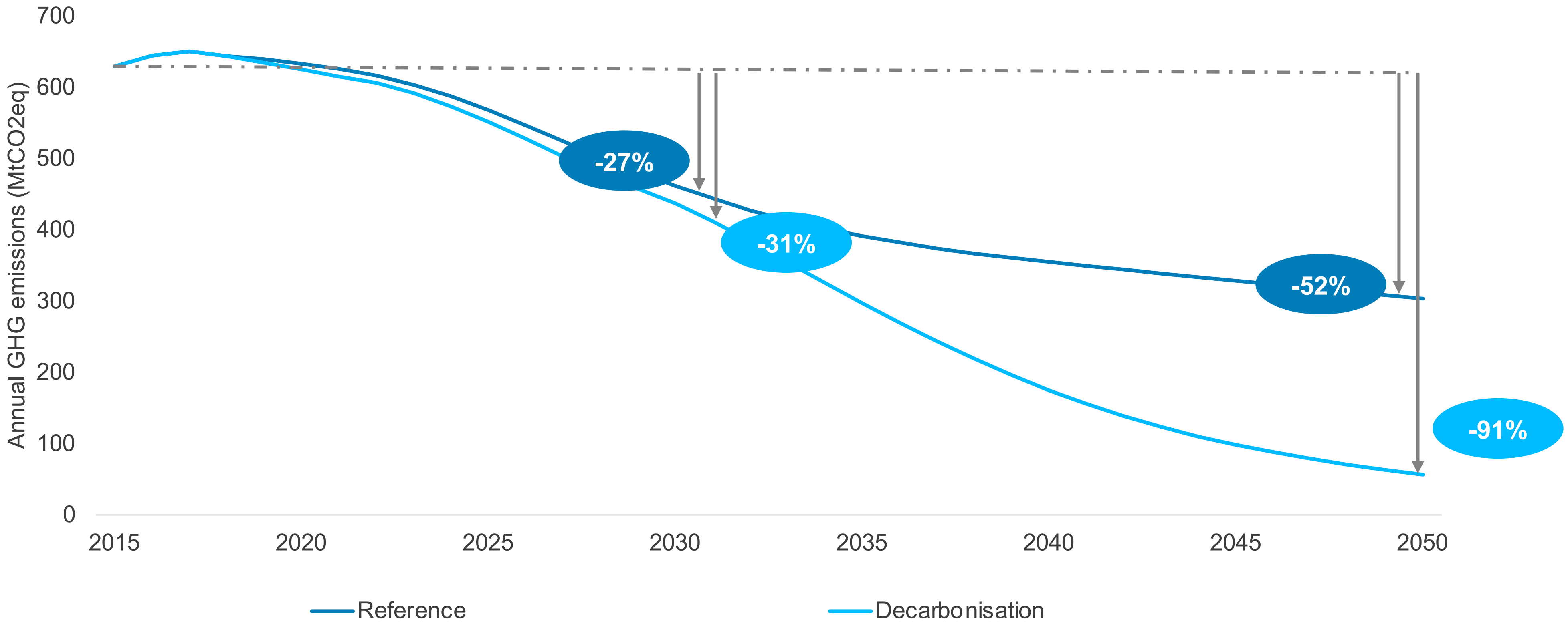
Source: Enerdata and CL

Notes: 1) Heat refers to district heating and solar heat from thermal solar panels
2) Bioenergies include biofuels and biomass.

To achieve net zero in 2050, the building sector has to decrease emissions by at least 30% in 2030 and 90% in 2050

- In 2030, the emissions reduction in the Reference and Decarbonisation scenarios are comparable: -27% in the Reference scenario from 630 MtCO2eq to 462 MtCO2eq, and -31% in the Decarbonisation scenario from 630 MtCO2eq to 438 MtCO2eq.
- The reduction in GHG emissions in the Decarbonisation scenario steps up after 2030 to reach 91% by 2050 (56 MtCO2eq in 2050 vs 304 MtCO2eq in the Reference scenario), driven both by energy efficiency improvements and decarbonisation of energy supply.

Gross GHG emissions (MtCO2eq), Reference vs. Decarbonisation scenarios



Source: Enerdata and CL

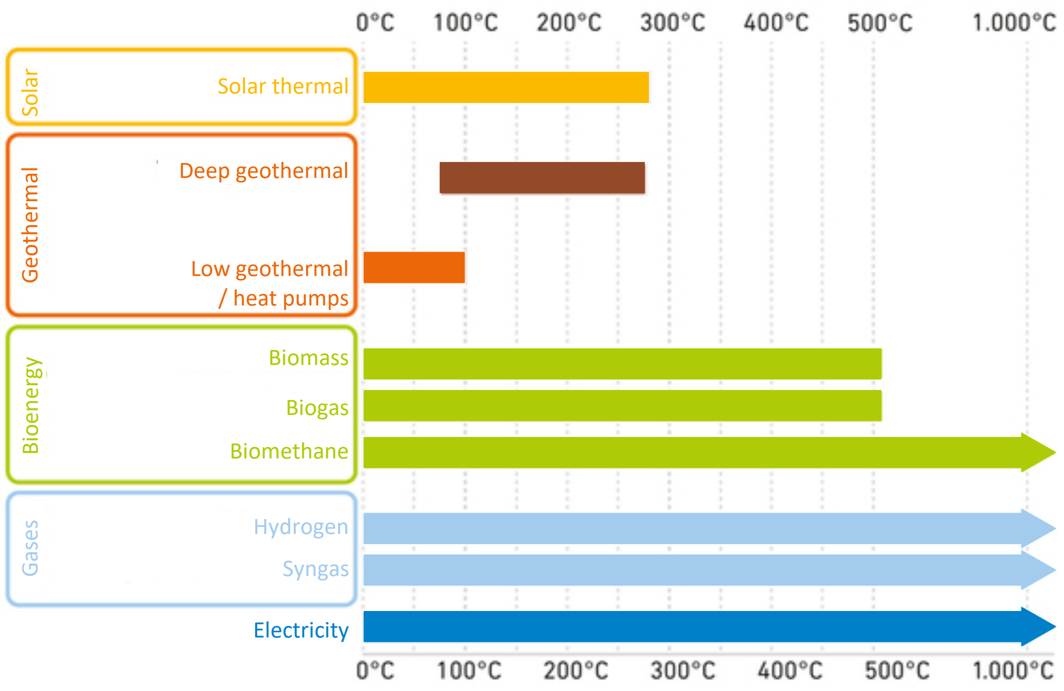
2.D Electrification of industrial processes combined with production of green hydrogen and e-fuels contribute to the decarbonisation

The decarbonisation approach and clean energy sources used for industrial applications depend on temperature and type of process

- **Low carbon options to reach high temperatures** (>=500 °C, about 60% of industrial heat demand) include:
  - Biomass and biogas – use of by-products in petro/chemical and food & beverage industries
  - Biomethane – benefit from existing infrastructure, use in high temperature processes in iron & steel, chemicals
  - Hydrogen and syngas
  - Electricity

- **Low carbon options to reach low-medium temperatures** (0-300 °C) include :
  - Solar thermal
  - Industrial heat pumps, using waste process heat as a heat source in drying, washing, evaporation and distillation processes

Suitability of alternative energy sources depending on industrial heat applications



Source: Honoré, 2019, The Oxford Institute for Energy Studies

COMPASS LEXECON Enerdata enel Foundation

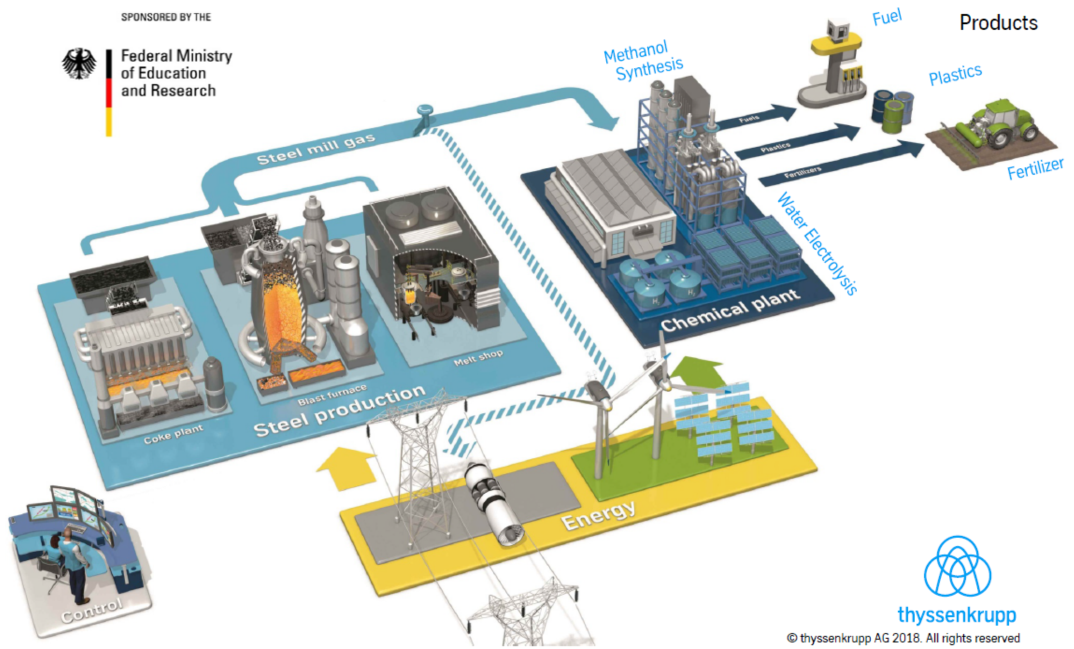
Sector coupling and integration of energy carriers drive significant energy efficiency gains in the Decarbonisation scenario

- **Sector integration and coupling has the potential to unleash significant energy efficiency gains**
- **Moving towards *integrated energy systems* (IES) leverages synergies in electricity, gas, heat and water**

Example of Carbon2Chem project by Thyssenkrupp

- Clear targets of the Group (July 2019) :
  - be climate neutral by 2050
  - 30% emissions reduction planned for 2030

- Carbon2Chem project
  - Sector integration between steel and chemical: using the gases generated by the steel industry to produce chemical substances (urea, methanol) that will serve as feedstock from end products (fertilisers, plastics, etc.)
  - Gases from the blast furnace are used on the steel site to generate electricity
  - In the chemical plant, excess production from RES sources will be used to generate hydrogen from the steel gases
  - Expected reduction : 20 million tonnes of CO2 emissions annually (if fully implemented)
  - Commercialization beyond 2030



Systematic overview of the Carbon2Chem concept

Industrial flexibility allows for a cost-effective decarbonisation of the grid

Industrial flexibility has potential to generate energy costs savings both for industries and for system operators

- Through demand side response, industrial users can receive payments for their dynamic interactions with the grid which in the end will benefit them through reduced network and policy costs
- For the system operator, participation of energy users can reduce whole system costs
- In the US, in the mature PJM Capacity Market **industries provide around 9% of peak load thanks to DSR.**

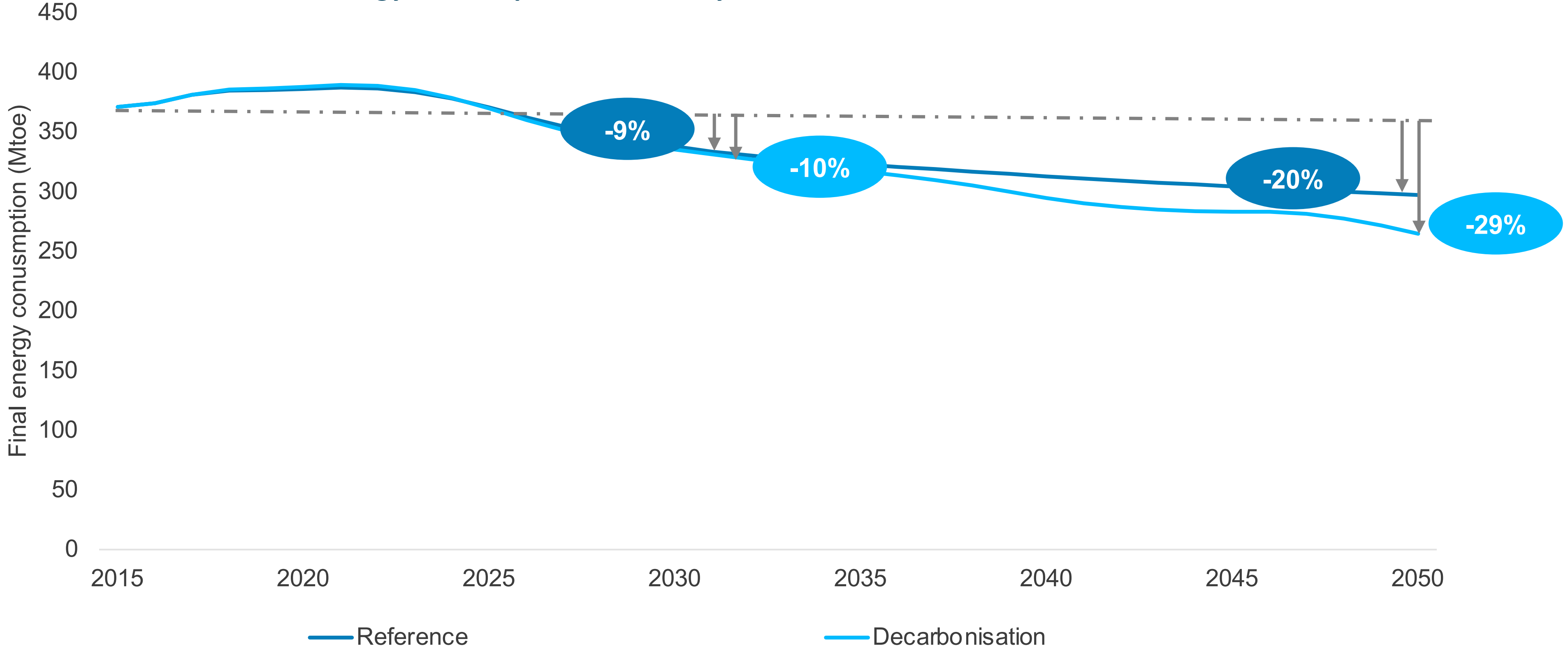
Industrial flexibility can support renewable deployment

- Flexibility can allow higher shares of renewable generation to be consumed when available, thereby increasing efficiency of energy system and lowering costs for users
- Two major ways to offer flexibility services: as an aggregator or as an energy optimizer. Aggregation has a significant scale advantage, and a large portfolio of diverse demand resources allows the aggregator to offer predictable, stable output for a longer period, while avoiding the cost associated with frequent or long dispatch of individual resources.

Industrial demand peaks in 2020 and declines thereafter due to necessary efficiency gains in the Decarbonisation scenario

- The **industrial sector potential for efficiency gains varies greatly by type of industrial process**, with significant gains possible especially in energy intensive sectors such as steel & iron, etc.
- The most significant efficiency gains in the Decarbonisation scenario take place after 2030 as substitute technologies become more mature and competitive with final energy consumption decreasing by 29% in 2050 compared to 2015 levels (from 371 Mtoe to 265 Mtoe) compared to 20% in the Reference scenario (from 371 Mtoe to 297 Mtoe).

Final energy consumption in industry, Reference vs. Decarbonisation scenarios

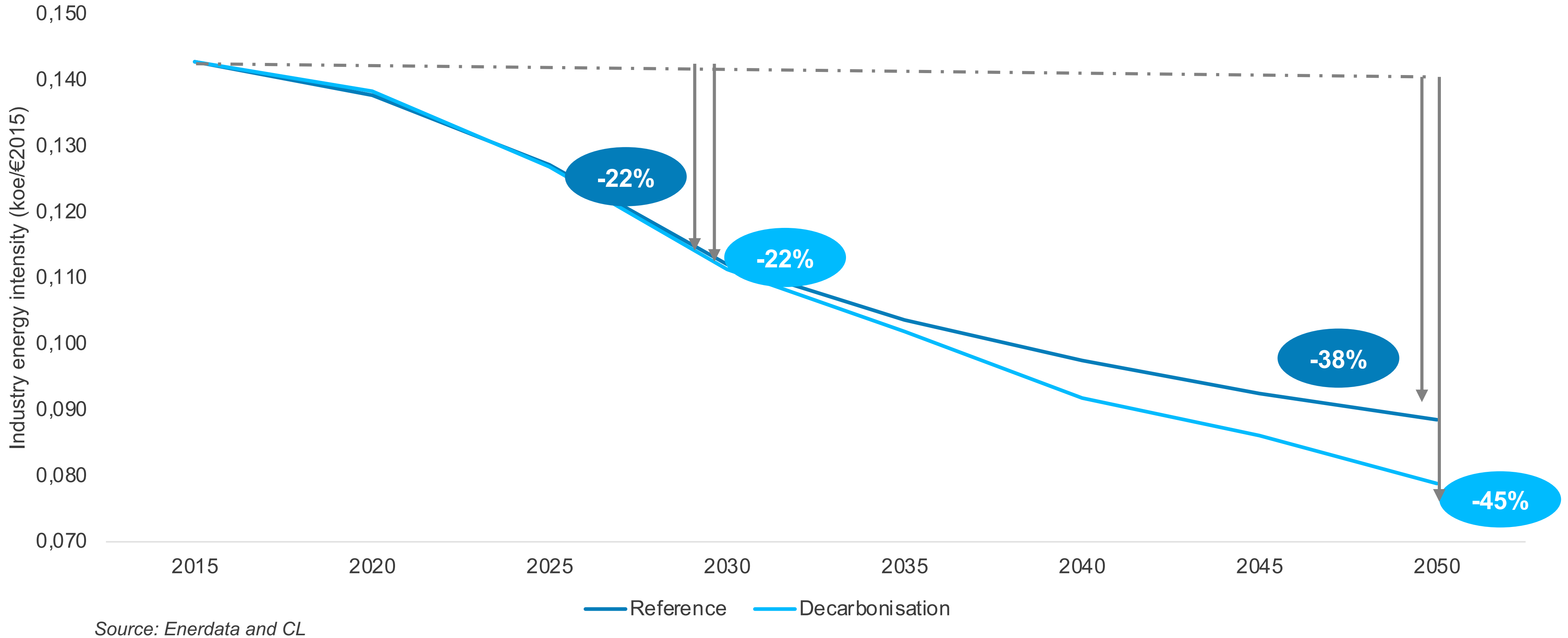


Source: Enerdata and CL

Energy efficiency gains are amplified in the Decarbonisation scenario thanks to process improvements, recycling, sector coupling and electrification

- Industrial energy intensity measured by koe/€ improves under both scenarios, with faster gains in the Decarbonisation scenario. Key measures include:
  - 2020s: gains mostly driven by energy efficiency measures, e.g. from waste heat recovery and heat pumps
  - 2040s: reuse and recycle measures through circular economy (waste and biomass replacing crude oil in industrial processes) and sector coupling at scale (hydrogen from renewable electricity as industrial feedstock)
  - 2050: electrification of ethylene production and electric arc furnaces (EAF)

Industry energy intensity, Reference vs. Decarbonisation scenarios



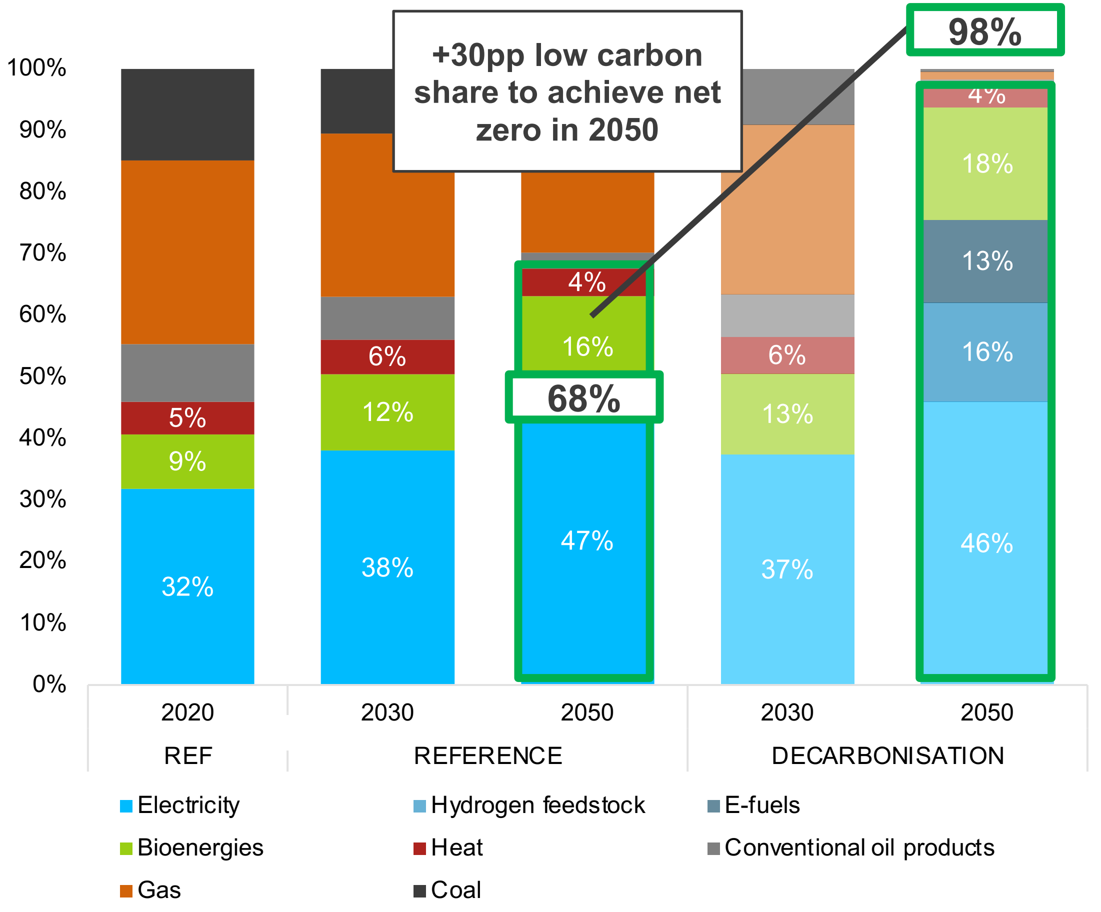
Source: Enerdata and CL

Electrification of industrial processes combined with production of green hydrogen and other e-fuels contribute to the decarbonisation

- **Electrification through direct electrification and indirect electrification almost triples in the Decarbonisation scenario by 2050:**
  - **Over 75% of industrial energy demand comes from electricity** including direct use of electricity and indirect use through hydrogen (16%) and e-fuels (13%)
  - Direct electrification (46%) results from the **fuel switching in industrial processes**, in industries such as iron and steel using electric arc furnaces, or the cement industry through the development of technologies for electrification of cement clinker production
  - Indirect electrification through the **production of green hydrogen and e-fuels** will also increase in the Decarbonisation scenario (compared to no indirect electrification in the Reference scenario)

- **Bioenergies** represent 18% of the energy demand in the Decarbonisation scenario in 2050 and are mostly used as a **substitute for fossil fuels in industrial processes.** Fuel switching to bioenergies will notably support the decarbonisation of the cement industry, along with a limited role for CCS.

Share of energy carriers in the industry sector, Reference vs. Decarbonisation scenarios



Source: Enerdata and CL

Notes: 1) Heat refers to district heating and solar heat from thermal solar panels
2) In hard to abate industry processes, there will be a role for CCS.
3) Bioenergies include biofuels and biomass.

Steel & iron has the largest GHG share out of industrial sectors, but also the most mature technology to reduce emissions through electrification

Key facts

- In 2016: 13% of industrial demand, 20% of industrial GHG emissions
- \- 47.5% in GHG emissions between 1990 and 2016

Drivers to further decarbonise the sector

- Production of direct reduced iron (DRI) by:
  - Electrolysis: no CSS/CCU needed as CO2 avoided, high TRL
  - New hydrogen plasma smelting reduction technology
- Shift from primary to secondary (recycled) steelmaking
- Increase using scrap metal in an electric arc furnace (EAF) powered by RES – possibly almost carbon free

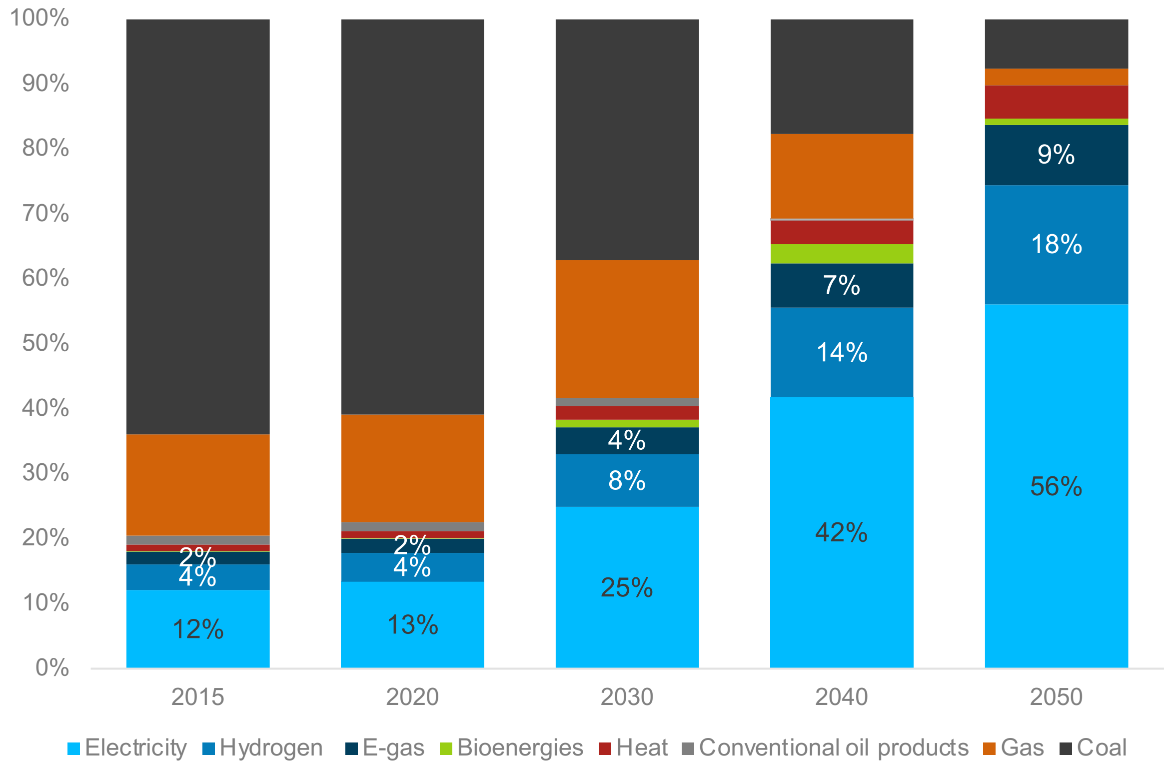
BUSINESS CASES

HYBRIT FOSSIL-FREE STEEL

SALCOS Steelmaking. Reinvented.

H2FUTURE Green Hydrogen

Share of energy carriers in steel & iron sector, Decarbonisation scenario



Source: Enerdata and CL
Notes: 1) Bioenergies include biofuels and biomass.
2) TRL= Technology Ready Level

Chemical sector has a strong potential for sector-coupling and diversified paths to tackle its emissions

Key facts

- In 2016: 14% of industrial demand, 14% of industrial GHG emissions
- - 43.6% in GHG emissions between 1990 and 2016

Drivers to further decarbonise the sector

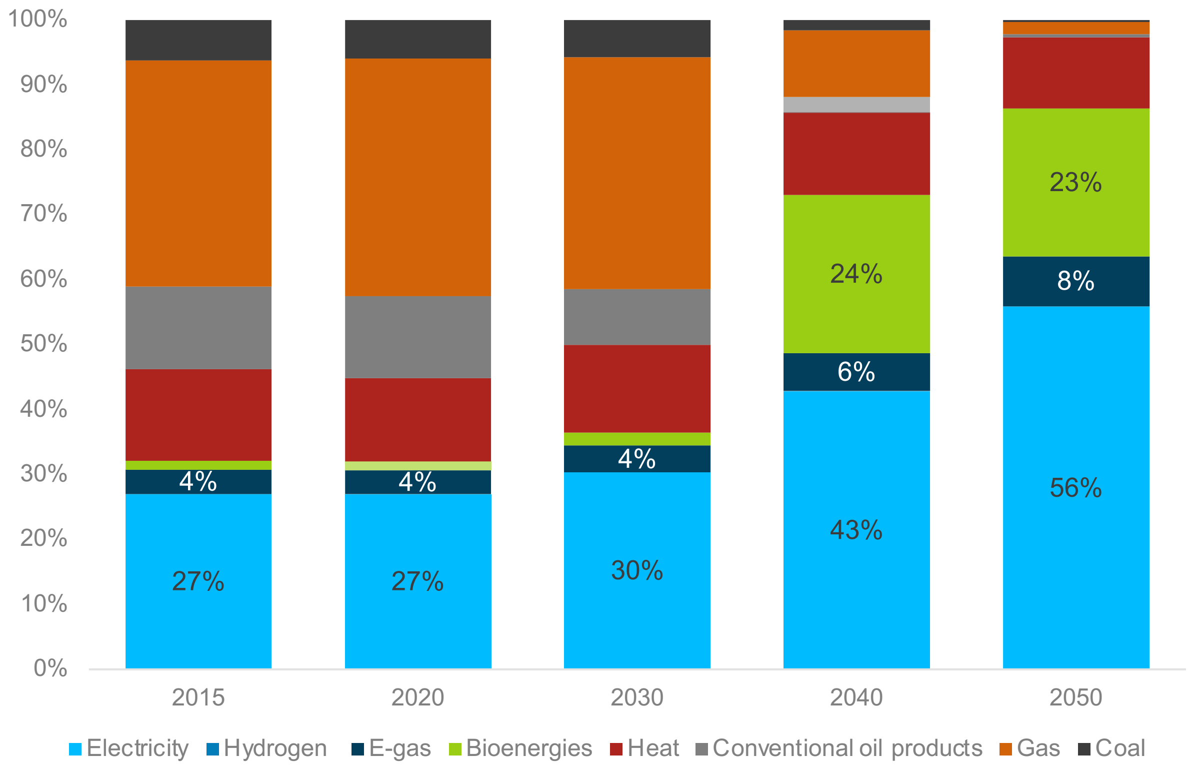
- Replacing fossil-based feedstock by green hydrogen and biomass feedstock
  - eg: bioethanol and biomethanol
- Hydrogen based ammonia and near market ready
- Power-to-X
  - Power to fuels (gases - H2, CH4; liquids - synthetic kerosene, methanol, formic acid; heat)
  - Power-to-chemicals
  - Power-to-fertilizers
- Use of biogas instead of fossil gas for processes

BUSINESS CASES

VOLTA CHEM

TNO innovation for life

Share of energy carriers in chemicals sector, Decarbonisation scenario



Source: Enerdata and CL

Note: Bioenergies include biofuels and biomass.

Non-metallic minerals are large GHG emitters but the technologies to reduce process emissions are not yet mature

Key facts

- In 2016: : 9% of industrial demand, 18 % of industrial GHG emissions
- - 36.7% in GHG emissions between 1990 and 2016

Drivers to further decarbonise the sector:

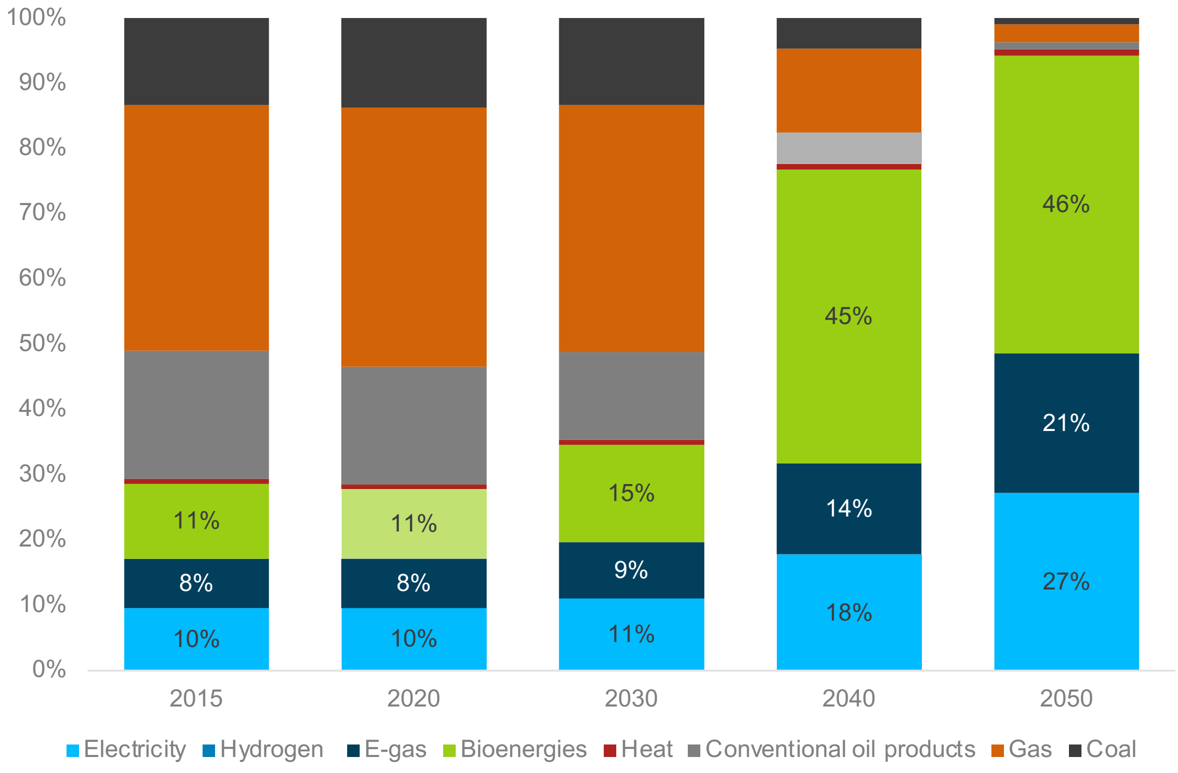
- Today's BAT techniques limited mitigation potential (2/3 emissions are process instead of energy related)
- Technological breakthroughs needed, high hopes for CCS/CCU
- Progress in fuel switching to biogas and biomethane and reduction of clinker content in cement
- Focus on circular measures (resource, material and product)
- Progress in CO2-cured concrete products

BUSINESS CASES

SOLIDIA

Leilac

Share of energy carriers in non-metallic minerals sector, Decarbonisation scenario



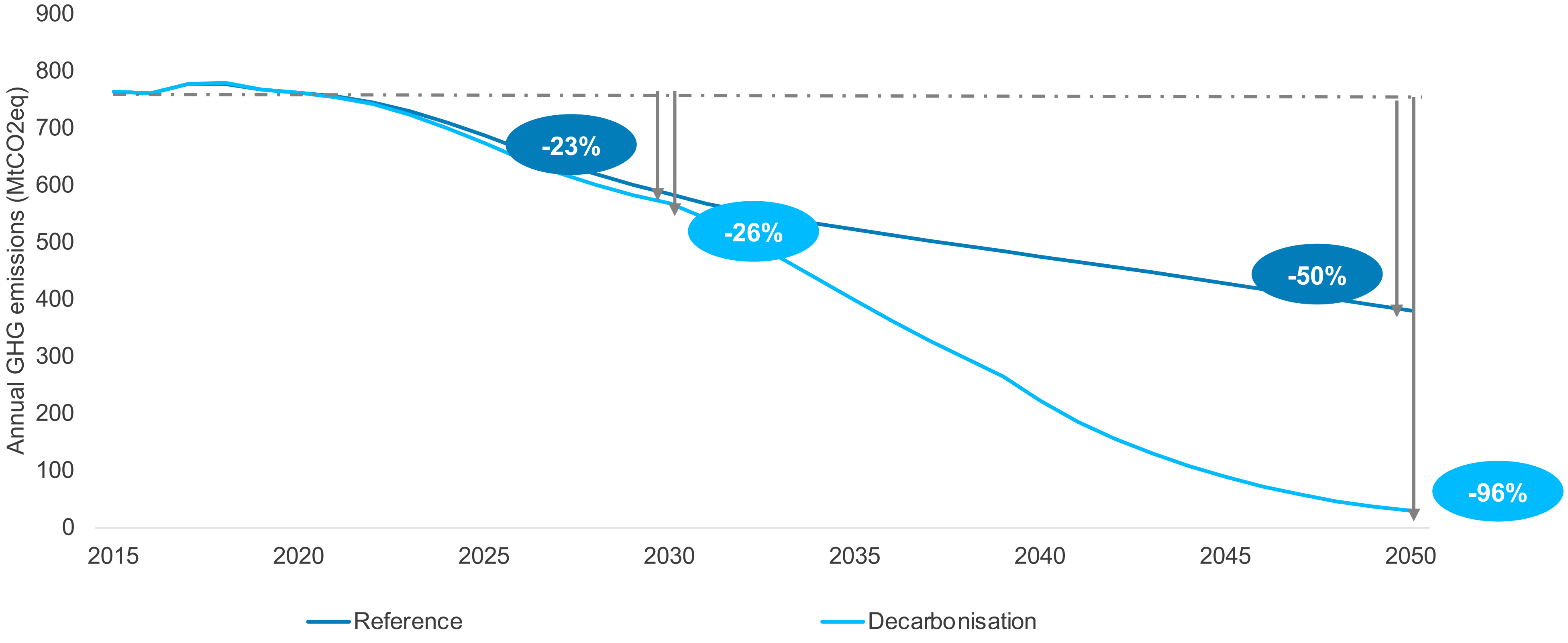
Source: Enerdata and CL

Note: Bioenergies include biofuels and biomass.

The Decarbonisation scenario features greater emission reductions in the industrial sector - in particular in energy intensive industries

- Currently industry emits about 15% total GHG emissions in the EU (heavily reliant on fossil fuels)
- Industry has decreased its GHG emissions by -44% from 1990 to 2016
- In 2030, the difference between the Reference and Decarbonisation scenario is small but in 2050, emissions reduction (compared to 2015) in the Decarbonisation scenario are doubled thanks to the electrification (direct and indirect use) of the industry.

Gross GHG emissions in industry, Reference vs. Decarbonisation scenarios



Source: Enerdata and CL

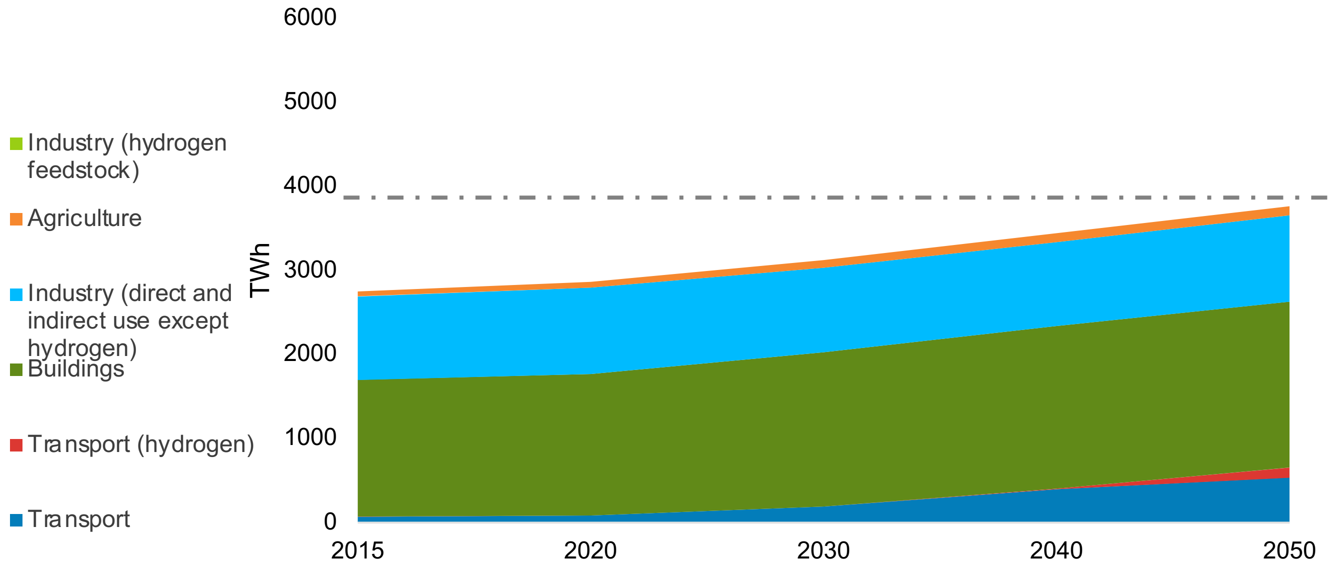
3. Faster and deeper decarbonisation of the power sector is achievable through increased RES and flexible technologies

3.A Achieving net zero in 2050 will increase power demand, notably in transports, in the industry and for hydrogen production

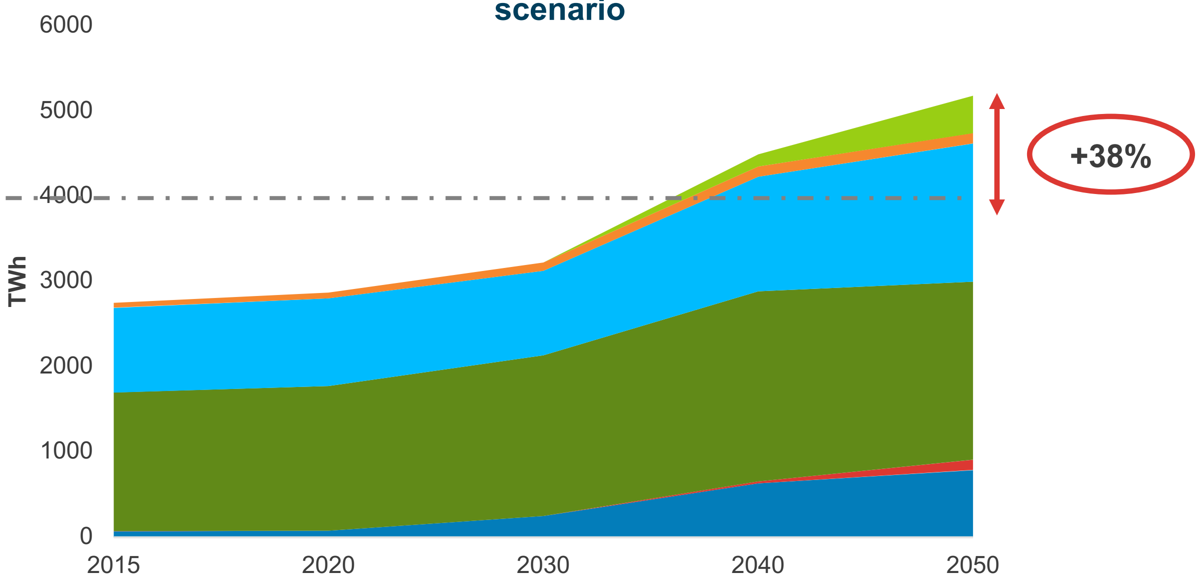
Achieving net zero in 2050 will push power demand growth, notably in transports (+46%), in the industry (+58%) and for hydrogen production

- **In 2030, the electricity demand in the Decarbonisation scenario is comparable to the Reference scenario** with a slight increase in total demand (3%) attributable to the electrification of the transport sector given the number of new private EVs more than doubles reaching a total fleet of 64m in 2030.
- **In 2050, electricity demand increases by 38% in the Decarbonisation scenario compared to the Reference scenario** due to:
  - **The increase in the industry with a 58% higher demand in 2050 than in the Reference scenario**, due to electrification of processes
  - **A 46% increase in transport demand in 2050** given the share of Low Emission Vehicles (LEVs) including EVs, hydrogen and hybrid vehicles, which reaches 100% of new private vehicles in 2050 in the Decarbonisation scenario
  - The **demand for electricity to produce hydrogen** via electrolysis to act as feedstock for the industry (21% of industrial electricity demand in 2050 in the Decarbonisation scenario) and for transport
  - The increase in buildings electricity demand mostly occurs between 2030 and 2040 as the rate of renovations in the Decarbonisation scenario averages 4% (vs 2% in the Reference scenario)

Final electricity demand by sector (TWh), Reference scenario



Final electricity demand by sector (TWh), Decarbonisation scenario



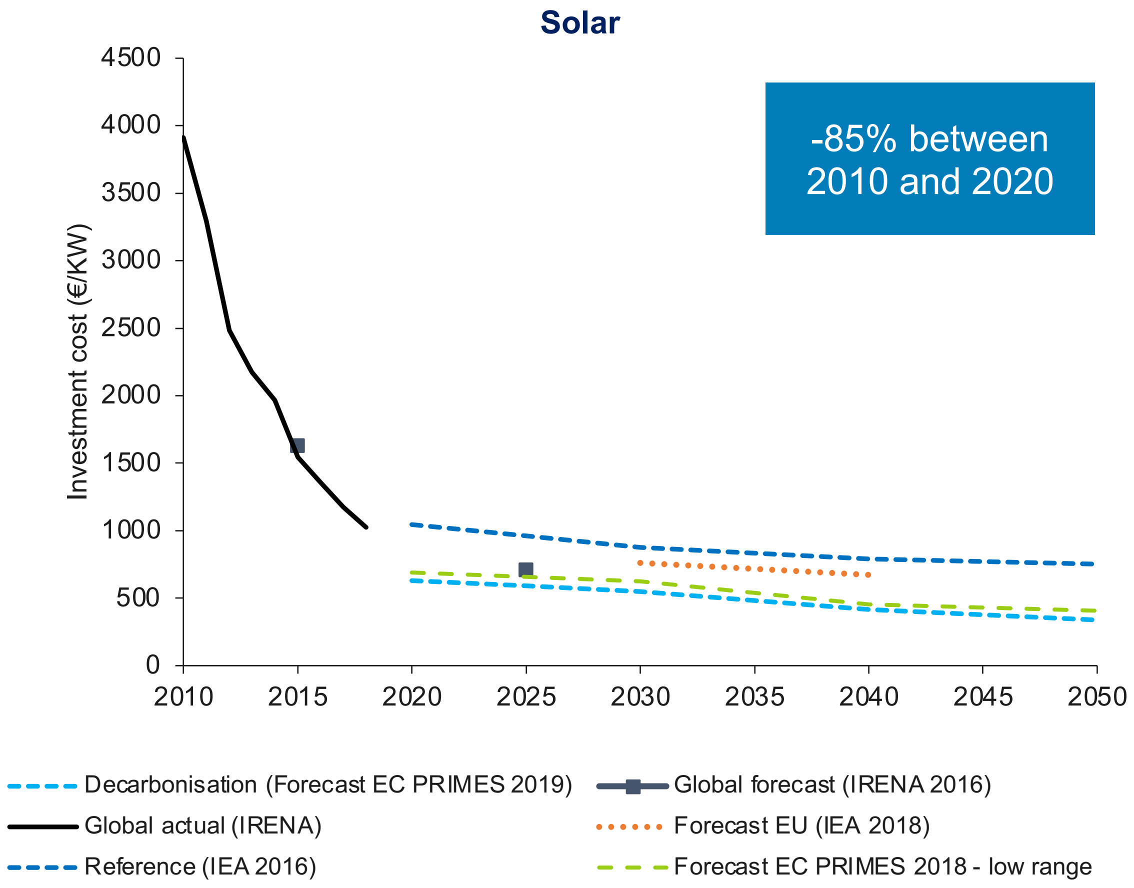
Source: Enerdata and CL

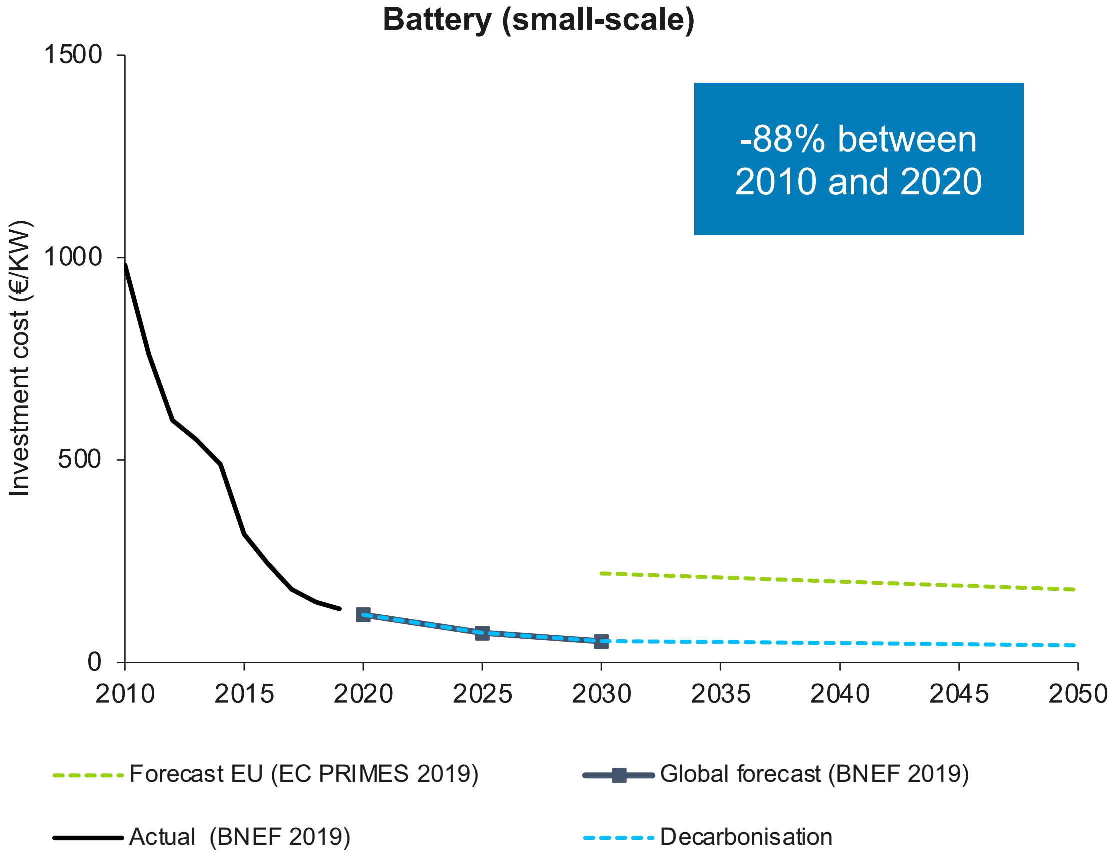
Note: Indirect use in the industry except hydrogen refers to clean gas

3.B Technological progress and regulatory policies have increased GHG reduction potential in the power sector

Technological progress has led to faster than anticipated cost reductions unlocking higher GHG reduction potential (1/2)

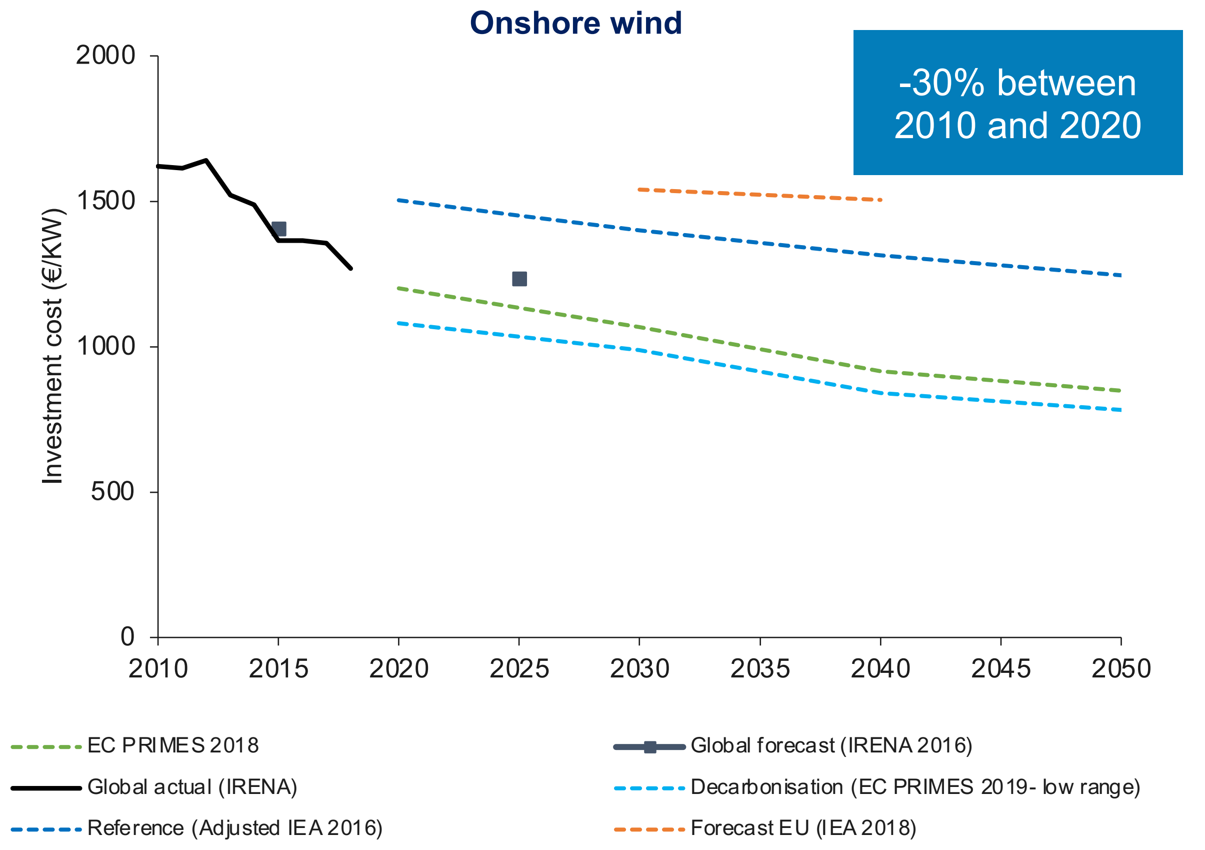
- **Recent technological progress and scale effects have led to significant cost reductions for Solar PV and batteries, faster than previously anticipated.** This cost reduction is reflected in the Decarbonisation scenario through reduced Solar and batteries cost:
  - Solar costs are aligned with the EC PRIMES 2019 forecast which is 74% lower in 2020 than the IEA 2016 forecast used for the Reference scenario.
  - For battery cost, forecasts assumed in the Decarbonisation scenario are aligned with the global BNEF 2019 forecast for 2030 while the Reference scenario is aligned with the IEA 2016 forecast.

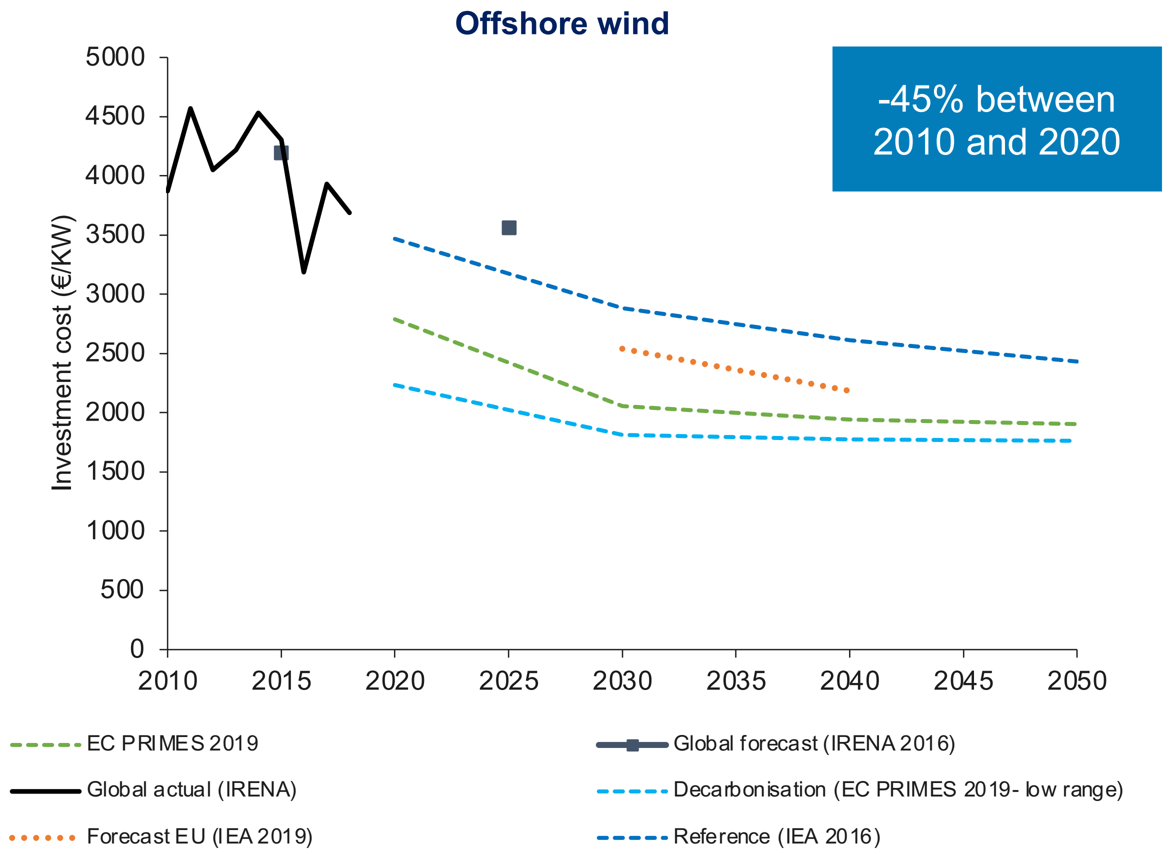




Technological progress has led to faster than anticipated cost reductions unlocking higher GHG reduction potential (2/2)

- **Recent technological progress has also led to faster cost reduction than anticipated for wind onshore and wind offshore which is reflected in the Decarbonisation scenario:**
  - Onshore and offshore wind costs are aligned with the EC PRIMES 2019 forecasts while in the Reference scenario, costs are aligned with the IEA 2016 forecasts.
  - In the Decarbonisation scenario, we take into account the recent costs reductions in onshore and offshore wind, representing respectively 30% and 45% between 2010 and 2020. In comparison, costs in the Reference scenario which are aligned with 2016 forecasts are 27% higher in 2020 than in the Decarbonisation scenario for onshore wind, and 37% higher for offshore wind.

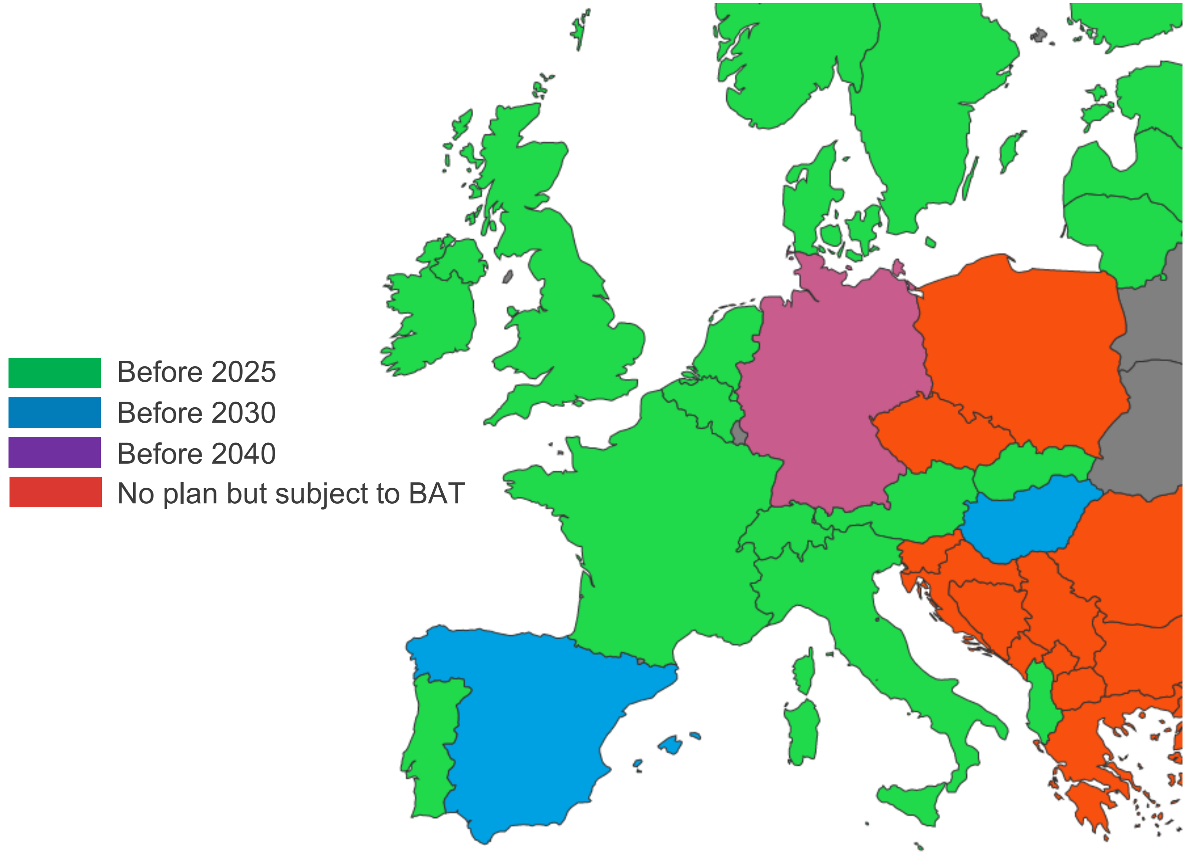




National commitments to accelerate coal phase-out enable increased ambition in the power sector for GHG reduction by 2030

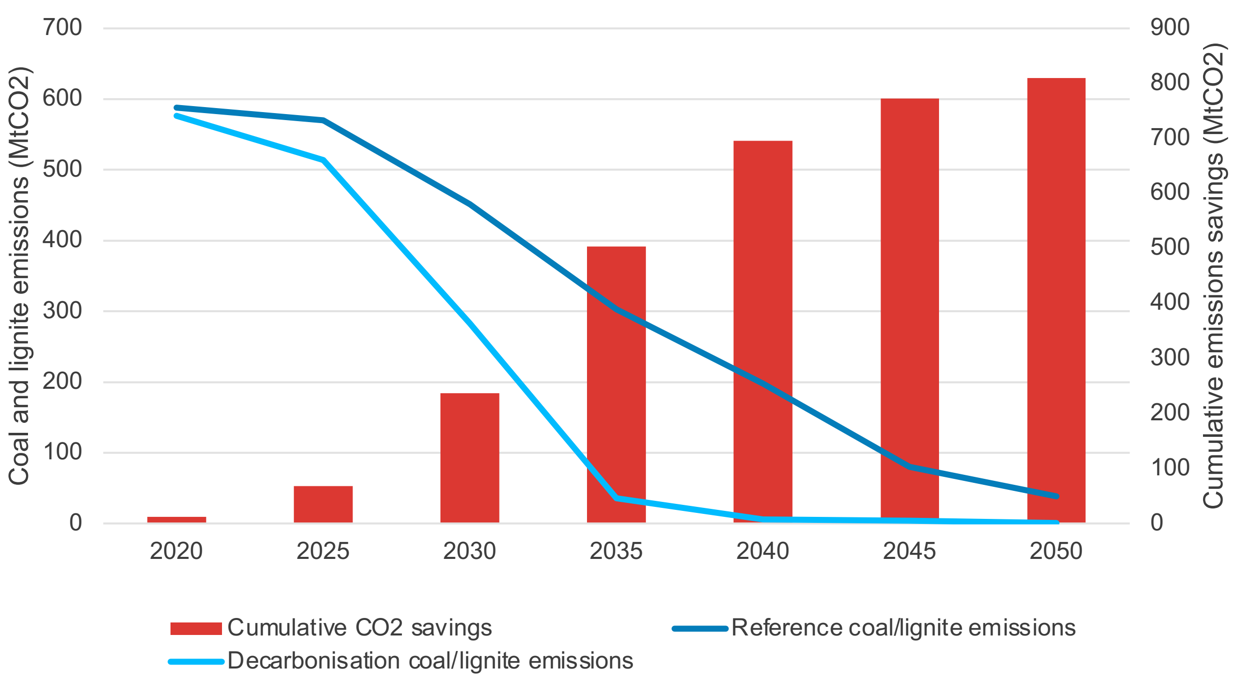
- **Recent national policies announcements to accelerate coal phase out allow to go further in the decarbonisation ambition in 2030.**
- Coal phase-out plans assumed in the Decarbonisation scenario allow to **reduce power emissions by an additional 23% by 2030** and will result in more than 800 MtCO2 of cumulated emissions avoided by 2050.

Map of coal plants phase-out in Europe



Cumulative emissions savings associated with coal phase-outs

- The combined national commitments would more than halve European coal and lignite capacities by 2030 from 111 GW in the Reference scenario to 54 GW in the Decarbonisation scenario.



Source: CL modelling

Note: Part of the cumulative emissions savings from coal phase outs will be offset by emissions from gas that will replace coal until RES takes over the main share of generation.

3.C With 84% share of renewables and coal phase out, the power sector is fully decarbonised in 2050 in the Decarbonisation scenario

With 84% share of renewables and the coal phase out, the power sector is fully decarbonised in 2050 in the Decarbonisation scenario

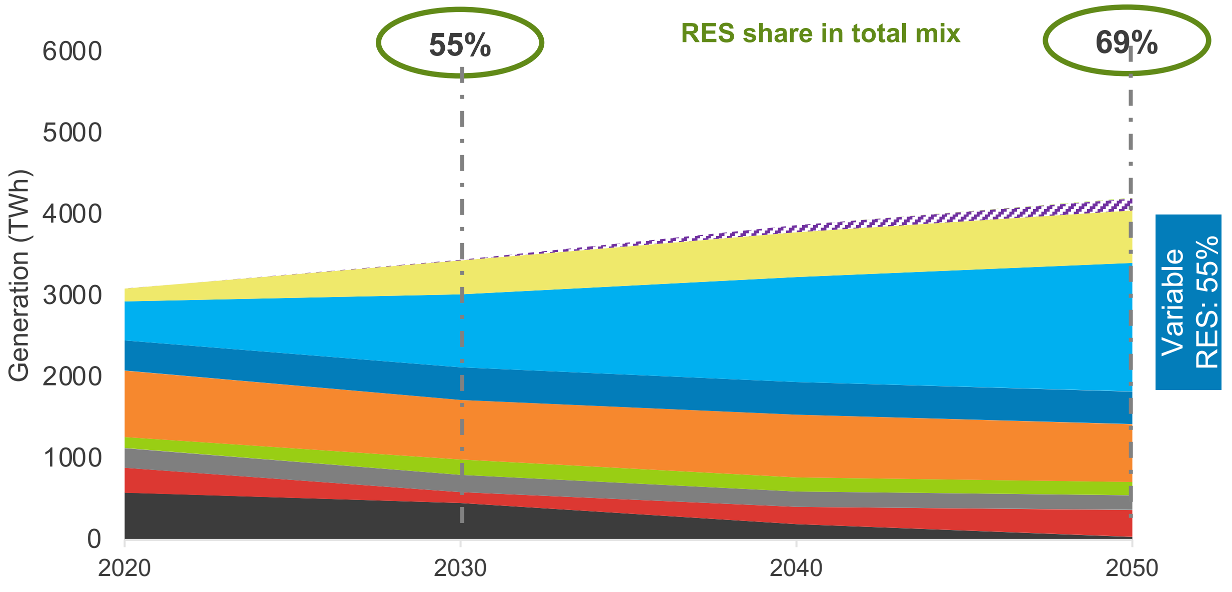
Faster and more ambitious deployment of RES supports decarbonation of the power sector:

- In the Reference scenario, RES reach 69% of total 2050 generation, with 55% penetration of variable RES.
- In the Decarbonisation scenario, RES reach 84% of total 2050 generation, with 74% penetration of variable RES.

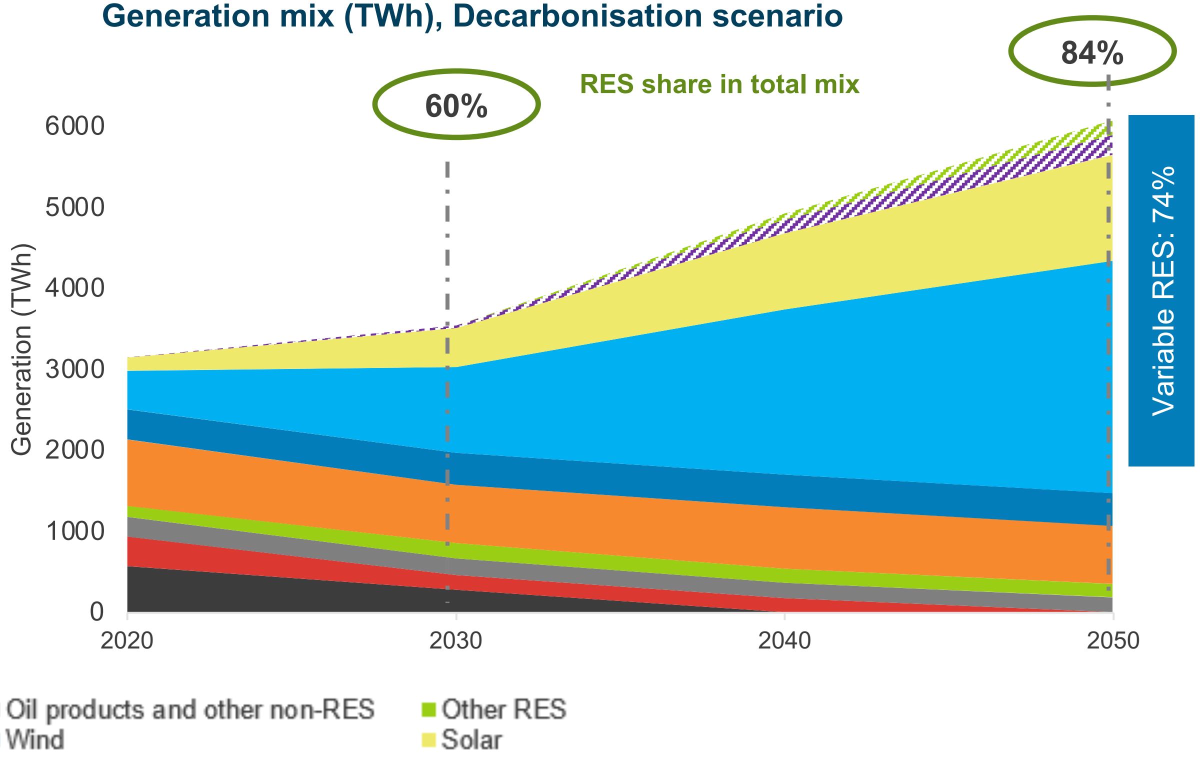
The deployment of a range of flexibility options enables the transformation of the electricity system:

- In the Reference scenario, RES would produce 7% of non consumed energy, 80% of which being stored and redistributed through P2G or batteries.
- In the Decarbonisation scenario, RES would produce 14% of non consumed energy, 86% of which being stored and redistributed through P2G or batteries.

Generation mix (TWh), Reference scenario



Generation mix (TWh), Decarbonisation scenario



Source: FTI-CL Energy modelling

Note: Batteries and P2P2G generation are shown on chart but cannot be added to the rest of the generation mix. Sum of generation is higher than net power demand due to storage consumption.

Renewable capacity in the Decarbonisation scenario would increase by 70% in 2050 reaching a total of 2210 GW in 2050

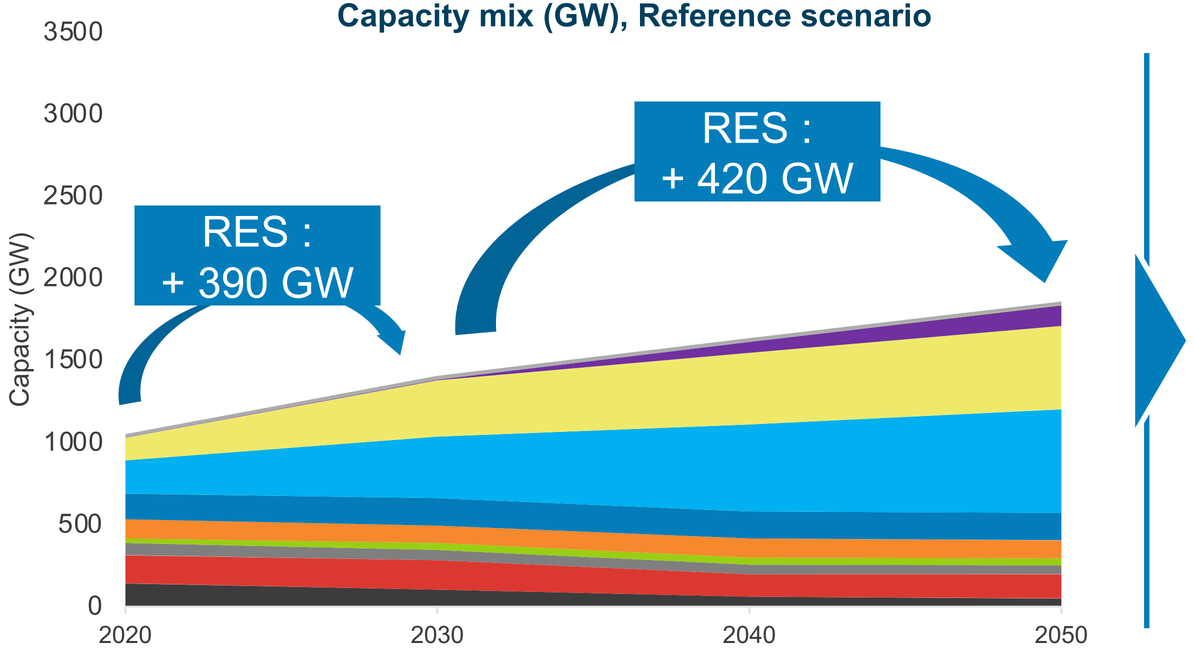
By 2050, the faster costs reduction in RES technologies in the Decarbonisation scenario allows a faster deployment of renewables (5% per year) compared to the Reference scenario (3% per year)

- Reference: 810 GW of new RES are installed between 2020 and 2050, reaching a total of 1300 GW including 510 GW of solar and 630 GW of wind.
- Decarbonisation: 1720 GW of new RES are installed between 2020 and 2050, reaching a total of 2210 GW including 960 GW of solar and 1090 GW of wind. Demand response will contribute with additional 43 GW by 2050.

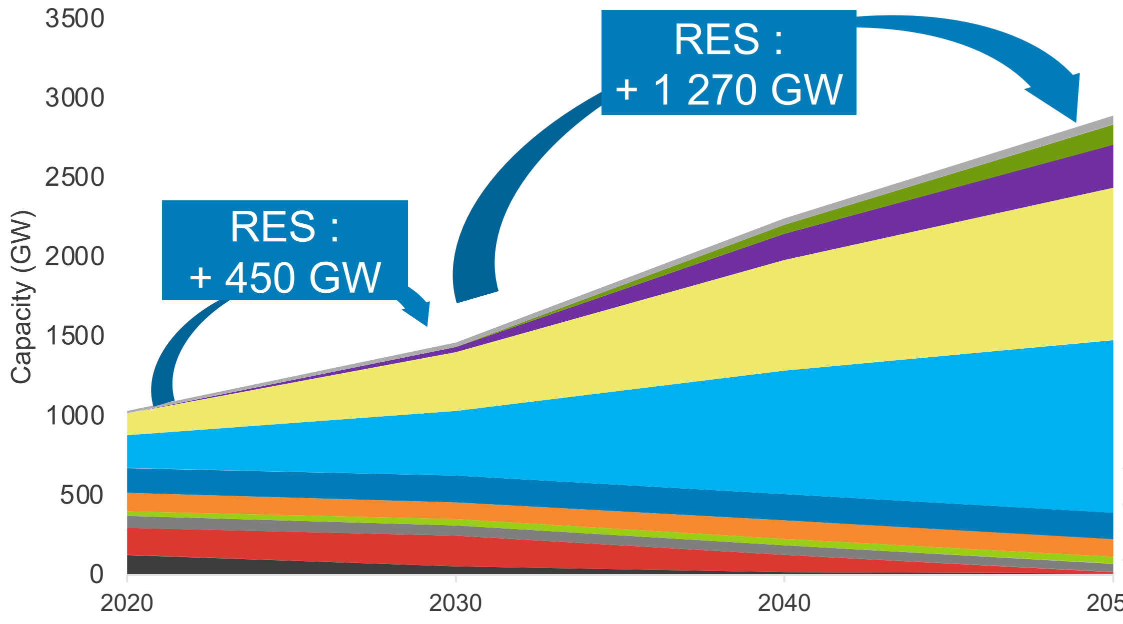
By 2030, the Decarbonisation scenario implies a significant and ambitious increase of 60 GW of RES capacity beyond the Reference scenario which is based on current NECPs[1].

- Additional RES capacity by 2030 is however limited by the potential constraints in each country (societal, land use or supply-chain constraints). In a scenario in which potential constraints are removed, RES capacity additions beyond NECPs would double in 2030 compared to the Decarbonisation scenario.

Capacity mix (GW), Reference scenario



Capacity mix (GW), Decarbonisation scenario



[1] : Between 2020 and 2030, 390 GW of new RES in the Reference scenario, reaching a total of 880 GW including 345 GW solar, 375 GW wind. In the Decarbonisation scenario, 450 GW of new RES, reaching a total of 940 GW including 370 GW solar, 410 GW wind.

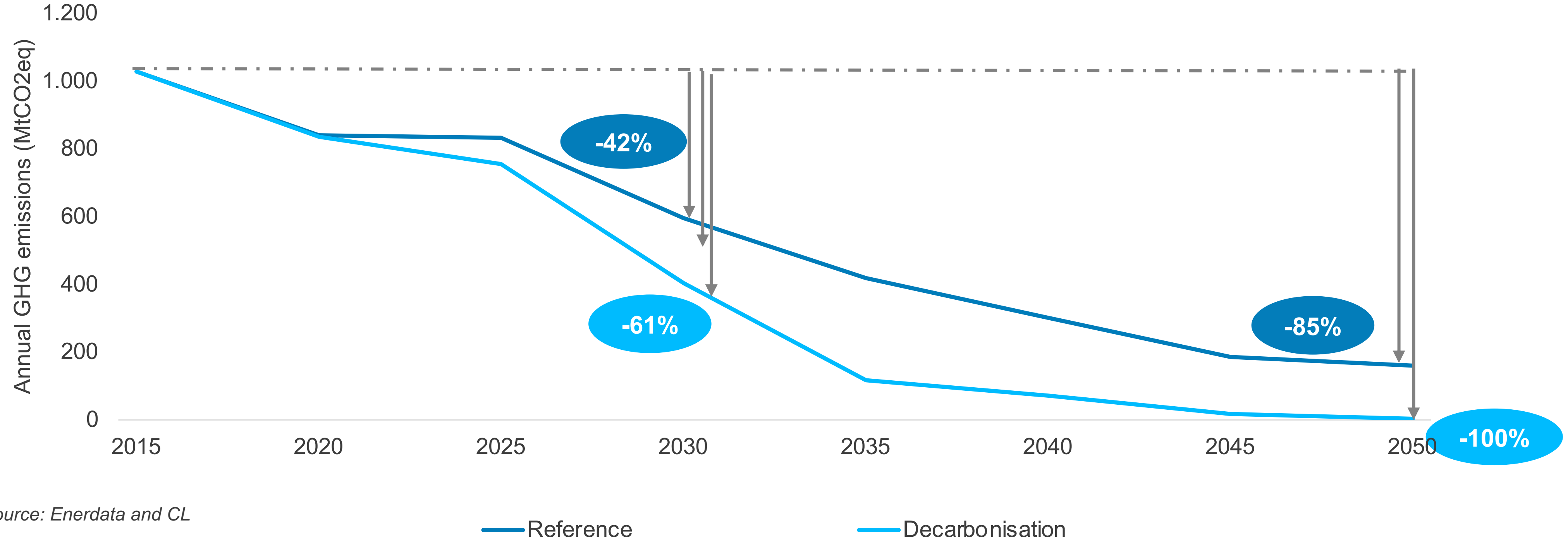
Source: FTI-CL Energy modelling

Coal and lignite
Nuclear
Batteries
Gas
Hydroelectricity
Power-to-gas-to-power
Oil products and other non-RES
Wind
Demand-side response
Other RES
Solar

The power sector is fully decarbonised in 2050 in the Decarbonisation scenario

- Thanks to the coal phase out and higher renewable share, the power sector reaches 61% GHG reduction by 2030 (from 1028 MtCO2eq in 2015 to 403 MtCO2eq in 2030) compared to 42% in the Reference scenario (from 1028 MtCO2eq to 595 MtCO2eq) and is fully decarbonised in 2050 in the Decarbonisation scenario (with almost full decarbonisation from 2045).
- Emissions from the power sector decrease by 85% in the Reference scenario (reaching 160 MtCO2eq in 2050) between 2015 and 2050 with fossil fuel energies still representing 14% of the energy mix in 2050 compared to a full decarbonisation in the alternative scenario.
- The power sector CO2 emission reductions represent 11% of CO2 emission reduction between the Reference and Decarbonisation scenario.

Gross GHG emissions of the power sector(MtCO2eq), Reference vs Decarbonisation scenarios



Source: Enerdata and CL

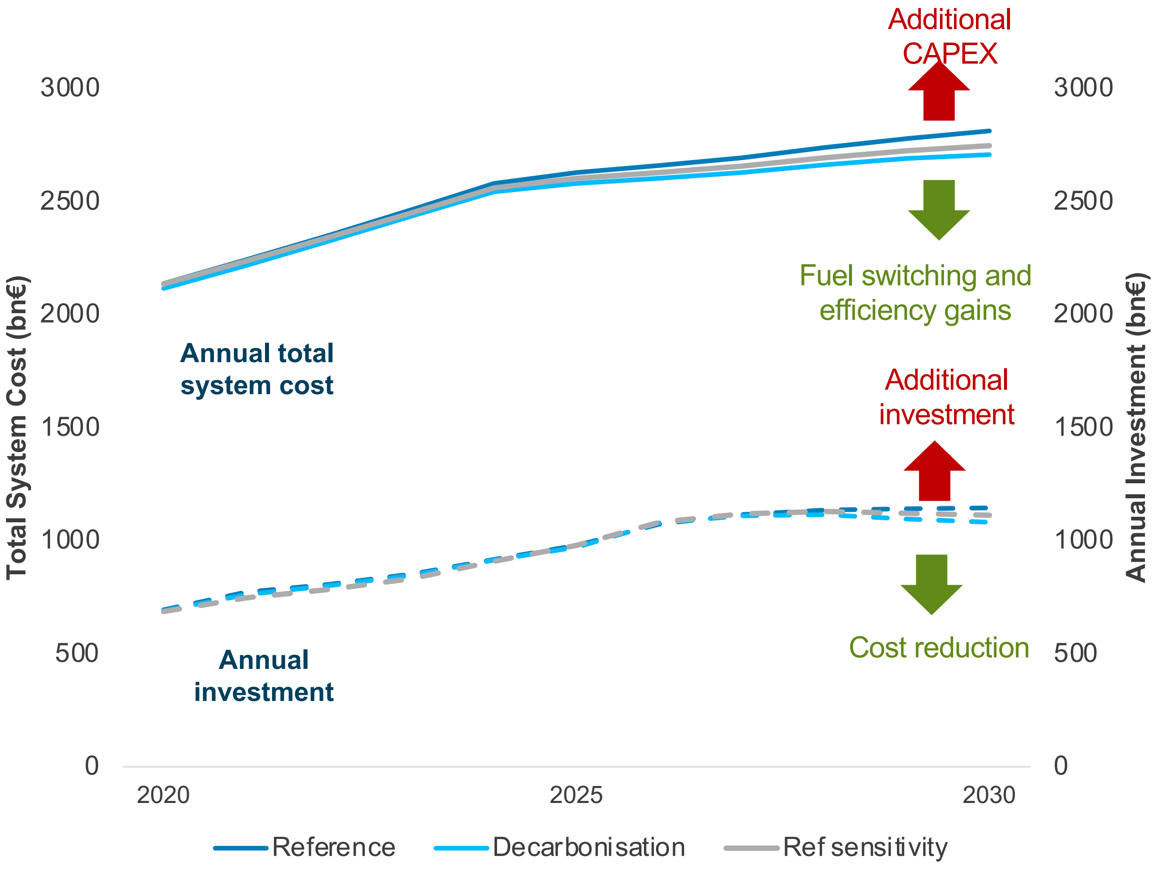
Note: Inflection points in 2025 and 2035 in the Decarbonisation scenario are mostly driven by coal pahse outs.

4. The reductions in costs of clean and flexible resources and new business models will help to contain costs

Increased ambition in 2030 can be reached with slightly reduced system cost and comparable investment

- **Annual investments in the Reference scenario increase by 65% between 2020 and 2030**.
- Despite the increased ambition in the **Decarbonisation scenario** and greater emission reductions in 2030, **annual investments remain similar thanks to the cost reductions in RES technologies and batteries.**
- Similarly, in the **sensitivity analysis of the Reference scenario, investments are lower than in the Reference scenario thanks to the costs reduction assumed in the power generation and transport sector**. However, investments are still higher than in the Decarbonisation scenario as a reduction of the passenger fleet is assumed in the Decarbonisation scenario therefore lowering the transport costs.
- **Total energy system costs in the Decarbonisation scenario are slightly lower than the Reference scenario**, thanks to energy efficiency gains and fuel switching.
- The increase in ambition to reach the higher 55% GHG emissions reduction in 2030 targets has thus no impact on consumers, and would be aligned with the objectives of the EU recovery plan to prioritise green investments and steering private and public investments towards green projects.

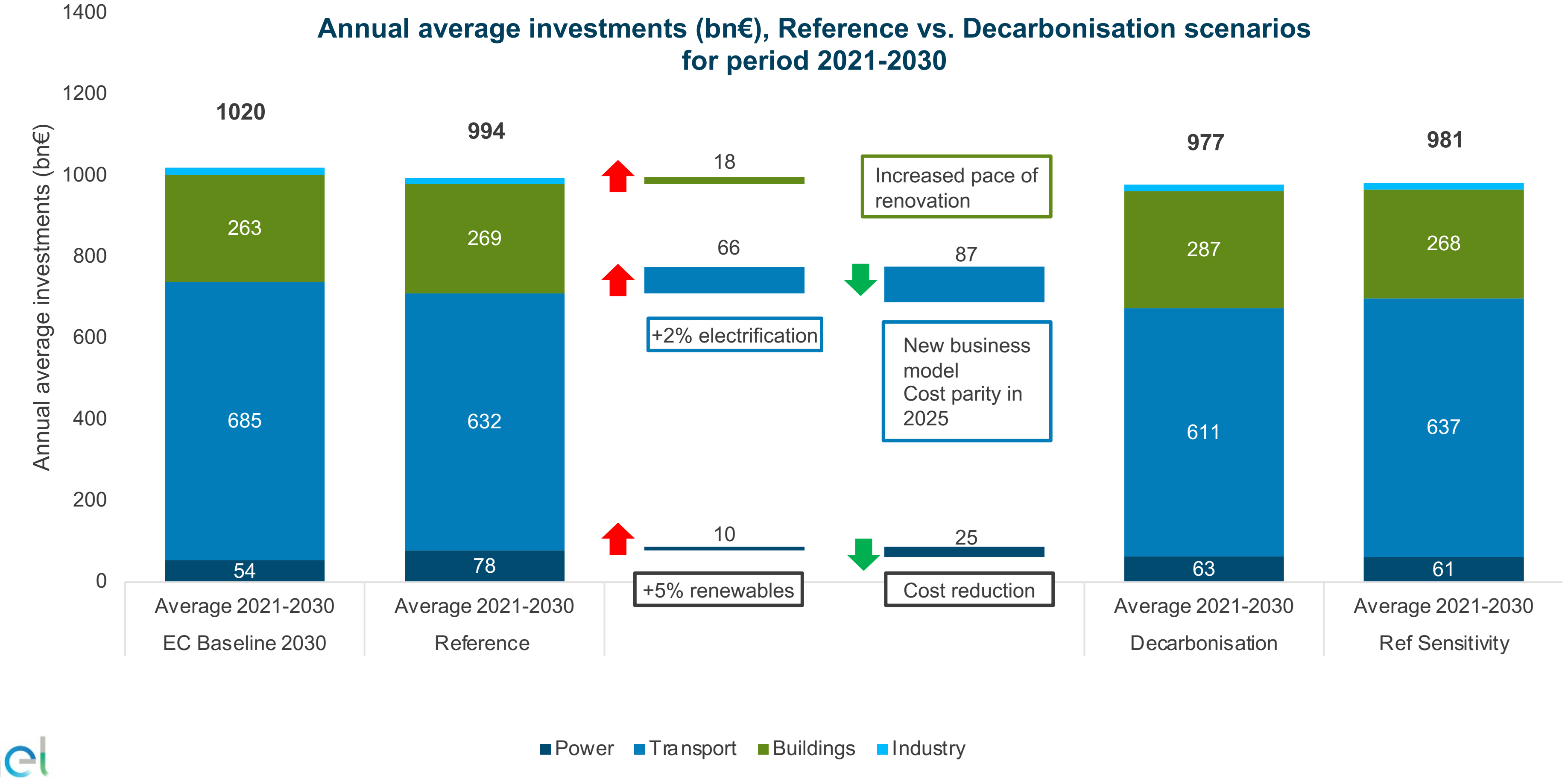
Annual total system costs and annual investments (bn€) in Reference, Decarbonisation and Reference sensitivity scenarios, 2021-2030



- Annual investments : CAPEX on a yearly basis excluding power network costs
- Annual total system costs : annualised CAPEX + OPEX + fuels costs (including network costs) on a yearly basis
- Capital expenditures are accounted for in the system costs as annuity payments. A discount rate of 5% is applied for all sectors to annualise the capex.

Technology cost reduction enables to reach more ambitious targets by 2030 with comparable annual expenditure

- **Expenditures in Decarbonisation scenario with increased ambition in 2030 are comparable to the Reference scenario** and remain lower than in the EC Reference scenario thanks to :
  - Cost reduction in the transport sector limiting the impact of further electrification
  - Cost reduction in the power sector limiting the impact of further RES development
  - Expenditures increase slightly in the buildings sector due to the slightly higher renovation rate over the period



Total system costs remain comparable in the Decarbonisation scenario, as increases in buildings offset reduction in power and transport sectors

- **Average total system costs are similar in both scenarios thanks to technology cost reduction and energy efficiency gains and fuel switching**
- The additional reduction in emissions achieved in the Decarbonisation scenario with comparable system costs to the Reference scenario is enabled thanks to:

Transport

- Reduction of annualised CAPEX of vehicles and infrastructure, thanks to the reduction of private vehicle fleet and reduction of EV unit cost reaching cost parity in 2025 more than offsetting the additional cost of infrastructure
- Reduction of fuel costs thanks to electrification of vehicles

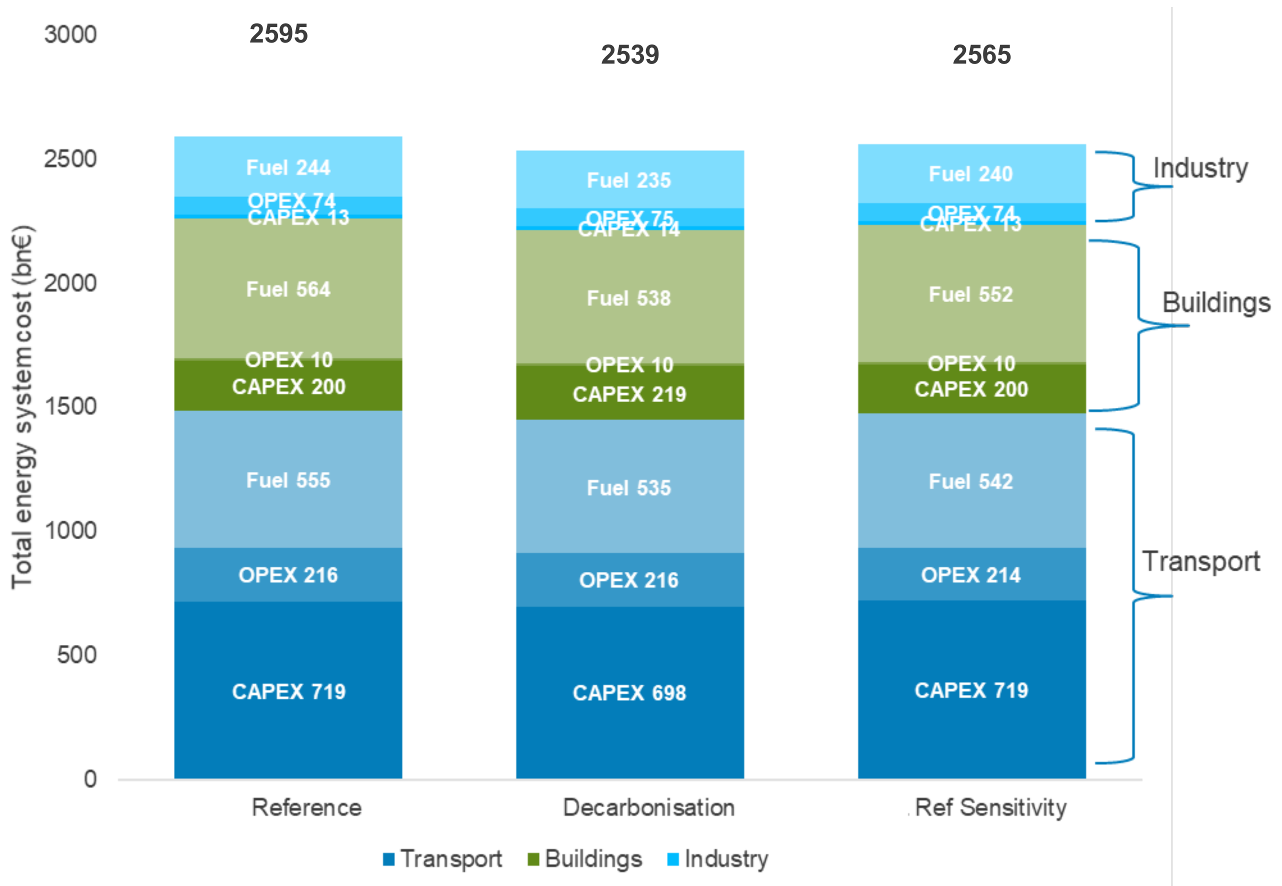
Buildings

- Increase of annualised CAPEX of buildings through slightly higher renovation pace by 2030- this increase is more than offset by the fuel opex reduction

Industry

- No material change between the two scenarios

Annual average total system cost (bn€) 2021-2030



Source: Enerdata and CL

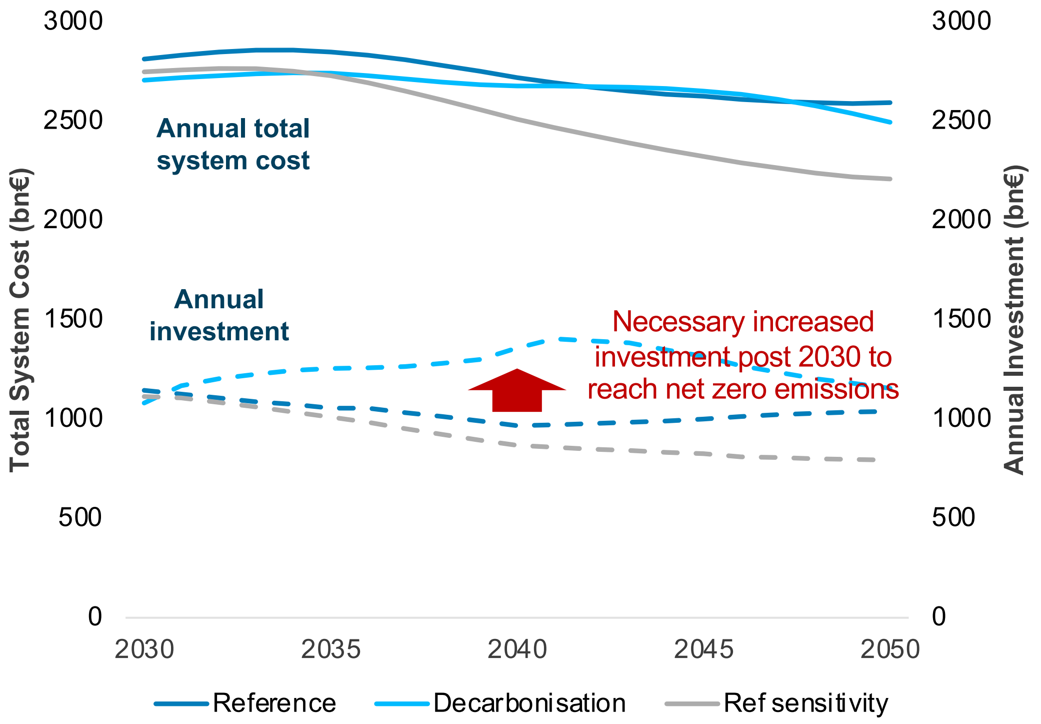
Complete decarbonisation in 2050 requires to sustain investment beyond 2030 but does not increase system costs thanks to the clean technologies cost decreases

- **Complete decarbonisation by 2050 requires increasing clean energy investment after 2030 and until 2040 compared to the Reference scenario**, in order to deploy clean technologies. Total investment starts declining in the last decade of the outlook (2040-2050) and eventually reaching similar levels to the Reference scenario beyond 2050.

- **Despite this temporary increase in investment, total energy system costs in the Decarbonisation scenario remain comparable to the Reference scenario throughout the outlook** thanks to the decrease in clean technologies costs, the decrease in flexibility technology costs on the supply side and the increase in embedded demand-side flexibility. Fuel switching to electricity enables end-uses to capture those reductions in costs and to achieve energy efficiency gains unlocked by EVs, HPs, and electrification.

- **By construction, the sensitivity analysis of the Reference scenario has both lower investments and system costs compared to both the Reference and Decarbonisation scenarios**, as it does not achieve higher climate ambition in 2050 but it benefits from the costs reduction in the power and transport sector.

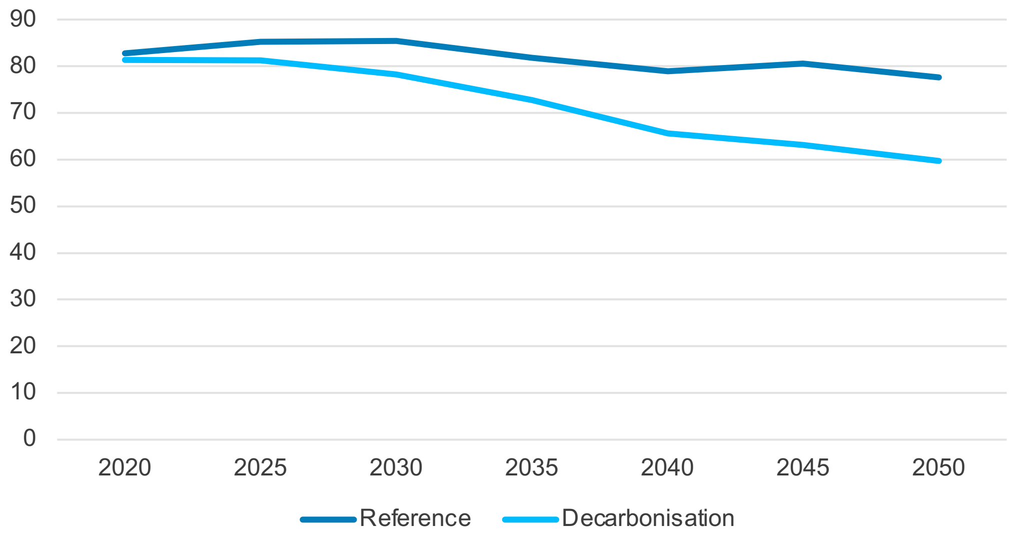
Annual total system cost and annual investment (bn€) in Reference, Decarbonisation and Reference sensitivity scenarios, 2031-2050



- Annual investments : CAPEX on a yearly basis excluding power network costs
- Annual total system costs : annualised CAPEX + OPEX + fuels costs (including network costs) on a yearly basis
- Capital expenditures are accounted for in the system costs as annuity payments. A discount rate of 5% is applied for all sectors to annualise the capex.

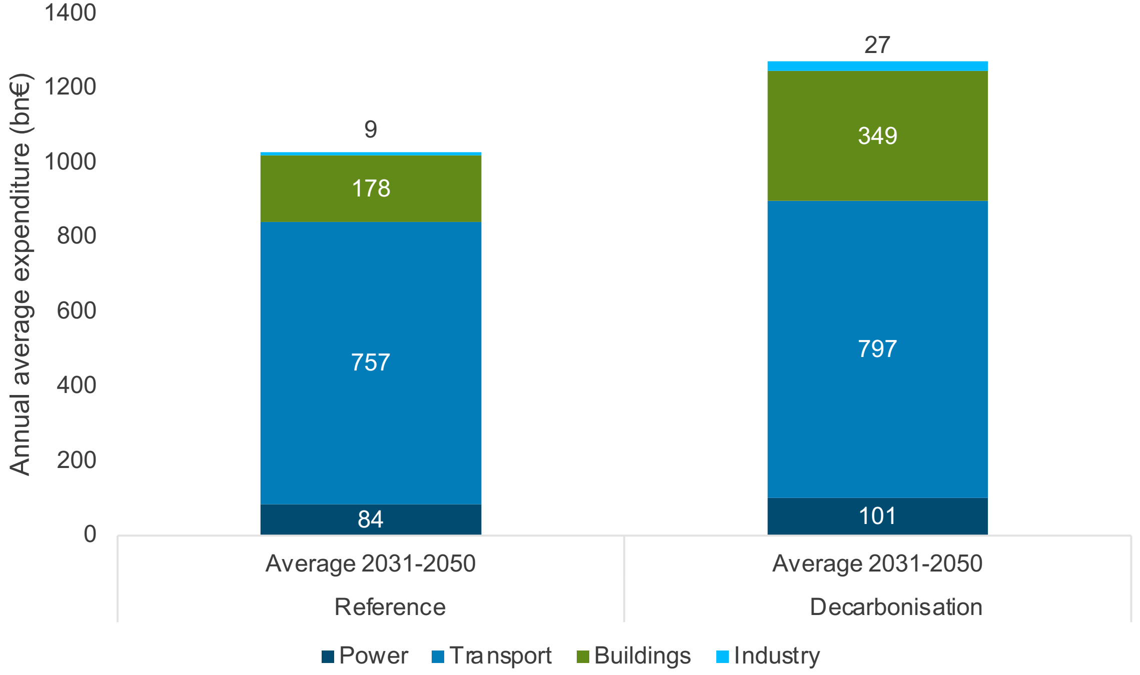
Despite increased investments to reach carbon neutrality in 2050, system costs remain comparable to the Reference scenario thanks to the decrease in power sector costs

Average LCOE in the power sector (€/MWh), Reference vs Decarbonisation scenarios, 2020-2050



- Thanks to the decrease in RES technology costs (wind and solar), flexibility technology costs and the digitalisation of power generation*, **the average LCOE in the Decarbonisation scenario is 23% lower** than in the Reference scenario in 2050.
- **The decrease in power costs will feed into the fuel costs** paid by the different sectors (industry, buildings, transport) and **generate system costs savings** for those sectors in the Decarbonisation scenario.

Average annual investments (bn€) in Reference vs Decarbonisation scenarios, 2030-2050



- **To reach carbon neutrality in 2050, average annual investments over the period 2030 and 2050 increase by 24% in the Decarbonisation scenario** compared to the Reference scenario with investments increasing in all sectors.

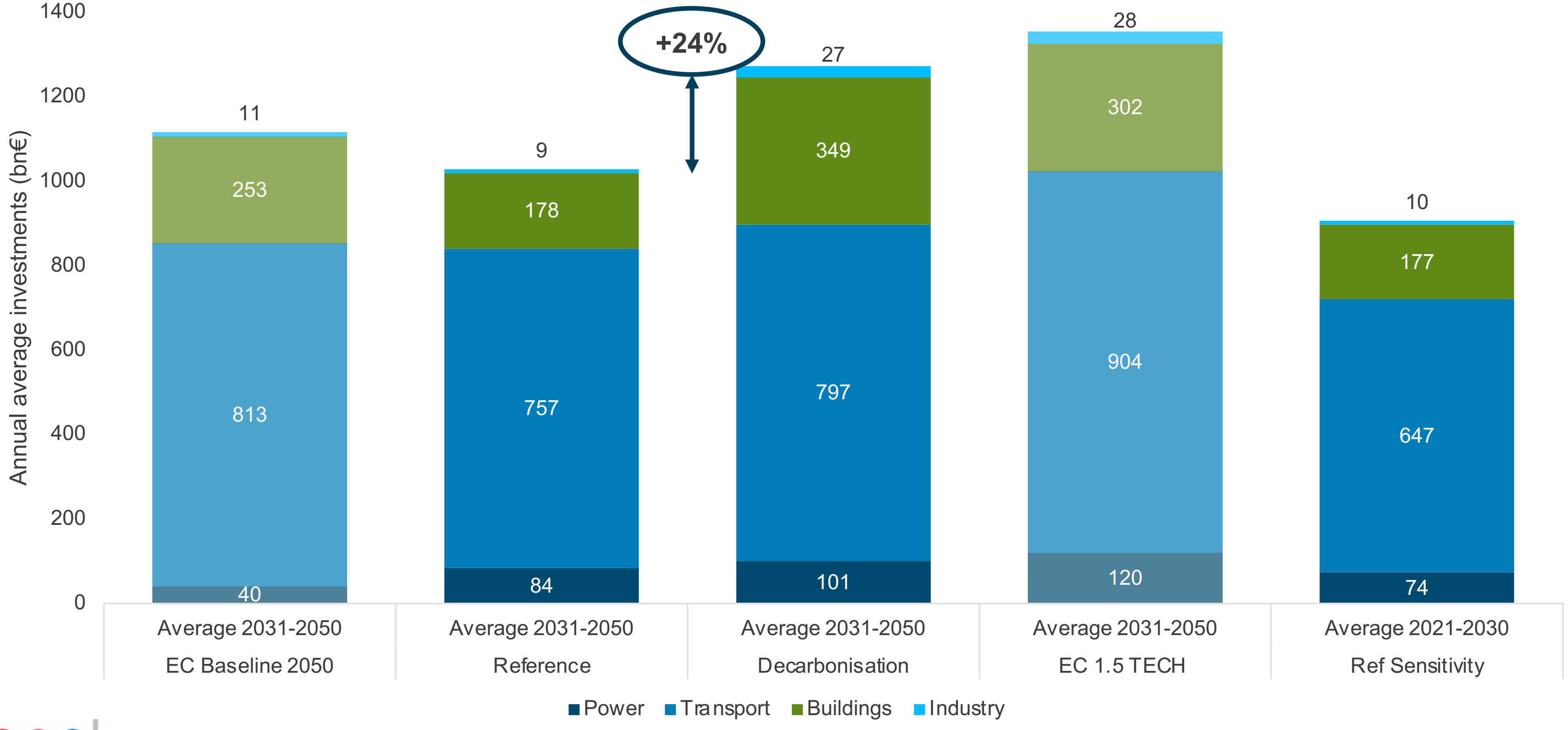
* See slide in Annex on digitalisation of power generation

Source: Enerdata and CL

Complete decarbonisation by 2050 requires a moderate increase of investments post 2030, reduced compared to the EC previous estimates

- **Further expenditures are necessary after 2030 to achieve net zero in 2050** (+24% average expenditures in the Decarbonisation scenario compared to the Reference scenario between 2031 and 2050)
  - Buildings expenditures to renovate the stock of existing dwellings (+96% increase in the Decarbonisation scenario)
  - Industrial expenditures to electrify processes and heat (expenditures multiplied by 3 in the Decarbonisation scenario)
  - In contrast, transport expenditures increase is limited (+5% in the Decarbonisation scenario) thanks to the reduction of vehicle fleet
- **Annual average expenditure to reach net zero are lower than previous EC scenario estimates**

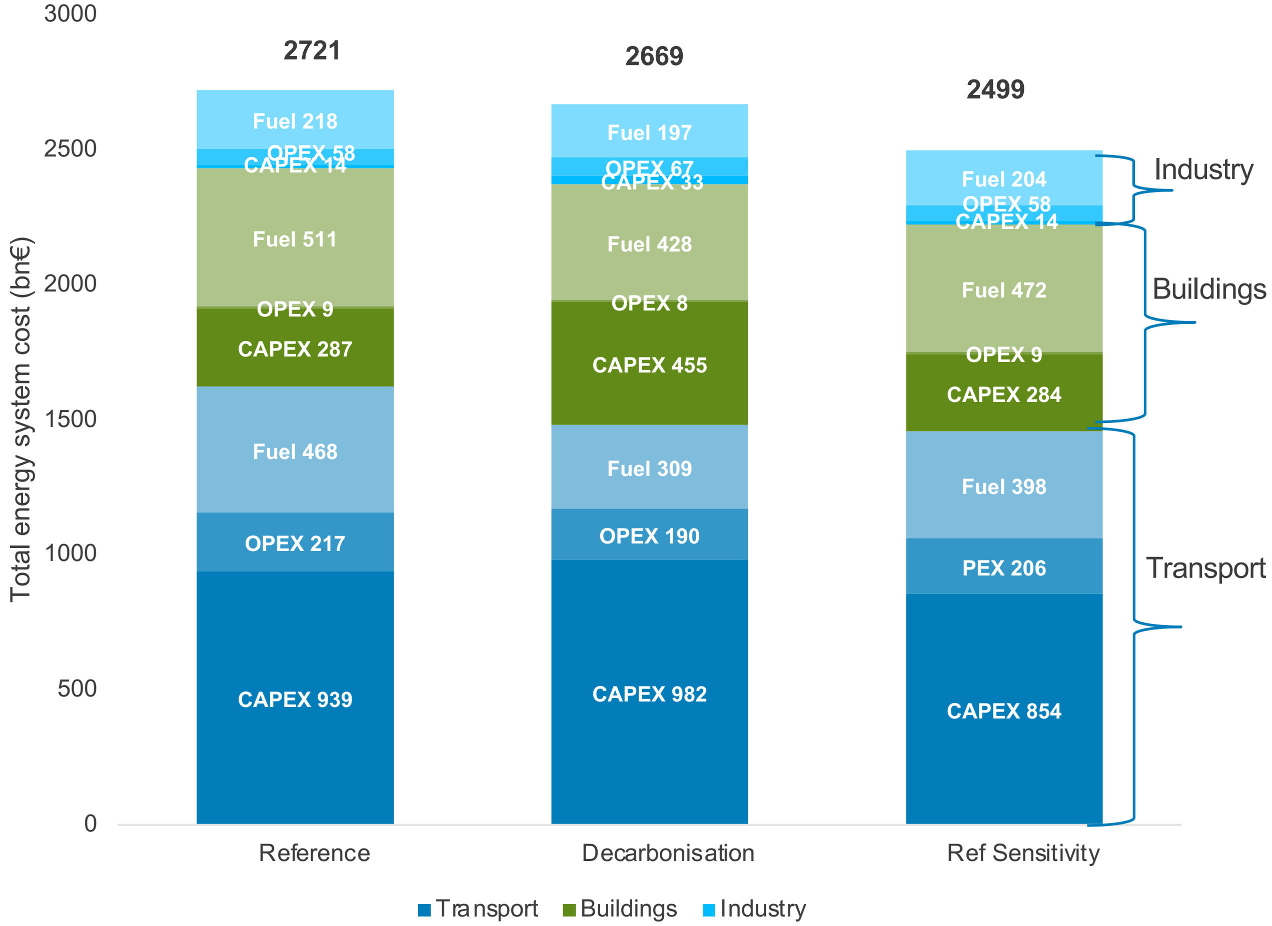
Annual average investments (bn€), Reference vs. Decarbonisation scenarios for period 2031-2050



Total system costs remain comparable in the Decarbonisation scenario, as increases in buildings offset reduction in power and transport sectors

- **System energy costs increase by 5% in the Reference scenario between the 2021-2030 average and the 2031-2050 average** (compared to 10% in the previous EC Baseline scenario)
- **Despite additional investments to reach net zero emissions in 2050, system costs in the Decarbonisation scenario are similar to the Reference scenario and indeed slightly lower. This is due to the decrease in clean and flexible technologies costs and the increase in embedded demand-side flexibility:**
  - The biggest growth in total energy system costs is in the buildings sector as significant investments are necessary to renovate buildings.
- This illustrates how increased ambition in 2030 would enable to reduce the necessary increase of total system cost to reach carbon neutrality in 2050.

Average total system cost (bn€) 2031-2050



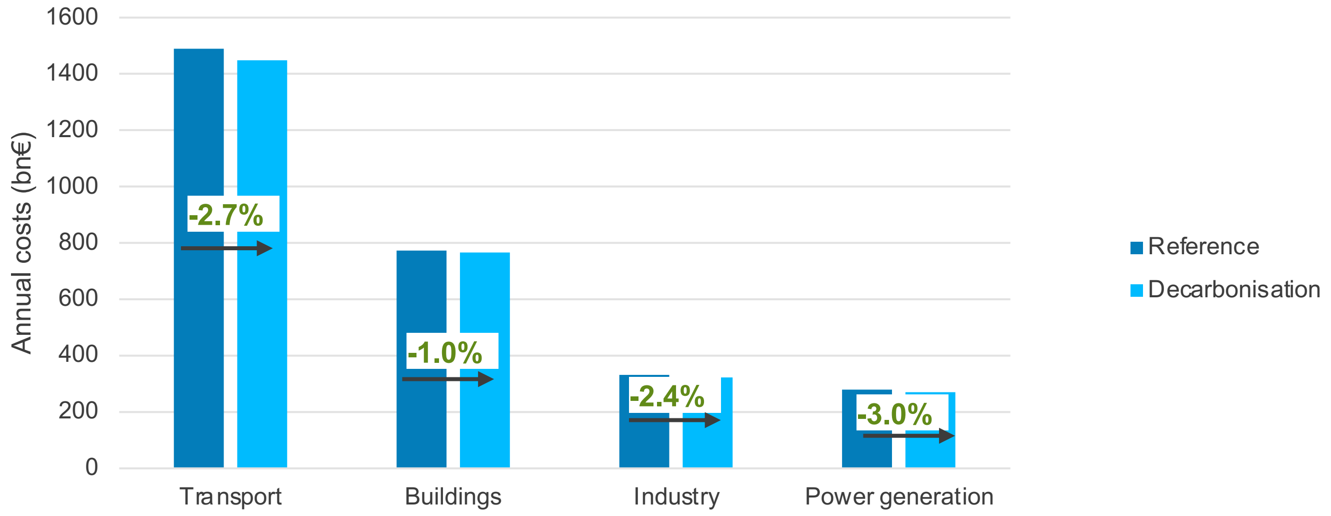
Source: Enerdata and CL

Notes: 1) Mitigated increase of system cost in Decarbonisation scenario is mainly driven by limited transport cost increase because of reduced private vehicle fleet
2) The increase in average system costs in the Decarbonisation scenario between 2021-2030 and 2031-2050 equals 5% compared to an increase of 22% in the EC 1.5 TECH 2050 scenario.

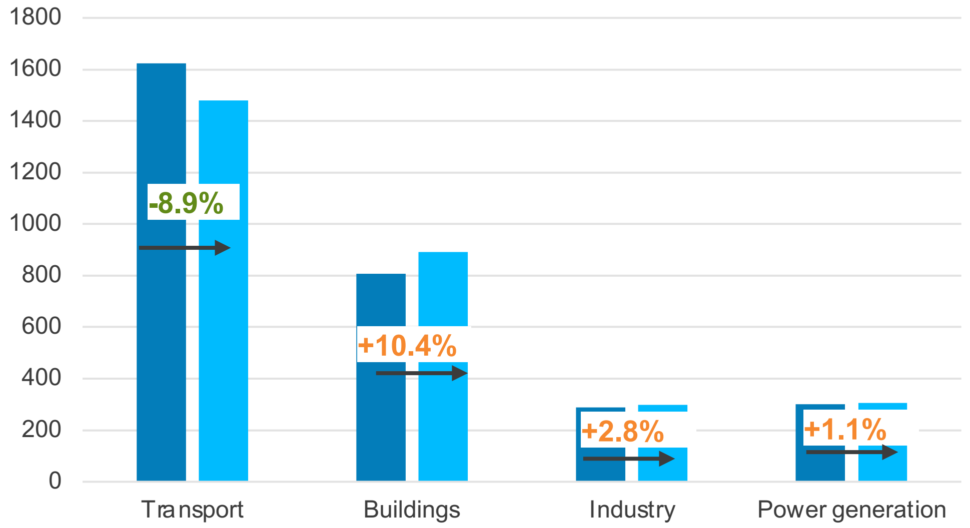
Costs decrease in RES technologies and batteries in the Decarbonisation scenario allow to achieve higher ambitions at comparable system costs to the Reference scenario

- **In all the sectors considered, the decarbonisation scenario with increased ambitions in 2030 can be achieved at a comparable or lower cost compared to the Reference scenario with lower ambitions**
  - In the power and transport sector, increased ambitions in 2030 result in reduced costs thanks to the costs decrease in RES (mainly onshore wind) and batteries for electric vehicles in transport
  - In the industry and building sectors, increased ambitions in 2030 are reached with comparable costs.
- **Carbon neutrality in 2050 is achieved at comparable cost to the Reference scenario on average although sectors will be affected differently:**
  - To achieve deep decarbonisation in 2050, increased efforts in the industry and buildings must be made resulting in greater costs (+2.8% and +10.4%)
  - The reduction in the transport sector costs (-8.9%) is driven by the reduction of EV costs, increased utilisation rate and efficiency gains
- In the Reference sensitivity scenario, by construction all system costs by sector are lower than in the Reference scenario over the period 2021-2050, with a particular decrease in transport costs thanks to the decrease in batteries costs. Buildings and industry system costs also see a decrease thanks the reduced electricity costs in these sectors as RES generation costs are lower than in the Reference scenario.

Annual total system costs and power generation costs, Reference vs. Decarbonisation scenarios, 2021-2030



Annual total system costs and power generation costs, Reference vs. Decarbonisation scenarios, 2031-2050

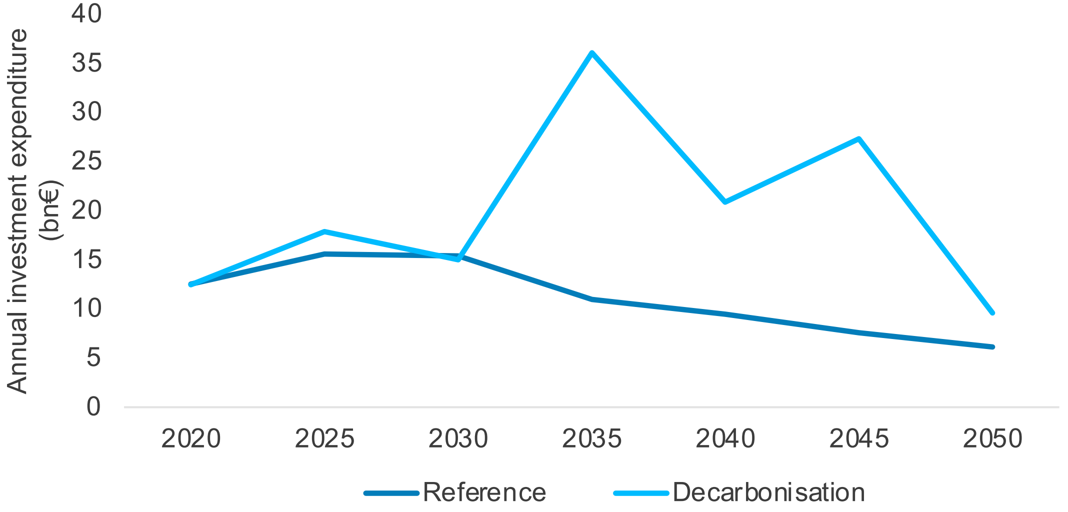


- Annual total energy system cost include industry, buildings and transport costs
- Industry, buildings, and transport system costs include energy capex, opex and fuel costs (including network costs)
- Power generation costs include generation capex, opex and fuel costs

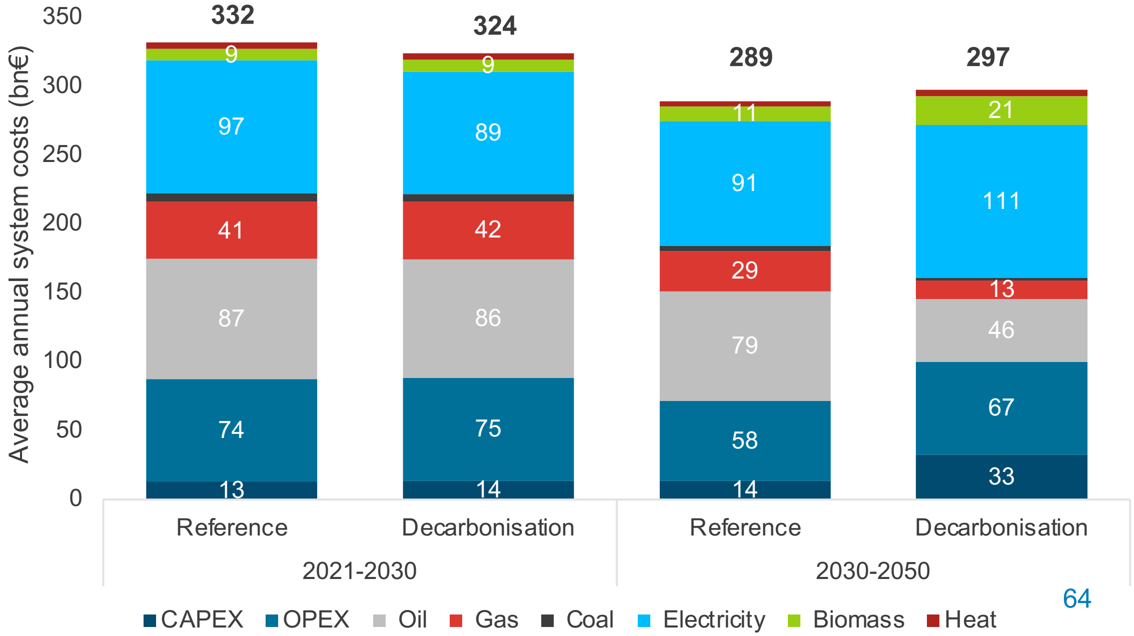
Industry system costs decrease driven by an increased energy efficiency as a result of new policies and regulations driven by the climate targets

- **Annual investments in the industry sector significantly increase after 2030 in the Decarbonisation scenario in order to achieve deep decarbonisation in 2050:**
  - Investments in fuel switching processes to decarbonise the sector are necessary after 2030.
- **Between 2021-2030 and 2031-2050, industry system costs decrease in both the Reference and Decarbonisation scenario** (by 13% in the Reference scenario and by 8% in the Decarbonisation scenario).
- **The decrease in industry system costs is driven by an increased energy efficiency in the sector that results from the regulation and targets for energy efficiency:**
  - In the Decarbonisation scenario industry energy intensity decreases by 30% after 2030 in order to achieve deep decarbonisation in 2050 (compared to 21% in the Reference scenario)
  - Additionally, a shift from industry to services in the economy is observed in Europe, as the industry added value increases at a slower rate than the GDP rate (+0.6% over 2020-2050 vs +1.5% for the GDP growth and +1.7% for services).
- The decrease in fuel costs from fuel switching and increased energy efficiency mitigates the increase in system costs in the Decarbonisation scenario (only +3% compared to the Reference scenario).

Annual investment expenditure in the industry sector(bn€), 2020-2050



Average total system costs in the industry sector(bn€), 2021-2050



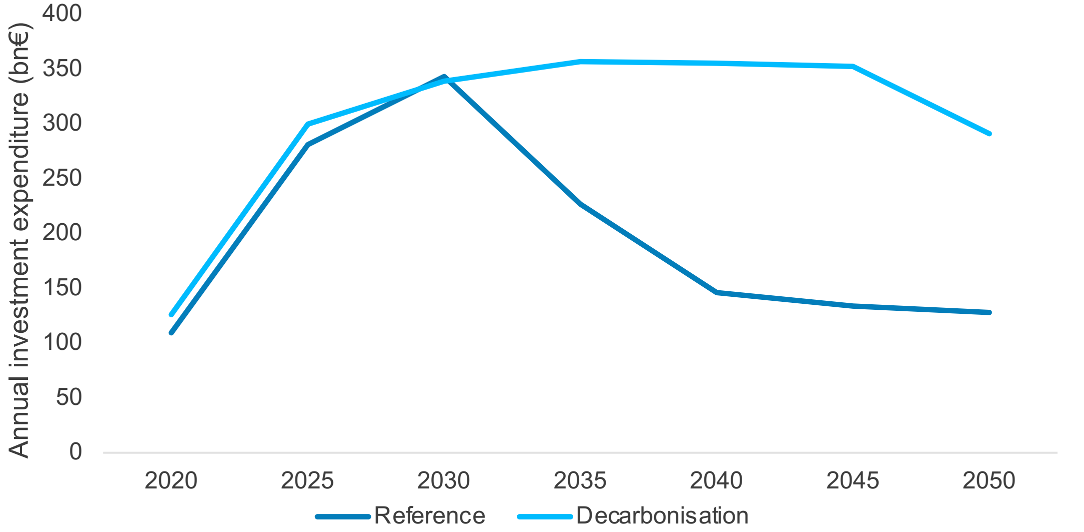
Source: Enerdata and CL

Note: Capital expenditures are accounted for in the system costs as annuity payments. A discount rate of 5% is applied for all sectors to annualise the capex.

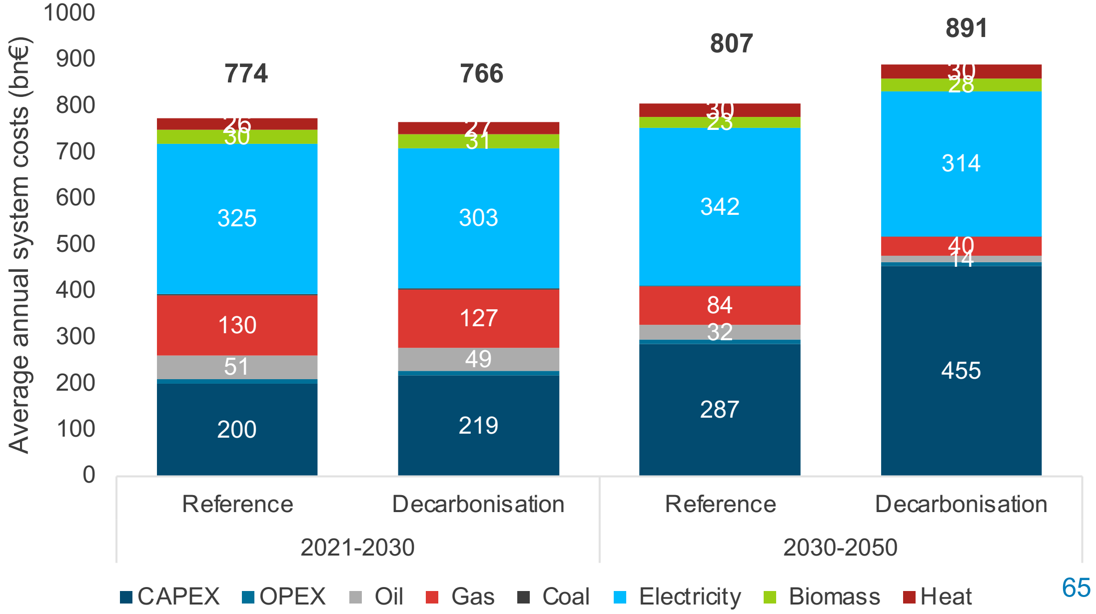
Building system costs increase as a result of the sustained pace of renovations after 2030 in order to achieve deep decarbonisation of the sector

- **Annual investments in the buildings sector are sustained after 2030 in the Decarbonisation scenario in order to achieve deep decarbonisation of the sector in 2050:**
  - The pace of renovation in the Decarbonisation and Reference scenario are similar until 2030 around 3%, but **after 2030 the renovation rate increases to 4% until 2045 in the Decarbonisation scenario** (compared to a drop to 1% in the Reference scenario).
- **Between 2021-2030 and 2031-2050, buildings system costs increase in both the Reference and Decarbonisation scenario** (by 4% in the Reference scenario and by 16% in the Decarbonisation scenario).
- **The increase in buildings system costs in the Decarbonisation scenario** compared to the Reference scenario (10% over the period 2031-2050) **is driven by the increased rate of renovations until 2045 in order to decarbonise the sector.**
- The increase in capex costs to decarbonise the buildings sector is mitigated by the reduction in fuel costs in the Decarbonisation scenario thanks to energy efficiency gains resulting from fuel switching.

Annual investment expenditure in the buildings sector(bn€), 2020-2050



Average total system costs in the buildings sector(bn€), 2021-2050



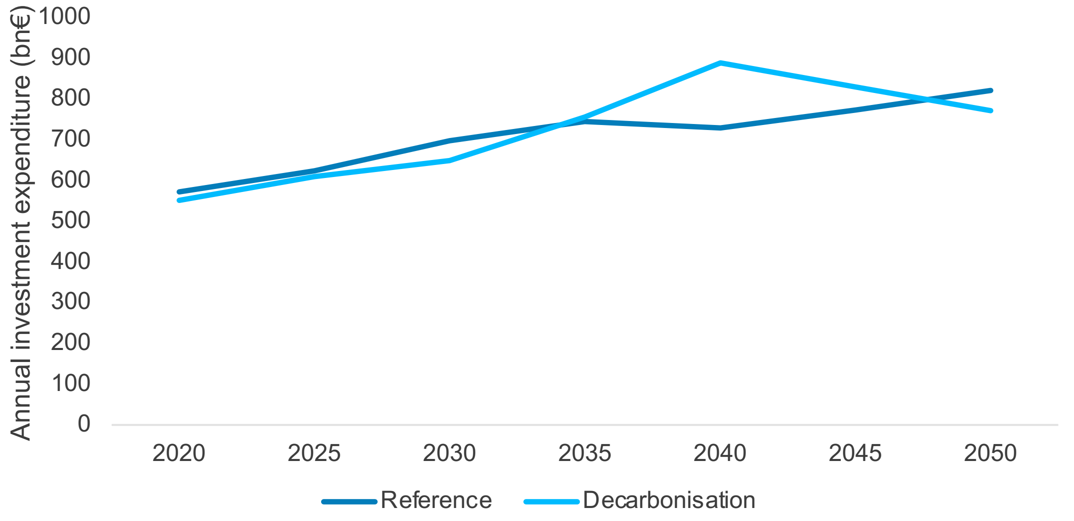
Source: Enerdata and CL

Note: Capital expenditures are accounted for in the system costs as annuity payments. A discount rate of 5% is applied for all sectors to annualise the capex.

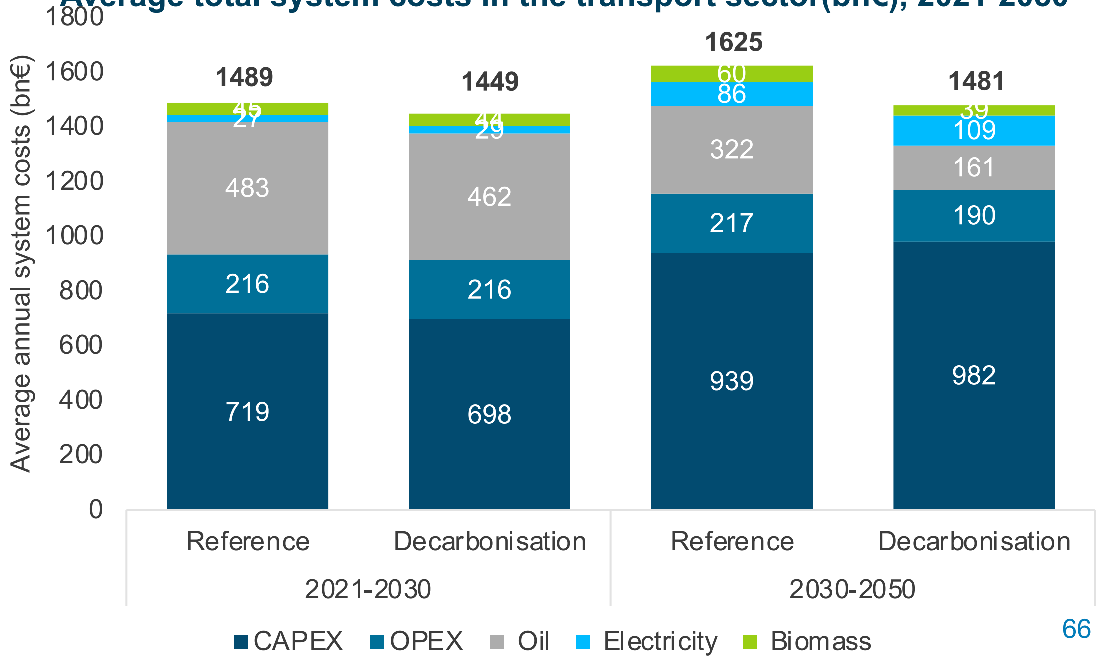
Transport system costs decrease in the Decarbonisation scenario in 2050 thanks to efficiency gains from electrification and changes in consumer behaviours

- **Annual investments in the transport sector increase in 2040 in the Decarbonisation scenario in order to achieve deep decarbonisation in 2050.**
  - Investments in the transport sector in the Decarbonisation scenario are comparable to the Reference scenario thanks to changes in consumer behaviours whereby passenger km and car ownership decrease resulting in increased utilisation rate of vehicles.
- **Between 2021-2030 and 2031-2050, transport system costs increase in both the Reference and Decarbonisation scenario** (by 9% in the Reference scenario and by 2% in the Decarbonisation scenario).
- **Between 2021-2030, transport system costs decrease by 3% in the Decarbonisation scenario compared to the Reference scenario:**
  - Capex costs decrease as a result of the decrease in passenger fleet due to the changes in consumer behaviours
  - Increased penetration of EVs lead to small costs savings
- **The transport system costs between 2031-2050 decrease by 9% in the Decarbonisation scenario compared to the Reference scenario:**
  - As a result of the electrification of the fleet with EVs representing more than 80% of new private vehicles after 2030, efficiency gains in the Decarbonisation scenario lead to reduced fuel costs compared to the Reference scenario.

Annual investment expenditure in the transport sector(bn€), 2020-2050



Average total system costs in the transport sector(bn€), 2021-2050



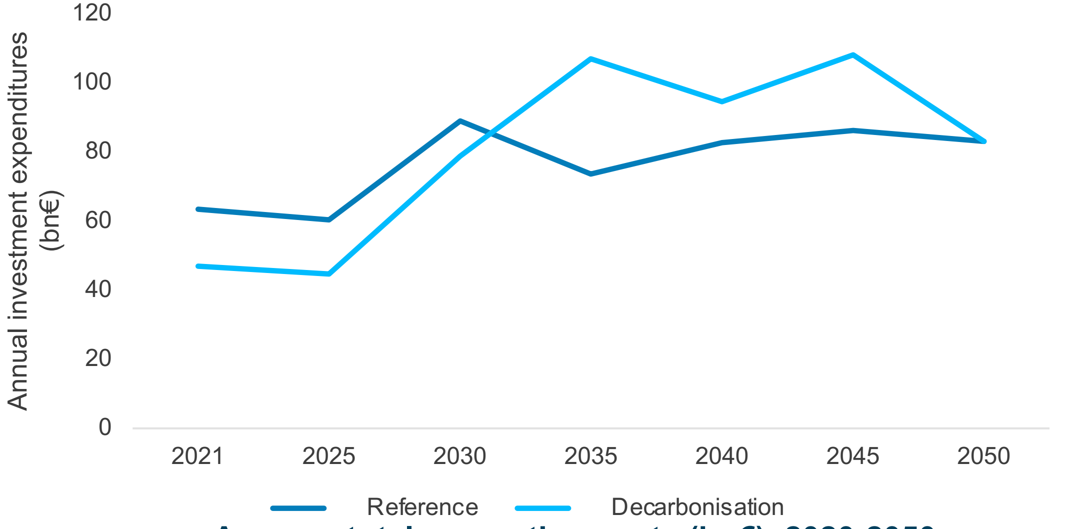
Source: Enerdata and CL

Note: Capital expenditures are accounted for in the system costs as annuity payments. A discount rate of 5% is applied for all sectors to annualise the capex.

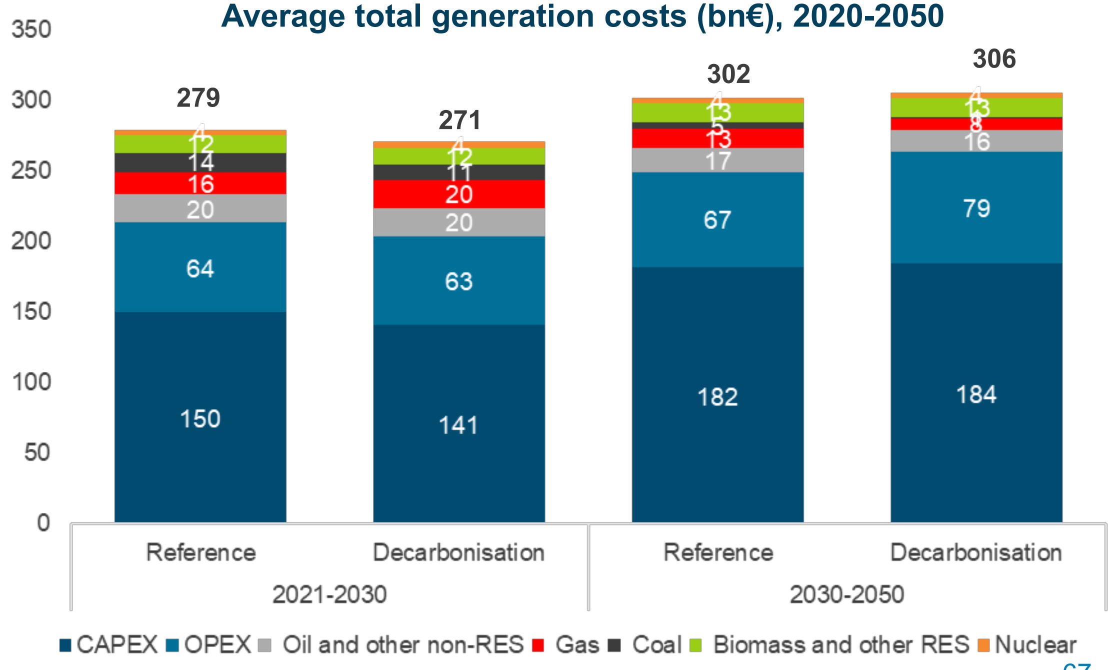
Power generation costs are slightly higher in the Decarbonisation scenario in 2050 despite increased investments in RES capacity thanks to reduced RES costs

- **On average between 2020 and 2030, annual investment costs decrease by 19% in the Decarbonisation scenario:**
  - Before 2030, ambitions in terms of CO2 reduction are relatively close in the Decarbonisation and Reference scenario
  - The cost reduction effect induced by technological improvement take precedence over increased costs due to additional RES capacity
- **On average between 2031 and 2050, annual investment costs increase by 20% in the Decarbonisation scenario:**
  - After 2030, ambitions in terms of CO2 reduction in the Decarbonisation scenario are much more constraining for the system
  - The higher CO2 reduction target of the Decarbonisation scenario would induce a significant cost increase. However, the cost reductions related to technological improvement would compensate a significant share of the increase.
  - Cost reduction would lower both costs of new RES capacity but also costs for replacing older RES capacity
- **By 2050, the total generation cost would increase by 1% in the Decarbonisation scenario compared to the Reference scenario:**
  - While CAPEX and OPEX slightly increase in the Decarbonisation scenario (given the significant volume of new investments and installed capacity), fuel costs are lower given the reduced dependence to fossil fuels.

Annual investment expenditure in the power sector(bn€), 2020-2050



Average total generation costs (bn€), 2020-2050



Source: Enerdata and CL

Note: Capital expenditures are accounted for in the system costs as annuity payments. A discount rate of 5% is applied for all sectors to annualise the capex.

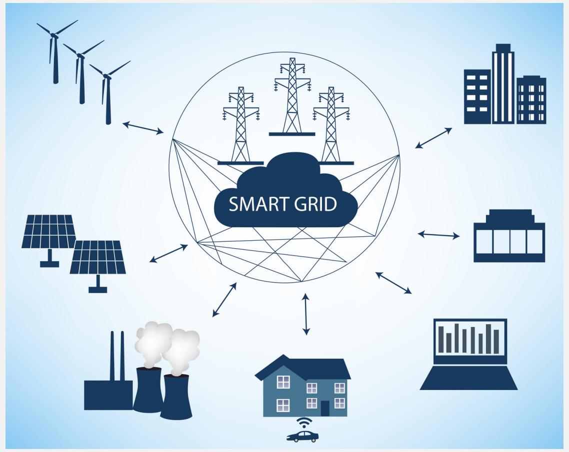
5. The study identifies the critical enablers to unleash the potential of decarbonisation and flexible resources in the power sector

5.A Smartening infrastructure will provide and unlock flexibility of the power system

Digitalisation of distribution grids supports the optimisation and reliability of the power system in the context of increased electrification and penetration of RES

- **The pace of decarbonisation and electrification of the energy system brings new challenges for power grids and systems:**
  - More requests for connection and capacity increases and increasingly diverse technologies requiring network access
  - Customers and distributed renewable generation plants asking grids for power to flow in increasingly less predictable ways
  - More need for real-time network visibility
- **"Smartening" electricity grids through digitalisation is key to provide and enable further flexibility of the power system:**
  - **Smart Grids** can help manage power flows more efficiently and therefore support the integration of more variable resources and distributed resources control
- **Digitalisation of grids provides the following benefits to the power system:**
  - Peak load demand reduction and congestion management
  - Grid losses reduction
  - Grid stability and reliability
  - Flexibility services capabilities from distributed energy resources assets, potentially deferring or reducing distribution grid reinforcement investments
  - Optimal network resource allocation

Smart Grid technologies



Digitalisation and smart grid technologies include:

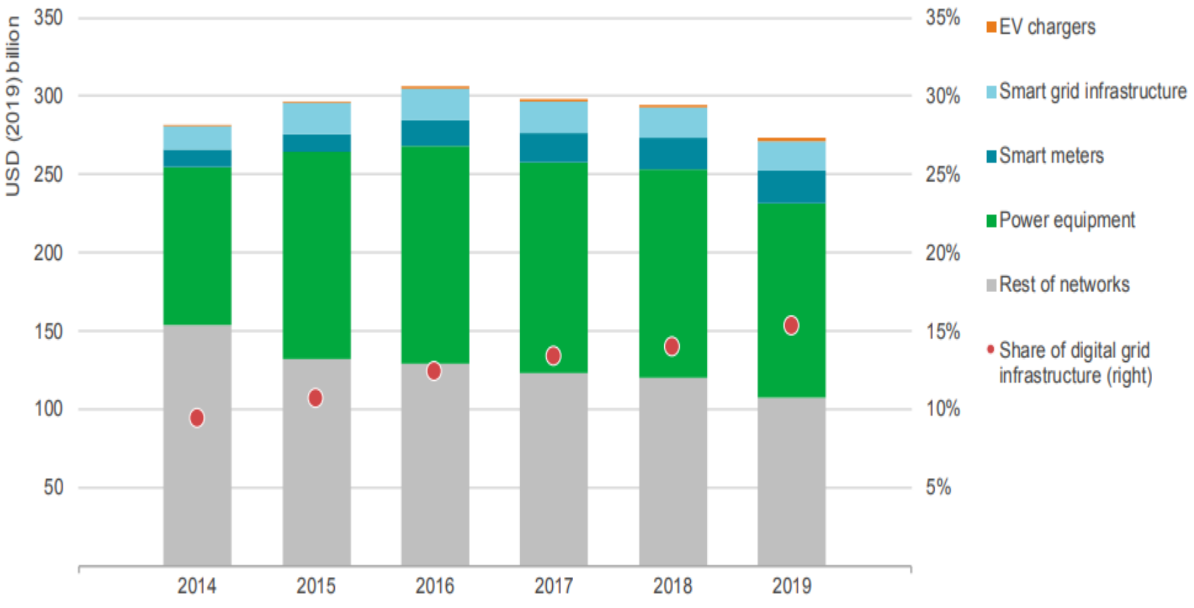
- Robust network system and security management protocols together with **cybersecurity technologies**
- **Installed advanced sensors** aimed at monitoring data analysis of the MV grid, loads of connected users and also Distributed Generation
- **Grid Automation** technologies, aimed at defining automatic operational schemes for real-time grid optimization, advanced fault detection and system restore
- **Big data analysis** could enable predictive maintenance programs, also thanks to the potential of **AI technologies**
- **Augmented reality and drones deployment** for inspection and maintenance activities

Smart grids enable the integration of Decentralised Energy Resources (DERs) and support demand-side flexibility

- **Smart grid technologies are necessary to enable DERs and demand-side flexibility:**
  - The increasing penetration of DERs will lead to a more frequent reverse of power flow, which can challenge the traditional planning and operation of distribution and transmission networks.
  - New market players (prosumers, aggregators and active consumers) pose new needs and require the introduction of third-party business models being introduced.
  - By procuring flexibility services such as voltage support and congestion management from their network users, once proper regulatory framework and market rules are defined, DSOs could optimize system operations and future grid investments, for the benefit of both the distribution grid and consumers.

- **Digitalisation of grids supports the integration of variable renewable energies:**
  - By using data and communication tools to manage the variability and uncertainty associated with RES and EV recharging network needs
  - Smart grids enhance the flexible operation of the grid, reduce the operational costs and improve efficiency

Investment in electricity networks by equipment type (USD billion), 2014-2019



Source : IEA (2020)

- Global investments in digital grid infrastructure are increasing year by year. Grids are becoming more digital, distributed and smart, depending less on traditional equipment and more on new drivers.
- Investment in digital grid infrastructure reached over 15% of investments in electricity networks in 2019 in the world

The increase in networks costs in the Decarbonisation scenario is driven by increased distributed RES and electrification of end uses

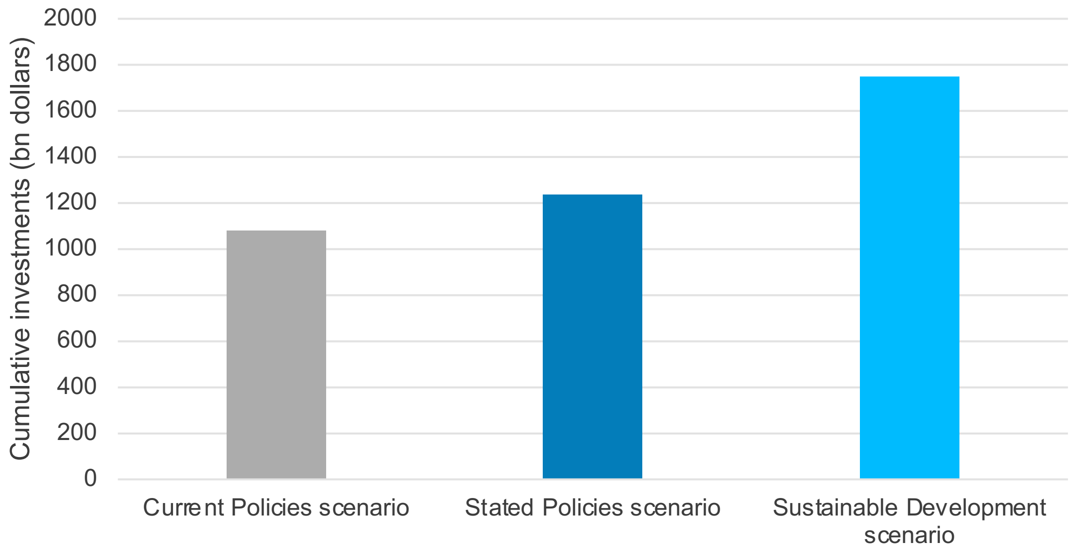
Network costs increase over 2020-2030 in the Decarbonisation scenario due to:

- The increase of distributed RES penetration
- The increase of electricity consumptions (peak demand) and electrification of mobility
- Modernisation and digitization of the grid

On average, annual network costs increase by more than 40% over 2030-2050 in the Decarbonisation scenario.

- The higher CO2 reduction target of the Decarbonisation scenario induces a significant cost increase of more than $500 bn in total network costs between 2019 and 2040 (IEA, 2019) due to the increased RES penetration and higher peak demand from the increased electrification of end-uses.
- Distribution network costs in EU, according to IEA World Energy Outlook, will increase from an average $30 bn/year in 2019 to a value between 40 $bn/year (Stated Policy Scenario – INECP) and $60bn/year in 2040 (Sustainable Development Scenario1).
- In addition other relevant reports estimate an investments range flooring in accordance with IEA scenarios (CPS) up to 60 $bn/year (e.g. DNV, BNEF) in 2030, in the current policy scenario.

Cumulative investments in power networks, 2019-2040 (bn dollars)



Source : IEA (WEO 2019) – nearly 70% of total network investments addressed to Distribution based on the current share

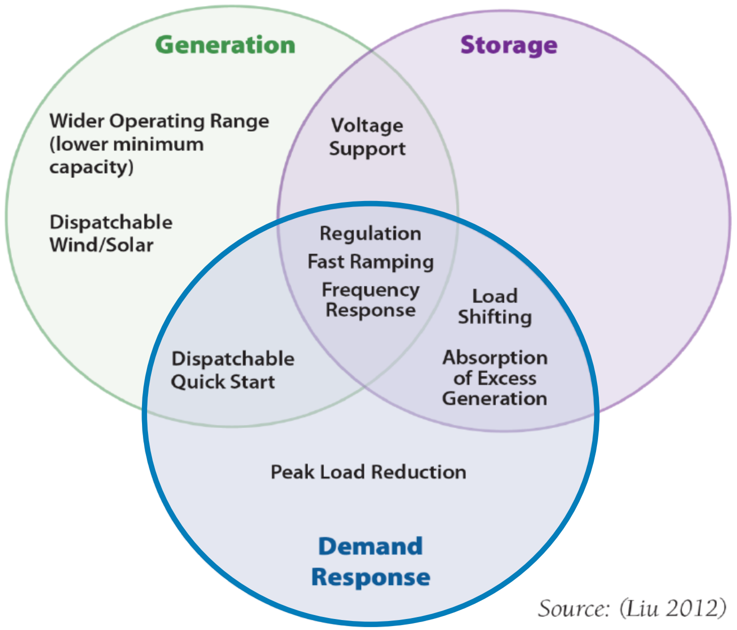
1 : IEA Sustainable Development Scenario: foreseen a rapid path of changes to meet 100% of the United Nations Sustainable Development Goals

5.B Flexibility of demand will be a key element to respond to the flexibility needs of the system

Flexibility of demand supports the integration of variable RES through peak load reduction and load shifting

- Flexibility of demand (or Demand Side Response (DSR)) can be defined as the actions taken by customers, or agents on their behalf, to change their electric usage at strategic or peak times.
- **Changes in consumption patterns occur in response to changes in the price of electricity over time, or to incentive payments** designed to induce lower electricity usage at times of high wholesale market prices or when system reliability is jeopardised.
- **Beyond peak load reduction, DSR provides services that compete with and/or complement generation and storage technologies:**
  - DSR mitigates the need for peak generation
  - DSR supports short term and long term system reliability
  - DSR supports the penetration of intermittent renewable energy resources by absorbing excess generation of solar and wind for example
- **Flexibility of demand in a Decarbonisation scenario can come from the following sources which we detail in the next slides:**
  - EVs charging
  - Heat Pumps and cooling demand
  - Hydrogen production in the industry

Services provided by DSR : more than just peak load reduction



Source: European Commission (2016)

Demand Side Response brings both system and consumer benefits

The potential benefits of DSR for the electricity system include :

- **Decreased need for long-term investment in peaking generation**
- **Decreased need for local network investments** possible once risks for energy supply are addressed (reliability in terms of flexibility products definition, market liquidity, DSOs long term contracts)
- **Lower operational costs of energy system** (replacing peaker plants and avoiding electricity generation loss) only if a mechanism with explicit and long-term commitment is put in place to ensure reliability of system
- **Customer benefits** through new customer services and potential financial benefits with dynamic tariff
- **Further decarbonisation by replacing often must-run fossil-fuelled power plants**

- The European Commission estimated in 2016 that the **benefits from DSR due to savings in generation and network costs could range from 4.4-6.2 bn euros per year** depending on the level of DSR potential activated.

Estimated generation and network benefits from DSR in 2030

MEUR/y	Network	Generation	Total
BAU	980	3,517	4,415
Option 1	1,068	3,772	4,840
Option 2	1,383	4,588	5,971
Option 3	1,444	4,736	6,180

Source: European Commission (2016)

Notes: 1) BAU scenario corresponds to the current potential of DSR.
2) Option 1 corresponds to DSR potential with smart meters and dynamic pricing contracts
3) Option 2 is Option 1 + incentives through demand response service providers
4) Option 3: Option 2 + more incentives for demand response service providers

The scenario with increased ambition in 2030 would create the conditions for the further deployment of DSR (through technological and regulatory support) and would generate significant system benefits.

Flexibility of EVs demand allows load shifting during hours of high solar production in the Decarbonisation scenario

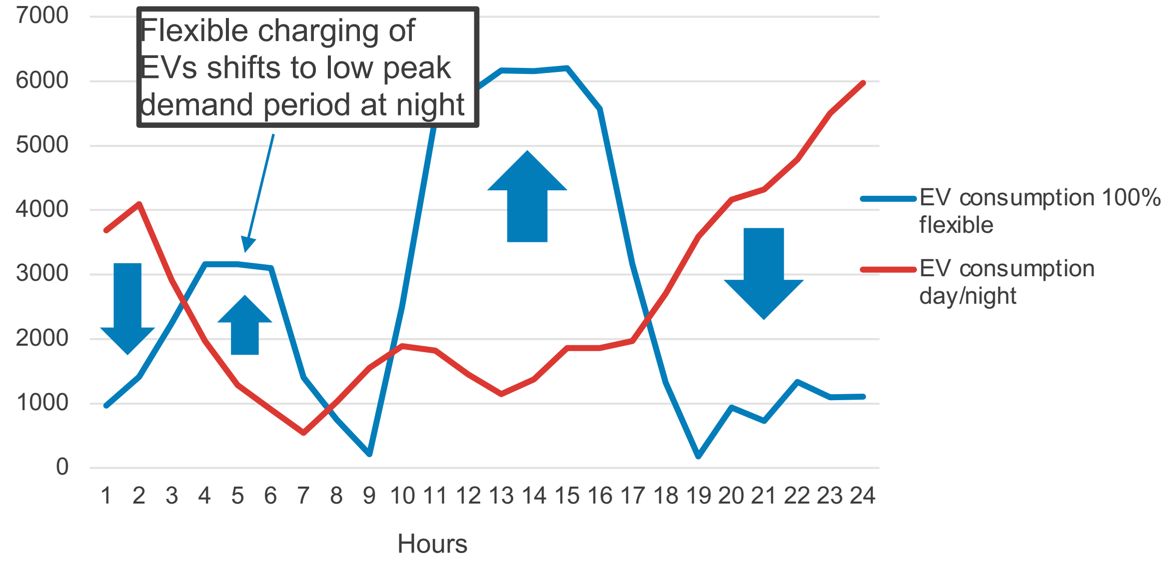
The increasing penetration of EVs raises challenges for the power system if vehicle charging is not monitored and optimised to avoid an increase in daily peak demand but also opportunities if smart charging is introduced

- Monitoring and optimising EVs charging would allow to adapt consumptions to variations in solar and wind production thereby avoiding renewable curtailment and allowing charging when production costs are the lowest.

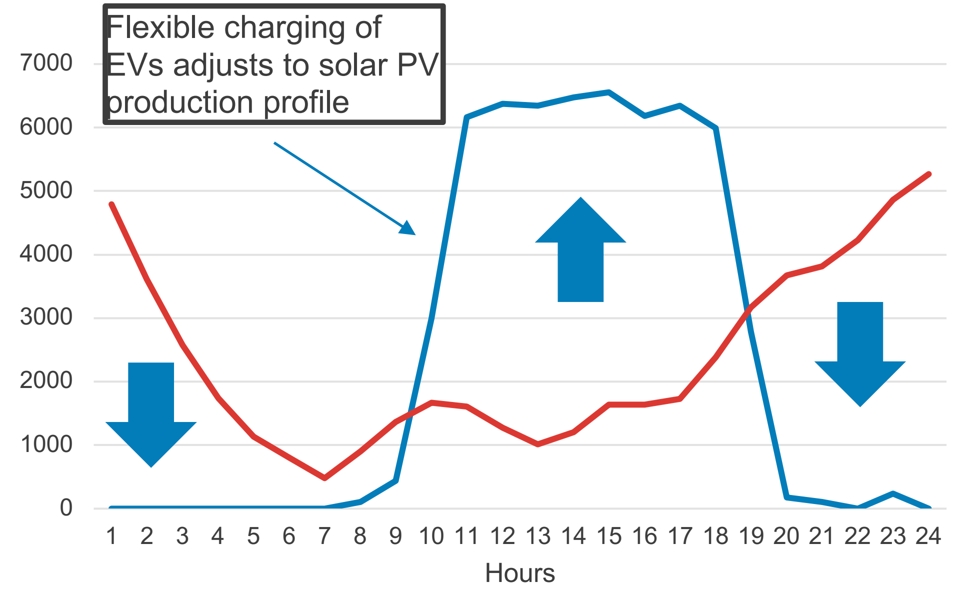
Moreover, the optimisation of EVs charging patterns provides a significant source of flexibility of demand allowing charging periods to match with system needs

- The optimised charging profile of EVs depends on the month: during summer months, flexible charging will typically happen during peaks of solar production, whilst during winter months, flexible charging will also typically concentrate during the drops in demand at night.
- In the Decarbonisation scenario, dynamic charging of EVs is assumed compared to a simple Time of Use charging (day/night) in the Reference scenario.

Average consumption of EVs during January (MW)



Average consumption of EVs during July (MW)



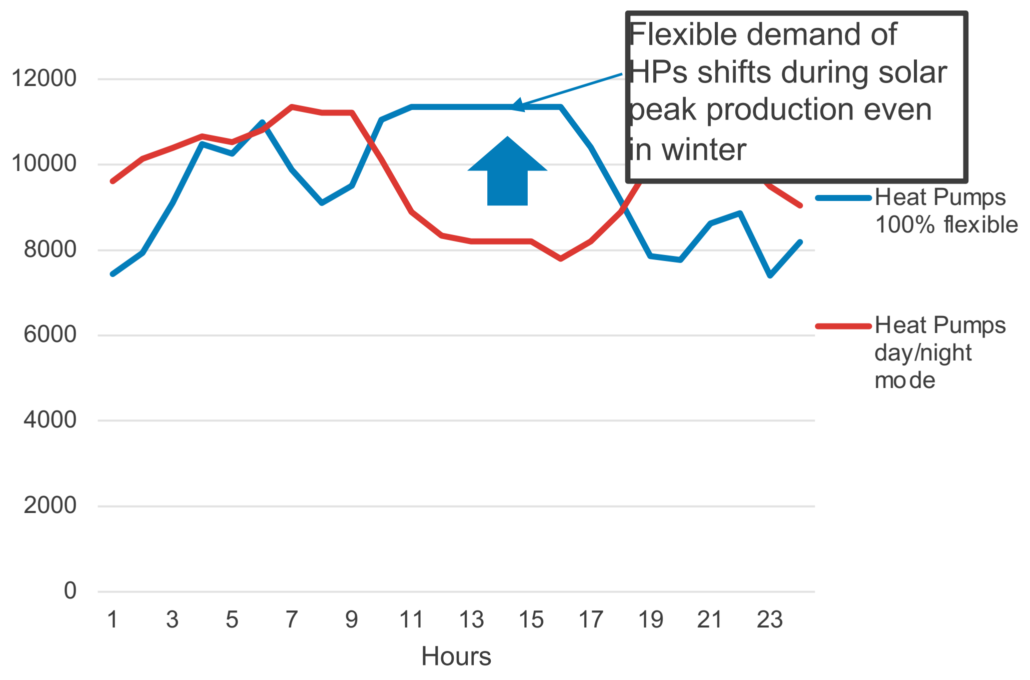
Source: CL modelling

Flexible demand of Heat Pumps and cooling leads to load shifting during peaks of solar production in the Decarbonisation scenario

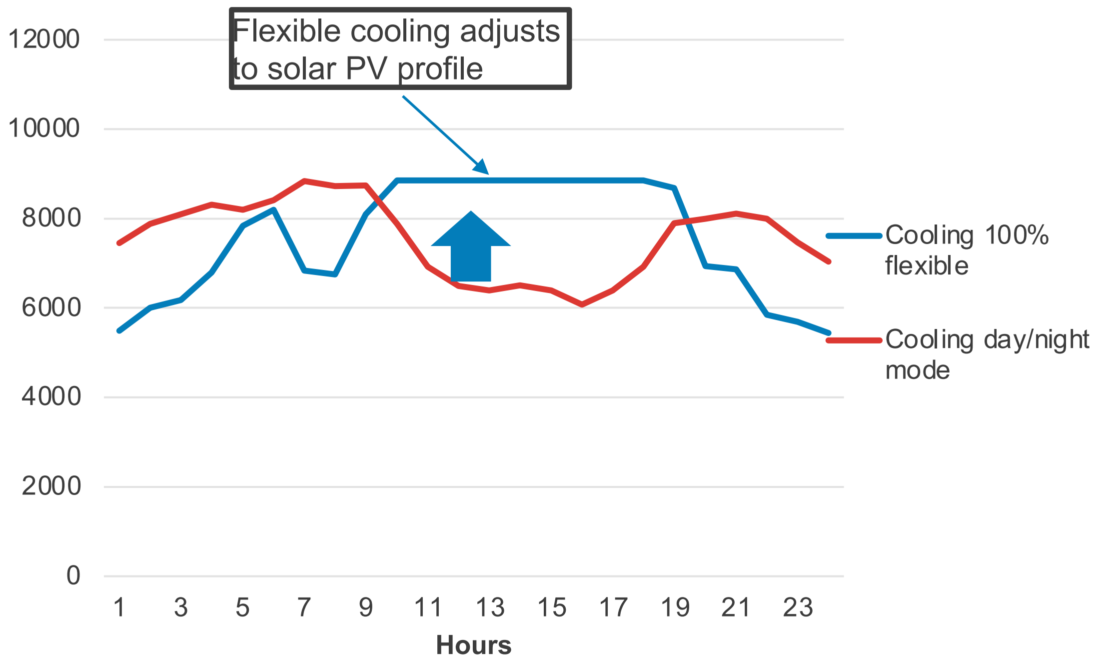
The electrification of buildings via Heat Pumps provides a significant source of flexibility of buildings demand that can be optimised to integrate RES generation

- For Heat Pumps (HPs) and cooling, daily needs allow little room for load shifting. Nonetheless, load shifting during hours of peak solar production (even in winter) provides some flexibility to the system.

Average consumption of HPs during January (MW)



Average consumption of cooling during July (MW)



Source: CL modelling

Further development of price-based (implicit) and incentive-based (explicit) DSR is possible with further regulatory and technological support

- **Price-based (or implicit) DSR:** the consumers is exposed to time-varying electricity prices or time-varying network grid tariffs, which reflect the system's balance.
  - This necessitates business models that rely on dynamic tariffs and require a careful design.
  - Additionally, consumers might adjust their flexibility according to tariff variations and not to system requirements (if tariffs are inconsistent with system requirements).
- **Incentive-based (or explicit) DSR**: demand-side resources are traded in the wholesale market (and if possible in capacity mechanisms), reserves/balancing markets.
  - Explicit DSR development is increasing but the progress is slow with only 6 Member States with commercially active explicit DSR in 2017.

- **The further deployment of DSR requires:**
  - **The deployment of smart devices** that will allow the digitalisation of demand management.
  - A **supportive market and regulatory framework** to allow access to the different markets and potential sources of revenues, and enable its participation.
  - The development of **aggregators**, whose role is to negotiate agreements with industry, commercial and residential electricity consumers to aggregate their capability to increase or reduce their demand and to sell it as a single resource. An adequate level of incentives rewarding DSR from end-users is needed to effectively succeed on the deployment of DSR, for example through revenue stacking and the right level of compensation for the service provided.

In the Decarbonisation scenario, both implicit and explicit DSR would be further developed compared to the Reference scenario with explicit DSR being fully unlocked through a supporting regulatory framework and new business models.

Access to real time consumer consumption and control of power-consuming devices are necessary technological conditions to enable DSR

- **Smart meters roll out**

Smart meters provide information on real-time consumption, enabling consumers to adapt their energy use to different energy prices throughout the day.

The target set by the EU was to achieve a 80% smart meters roll-out by 2020 wherever it is cost-effective to do so.

In 2020, 13 Member States are expected to have achieved a wide-scale roll out (80% of all consumers) and by 2025, 19 Member States.

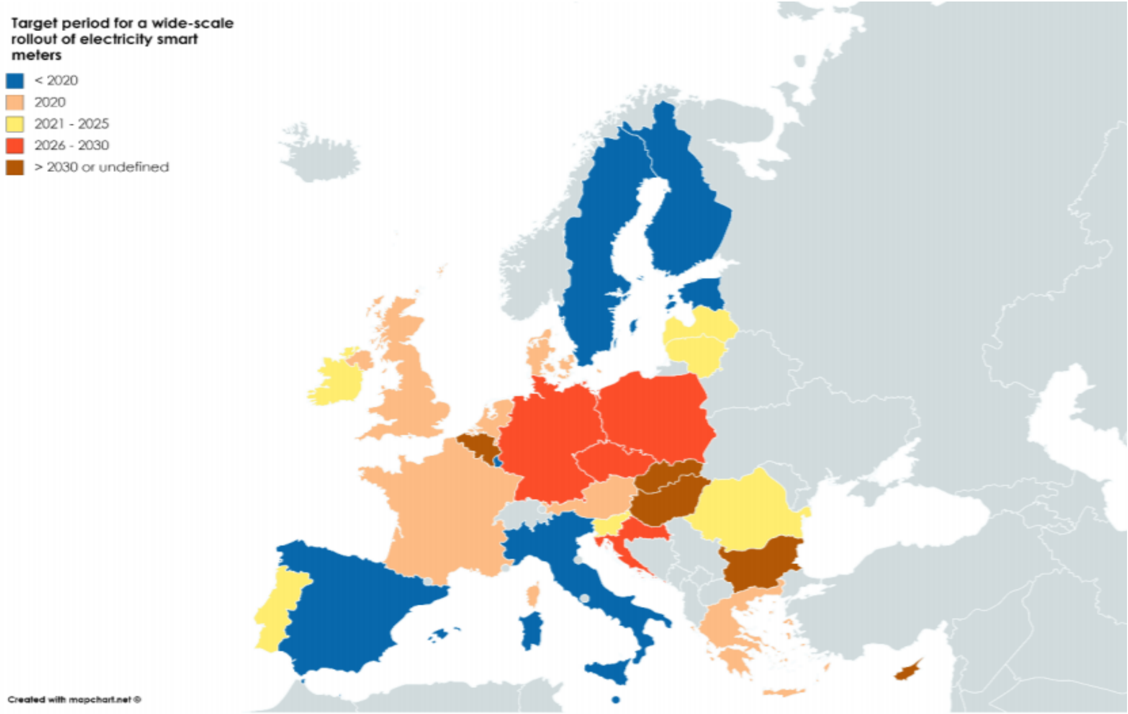
In the Decarbonisation scenario with increased ambition in 2030, a wide-scale roll out of smart meters across the EU would be achieved by 2025.

- **Smart appliances and monitoring devices deployment**

In the residential sector, smart appliances refer to devices including the intelligence and communications to enable their automatic or remote control based on user preferences or external signals (such as dynamic tariffs).

In the Decarbonisation scenario, the deployment of smart appliances as well as devices to monitor electric appliances at home would be accelerated by 2025.

Overview of target period for the completion of a wide-scale rollout of electricity smart meters



Note: Wide scale rollout of at least 80% of all consumers
Source: Tractabel/Engie (2019)

A supportive regulatory framework is necessary to unlock the potential of explicit DSR

Regulatory measures	Description	Conditions
Access to markets	- Allow DR as a resource within the different national markets (i.e. wholesale, balancing, ancillary services, capacity mechanism, etc.).	- Allow aggregated load to markets for a significant quantity of DSR and enable its effective participation - Allow revenue stacking
Service Providers access to markets	- Allow independent service providers (e.g. aggregators) to offer services to the consumer and access markets, without prior consent of the consumer's retailer	- Need to define relationships between retailers, Balancing responsible Parties (BRPs) and aggregators. - Framework for information flows, as well as financial settlements (in particular for Transfer of Energy mechanisms between BRPs and Flexibility Service Providers)
Product design changes	- Adapt product requirement that were historically designed for generators to allow a level playing field	- Change product design associated with activation time, symmetrical response, delivery time, number of activations
Changes in regulatory framework for network operators	- Change in the regulatory approach for revenues of the network operators to incentivize TSOs/DSOs to resort to flexibility services	- Trade off between flexibility and DSOs grid capex optimization requires a totex approach and regulatory flexibility - Risk for network operators when opting for flexibility services should be remunerated accordingly to incentivise DSOs to opt for flexibility

The further development of business models relying on aggregation of load is necessary to increase the potential of DSR

- **New business models supporting aggregation of DSR are required to unlock the potential of flexible demand that can participate to the wholesale, capacity, and reserve/balancing markets.**
- In order to provide a significant capacity resource to those markets, flexible demand needs to be aggregated. **A range of new business models are emerging through aggregators** who can either be 'pure players', suppliers, or large energy consumers that are taping into the potential of flexibility demand using new technologies and digitalisation.

Enel X aggregator business model

- **Commercial load**

Enel X signed an agreement in 2019 with Unieuro, the leader of distribution of consumer electronics in Italy, to provide demand response services at 9 of their chain's stores.

- **Transport infrastructure load**

Enel X is supporting Dublin Airport Daa for its participation in the DS3 programme in Ireland (grid balancing scheme) in which they provide ancillary services with 11+MW flexible capacity.

- **Commercial and Industrial load**

Enel X signed an agreement in 2019 with Ameren Missouri, the largest utility in this US state, to deliver 100 MW of DSR from the portfolio of C&I customers. Enel X will optimise usage during peak periods by interruption consumption temporarily when demand on system is highest.

Voltalis aggregator business model

- **Residential and commercial load**

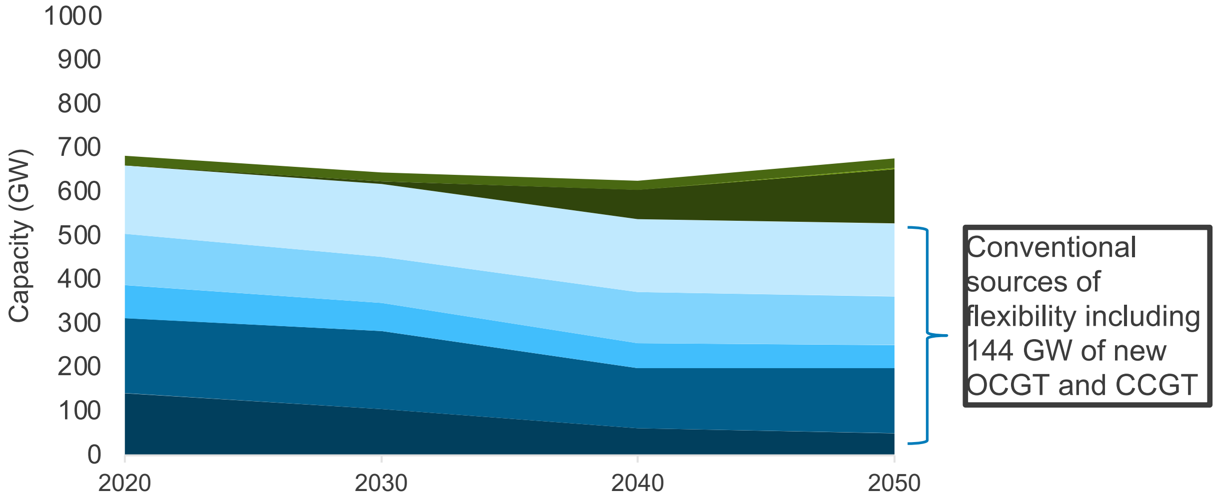
Voltalis, a Paris-based company, monitors electric appliances in homes and offices, and delivers demand response services to the grid operator and to the wholesale market, as well as the capacity mechanism.
The company covers around 300 MW of capacity aggregated from a million electrical appliances mainly in homes, but also in commercial premises, offices, and public buildings.

5.C Supply side flexibility will also play a central role in integrating additional RES

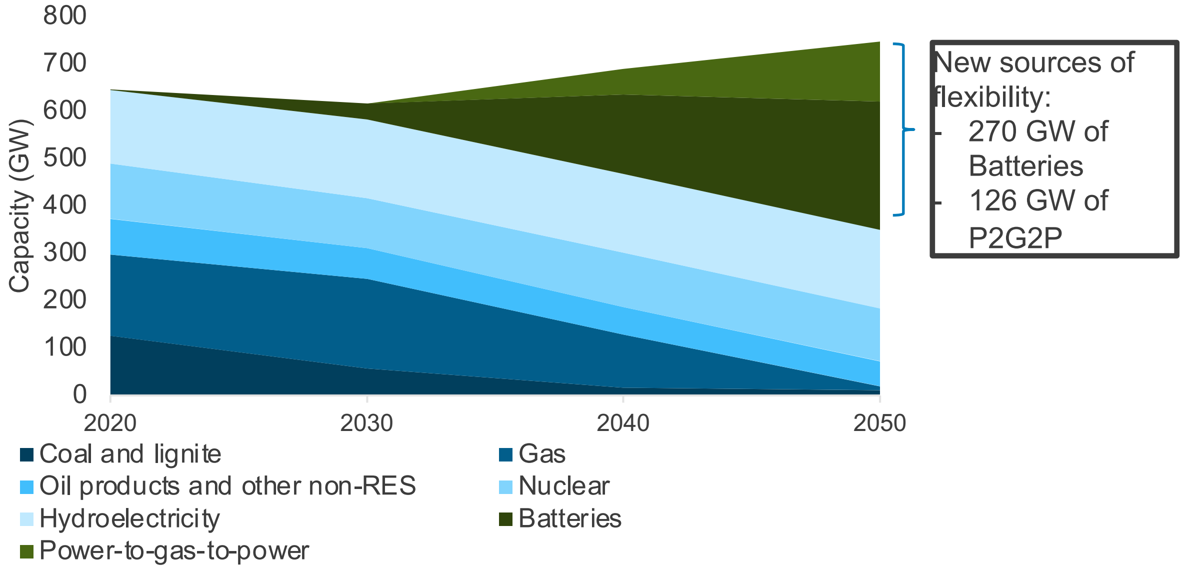
The development of storage technologies (batteries, P2G) in addition to demand flexibility is necessary to meet the growing flexibility system needs

- **The significant increase in 2050 of variable RES generation to achieve deep decarbonization will increase the flexibility needs of the system:**
  - The increase in flexibility needs will be particularly striking during the day due to the solar peak production
  - On a weekly basis, wind generation creates the most flexibility needs
  - On an annual basis, flexibility needs are more moderate given the inverse seasonality of wind and solar generation
- **The development of new sources of flexibility including storage technologies such as batteries and Power-to-Gas-to-Power (P2G2P)** is necessary to meet the flexibility needs of the system in a Decarbonisation scenario with increased RES penetration.
- **By 2050, 270GW of new batteries will be developed in the Decarbonisation scenario, of which:**
  - 220 GW of stationary large scale batteries
  - 10 GW of behind-the-meter batteries, associated with PV solar
  - 40 GW of batteries embedded in Vehicle-to-Grids
- **Stationary batteries can provide a range of key energy services in an affordable manner.** As the cost of emerging technologies falls further, storage will become increasingly competitive, and the range of market services it can provide will only increase.

Flexible resource capacity in Reference scenario (GW)



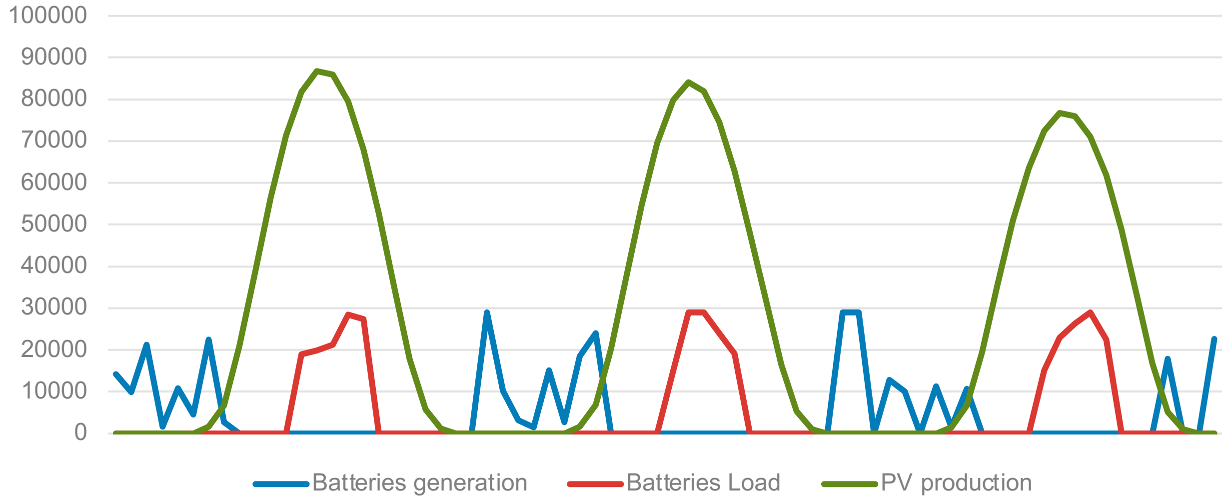
Flexible resource capacity in Decarbonisation scenario (GW)



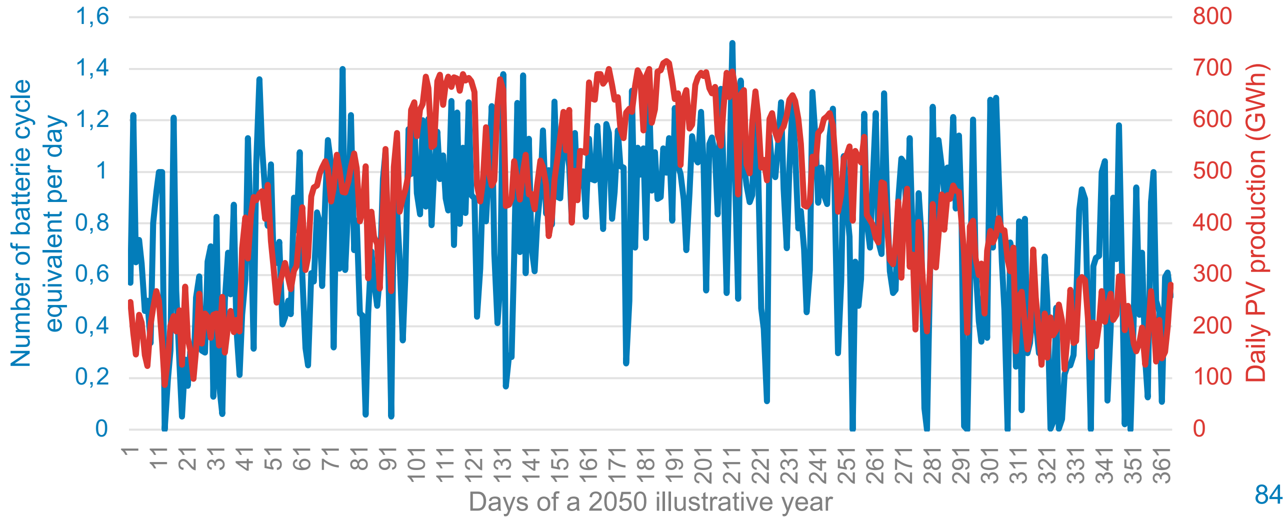
Batteries play an important role in providing short term daily storage and ensuring day/night flexibility

- Batteries typically operate a storage cycle of several hours (from 1 to 4 hours in the modelling, depending on the type of batteries – large-scale batteries, behind-the-meter batteries or EV batteries) : they usually complete **their charge/discharge cycle within the same day.**
- The number of charge/discharge cycles is highly dependent on sunshine conditions as described on the bottom graph for an illustrative 2050 year in France : the higher the PV generation (in particular during summer), the higher the batteries utilisation (measured by the number of cycles)
- The modularity of batteries, short lead times, wide range of applicability, economies of scale and overall technological progress underpin the **significant growth of batteries in the Decarbonisation scenario.**
- Continuing recent trends, **many utility-scale battery installations are set to be paired with solar PV and wind** power to increase their dispatchability, gain revenues from energy arbitrage and to offer ancillary services to the grid.
- Batteries embedded in vehicle-to-grid will also significantly ease RES integration by providing daily flexibility (40 GW of EV batteries are expected to be developed in 2050 in the decarbonisation scenario)

Illustration of battery operation over 3 days in July 2050 (GW)



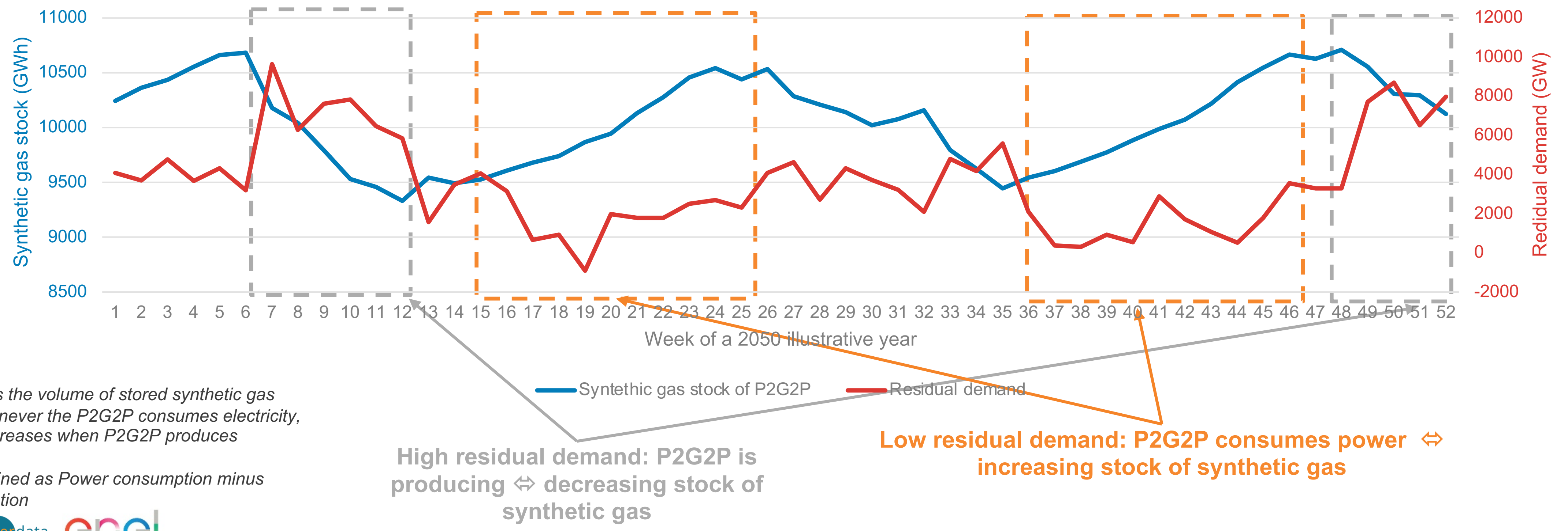
Evolution of the number of battery cycles per day and the daily PV production over an illustrative 2050 year in France



Seasonal storage is also necessary (e.g. power-to-gas-to-power) to meet flexibility needs induced by seasonal variations of residual demand

- **Long duration storage is essential to stabilise the power system by capturing excessive production and generating during scarcity situations.**
  - Power-to-gas-to-power (P2G2P) can provide such long-term storage: by consuming electricity during periods with excess RES generation, P2G2P will produce synthetic gas (including hydrogen), that will be stored and burnt later on (e.g. in OCGT or CCGT power plants) to produce electricity during scarcity situations.
  - Given the large gas storage volume, P2G2P can provide seasonal flexibility and follow seasonal fluctuations in residual demand
- **For instance, based on the below illustrative graph for 2050, P2G2P will tend to:**
  - Generate in February-March and December given the high residual demand (explained by a high consumption and moderate RES production)
  - Consume in April-May and September-October given the low residual consumption (due to moderate demand and high RES production)

Evolution of P2G2P stock[1] and residual demand[2] in 2050 – illustration for France (weekly average)

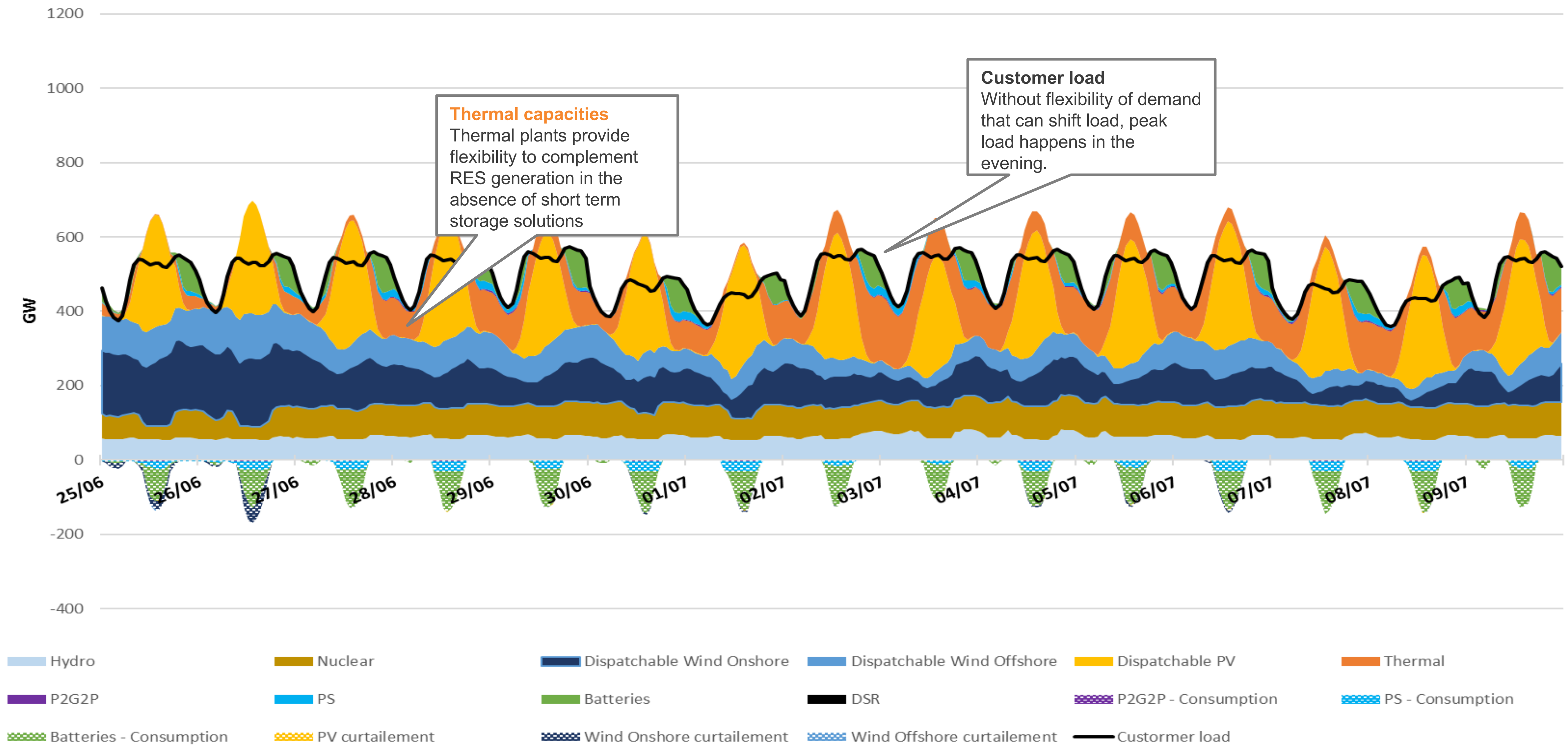


1: P2G2P stock represents the volume of stored synthetic gas (including hydrogen). Whenever the P2G2P consumes electricity, this stock increases. It decreases when P2G2P produces electricity.
2: Residual demand is defined as Power consumption minus variable renewable generation

5.D Flexibility of supply and demand supports the integration of variable RES in the Decarbonisation scenario

During peaks of solar production in 2050, thermal capacities provide day flexibility to complement RES production in the Reference scenario

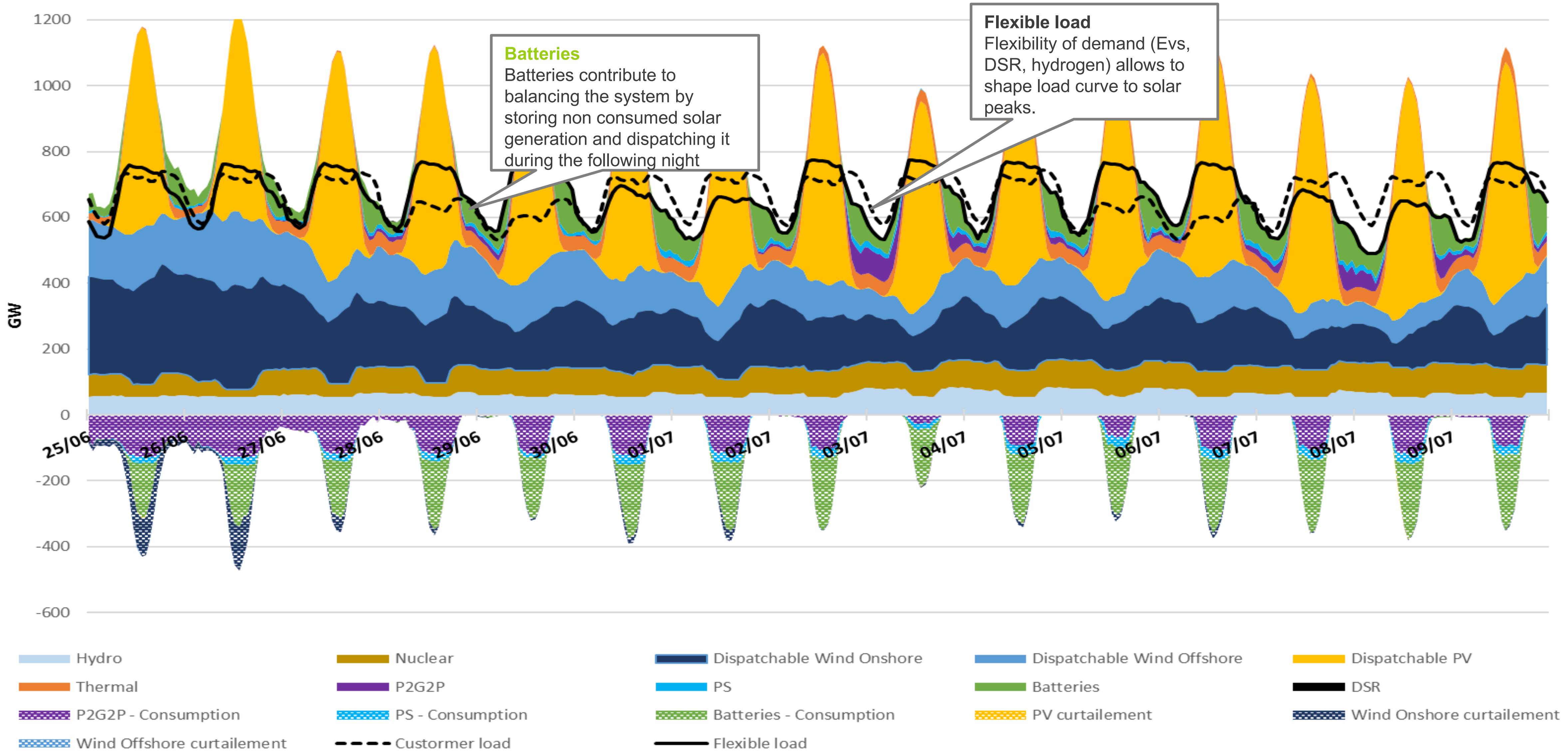
Hourly generation mix during a summer peak production in 2050- Reference scenario



Source: CL modelling

During peaks of solar production in 2050, batteries and flexibility of demand absorb the surplus of RES generation in the Decarbonisation scenario

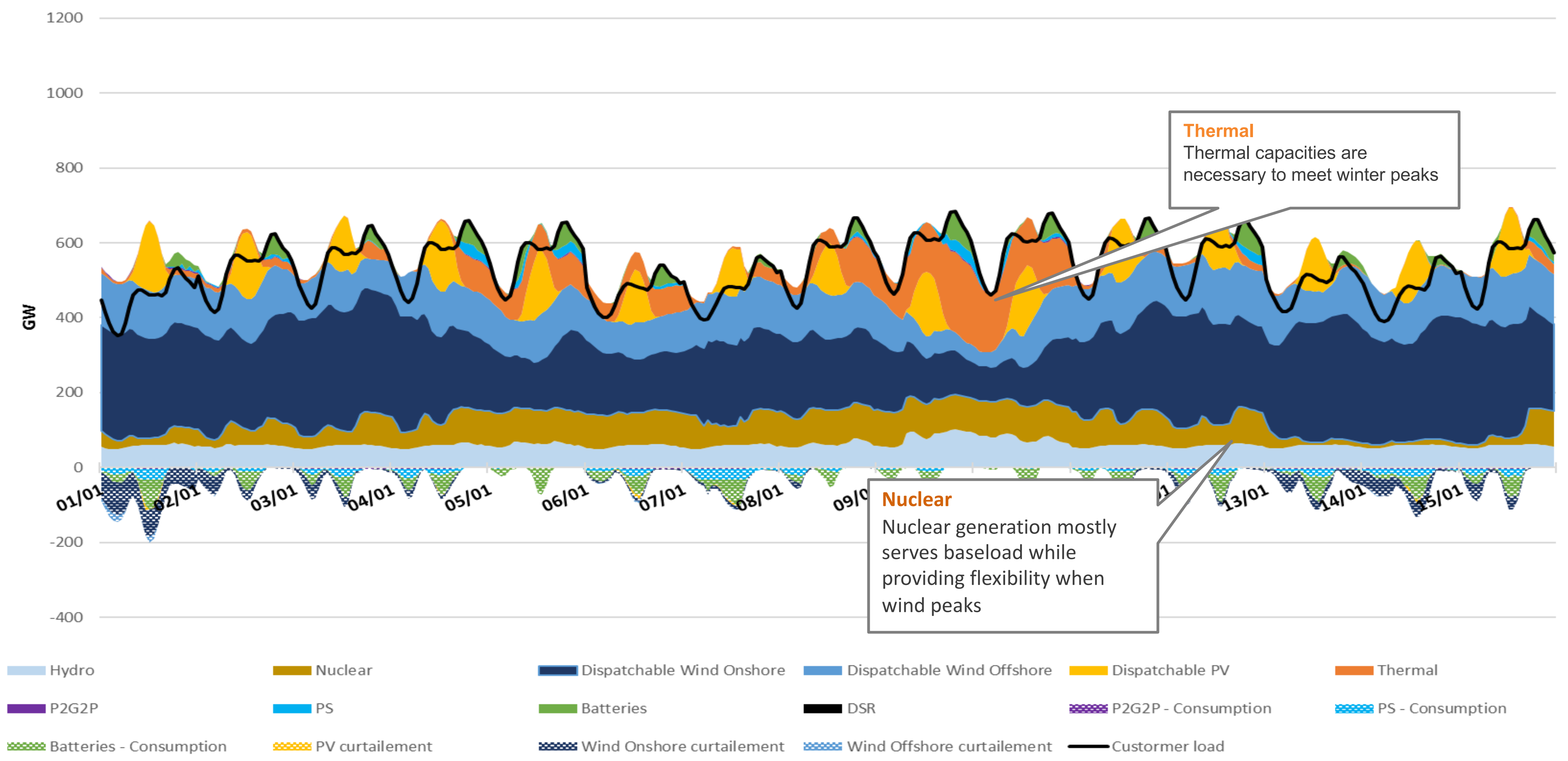
Hourly generation mix during a summer peak production in 2050- Decarbonisation scenario



Source: CL modelling

During peaks of wind production in 2050, thermal capacity and nuclear provide flexibility to complement wind peaks in the Reference scenario

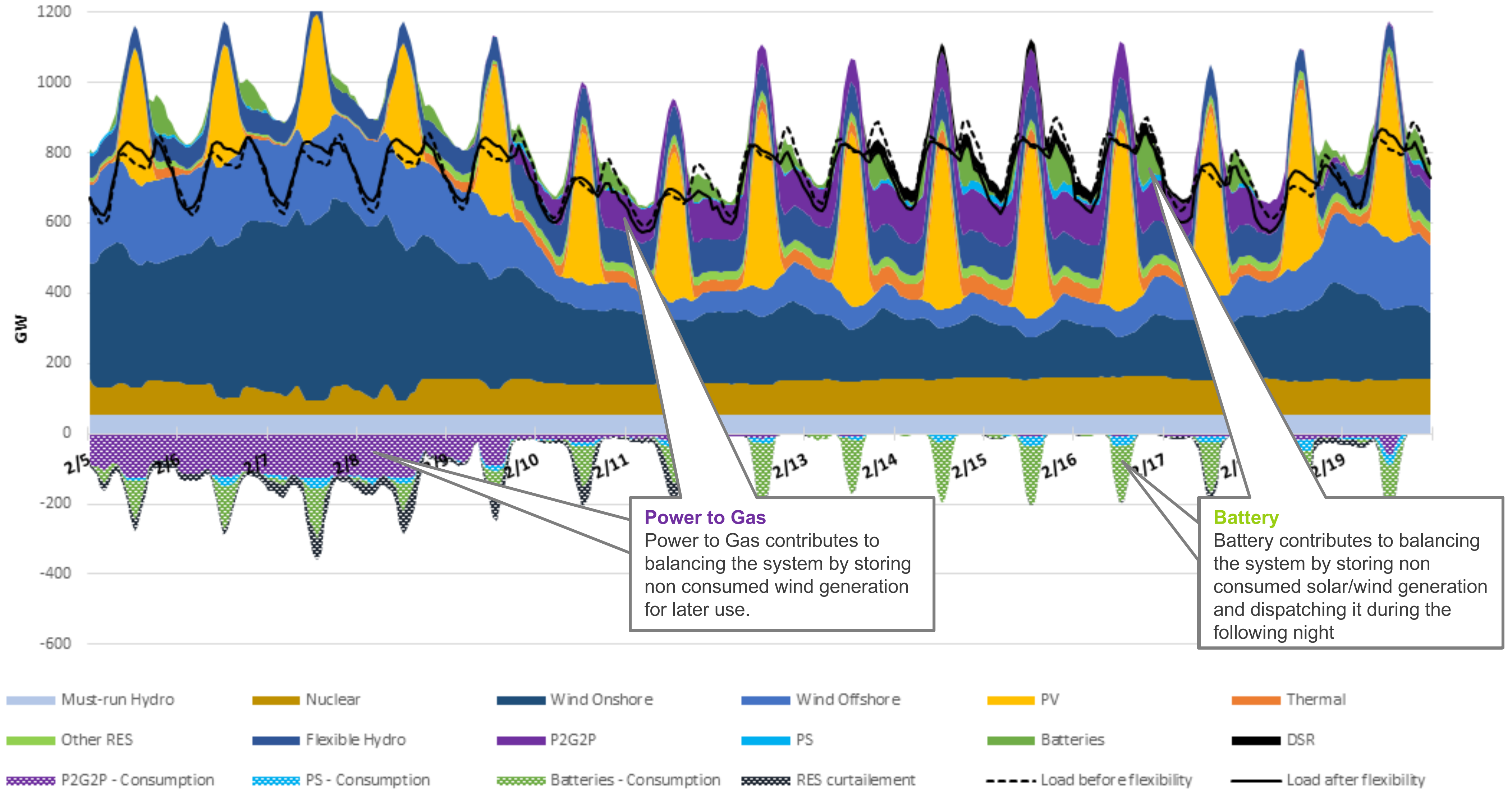
Hourly generation mix during a winter peak production in 2050 – Reference scenario



Source: CL modelling

During peaks of wind production in 2050, increased batteries and P2G storage and flexibility of demand absorb the surplus of RES production in the Decarbonisation scenario

Hourly generation mix during a winter peak production in 2050 – Decarbonisation scenario



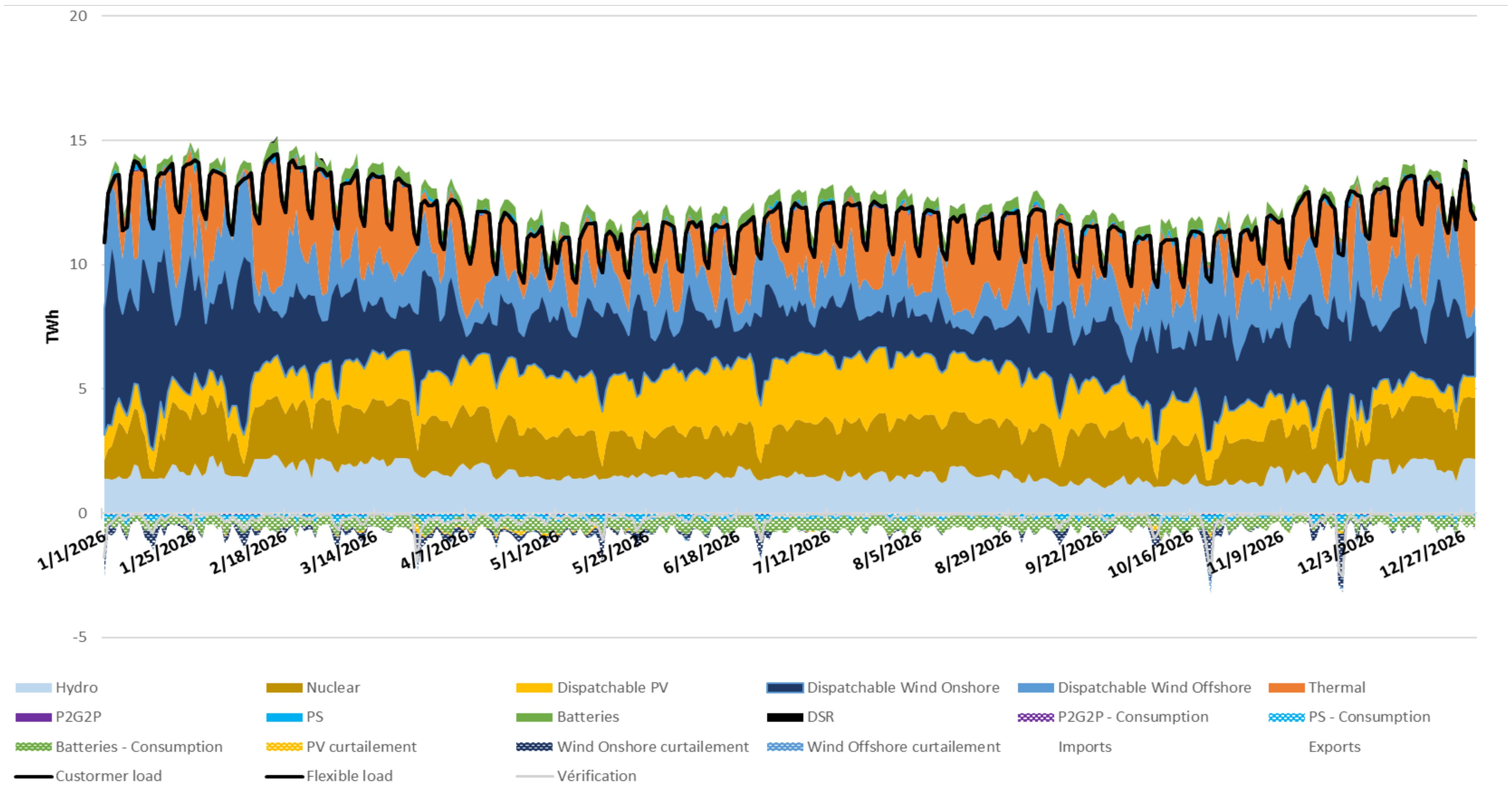
Power to Gas
Power to Gas contributes to balancing the system by storing non consumed wind generation for later use.

Battery
Battery contributes to balancing the system by storing non consumed solar/wind generation and dispatching it during the following night

Source: CL modelling

Thermal capacities provide seasonal flexibility in 2050 in the Reference scenario

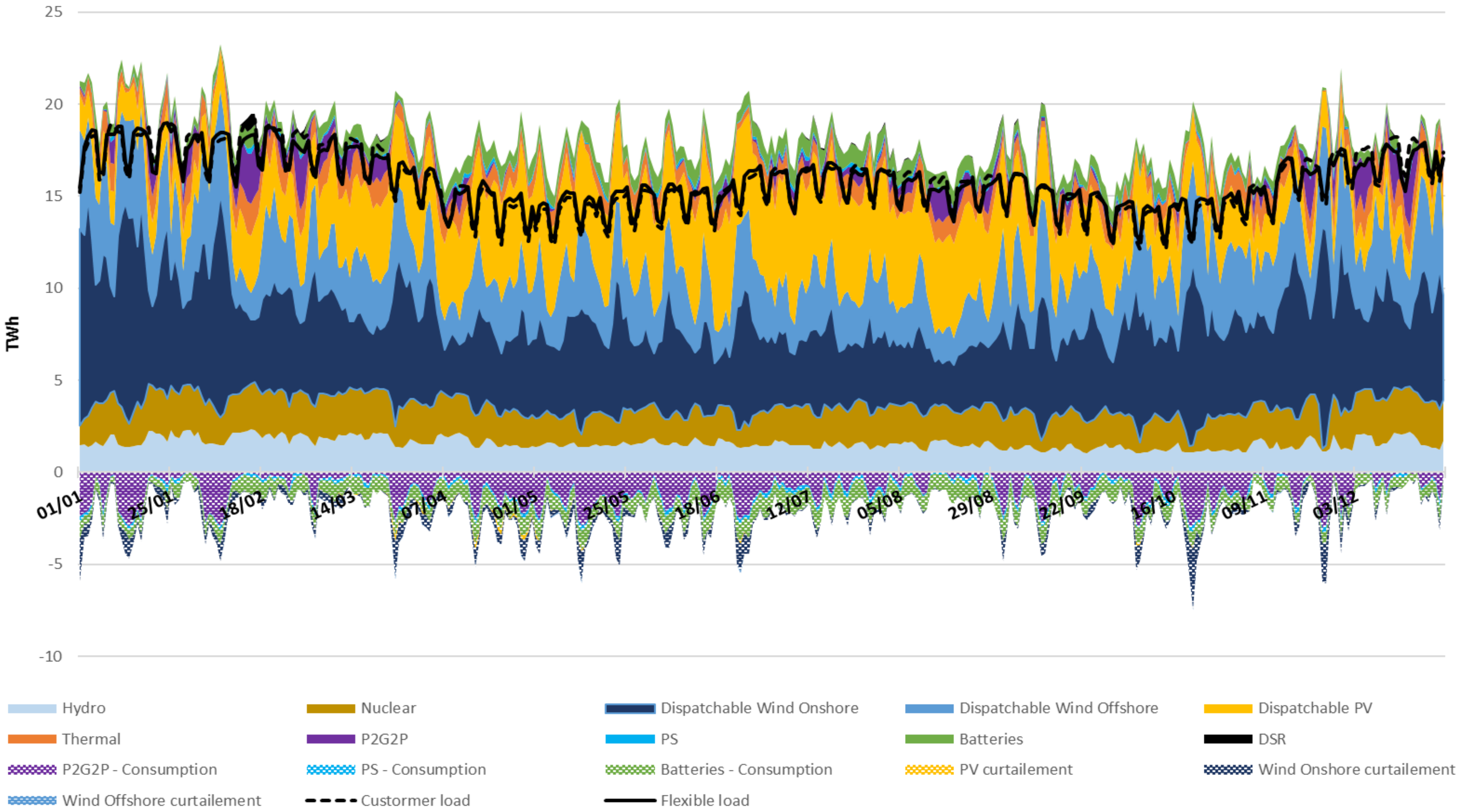
Daily generation mix in 2050 - Reference scenario



Source: FTI-CL Energy modelling

Long term storage provides seasonal flexibility in 2050 in the Decarbonisation scenario

Daily generation mix in 2050 - Decarbonisation scenario



Source: CL modelling

6. Conclusion

Deep decarbonisation supports the economic recovery effort and future sustainable growth thanks to feasible and affordable clean, flexible technologies, and sector coupling

- **Increased ambition to achieve close to 55% emissions reduction in 2030 is feasible in the Decarbonisation scenario and is key stepping stone to achieve net zero emissions in 2050 thanks to:**
  - **Recent technological advances** in RES and batteries for electric vehicles enabling faster decarbonisation
  - **Sector coupling and the electrification** of end uses in the transport, building and industry sectors
  - **Business initiatives** deploying innovative solutions and business models leveraging clean technologies and digital solutions that unlock additional GHG emission reduction potential across the transport sector
  - **New national and local energy policies and regulations** including coal phase-out, ICE bans, tighter emission limits, regulatory frameworks supporting flexibility services and aggregators that enable deeper ambition for decarbonisation

- **The power sector plays a key role as enabler of deep decarbonisation through sector coupling. Developments in the power sector allow it to act as a catalyser for decarbonisation and fast track emissions reductions to 2030:**
  - **Costs reduction in RES** allow greater penetration of variable RES
  - **Coal phase out policies** drive further emission reductions in the next decade
  - **Development of flexible solutions on the demand and supply side** allow to meet increasing flexibility needs arising from the integration of RES:
    - Short term and long term storage with batteries and P2G2P installations
    - Flexibility of demand through EVs, Heating and Cooling, and hydrogen production
  - **The digitalisation of distribution grids will support the integration of variable RES** unlocking the flexibility potential of demand-side response as well as ensuring the reliability of the system

- **Increased decarbonisation requires additional investment but the 55% target by 2030 can be achieved at a slightly lower cost for consumers than the previously agreed 2030 target, and complete decarbonisation by 2050 does not increase system costs:**
  - Total energy system costs in the Decarbonisation scenario are slightly lower than in the Reference scenario featuring lower ambitions until 2030, thanks to energy efficiency gains and fuel switching despite the necessary increase in investments to reach the increased ambition in 2030.
  - Achieving complete decarbonisation in 2050 requires to increase investments beyond 2030 until 2040, but system costs remain affordable and comparable to the Reference scenario thanks to the decrease in clean technologies costs, new business models as well as policies and regulations.

- **Increased ambition for 2030 supports the economic recovery effort and green transition by providing more renewable capacity, infrastructure, and energy efficiency investments for buildings with a limited impact on costs thanks to the reduction of clean technologies.**

Effective EU policy design can support a clean and affordable energy transition and enhance the potential technologies have to increase EU decarbonization ambition

- **EU policies should support increasing 2030 GHG ambition to 50-55% and a 2050 climate neutrality objective with corresponding amendments of RES and EE targets**
  - **An increased GHG ambition policy framework should be based as much as possible on the realistic potential of decarbonization technologies** taking into consideration most recent cost evolution and their resilience to change while promoting innovation and technological disruption
  - **The "technology neutrality" concept should evolve to encompass other SDGs** such as air quality and circular economy and carefully assess distributional impacts.
  - **The impacts on regions, communities, workers and consumers need to be managed** so as to ensure that through *a just transition* process no one is left behind
  - **The assessment should take into account cross-sectorial synergies** and not limit itself to optimize individual sectorial contributions
- **The power sector can effectively contribute to deeper decarbonization provided that an investment framework for RES and carbon neutral firm and flexible capacity is adequately designed and in place**
  - **A revised market design is needed to support increased RES penetration**
  - **Wind and solar renewable energy technologies should be acknowledged as key strategic value chains**
  - **Corporate Power Purchasing Agreements (PPAs) should be promoted** in order to encourage the participation on the industry demand side
- **Electrification of end-use sectors (transport, buildings and industry) is an unprecedented opportunity to decarbonize the uses of energy**
  - **Clean and smart electrification is the cheapest and simplest route to decarbonize large portions of total final energy uses.** This is already valid for light-duty transport, domestic and water heating and cooling and many industrial and manufacturing processes
  - **A roadmap with concrete milestones on the electrification of energy demand is needed to support the decarbonisation of the economy by 2050**
  - **The smart integration of electricity with final electric uses should be promoted more strongly** as it provides much needed additional flexibility to manage increasing volumes of variable RES. When smartly integrated in a power grid, EVs, heat pumps and electric boilers can help by adjusting their demand profile based on price signals and providing a source of energy storage as well as demand response
- **The energy infrastructure needs to be enhanced and digitalized in order to exploit cross-sector synergies, leveraging on increased decentralization, electrification of end-uses and increasingly active consumers, ensuring at the same time adequacy, security and resilience**
  - **There is an urgent need to boost investments in infrastructures** to accommodate new electrification technologies and increase RES penetration
- **Direct electrification can be complemented by indirect electrification (Hydrogen and P2X technologies) to decarbonize hard-to-abate sectors**
  - **Green hydrogen produced by RES power via electrolysis is the only future proof sustainable solution.** Hydrogen needs to be produced on a 100% RES basis and must be produced mainly locally

Annexes

Annexes

A.1. Description of models (POLES and PLEXOS) and modelling approach

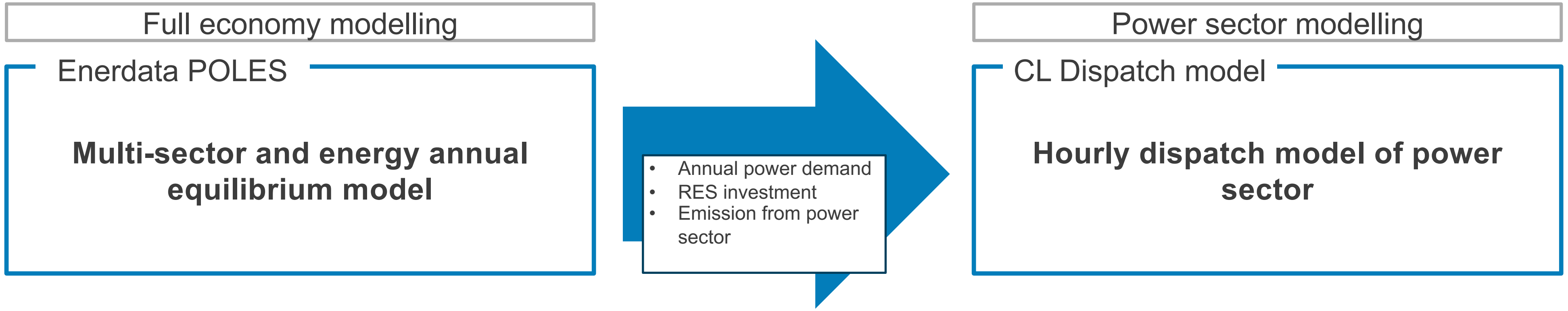
Modelling approach – 2 models coupled to cover full economy and deep dive on power sector

Full economy modelling

- In order to assess the impact of different technology cost reduction on the EU decarbonisation objectives, **we used the POLES energy model which covers all sectors in the EU economy**
  - The POLES model is a similar model to the PRIMES model and it is commonly used by the JRC of the European Commission and numerous energy market participants, both public and private organizations.
  - Our modelling approach compares **two scenarios**:
    - **One reference scenario** reaching the current EU32-32.5 targets (48% GHG reduction) by 2030 and 65% GHG reduction for 2050.
    - **One alternative increase ambition scenario**. This scenario aims at reaching **more ambitious targets by 2030** (around **55% GHG reduction**) and **net carbon neutrality by 2050**.
- POLES results were completed with sector specific in-depth analyses to derive key metrics of the decarbonisation

Power sector modelling

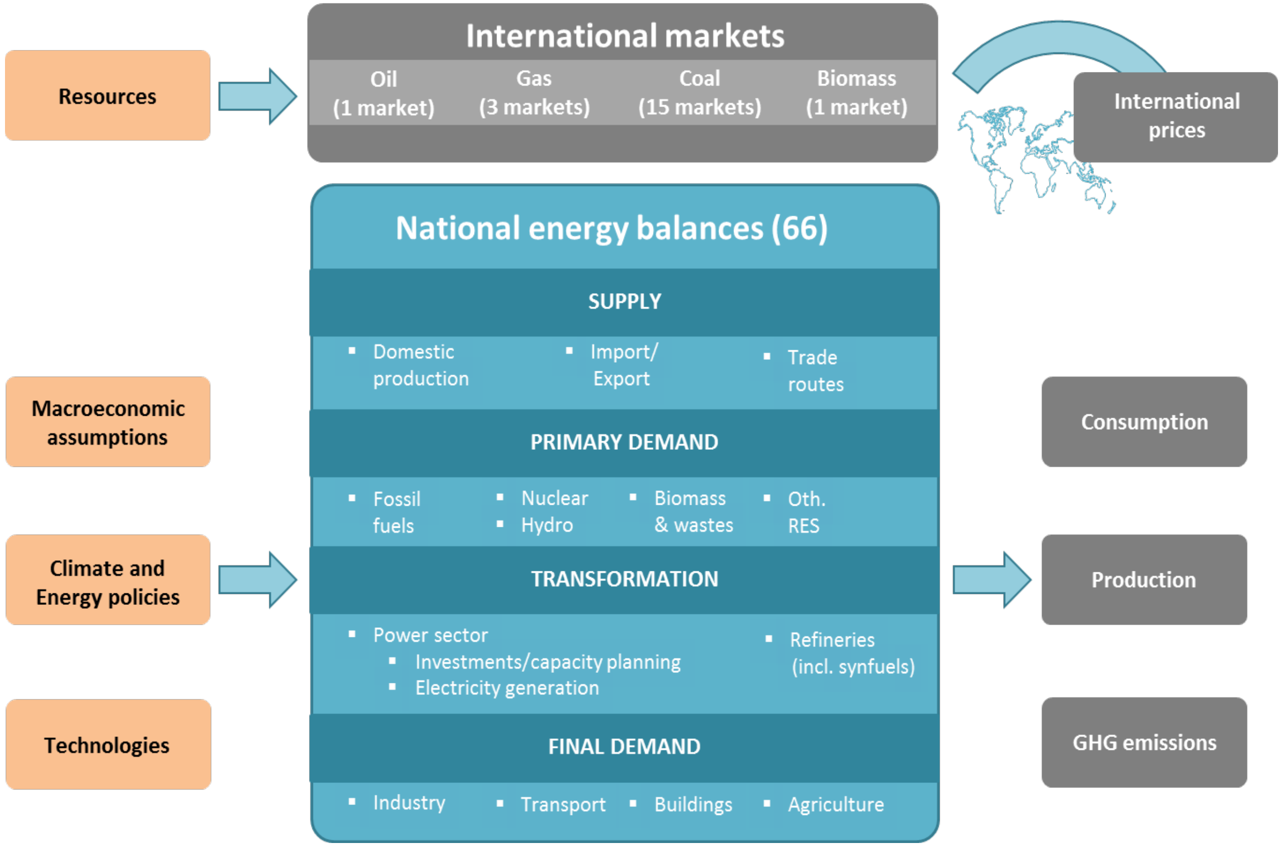
- We then used the **CL dispatch model to perform a deep dive on the power sector decarbonisation.**
  - Granular modelling of the power sector decarbonisation (hourly resolution) accounting for deep penetration of RES, batteries, demand response and digitalisation



Enerdata POLES model introduction

- ENERDATA POLES model is a recognised multi-issue energy model (similar to PRIMES) that relies on national energy balances combined with economic, policy and technological scenarios to withdraw energy production, consumption and greenhouse gas (GHG) emissions. POLES' geographical coverage includes the EU27 countries.
- ENERDATA co-developed and uses the world recognised POLES model to provide quantitative, scenario-based, empirical and objective analyses.
- As the POLES model is used for many members of the energy sector (industry, governments, European Commission, etc.), it is very well adapted to forecast the effects of different energy-related engagements (demand-supply, GHG emissions limitations, promotion of renewables and energy efficiency, energy security issues, etc.).
- The simulation process uses dynamic year-by-year recursive modelling, with endogenous international energy prices and lagged adjustments of supply and demand by world region which allows for describing full development pathways to 2050.

Enerdata POLES model



Enerdata POLES model: key drivers and outputs

Energy Demand

- 66 countries
- 15 detailed sub-sectors industry, buildings & transportation, incl. detailed description of large energy intensive industries (steel, chemicals, etc.)
- All key energies: oil, gas, coal, power, biomass, solar, wind
- End consumer prices
- Detailed demand (in particular transport)
- Demand function based on activity levels, prices effects, autonomous technological change

Energy supply

- Oil, gas, coal, and renewables
- Resources, discoveries and reserves for 88 producing countries
- Production strategies (countries)
- Unconventional oil and gas
- International and regional prices: oil, gas, coal, biomass
- Development potential for renewables
- Oil, gas, coal, and biofuels, imports & exports

Electricity

- 30 different power generation technologies
- Simulation of future power generation mix by country
- Power capacity planning
- Electricity load forecasting
- Power price analysis
- Technology availability scenarios: Nuclear revival or phase-out, CCS, wind & intermittency…
- Impact of support schemes for renewables (feed-in tariffs…)
- Hydrogen

Disaggregation of final energy demand

In each sector, energy consumption is calculated separately for substitutable fuels and for electricity, with specific energy consumptions:

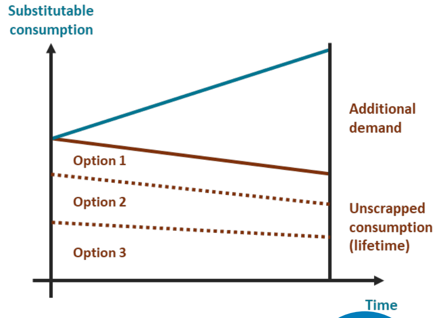
- Electrical processes and coke for other processes in steel-making
- Oil and gas as raw material for chemical industry
- Electricity for specific uses in the residential and service sectors

Sector	Sub-sector
Industry	Steel Non-metallic minerals Chemistry Chemical feedstock Other industry Non-energy use
Buildings and agriculture	Residential Services Agriculture
Transport	Road Rail Air Other transport
Bunkers	International air International maritime

Energy demand in Poles – General principles

1 Principle

POLES uses a « putty-clay » approach to determine the inter-fuel substitution process:
Industry: oil, gas, coal, biomass
Buildings: oil, gas, coal, biomass, substitutable elec.
Transport: competition takes place between vehicles

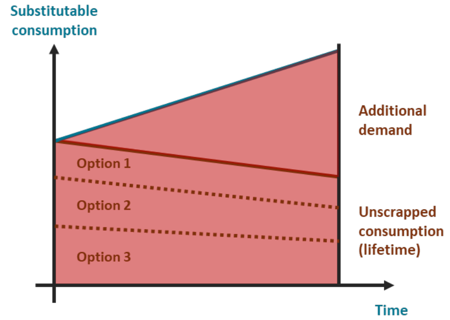


2 Demand

- **Price effects**: short term elasticity ($\alpha1$, 1-2 years) & long-term ($\alpha2$, 3+ years)
- **Activity effect**: activity elasticity (β)
- **"Autonomous technological change"**: exogenous trend (Tr)

$$E = f(P_{(-1,-2)}^{\alpha1} * P_{(-2,-t)}^{\alpha2} * A^{\beta} * Tr)$$

Global enveloppe for substituable consumption



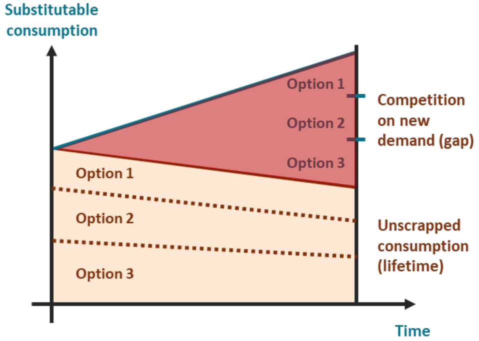
3 Competition process

- Competition occurs on new equipment only (new consumption and replacement of scrapped capital),

$$\text{Market share} = \alpha * Ci^{\beta} / \Sigma(\alpha * Ci^{\beta})$$

with :
- C cost for the user (inc. taxes)
- α: calibrated on historical data
- β: sensitivity to price / cost (negative)

Energy mix for new equipment



POLES model results are completed with sector specific in-depth analyses to derive key metrics of the EU decarbonisation - 1/4

Power

- From POLES generation and installed capacity results, we derive :
  - The cost associated with the deployment of new capacities based on EC REF 2016 data updated to factor recent renewable cost reduction

POLES

- Electricity production by energy source
- Electric capacity by energy source
- Annual electric capacity additions
- Fuels costs

CL sector specific analysis

Data added - Treatment	Results
- Technology costs from EIA 2018 and EC Primes 2018/2019 - OPEX	- Annual investment and O&M expenditures

POLES model results are completed with sector specific in-depth analyses to derive key metrics of the EU decarbonisation - 2/4

Transport

- From POLES number of vehicle per fuel type, number of annual additions per fuel type and total traffic based on each scenario cost evolution and relative competitiveness of each fuel, we derive :
  - The penetration of Low Emission Vehicle (LEV) in new sales and the average utilisation rate of the fleet of vehicles.
  - The cost associated with the deployment of LEV as well as the associated infrastructure based on EC PRIMES 2019 technology pathways data updated to factor recent battery cost reduction

POLES

- Size of vehicles' fleet by type (private vehicles, light and heavy trucks) and by fuel
- Efficiency of new vehicles
- Annual number of new sales by fuel
- Traffic (passenger-kilometre and tonne-kilometre)
- Fuel costs

→

CL sector specific analysis

Data added - Treatment	Results
- Ratio infrastructure / number of vehicles - Investment costs: • Vehicles (EC Primes 2019 and own calculations) • Infrastructures - OPEX	- EV penetration - Annual investment for new vehicles and infrastructures expenditures - O&M expenditures

POLES model results are completed with sector specific in-depth analyses to derive key metrics of the EU decarbonisation - 3/4

Industry

- From POLES whole energy results per aggregated industry sectors (Steel & Iron, Chemistry, Non-metallic minerals, Other industry and Non-energy uses), we derive :
  - The implied conversion capacity per fuel type per industry sectors assuming that on average industry operates at 95% load
  - The cost associated with the conversion and replacement of the industrial plants based on EC PRIMES 2019 technology pathways

POLES

- Energy consumption by source, aggregated for each of the 4 sub-sectors (steel, non-metallic minerals, chemistry and others)
- Industry energy intensity
- Industry value added for each sub-sector
- Fuel costs

CL sector specific analysis

Data added - Treatment	Results
- Conversion into annual added capacity per fuel type per sub-sector (considering sub-sectoral energy efficiency improvements) - Cost associated with the conversion and the replacement of industrial processes from EC Primes 2019 - Split between direct and indirect electrification as a whole and per sub-sector	- Share of direct and indirect electrification - Annual investment expenditures - O&M expenditures

POLES model results are completed with sector specific in-depth analyses to derive key metrics of the EU decarbonisation - 4/4

Buildings

- From POLES whole energy results for residential and services, we derive :
  - The average renovation rate assuming that a renovation (resp. new built) yields 60% (resp. 80%) saving on heat related energy consumption.
  - The cost associated with the renovation and replacement of the heating technology based on EC PRIMES 2019 technology pathways
  - Note: It is assumed that all renovations converting to electricity install heat pumps

POLES

- Population
- Total number of dwellings
- Value added for services
- Energy consumption by source for residential and services

→

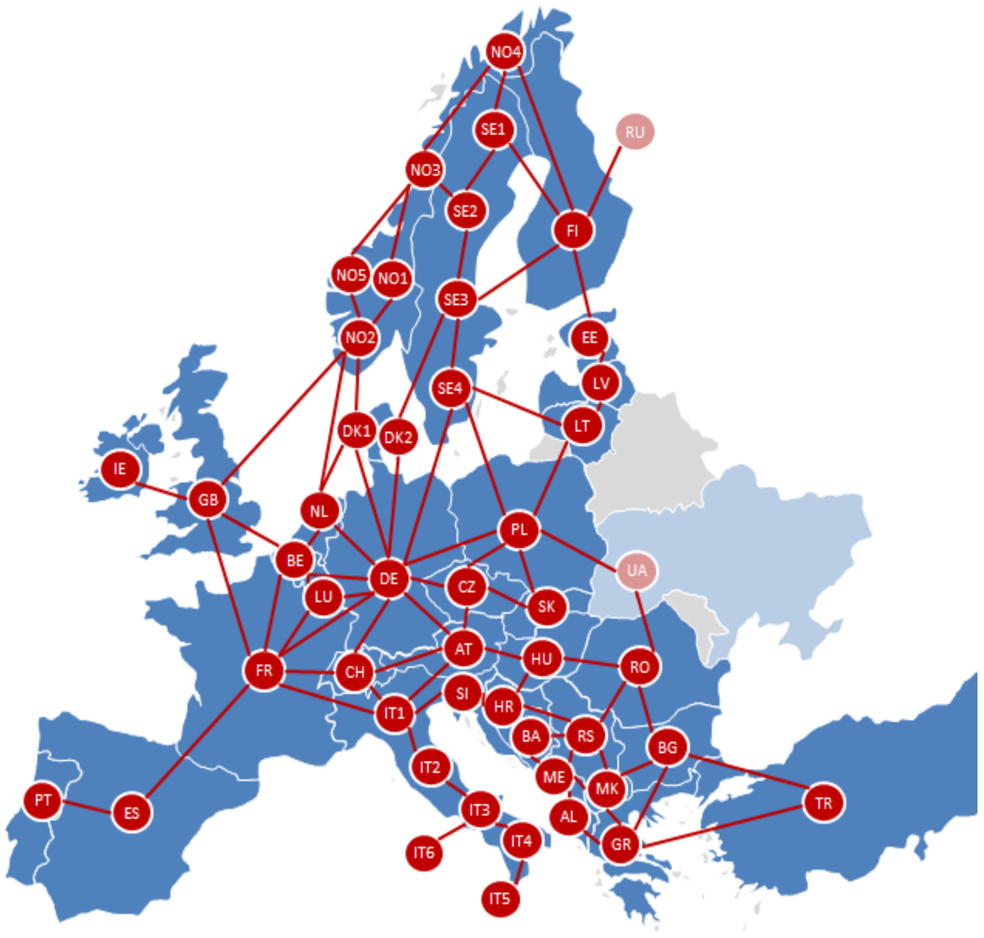
CL sector specific analysis

Data added - Treatment	Results
- Split of the energy consumption into consumption for non-renovated, renovated and new dwellings to determine the extent of renovation and new constructions - Cost associated with the renovation and replacement of the heating technology from EC Primes 2019	- Renovation rate - Annual investment and O&M expenditures - Number of heat pumps

CL European power market model covers the power markets of EU27+ with fine granularity

- CL Energy's power market model covers the **EU-27 countries as well as the United Kingdom, Switzerland, Norway, the Balkans and Turkey**.
  - Countries beyond this geographic scope are modelled at an aggregate level.
  - The model is run on a commercial modelling platform Plexos® using data and assumptions constructed by CL Energy for demand, supply, commodity price and interconnection.
- CL Energy's power market model constructs **supply in each price zone based on individual plants and simulates the market with hourly resolution**
  - European power plants database containing technical parameters of all thermal European plants
  - Zonal prices are found as the marginal value of energy accounting for generators' bidding strategies.
  - Model takes into account cross-border transmission and interconnectors and unit-commitment plant constraints.

Geographic scope of the model

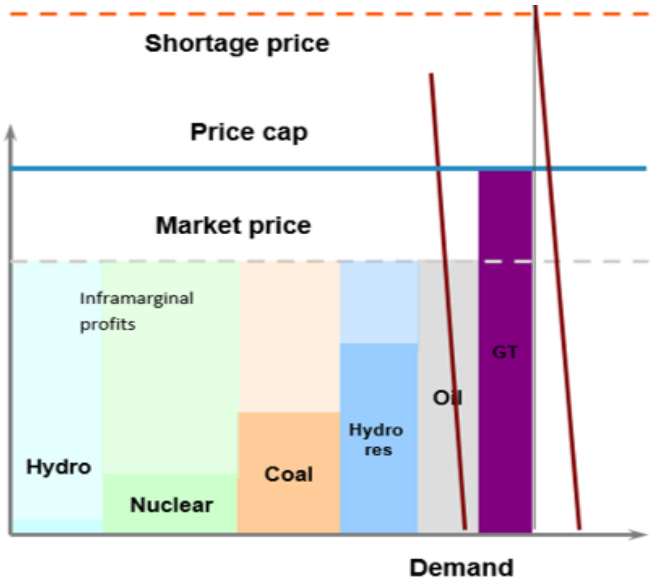


Source: CL Energy

CL model relies on a dispatch optimisation software applied to short to long term capacity scenarios

Short term dispatch optimisation

- **Model constructs supply hourly in each price zone based on individual plants unit commitment constraints:**
  - European power plants database containing technical parameters of all thermal European plants
  - Zonal prices are found as the marginal value of energy accounting for generators' bidding strategies
  - Model takes into account cross-border transmission and interconnectors



Source: CL Energy

Long term capacity scenarios

- **Short term dispatch optimisation is applied on short to long term capacity scenarios derived from two distinct approaches:**
  - **Dynamic long term optimisation** : Based on cost reduction assumptions, the capacity mix is optimized to minimise the cost of the system while meeting a number of constraints such as security of supply or CO2 emission reduction target.
  - **Long term capacity scenarios based on energy policies and regulation:** Capacity projections are based on national and European energy policies and regulation which would structure the evolution of the capacity mix (coaL closure policies, nuclear policies, renewable policies, …)
- The dynamic approach is well-suited to capture the impact of the retirement of dispatchable plants with higher level of Renewable energy penetration.

Simplification and limitations of the modelling approach

Our modelling approach is based on several simplifying modelling assumptions:

- The optimizations are carried out over a climatic reference year. This simplification makes it possible to correctly model the impact of RES variability on wholesale markets, but does not take into account climate change or the diversity of climate years.
- Optimisations are carried out for the "certain future", i.e. each player knows the future perfectly well. Forecasting errors (on RES demand or production), as well as storage strategies in "uncertain future" are therefore not taken into account.

A.2. Modelling assumptions

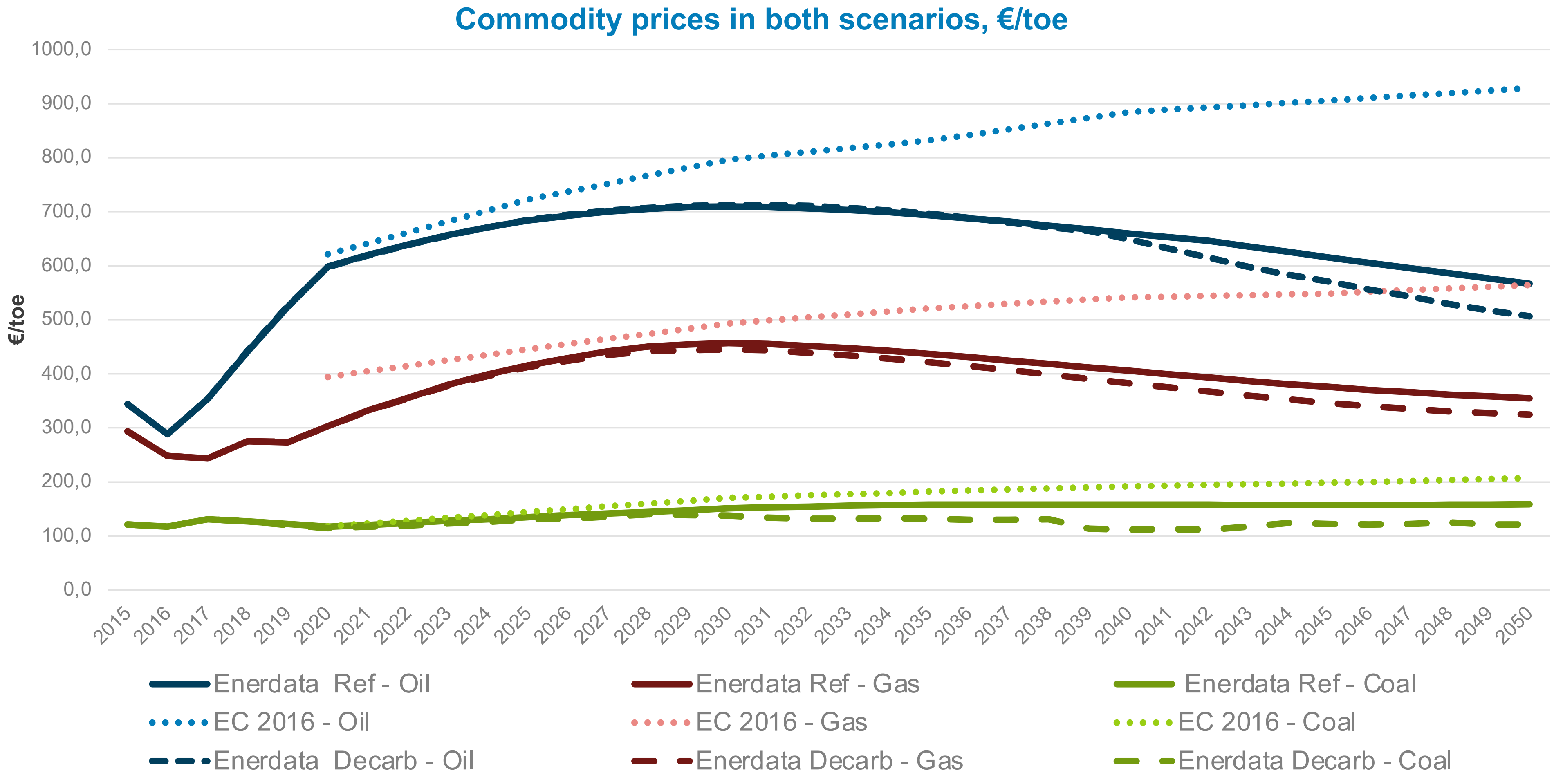
Both scenarios relies on a set of assumptions from the EU 2050 Roadmap updated with recent technological progress and policies

		Reference	Decarbonisation
GDP		Based on EU REF 2016 (*1.5% CAGR*)	
Population growth		Based on EU REF 2016 (*0.1% CAGR*)	
International fuel prices		Endogenous in POLES but starting point in line with EU REF 2016	Endogenous prices, therefore evolving compared to the REFERENCE scenario
Technology costs	**Power generation**	Based on IEA WEO cost curves in line with EU REF 2016	Based on lower range of EC PRIMES 2018
	Transport	Based on EC PRIMES 2018	Assumed Cost parity between EVs and ICEs in 2025
	Building and Industry		Based on EC PRIMES 2018
Energy policies		EU3232.5 in 2030 + EU REF 2016 in 2050*	50-55% GHG emission reduction by 2030 + Net zero in 2050

** The 2050 point in the Reference scenario has been recalibrated compared to EU REF 2016 given the 2030 target in the Reference scenario has increased compared to EU REF 2016 and is in line with the EUCO3232.5 scenario*

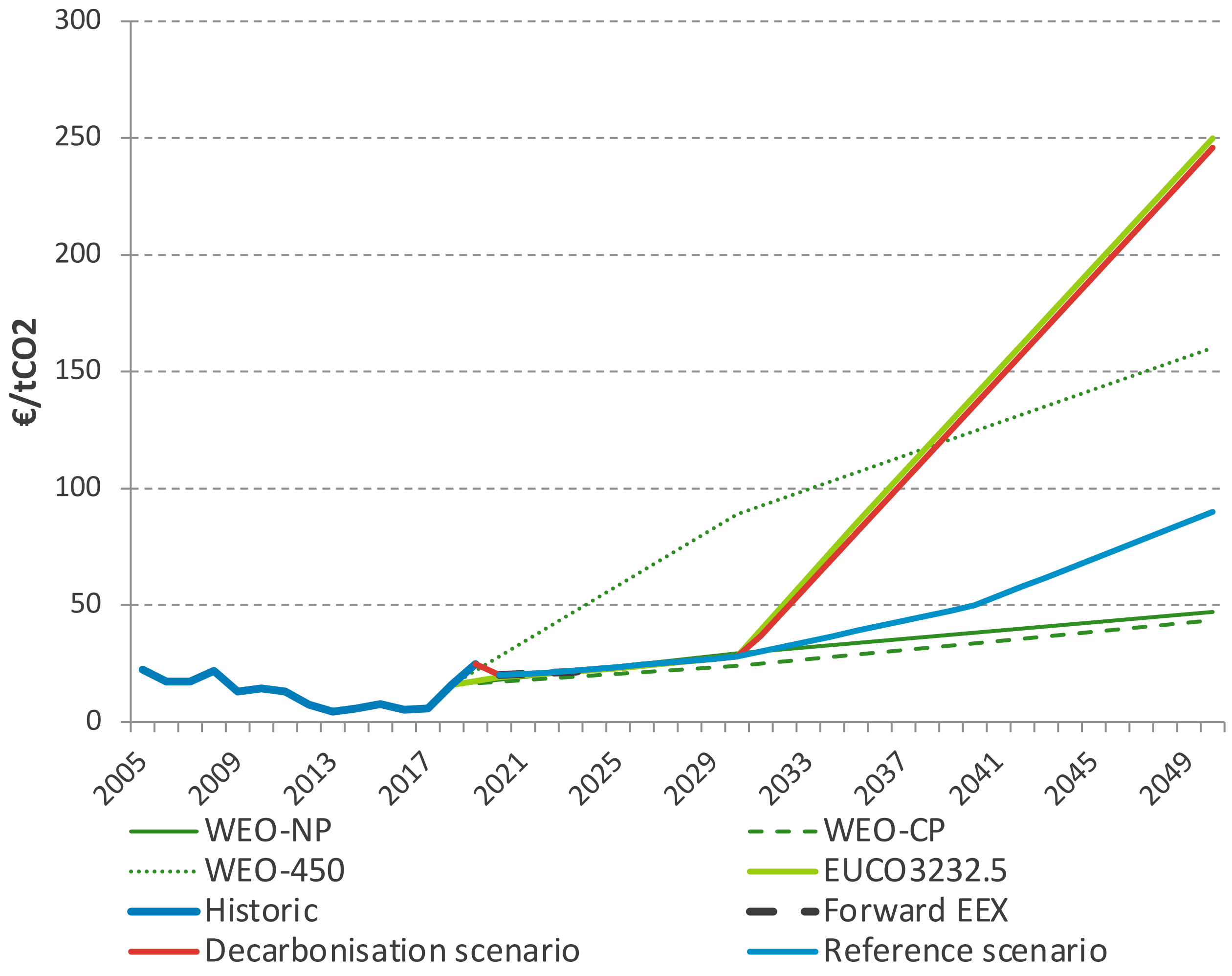
Commodity prices are based on Enerdata endogenously calculated oil, coal and gas prices

- The coal and gas price trajectories are defined based on Enerdata endogenously calculated oil, coal and gas prices
- Endogenous calculation of commodity prices lead to much lower prices than the European Commission 2016 reference scenario, thanks to further fossil fuel demand reduction in both scenarios



The value of CO2 in the Decarbonisation scenario is based on the latest scenarios of the European Commission, aiming at a strong reduction of GHG emissions in 2050

Value of CO2 in €/tCO2

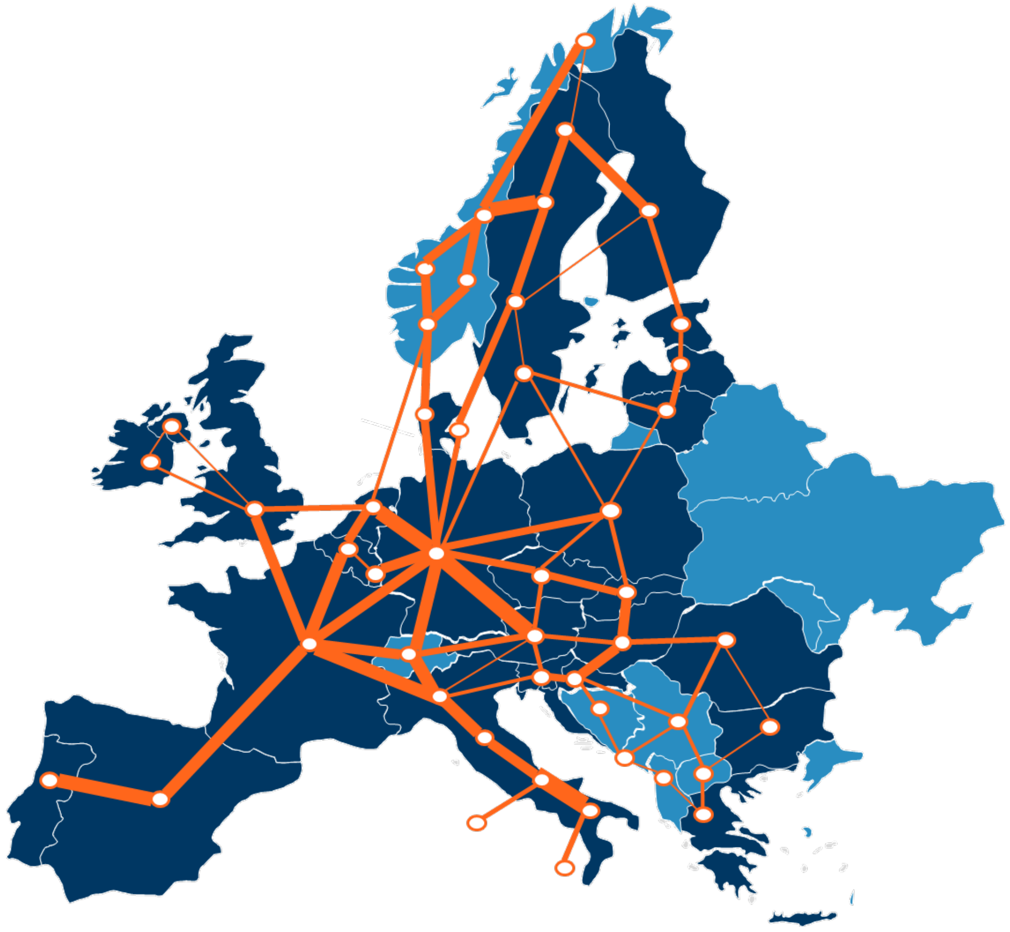


Note: The EUCO3232.5 trajectory curve was slightly shifted for graphical reasons to avoid overlapping with the Decarbonisation scenario curve. In reality, from 2030 onwards, these two curves are exactly the same.

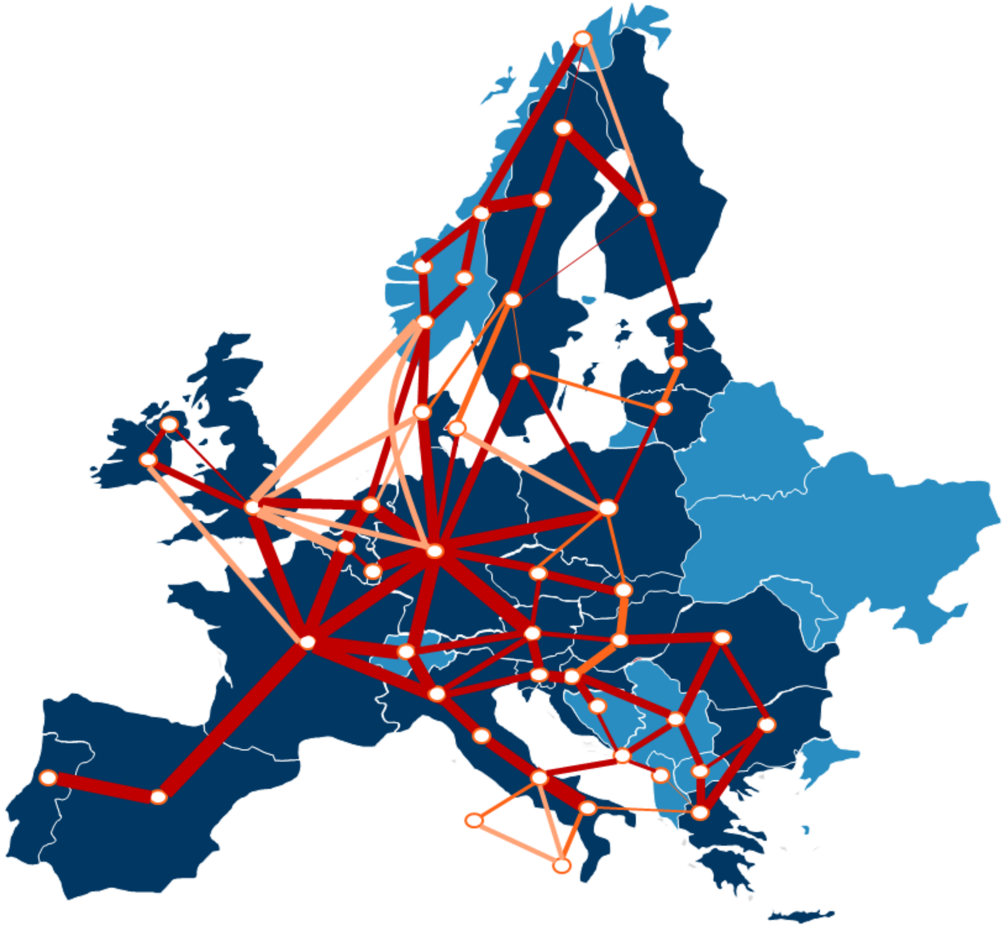
- The value of CO2 represents the marginal abatement cost of CO2. It both considers the explicit and implicit values of CO2.
- Explicit CO2 price (the EU ETS price) was historically low due to a surplus of emission allowances.
- However, recent reforms of the EU ETS market have led to an increase in this price, now around €28 per tonne (July 2020).
- Our long-term projection is based on :
  - For the reference scenario: end point of 90€/t in 2050, aligned with EC reference 2016 scenario trajectory
  - For the Decarbonisation scenario: end point of 250€/t in 2050 in line with the European Commission's EUCO3232.5 scenario
  - In both scenarios, we align the 2030 price with the higher 2030 RES target (ETS price estimated at 28€/t in 2030)
- The CO2 value trajectory in the European Commission’s EUCO3232.5 scenario reflects the implicit carbon price (e.g. marginal carbon abatement cost) of the different policies implemented to reach an ambitious decarbonisation by 2050.
- This does not necessarily imply that the EU ETS price would reach these carbon prices, but reflects the equivalent carbon price embedded in the different policies and measure implemented.

Our interconnection NTC development is based on ENTSOE TYNDP 2018 development plan featuring a doubling of NTC by 2050

Network in 2015 **NTC: 225 GW**



Network in 2050 **NTC: 439 GW**



Upgraded line

New line

200 500 1000 2000 4000 6000 10000 MW

Note: NTC stands for Net Transfer Capacity

The power market model is set up with a range of inputs derived from latest announcements from TSOs, regulators and market players

Key power price driver	Sources	Optimization
Demand		
Power demand	■ Long term electrification based on Enerdata results	■ Fixed set as demand to be met
Supply		
RES capacity	■ Meet EU objective of 56% RES-E penetration share by 2030 ■ CAPEX and OPEX outlook based on latest data from EC PRIMES (June 2018)	■ Capacity dynamically optimised thereafter based NPV of anticipated costs and revenues
Nuclear capacity	■ Latest National plans on phase-down or phase-out ■ Latest announcement on plants' life extension and new projects	■ Dispatch optimized by hourly dispatch model
Thermal capacity	■ Latest announcements from operators and National plans on phase-out or conversion to biomass ■ Latest announcement on refurbishment and new projects in the short-term ■ CAPEX and OPEX outlook based on latest data from EC and E3M (June 2018)	■ Capacity dynamically optimised in the longer term based on NPV of anticipated costs and revenues ■ Dispatch optimized by hourly dispatch model
Storage technologies	■ CAPEX and OPEX outlook based on latest data from EC and E3M (June 2018)	
Commodity prices		
Gas	■ Forwards until 2020, converge to IEA WEO 2019 New Policy by 2030	■ Endogenously calculated
Coal ARA CIF	■ Forwards until 2021, converge to IEA WEO 2019 New Policy by 2030	■ Endogenously calculated
CO2 EUA	■ Forwards until 2021, converge to EUCO33 by 2025, EUCO30 by 2030/35	■ Fixed set as an input
Interconnections		
Interconnection	■ ENTSO-E TYNDP 2018 outlook for new and existing interconnections	■ Fixed set as an input

(1) MAF: Medium term adequacy forecast; (2) TYNDP: Ten Years Network Development Plan; (3) WEO: International Energy Agency World Energy Outlook

On the demand side, new uses of electricity provide additional flexibility capacity in the Decarbonisation scenario

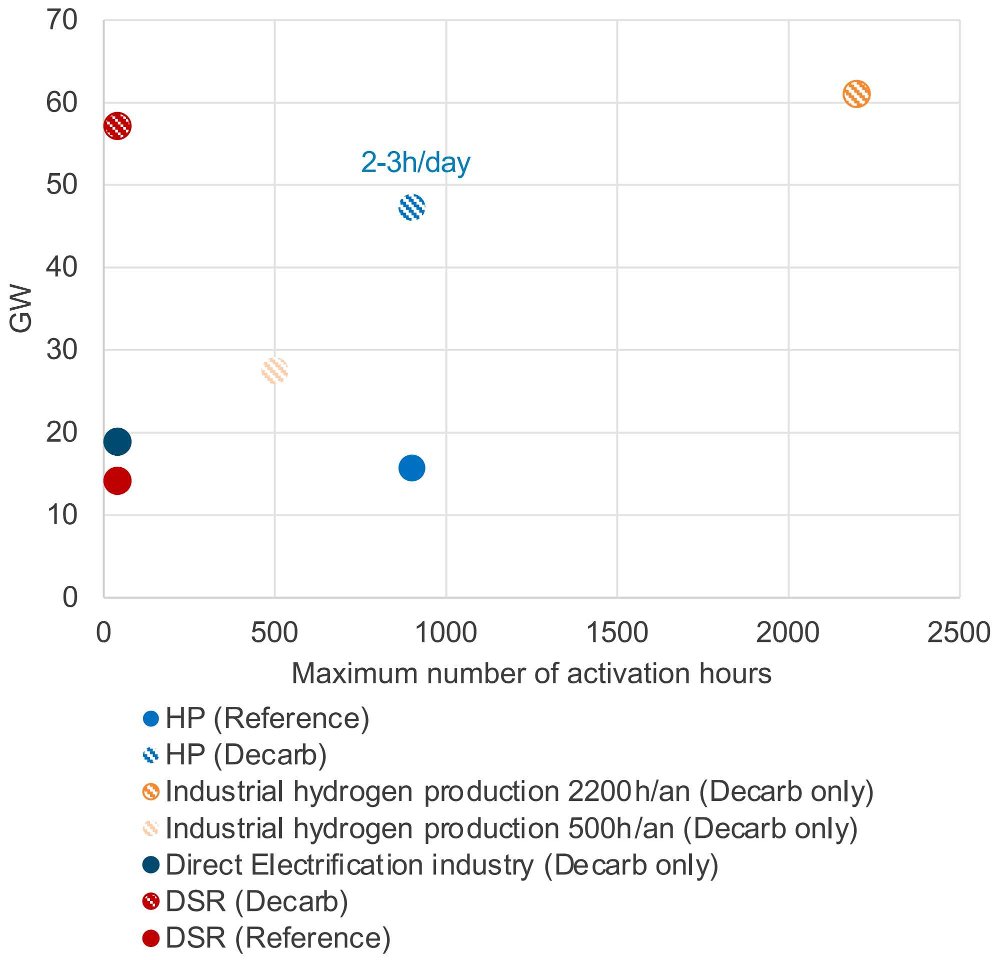
Sources of flexibility of demand available for DSR:

- **We assume that DSR** can be activated 40 hours per year
- **Heat pump and cooling**
  - In addition to day/night optimisation, 50% of the heat pumps are dynamically controlled in response to the market price, making possible the modulate of consumption over 2-3 hours.
- **Direct Electrification industry (only Decarbonisation scenario)**
  - New industrial electricty demand can be reduced 40 hours per year at 60% of its power
- **Industrial hydrogen production (only Decarbonisation scenario)**

To reflect the future potential for flexibility provided by hydrogen production for industry:

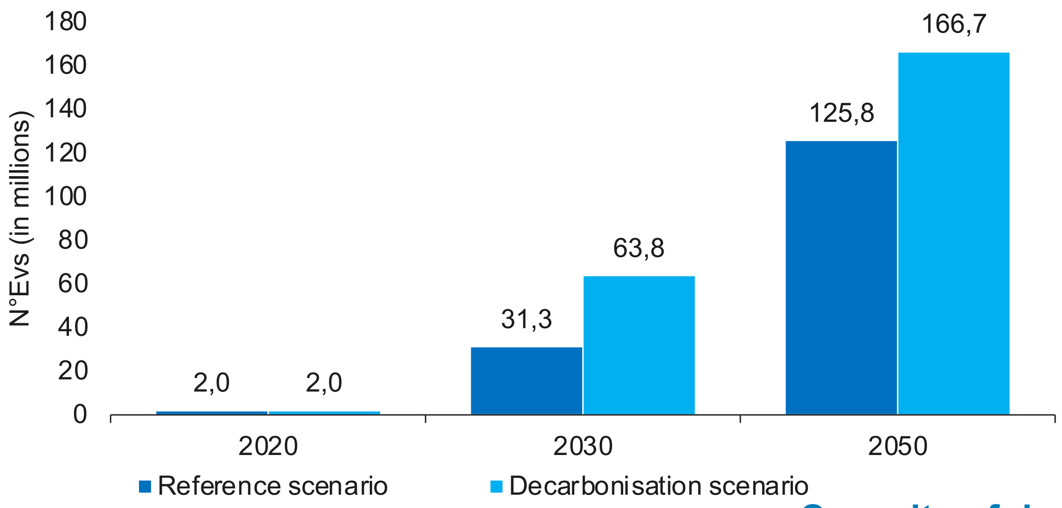
  - 50% of industrial hydrogen production can be reduced 500 hours per year at 60% of its power.
  - 50% of industrial hydrogen production can be stopped 2200 hours per year

Capacity of demand flexibility in Europe - 2050



EVs provide flexibility through dynamic charging and can also act as storage units in the Decarbonisation scenario

Electrification of transport in Europe- 2020-2050

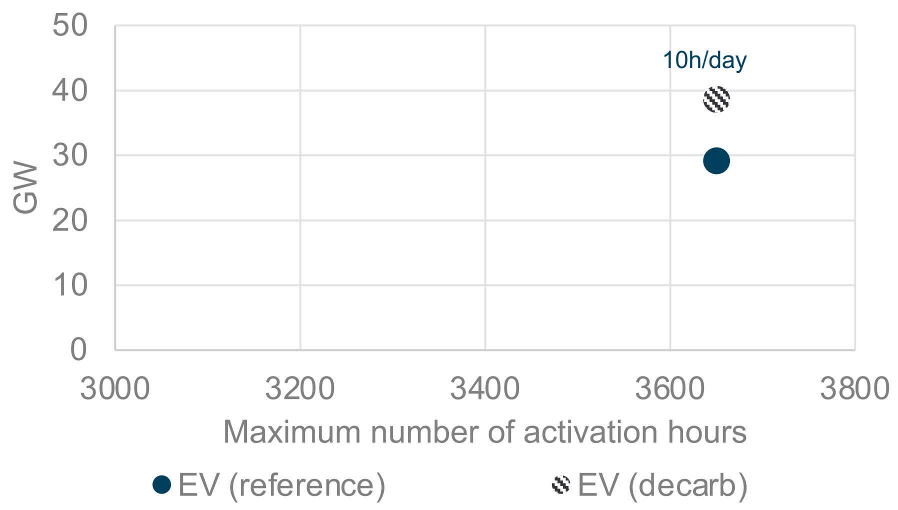


Utilisation rate	2020	2030	2050
Reference scenario	1.7	1.5	1.7
Decarbonisation scenario	1.7	1.7	2.5
Netzero study	1.6	2	2.4

Capacity of demand flexibility in Europe - 2050

- In the Reference scenario, we assume 100% of EVs rely on Time of Use charging (day/night optimisation) which is non flexible.
- In the Decarbonisation scenario, in addition to day/night optimisation, 25% of the vehicles are capable of optimising their load in response to the market price, making possible the modulation of consumption over about ten hours. We also consider a small share of V2G capacity in the Decarbonisation scenario that will act as additional batteries (which can consume/produce depending on power prices).

	2020	2030	2040	2050
V2G penetration	0%	3%	10%	16%
Cars available for V2G	70%	70%	70%	70%
Available capacity kW	1.8	2.2	2.6	3



In our Decarbonisation scenario, digitalisation supports the optimisation of maintenance and operation of power plants

Power plants efficiency and O&M – 2050 (Decarbonisation scenario only)

O&M costs savings

- Taking into account digitalisation of power plants in the **Decarbonisation scenario**, we assume a 5**% O&M costs savings** (compared to a Reference scenario with no savings).

Load factor

- Taking into account digitalisation of power plants in the **Decarbonisation scenario**, we assume that **load factors increase by a few percentage points** (< 5**%)** compared to the Reference scenario.

A uniform WACC of 5% reflecting low financing costs for clean technologies is used

- Discount rate varies by investor type and by technologies considered:
  - Less mature technologies are deemed as more risky.
  - Exposure to volatile market prices can increase cost of capital.

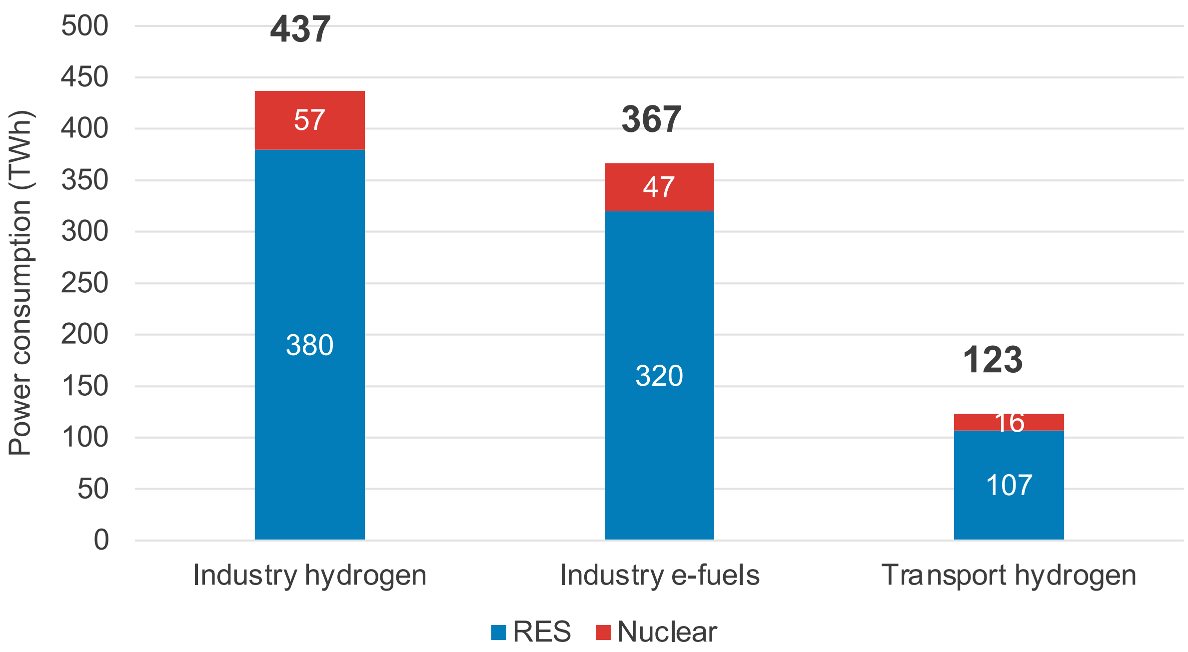
- Clean technologies (wind, solar, batteries, etc) are capital-intensive and low financing costs is essential to ensure their competitiveness:
  - Revenue contracts and/or sharing risks mechanism are systematic in Europe.
  - Those disposals tend to reduce capital costs.

- We take the assumption of a 5% WACC for different clean technologies based on:
  - The drop in debt yields that will lower the capital costs of infrastructure firms that typically have a high gearing ratio.
  - The principle of long-term contracts and transfer of risks that are necessary to secure massive investments in low carbon technologies necessary for transition. The regulation of those revenues therefore lower the cost of capital compared to merchant assets.

Hydrogen (and e-fuels) energy carriers would be used in hard-to-electrify uses in the Decarbonisation scenario

- Hydrogen as well as e-fuels are used in **hard-to-electrify applications** in the Decarbonisation scenario:
  - Industry as feedstock
  - Transport long distance
  - Long-term storage for power sector
- Indirect electrification (green hydrogen and e-fuels) represents 13% in the Decarbonisation scenario (vs 1% in the Reference scenario) in 2050:
  - Transport: 10% hydrogen
  - Industry: 16% hydrogen and 13% e-fuels (excluding non-energy uses)
- **The production of green hydrogen and e-fuels is modelled to come at 87% from RES and 13% from nuclear.**

Power consumption for hydrogen and e-fuels in 2050 (TWh), Decarbonisation scenario



Fuel switching of industrial processes increases in the Decarbonisation scenario

- Fuel switching is assumed to be 70% for industrial processes and 30% for heating.
- In the POLES model, energy balances are modelled for 4 categories of industries:
  - Steel & iron
  - Non-metallic minerals
  - Chemistry
  - Others
- As a post treatment, we break down the industrial processes for each of the 4 sectors and assume an equal share of energy consumption for those processes in a category of industries.
- We model for each of those industrial processes the amount of fuel switching per year by energy type and multiply those equivalent capacities by the EC Primes 2018 costs to estimate the costs of fuel switching by category of activities.

Industrial processes	Timing of fuel switching and amount (GW)
Steel & iron - *integrated steelworks* - *scrap processing* - *ferro-alloys*	• Electricity: from 2020 to 2030 – 7.6 GW • Bioenergies: from 2020 to 2030 – 0.4 GW
Non-metallic minerals - *cement* - *basic glass* - *ceramics* - *other non metallic minerals*	• Electricity: mainly from 2035 to 2045 – 7.4 GW • Bioenergies: mainly from 2030 to 2035 – 10.1 GW
Chemistry - *fertilizers* - *petrochemicals* - *inorganic and basic chemicals*	• Electricity: mainly from 2035 to 2045 – 18.2 GW • Bioenergies: from 2030 to 2040 – 14 GW
Other - *paper and pulp* - *food drink and tobacco* - *textiles and leather* - *engineering and equipment industry* - *other industries* - *non ferrous metals*	• Electricity: mainly from 2035 to 2045 – 96.7 GW • Bioenergies: mainly from 2030 to 2035 – 20.9 GW

A.3. Detailed KPIs and results

KPIs of the two scenarios for 2030 are comparable to EC baseline and EUCO, TYNDP scenarios and Eurelectric pathways study

Comparison for 2030

	EC 2050 Roadmap Baseline 2030	EUCO 3232.5 2030	CL Reference 2030	CL Decarbonisation 2030	Eurelectric Scenario 3 2030	ENTSOE TYNDP 2020 2030
Energy efficiency (2030)	**-32.50%**	**-32.50%**	**-32%**	**-35%**		
RES share in the power sector	**57%**	**56%**	**55%**	**60%**	**61%**	**62%**
Direct Electrification share *(excluding non-energy uses)*	**29%**	**28%**	**29%**	**31%**	**38%**	**30-32%**
Transport	*4%*		*6%*	*8%*		
Residential	*39%*		*31%*	*33%*		
Services	*64%*		*58%*	*59%*		
Industries (including non-energy uses)			*26%*	*25%*		
Industries (excluding non-energy uses)			*38%*	*37%*		

KPIs of the two scenarios for 2050 are comparable to EC baseline and 1.5 TECH scenarios and Eurelectric pathways study

Comparison for 2050

	EC 2050 Roadmap Baseline 2050	CL Reference 2050	CL Decarbonisation 2050	EC 2050 Roadmap 1.5 TECH	Eurelectric Scenario 3 2050
RES share in the power sector	**73%**	**69%**	**84%**	**83%**	**81%**
Direct Electrification share *(excluding non-energy uses)*	**40%**	**40%**	**60%**	**50%**	**60%**
Transport	*11%*	*19%*	*63%*	*26%*	**63%**
Residential	*54%*	*39%*	*60%*	*64%*	**63%**
Services	*79%*	*70%*	*89%*	*80%*	
Industries (including non-energy uses)		*30%*	*41%*		
Industries (excluding non-energy uses)		*47%*	*46%*		**50%**
Indirect Electrification share *(excluding non-energy uses)*	**1%**	**1%**	**13%**	**23%**	**5%**
Transport	*2%*	*4%*	*10%*	*42%*	*4%*
Buildings					
Industries (including non-energy uses)		*0%*	*26%*		
Industries (excluding non-energy uses)		*0%*	*29%*		*10%*

Comparison with other studies pathways costs KPIs

	EC 2030 Impact assessment 27% RES/30% EE	EC 2030 Impact assessment 33% RES/33% EE	EC 2050 Roadmap Baseline 2030	EC 2050 Roadmap Baseline 2050	CL Reference		CL Decarbonisation		EC 2050 Roadmap 1.5 TECH
					2030	2050	2030	2050	
Total energy system cost (average 2021-2030)	**€1948 bn**	**€1972 bn**	***€1994 bn***		**€2412 bn**		**€2408 bn**		
Total energy system cost (average 2021-2050)	**€2248 bn**	**€2266 bn**		***€2121 bn***	**€2492 bn**		**€2540 bn**		
Total energy system cost (average 2031-2050)	***€2398 bn***	***€2413 bn***		***€2184 bn***	***€2531 bn***		***€2606 bn***		***€2432 bn***
Annual average investment expenditure	**€377 bn**	**€488 bn**	**€396 bn** **(€1081 bn incl transport)**	**€377 bn** **(€1190 bn incl transport)**	**€383 bn** **(€1015 bn incl transport)**	**€265 bn** **(€1022 bn incl transport)**	**€392 bn** **(€1003 bn incl transport)**	**€498 bn** **(€1295 bn incl transport)**	**€576 bn** **(€1480 bn incl transport)**
Power grid	€36 bn	€47 bn	€59 bn	€71 bn					€103 bn
Power plants	€38 bn	€54 bn	€54 bn	€40 bn	€99 bn	€76 bn	€89 bn	€117 bn	€120 bn
Industry	€18 bn	€23 bn	€18 bn	€11 bn	€15 bn	€10 bn	€16 bn	€33 bn	€28 bn
Residential	€214 bn	€259 bn	€199 bn	€199 bn	€269 bn	€178 bn	€287 bn	€349 bn	€226 bn
Tertiary	€68 bn	€102 bn	€64 bn	€54 bn					€76 bn
Transport			€685 bn	€813 bn	€632 bn	€757 bn	€611 bn	€797 bn	€904 bn

Note : 1) EC 1.5 scenarios assume higher EV cost than our Decarbonisation scenario thus leading to a lower electrification by 2050

DETAILED RESULTS – ENERGY CONSUMPTION BY SECTOR

Consumption by sector (Mtoe), Reference scenario, EU-28 (non-energy uses excluded)

	2015	2020	2025	2030	2035	2040	2045	2050
Final energy consumption (Mtoe)	**1035**	**1068**	**1010**	**921**	**859**	**826**	**807**	**788**
Residential, of which	**277**	**283**	**274**	**250**	**232**	**222**	**214**	**207**
Conventional oil products	34	32	27	22	19	17	16	15
Gas	100	107	101	84	72	65	59	53
Coal	9	8	5	3	1	0	0	0
Electricity	68	71	74	77	79	80	80	81
Bioenergies	42	41	40	36	32	30	28	26
Heat	23	24	26	28	29	30	30	31
Services, of which	**148**	**153**	**149**	**139**	**132**	**130**	**128**	**126**
Conventional oil products	16	15	12	9	8	7	6	6
Gas	46	48	43	33	26	23	20	18
Coal	1	1	1	0	0	0	0	0
Electricity	71	74	78	81	84	86	88	88
Bioenergies	5	4	4	4	3	3	2	2
Heat	10	11	10	11	11	11	12	12
Transport, of which	**312**	**326**	**301**	**278**	**258**	**248**	**244**	**239**
Transport, by energy								
Conventional oil products	291	295	262	230	197	176	159	132
Bioenergies	14	24	29	32	34	37	42	50
Electricity	6	7	10	16	26	34	39	46
Hydrogen	0	0	0	0	0	1	4	10
Transport, by mode								
Road	294	307	283	260	240	230	227	222
Rail	7	7	8	8	8	8	8	8
Air (domestic)	6	7	6	5	5	6	6	6
Other (maritime domestic)	5	4	4	4	4	4	3	3
Industry	**273**	**279**	**258**	**227**	**209**	**199**	**193**	**189**
Industry, by energy								
Conventional oil products	26	26	21	16	12	9	6	5
Gas	78	83	76	60	52	49	46	44
Coal	43	41	33	24	19	16	14	13
Electricity (including direct and indirect uses)	86	89	89	86	85	86	87	88
Bioenergies	24	25	26	28	28	29	29	31
Heat	15	15	14	13	12	11	10	8
Industry, by sector								
Steel	49	47	35	25	18	14	11	9
Non-metallic minerals	34	34	32	28	26	24	24	23
Chemistry	51	52	50	45	43	42	41	41
Other industry	139	145	140	129	122	119	117	117
Agriculture	**25**	**27**	**27**	**28**	**27**	**28**	**28**	**28**
Fossil energies	18	20	19	16	14	14	13	14
Electricity	5	5	6	8	9	9	9	9
Bioenergies	2	2	2	4	5	5	5	5

Consumption by sector (Mtoe), Decarbonisation scenario, EU-28 (non-energy uses excluded)

	2015	2020	2025	2030	2035	2040	2045	2050
Final energy consumption (Mtoe)	**1035**	**1071**	**1000**	**894**	**809**	**730**	**669**	**613**
Residential, of which	277	283	271	246	221	196	169	147
Conventional oil products	34	32	27	20	13	7	3	1
Gas	100	107	100	80	53	29	14	7
Coal	9	8	3	1	1	0	0	0
Electricity	68	71	76	80	91	97	93	88
Bioenergies	42	41	39	35	35	35	31	23
Heat	23	24	26	29	29	29	28	28
Services, of which	**148**	**153**	**148**	**138**	**129**	**121**	**112**	**103**
Conventional oil products	16	14	12	8	5	2	1	1
Gas	46	48	42	31	17	8	3	1
Coal	1	1	0	0	0	0	0	0
Electricity	71	74	79	82	90	95	94	92
Bioenergies	5	4	5	5	5	5	3	0
Heat	10	10	10	11	11	11	11	10
Transport, of which	**312**	**327**	**294**	**256**	**214**	**166**	**128**	**107**
Transport, by energy								
Conventional oil products	291	296	254	204	140	81	39	18
Bioenergies	14	24	29	30	37	28	17	11
Electricity	6	7	11	21	37	54	66	68
Hydrogen	0	0	0	0	0	2	6	11
Transport, by mode								
Road	294	308	277	240	200	155	119	99
Rail	7	7	8	8	7	6	6	5
Air (domestic)	6	7	5	5	5	4	3	2
Other (maritime domestic)	5	4	4	3	2	0	0	0
Industry	**273**	**281**	**259**	**228**	**219**	**223**	**237**	**234**
Industry, by energy								
Conventional oil products	26	27	21	16	9	4	2	1
Gas	78	84	79	63	37	17	7	3
Coal	43	41	30	21	12	6	2	1
Electricity (including direct and indirect uses)	86	89	88	85	98	128	163	177
Bioenergies	24	25	28	30	50	56	51	43
Heat	15	15	14	14	13	12	11	10
Industry, by sector								
Steel	49	48	35	25	18	13	10	8
Non-metallic minerals	34	35	32	28	25	22	20	17
Chemistry	51	53	50	45	43	42	42	40
Other industry	139	146	142	130	133	146	166	169
Agriculture	**25**	**27**	**27**	**26**	**25**	**24**	**23**	**22**
Fossil energies	18	19	16	13	10	8	5	4
Electricity	5	6	7	8	9	10	10	11
Bioenergies	2	2	4	5	6	6	7	8

DETAILED RESULTS – POWER CAPACITY AND GENERATION

Power generation (TWh) and capacity (GW), Reference scenario, EU-28

	2020	2025	2030	2035	2040	2045	2050
Electricity production (TWh)	**3095**	**3247**	**3444**	**3637**	**3869**	**4044**	**4208**
Coal and lignite	583	570	451	303	198	80	38
Gas	305	261	136	167	206	273	332
Conventional oil products and other non-RES	241	222	215	201	196	185	179
Bioenergies and waste	129	120	182	167	162	153	148
Nuclear	816	756	728	800	766	760	713
Hydroelectricity	372	385	399	405	402	404	402
Geothermal energy	8	10	10	10	11	13	14
Wind	480	658	904	1103	1295	1451	1581
Solar	160	260	411	469	553	605	648
Batteries	1	4	8	12	80	112	143
Power-to-gas-to-power	0	0	0	0	0	8	8
DSR	0	0	0	0	0	0	0
Electric capacity (GW)	**1056**	**1178**	**1407**	**1495**	**1637**	**1743**	**1861**
Coal and lignite	142	115	105	79	62	53	51
Gas	171	178	178	162	137	130	148
Conventional oil products and other non-RES	75	67	64	60	57	55	53
Bioenergies and waste	27	27	41	41	41	40	40
Nuclear	117	109	106	119	116	117	111
Hydroelectricity	155	156	166	166	166	166	166
Geothermal energy	1	1	2	2	2	2	2
Wind	208	279	374	459	530	586	631
Solar	137	220	344	376	438	476	509
Batteries	1	3	5	9	67	94	124
Power-to-gas-to-power	0	0	0	0	0	3	3
DSR	21	21	21	21	21	21	21

Power generation (TWh) and capacity (GW), Decarbonisation scenario, EU-28

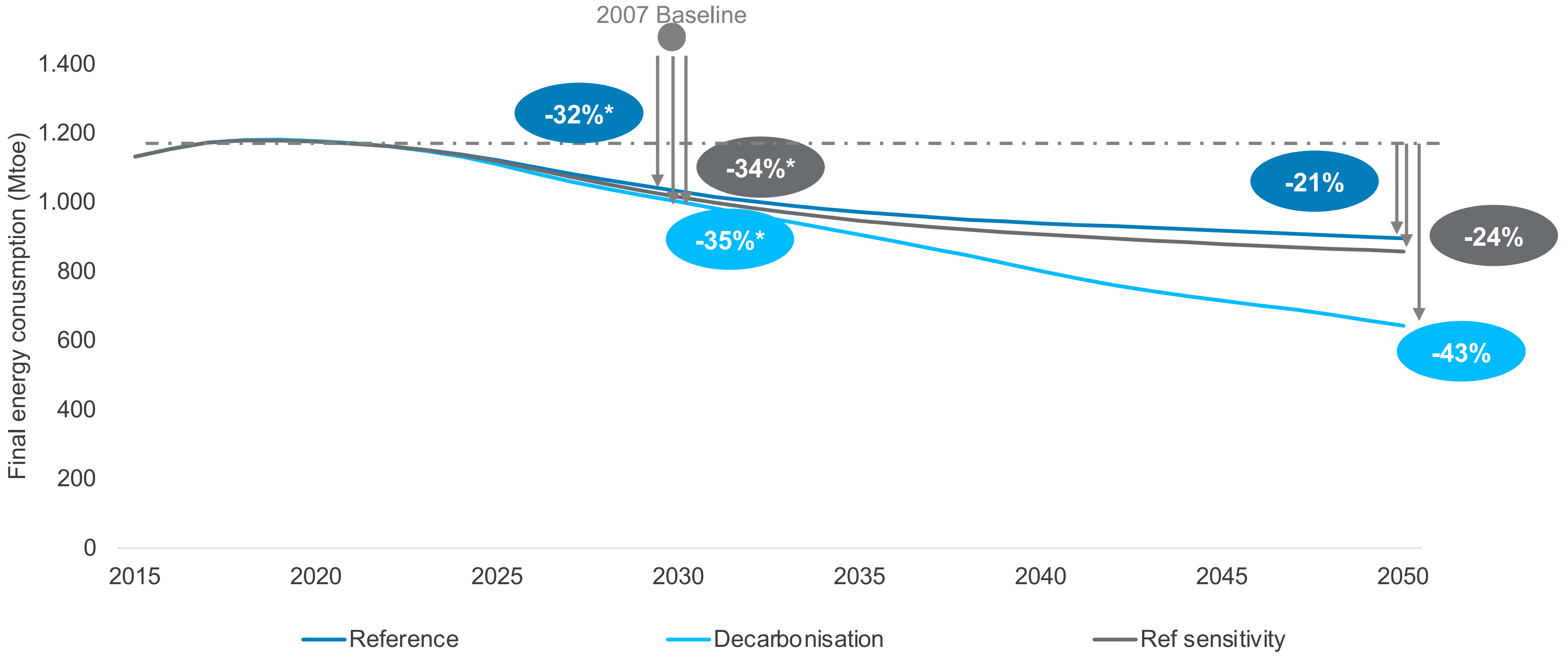
	2020	2025	2030	2035	2040	2045	2050
Electricity production (TWh)	**3153**	**3340**	**3553**	**4238**	**4934**	**5741**	**6087**
Coal and lignite	576	514	283	36	5	4	1
Gas	367	364	182	212	176	39	8
Conventional oil products and other non-RES	242	226	210	196	193	200	185
Bioenergies and waste	130	122	176	160	155	160	150
Nuclear	818	760	720	786	759	769	715
Hydroelectricity	372	383	399	405	404	405	404
Geothermal energy	8	10	10	11	15	17	14
Wind	480	684	1058	1606	2044	2542	2874
Solar	160	273	479	705	942	1199	1307
Batteries	1	5	38	79	166	252	247
Power-to-gas-to-power	0	0	0	41	75	154	182
DSR	0	0	0	0	0.4	1.4	0
Electric capacity (GW)	**1040**	**1177**	**1465**	**1863**	**2248**	**2654**	**2894**
Coal and lignite	126	89	56	30	17	16	11
Gas	171	203	190	157	112	19	8
Conventional oil products and other non-RES	75	67	64	60	57	55	53
Bioenergies and waste	27	27	41	41	41	40	40
Nuclear	117	109	106	119	116	117	111
Hydroelectricity	155	156	166	166	166	166	166
Geothermal energy	1	1	2	2	2	2	2
Wind	208	279	409	607	775	951	1087
Solar	137	220	369	534	698	878	961
Batteries	1	4	33	77	167	257	271
Power-to-gas-to-power	0	0	0	34	55	103	126
DSR	21	21	28	35	42	50	57

A.4. Sensitivity analysis of the Reference scenario results

Energy efficiency gains achieved in the Reference sensitivity are comparable to the Reference scenario

- In the Reference sensitivity, final energy demand is reduced by 24% in 2050 compared to 2015 (vs a 21% reduction in the Reference scenario).
  - 34% energy efficiency rate (compared to PRIMES 2007) in 2030, vs 32% in the Reference scenario achieved mostly thanks to the higher uptake of EVs which reduces the final energy demand of the transport sector
  - Additional efficiency gains in 2050 are driven by efficiency gains in the transport sector only

Final energy demand (Mtoe), Reference, Decarbonisation and Ref sensitivity scenarios



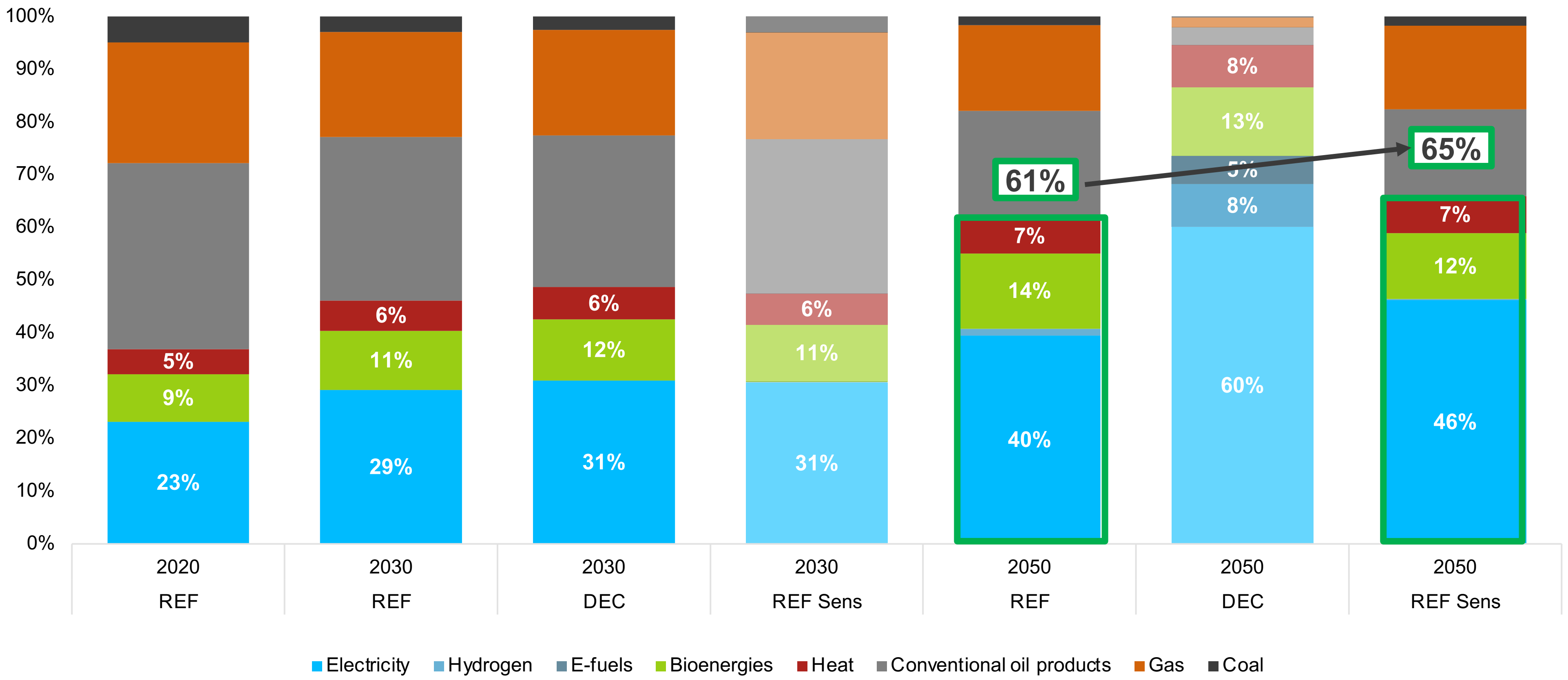
Source: Enerdata and CL

**Final energy demand in POLES represented on the figure includes non-energy uses. For the comparison with the 2007 EC Baseline, we add international flights and remove non-energy uses to calculate the energy efficiency targets in 2030 on the same perimeter as the European Commission's.*

The energy mix in the Reference sensitivity is similar to the Reference scenario with a small increase in electrification due to the uptake of EVs

- The electricity share in final energy demand increases by 6 pp in the Reference sensitivity compared to the Reference scenario in 2050 due to the higher electrification rate of the transport sector in the sensitivity scenario.
- The overall energy mix in the Reference sensitivity is similar to the Reference scenario with over 35% of energy still coming from fossil fuel energies in 2050.

Share of energy carriers, Reference, Decarbonisation and Ref sensitivity scenarios



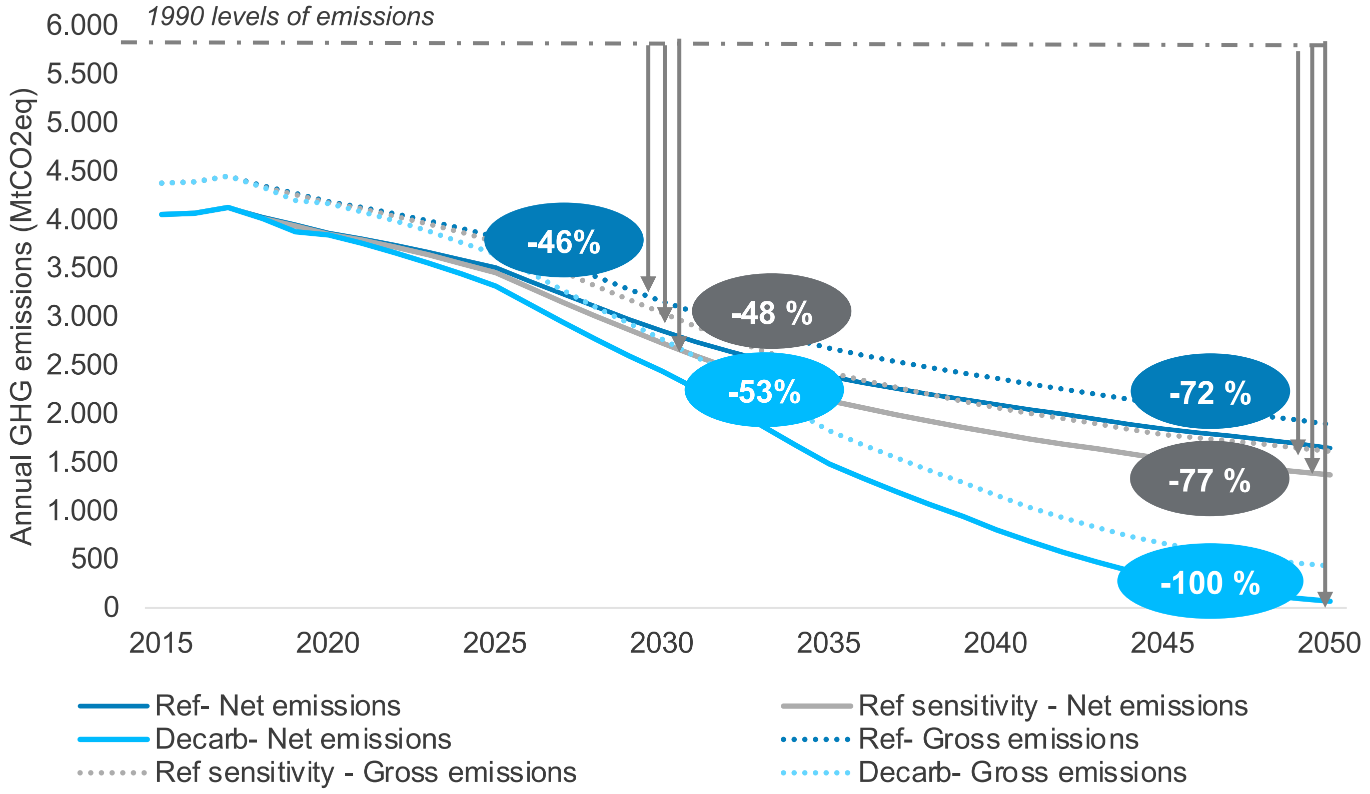
Notes : 1) e-fuels are synthetic fuels produced from decarbonised electricity, including e-gas and e-liquids
2) Heat refers to district heating and solar heat from thermal solar panels
3) CCS/CCU are also introduced from 2040 onwards but their development remains limited and will support the net off of emissions in the industry in 2050
4) Excludes non-energy uses

Source: Enerdata and CL

Emissions reduction in 2050 are slighter higher in the Reference sensitivity thanks to the transport and power sectors contributions

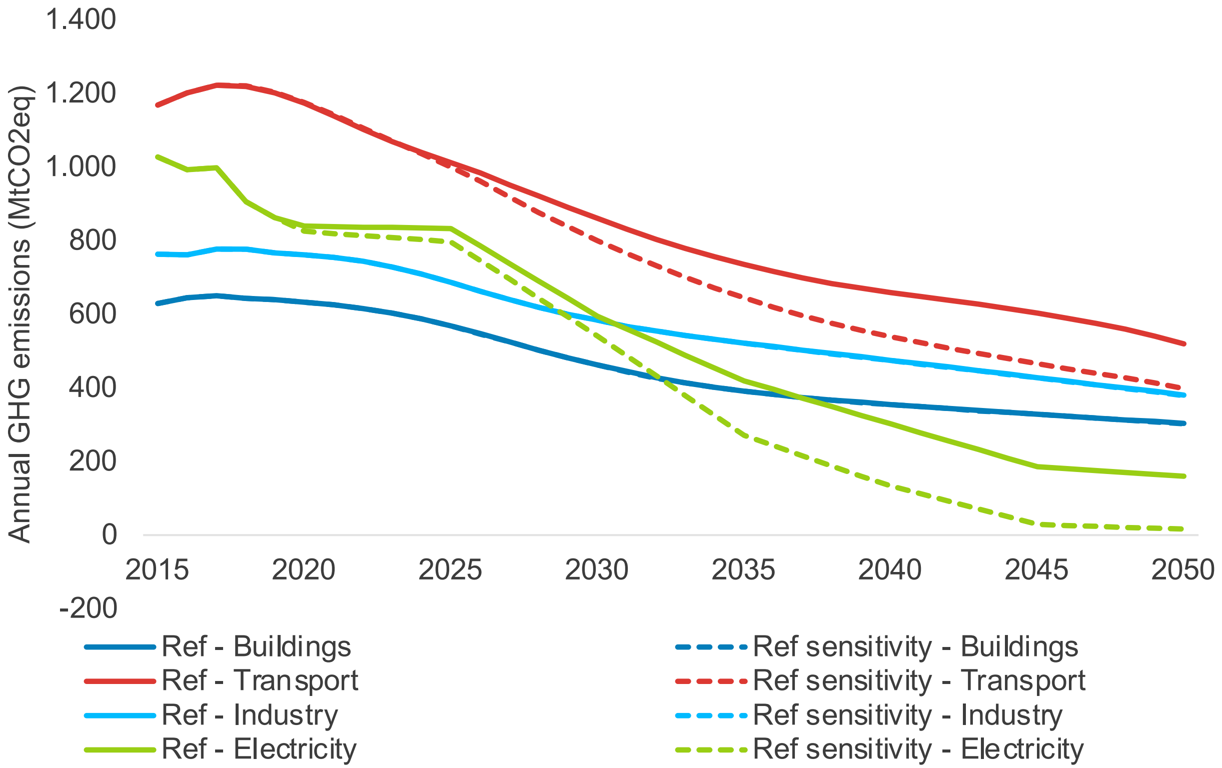
- Additional gains in emissions reduction achieved in the Reference sensitivity scenario come from:
  - The transport sector where the decrease in batteries cost brings a deployment of EVs comparable to the Decarbonisation scenario.
  - The power sector where the decrease in RES costs leads to a higher RES penetration in 2030 and therefore emissions savings.
- The industry and buildings sector do not see any changes in emissions reduction without regulatory enablers.

Net and gross GHG emissions (MtCO2eq)



Source: Enerdata and CL

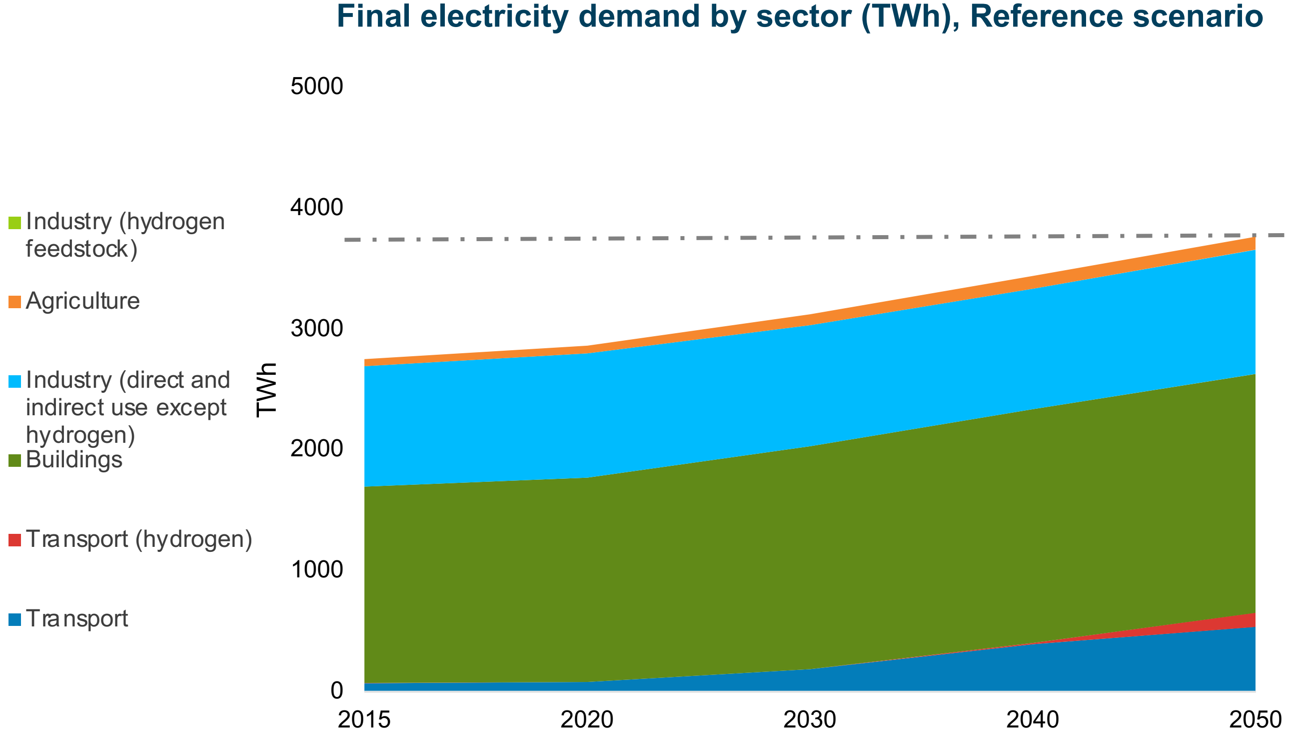
Gross GHG emissions (MtCO2eq) per sector, Reference vs. Reference sensitivity scenarios

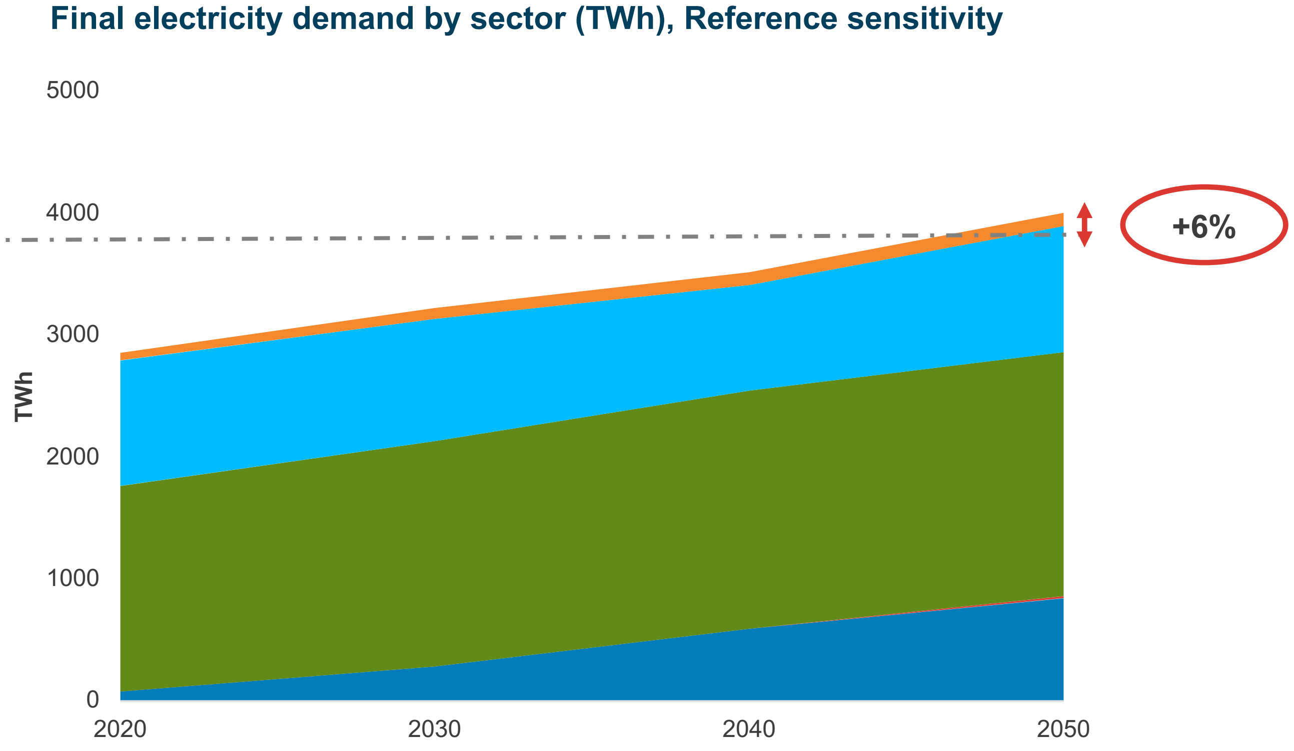


Notes: 1) Difference between gross and net emissions is the Land Use, Land and-use change and forestry (LULUCF) activities
2) 1990 levels of emissions exclude LULUCF (to avoid complexity of accounting) and include international aviation. With LULUCF, emissions reduction in the Decarbonisation scenario would be 54% (and 48% in the Reference scenario).

Electricity demand increases by 6% in the Reference sensitivity pushed by an increase in transport demand (including hydrogen) of 31%

- **Electricity demand increases by 6% in the Reference sensitivity in 2050** compared to the Reference scenario.
- The increase in electricity demand in the Reference sensitivity is mainly caused by:
  - **An increase in transport demand by 31% when including hydrogen, and by 57% when excluding it**. In the Reference sensitivity, the decrease in batteries cost leads to a higher uptake of EVs than in the Reference scenario, and as a result a much smaller deployment of hydrogen vehicles in 2050.
  - The demand from other sectors remain stable between the two scenarios in 2050.



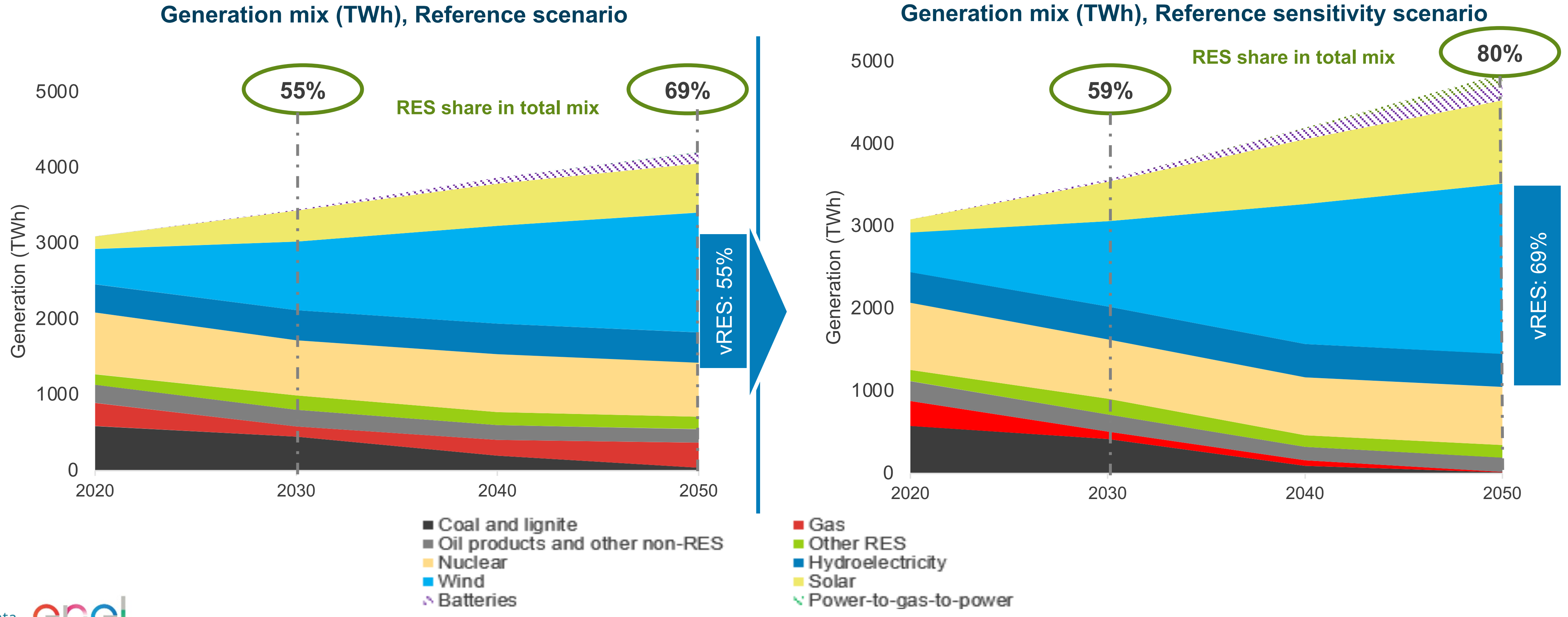


Source: Enerdata and CL

With the reduction in RES costs, 80% share of renewables is achieved in 2050 in the Reference sensitivity

RES penetration:
- In the Reference scenario, RES reach 69% of total 2050 generation, with 55% penetration of variable RES.
- In the Reference sensitivity scenario, RES reach 80% of total 2050 generation, with 69% penetration of variable RES.

Storage :
- In the Reference scenario, RES would produce 280 TWh of non consumed energy, 225 of which being stored and redistributed through P2G or batteries.
- In the Reference sensitivity scenario, RES would produce 600 TWh of non consumed energy, 520 of which being stored and redistributed through P2G or batteries.



Source: FTI-CL Energy modelling

Renewable capacity in the Reference sensitivity would increase by 1220 GW reaching a total of 1710 GW in 2050

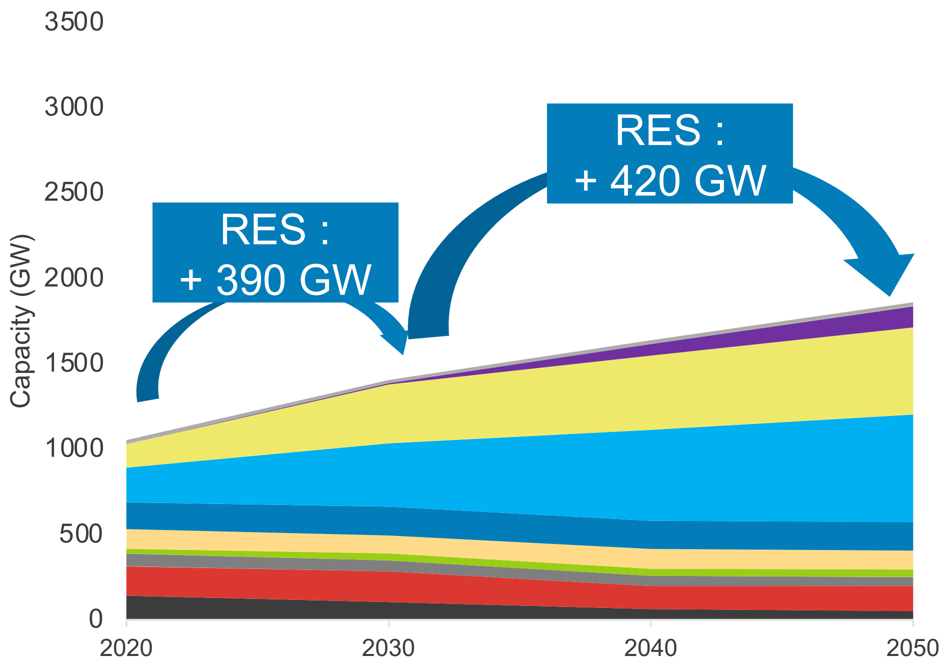
Installed capacity outlook in the Reference scenario

- 810 GW of new RES are installed between 2020 and 2050, reaching a total of 1300 GW including 510 GW of solar and 630 GW of wind.
- Additionally, 190 GW of new flexible capacity is installed, of which 123 GW of batteries and 3 GW of Power to Gas.

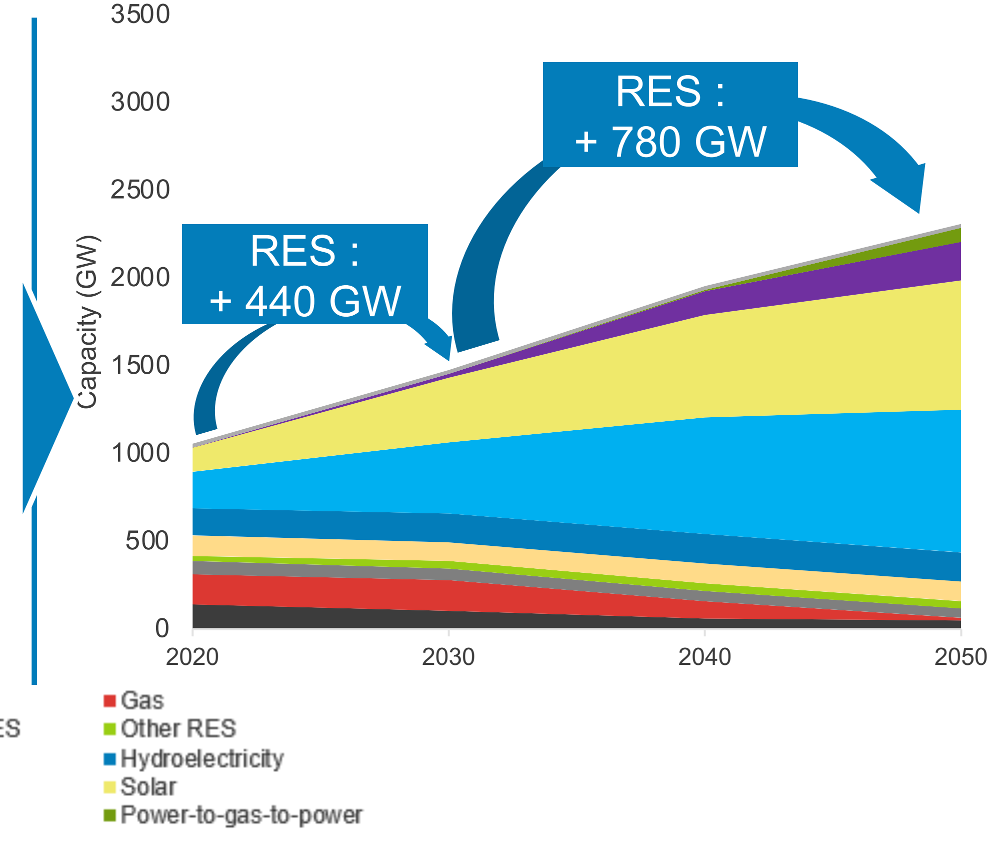
Installed capacity outlook in the Reference sensitivity scenario

- 1220 GW of new RES are installed between 2020 and 2050, reaching a total of 1710 GW including 736 GW of solar and 810 GW of wind.
- Additionally, 310 GW of new flexible capacity is installed, of which 220 GW of batteries and 80 GW of Power to gas.

Capacity mix (GW), Reference scenario



Capacity mix (GW), Reference sensitivity scenario

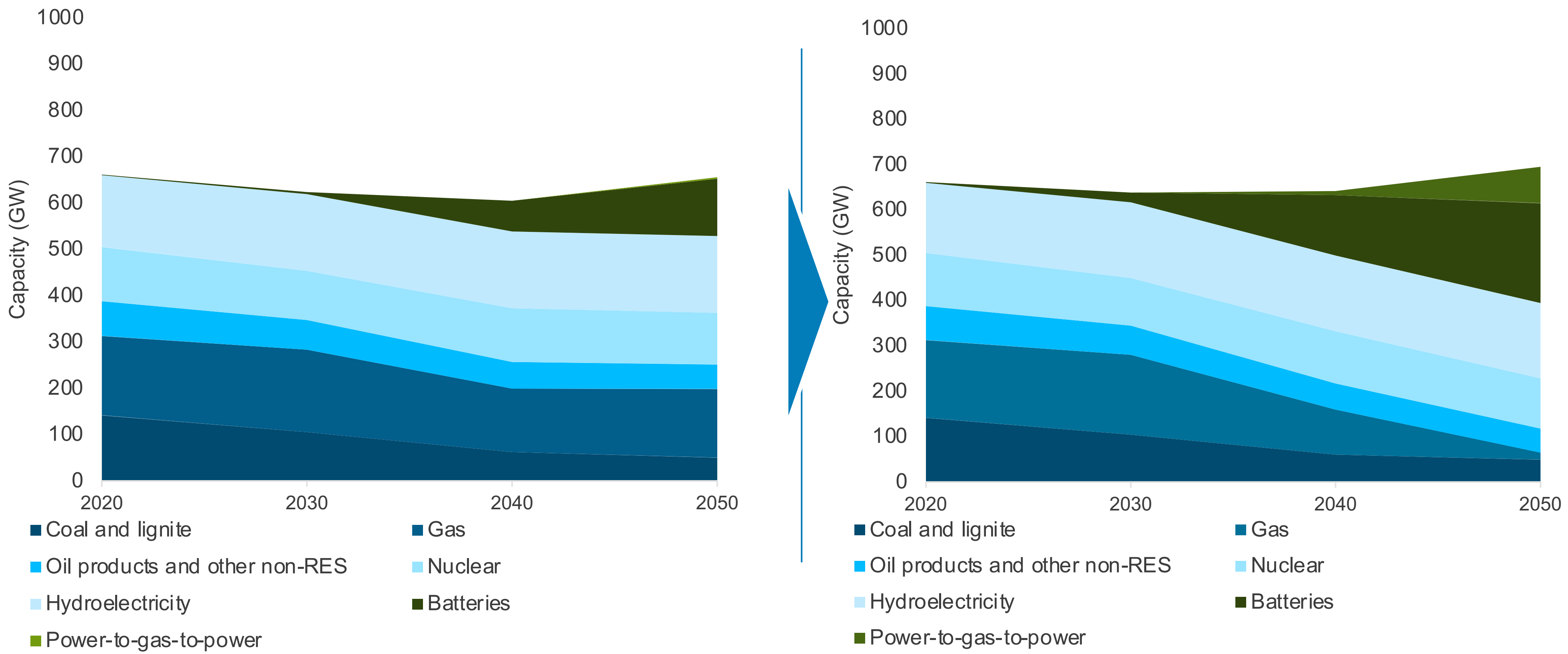


Source: FTI-CL Energy modelling

100% more flexible capacity (batteries, P2G) are built in the Reference sensitivity compared to the Reference scenario

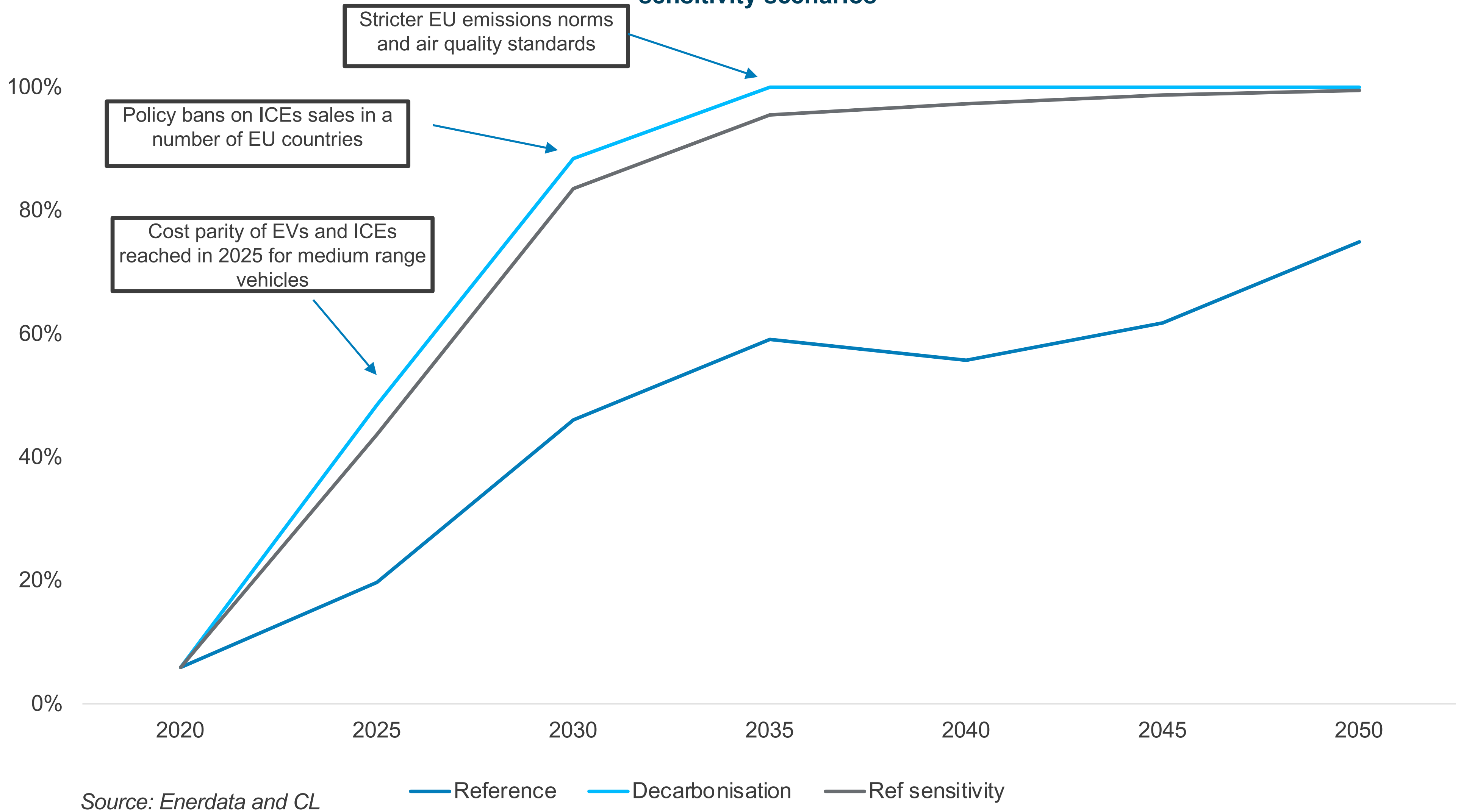
- **Given the higher RES development and the lower thermal capacity, the sensitivity scenario requires higher investment in flexible capacity:**
  - 220 GW in batteries and 80 GW in Power-to-gas-to-Power
  - In contrast, the reference scenario mainly relies on existing and new thermal units to provide flexibility (including 144 GW of new OCGT and CCGT) and limited development of new storage facilities

Resource capacity in both scenarios (GW)



LEVs share in new sales reaches 84% by 2030 in the Reference sensitivity thanks to cost parity with ICEs

Private Low Emission Vehicles (LEVs) penetration rate in new sales, Reference, Decarbonisation, and Reference sensitivity scenarios



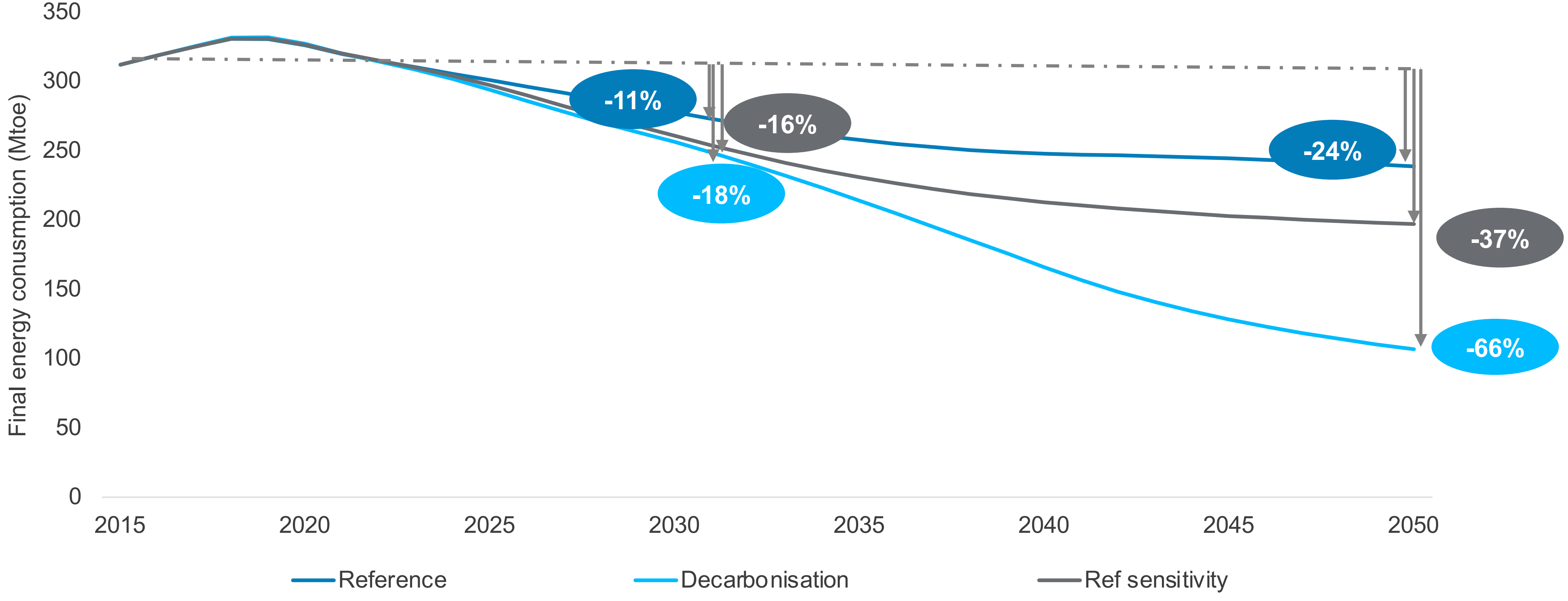
Source: Enerdata and CL

LEVs (Low Emission Vehicles) include hybrid, electric and hydrogen vehicles

Thanks to the higher uptake of EVs in the Reference sensitivity, energy demand in transport drops by 37% in 2050

- The faster deployment of clean and more efficient vehicles (EVs) in the Reference sensitivity thanks to the cost parity achieved in 2025, allows for a similar final energy demand reduction in 2030 as in the Decarbonisation scenario (16% vs 18%).
- By 2050 the deployment of EVs contributes to an additional 13 pp of demand reduction in the Reference sensitivity compared to the Reference scenario. However without new business models and further regulatory support, the transport sector does not achieve the same efficiency gains in the Reference sensitivity as in the Decarbonisation scenario.

Final energy demand (Mtoe), Reference, Decarbonisation and Reference sensitivity scenarios

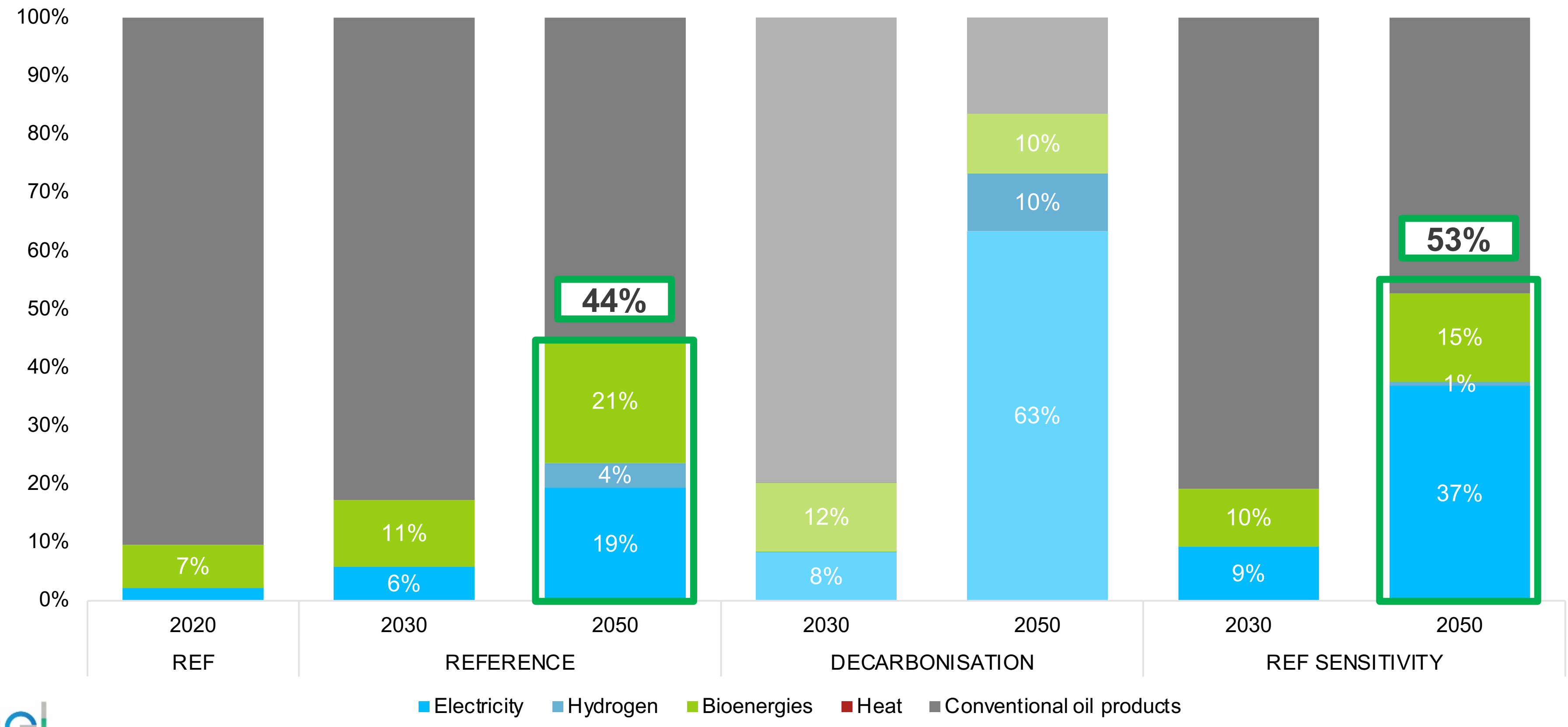


Source: Enerdata and CL

A higher electrification of road transport contributes to the additional emissions reduction in the Reference sensitivity

- In the Reference sensitivity, the decrease in batteries cost contributes to a faster deployment of Evs following the same trend as in the Decarbonisation scenario and thereby contributing to the increase in electrification in 2030 and 2050.
- In 2050, the share of Evs in new private vehicles is 73% in the Reference sensitivity compared to only 49% in the Reference scenario. This explains the 18pp increase in electrification between the two scenarios. The high uptake of Evs in the Reference sensitivity replaces the deployment of hydrogen vehicles in the light trucks and private vehicles segments thereby explaining the higher share of hydrogen in the Reference scenario compared to the sensitivity one (4% vs 1%).

Share of energy carriers, Reference, Decarbonisation, and Ref sensitivity scenarios

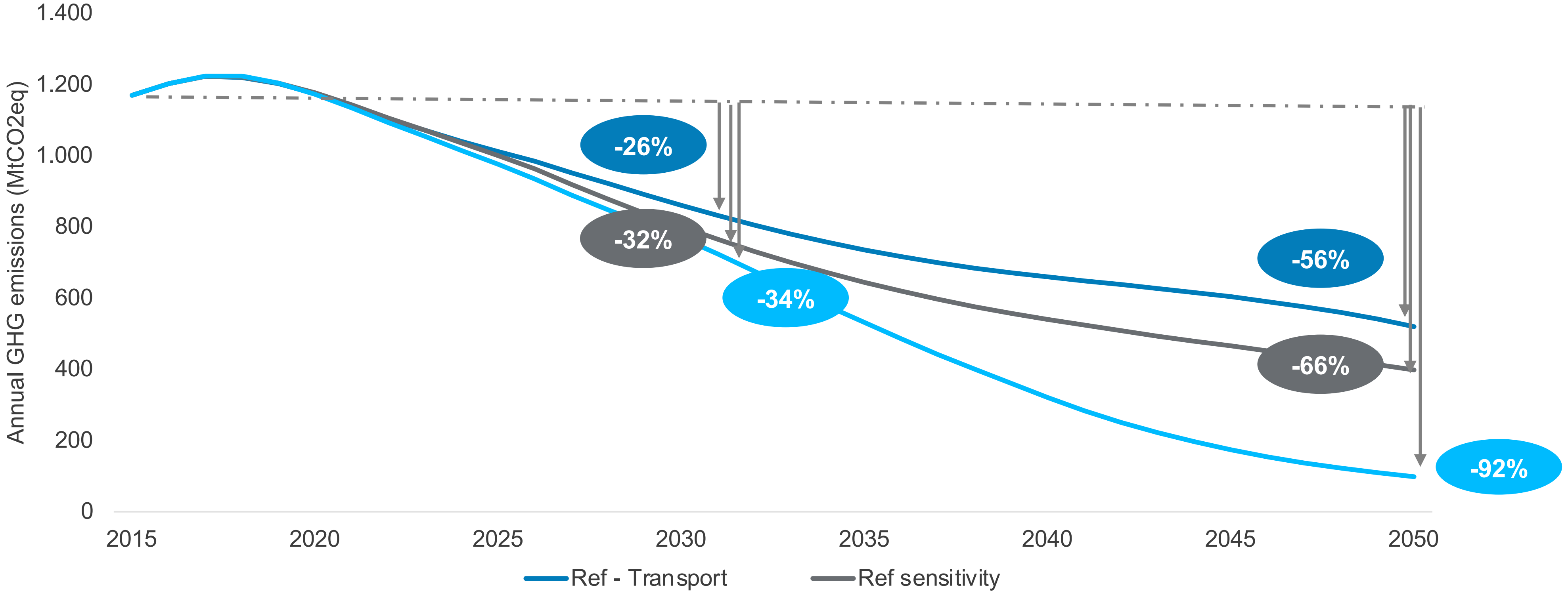


Source: Enerdata and CL

Further decarbonisation of the transport sector can be achieved in the Reference sensitivity

- Thanks to the fast deployment of Evs in the Reference sensitivity (share of new private vehicles more than double the one in the Reference scenario), emissions reduction increase in 2030 to reach 32% (vs 26% in the Reference scenario).
- In 2050, the higher uptake of Evs in the Reference sensitivity contributes to a 10 pp increase in the emissions reduction compared to the Reference scenario.

Gross GHG emissions (MtCO2eq), Reference, Decarbonisation, and Ref sensitivity scenarios

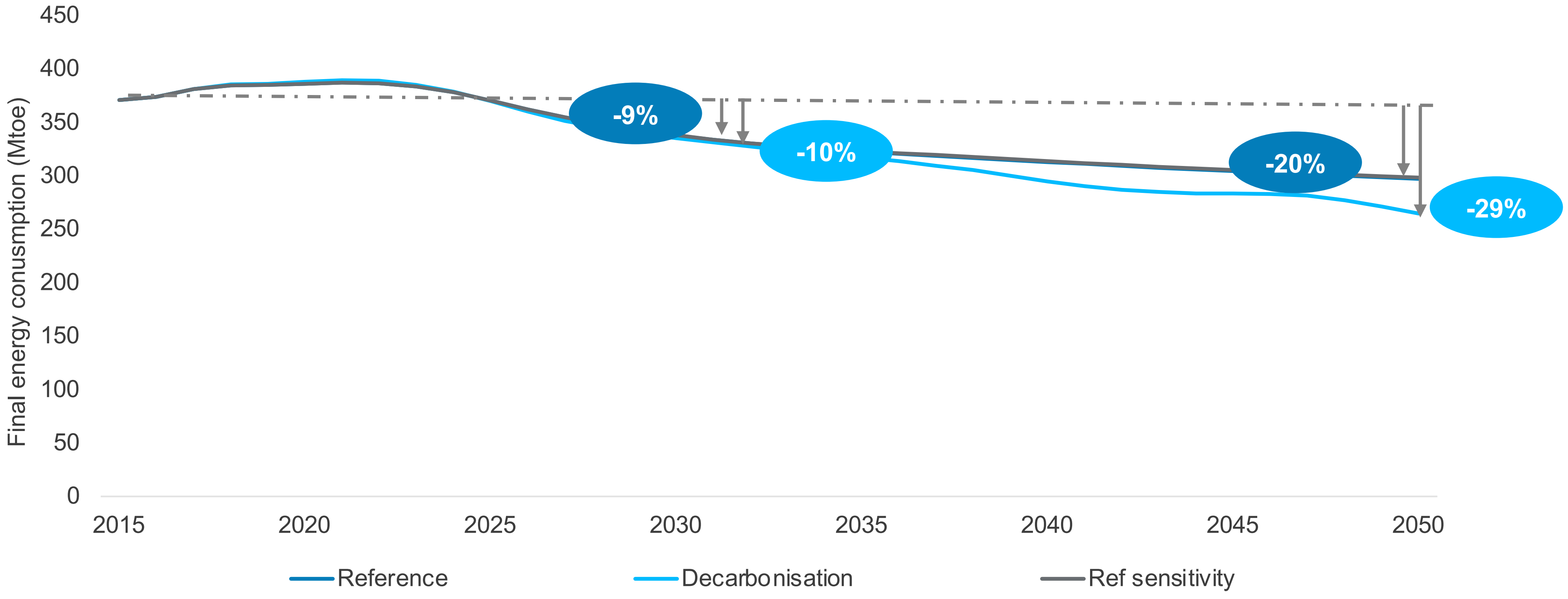


Source: Enerdata and CL

Industrial demand remains the same in the Reference sensitivity

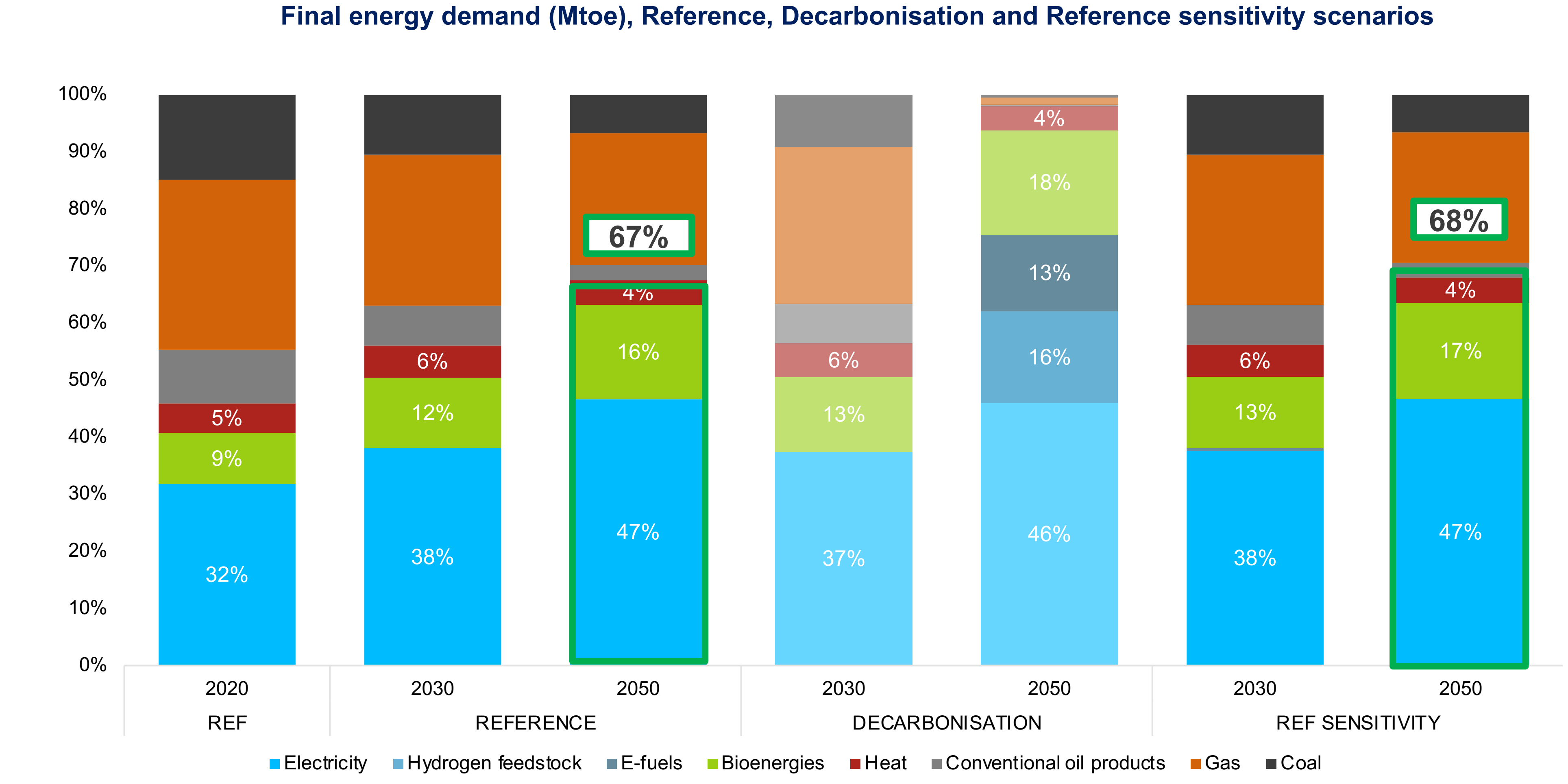
- The industrial sector potential for efficiency gains varies greatly by type of industrial process, with significant gains possible especially in energy intensive sectors such as steel & iron.
- The most significant efficiency gains in the Decarbonisation scenario take place after 2030 as substitute technologies become more mature and competitive

Final energy consumption in industry, Reference, Decarbonisation and Ref sensitivity scenarios



Source: Enerdata and CL

Fuel mix in the Reference sensitivity still include a significant share of fossil fuels (more than 30%)



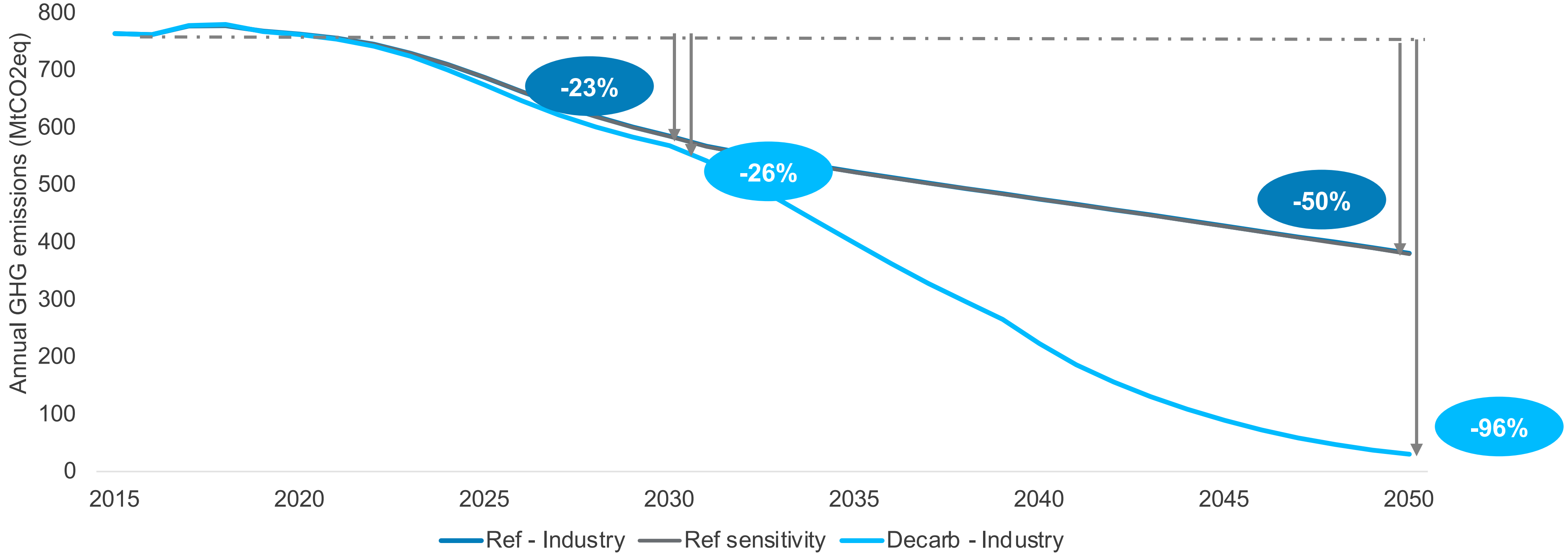
Source: Enerdata and CL

NB : 1) e-fuels are synthetic fuels produced from decarbonised electricity, including e-gas and e-liquids
2) Heat refers to district heating and solar heat from thermal solar panels
3) All ratios are calculated to total industry demand excluding non-energy uses

No additional emissions reduction is achieved in the Reference sensitivity

- Currently industry emits about 15% total GHG emissions in the EU (heavily reliant on fossil fuels)
- Industry has decreased its GHG emissions by -44% from 1990 to 2016
- In 2030, the difference between the Reference and Decarbonisation scenario is small but in 2050, emissions reduction (compared to 2015) in the Decarbonisation scenario are doubled thanks to the electrification (direct and indirect use) of the industry.
- There is no additional emissions reduction in the industry sector in the Reference sensitivity scenario compared to the Reference scenario as by construction this sensitivity does not change any assumptions for the industry sector.

Gross GHG emissions in industry, Reference, Decarbonisation, and Reference sensitivity scenarios

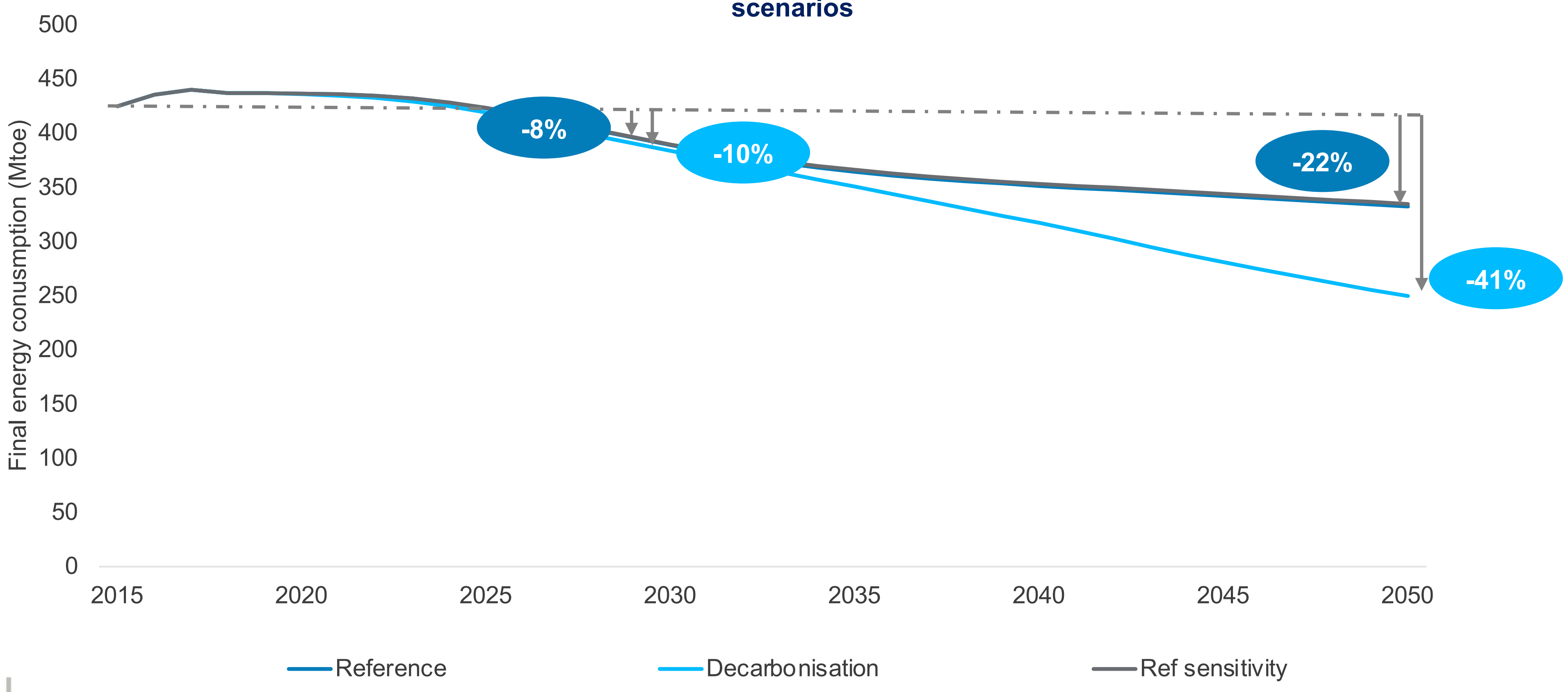


Source: Enerdata and CL

Without supporting regulatory policies, no further efficiency gains are achieved in the Reference sensitivity

- The reduction in final energy demand in the Reference scenario in 2030 is relatively small compared to 2015, and is expected to reach only 22% by 2050.
- In the Decarbonisation scenario, the reduction in final energy demand doubles in 2050 compared to the Reference scenario, to reach a 41% cut compared to 2015 levels.
- No additional efficiency gains are achieved in the Reference sensitivity scenario compared to the Reference scenario as by construction this sensitivity scenario does not change any assumptions for the buildings sector.

Final energy demand (Mtoe), Reference, Decarbonisation and Reference sensitivity scenarios

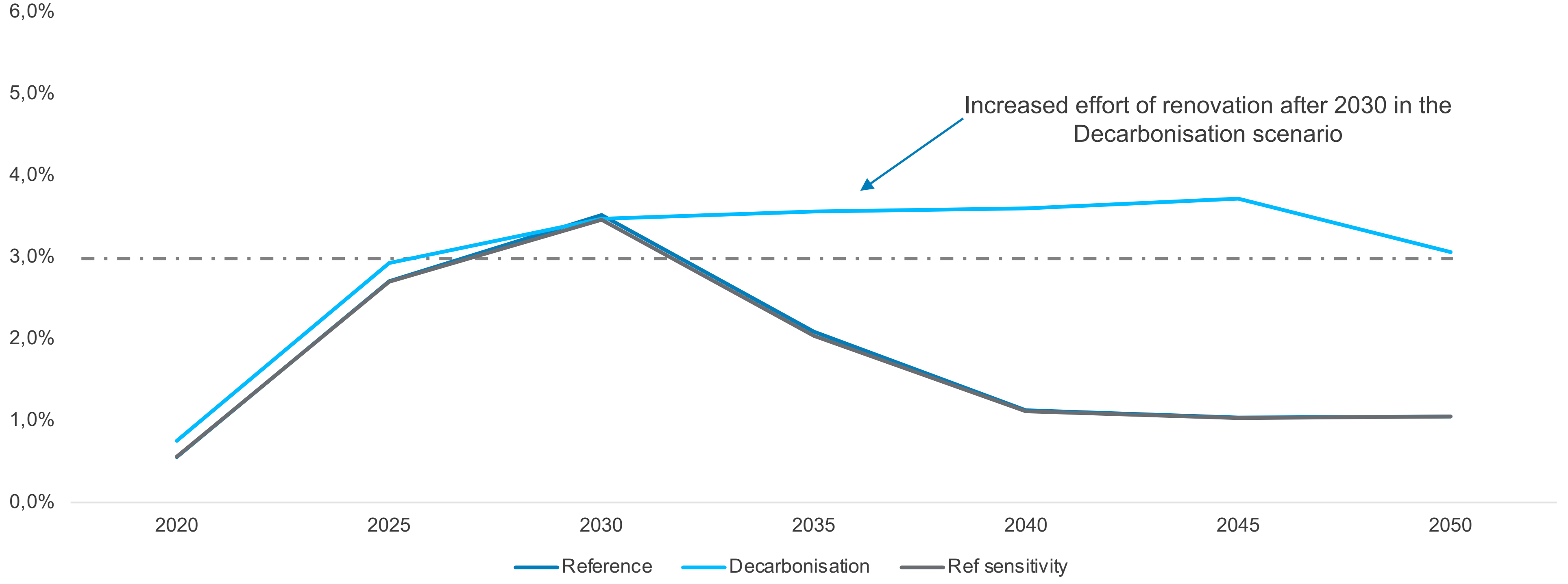


Source: Enerdata and CL

Renovation effort in the Reference sensitivity remains the same without further regulatory support

- In the Decarbonisation scenario, the pace of renovation rate increases (at least 3% until 2045) driven by EU and national policies:
  - EU regulation of 3% target for public buildings renovation
  - Green Deal announced by the European Commission : "Today the annual renovation rate of the building stock varies from 0.4 to 1.2% in the Member States. This rate will need at least to double to reach the EU's energy efficiency and climate objectives."
  - Other institutes such as the Renovate-Europe of Buildings Performance Institute Europe support the vision for a 3% renovation rate to achieve the minimum Paris climate targets
- We don't assume further renovation effort in the Reference sensitivity scenario compared ot the Reference scenario as by construction we do not change any assumptions in the buildings sector in this sensitivity scenario.

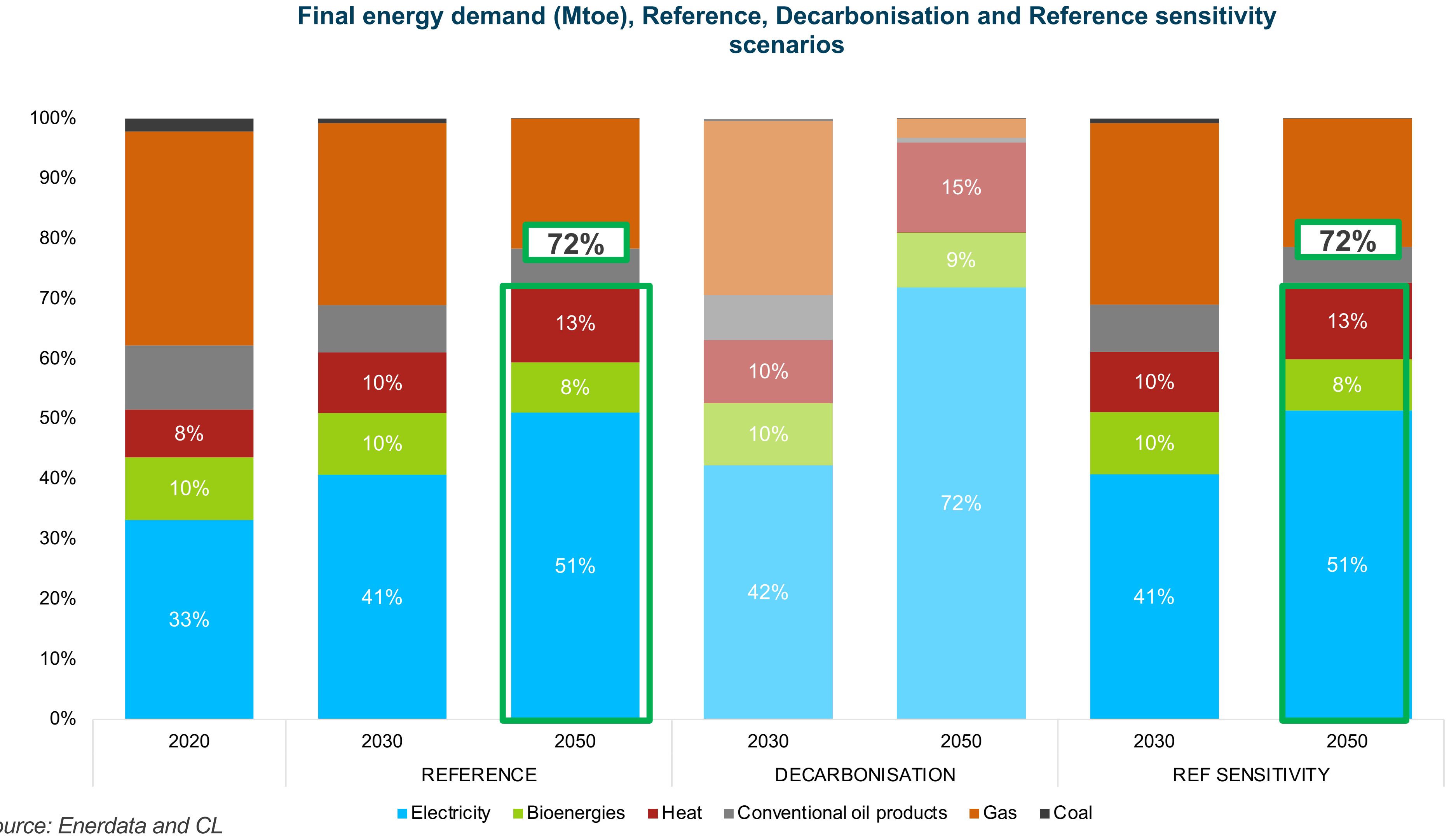
Renovation rate, Reference, Decarbonisation and Ref sensitivity scenarios



Source: Enerdata and CL

Renovation rate is the average renovation rate of the dwelling stock and includes both insulation as well as efficiency gains of heating solutions

The same level of deployment of Heat Pumps in the Reference sensitivity drives the same level of electrification

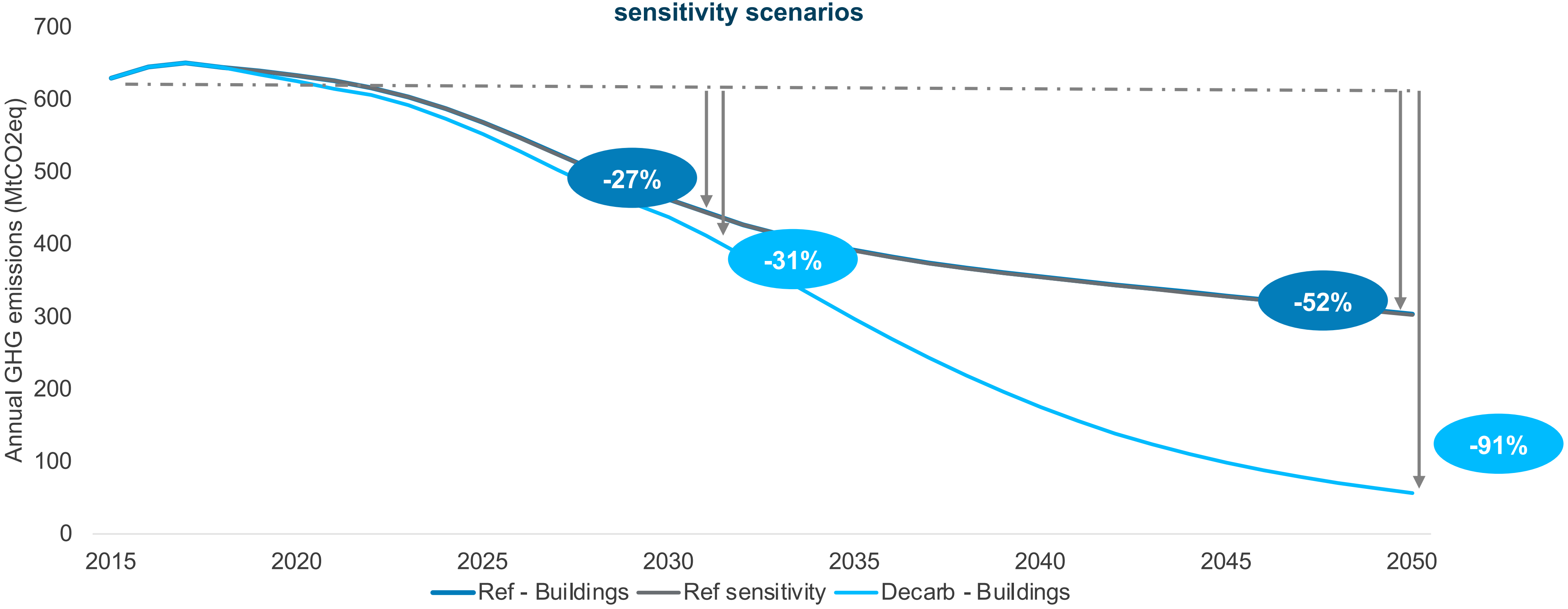


Source: Enerdata and CL

Emissions reduction in the Reference sensitivity remains at the same level without further electrification and energy efficiency

- The reduction in GHG emission in the Decarbonisation scenario steps up after 2030 to reach 91% by 2050, driven both by energy efficiency improvements and decarbonisation of energy supply.
- Without changes to the assumptions in the buildings sector in the Reference sensitivity scenario, no further emissions reduction is achieved compared to the Reference scenario.

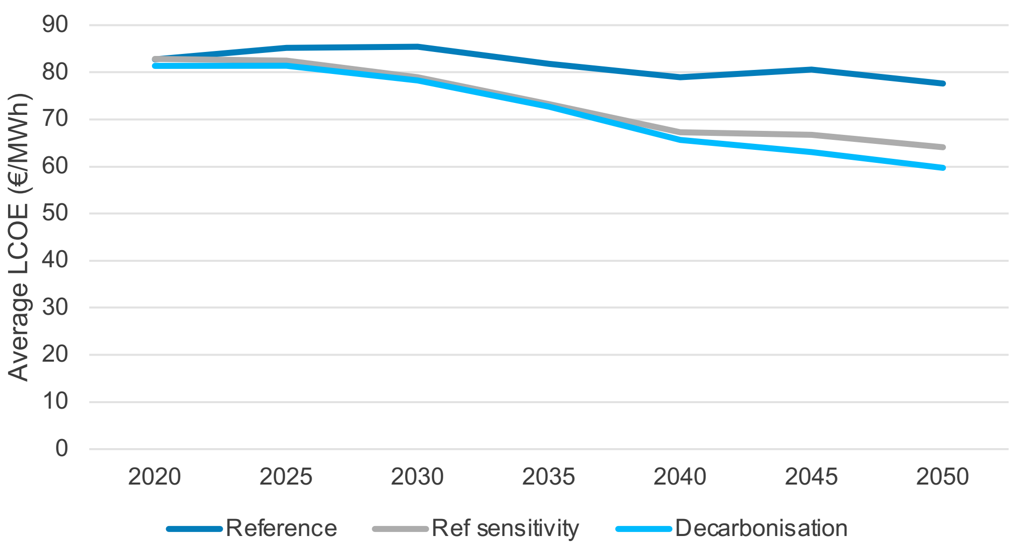
Gross GHG emissions (MtCO2eq), Reference vs. Decarbonisation and Reference sensitivity scenarios



Source: Enerdata and CL

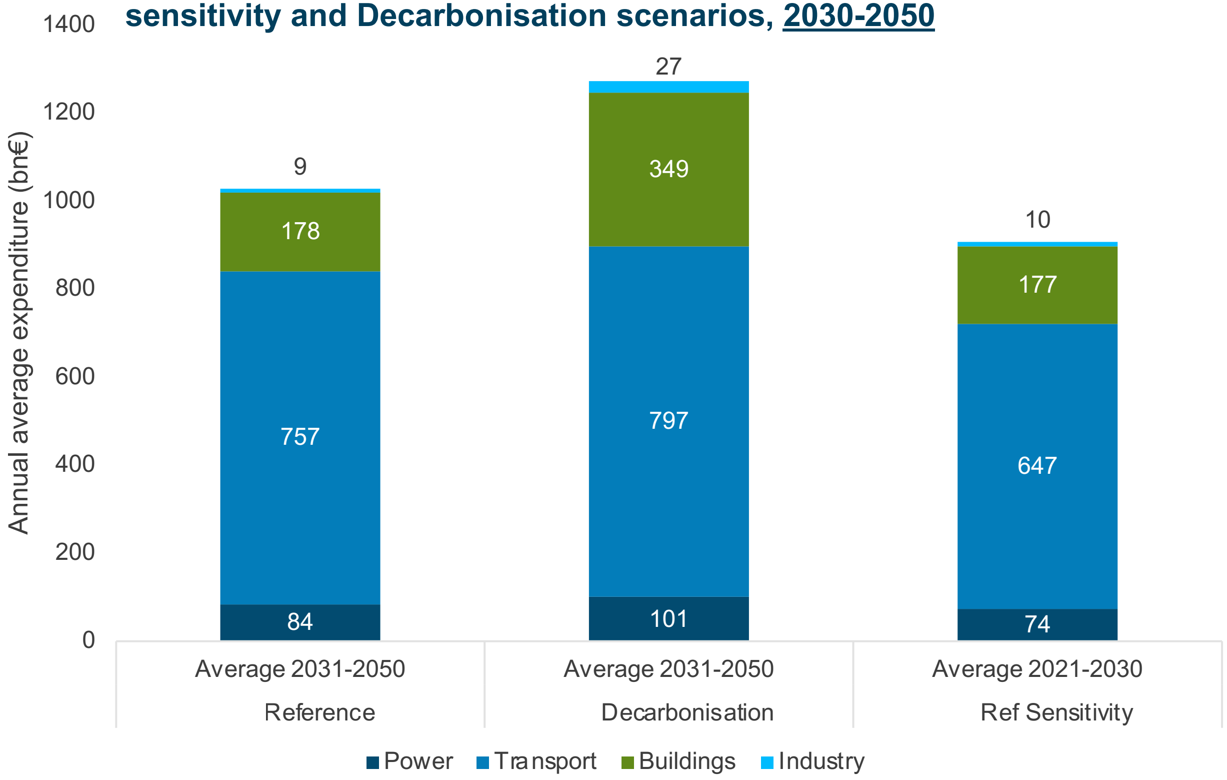
System costs in 2050 in the Reference sensitivity are the lowest thanks to decreased power sector costs feeding into sector's fuel costs, and decreased transport costs

Average LCOE in the power sector (€/MWh), Reference vs Reference sensitivity and Decarbonisation scenarios, 2020-2050



- Thanks to the decrease in RES technology costs (wind and solar) and flexibility technology costs, **the average LCOE in the Reference sensitivity is 17% lower** than in the Reference scenario in 2050. Increased capacity factor in the Decarbonisation scenario explains the further decrease in LCOE.

Average annual investments (bn€) in Reference, Reference sensitivity and Decarbonisation scenarios, 2030-2050

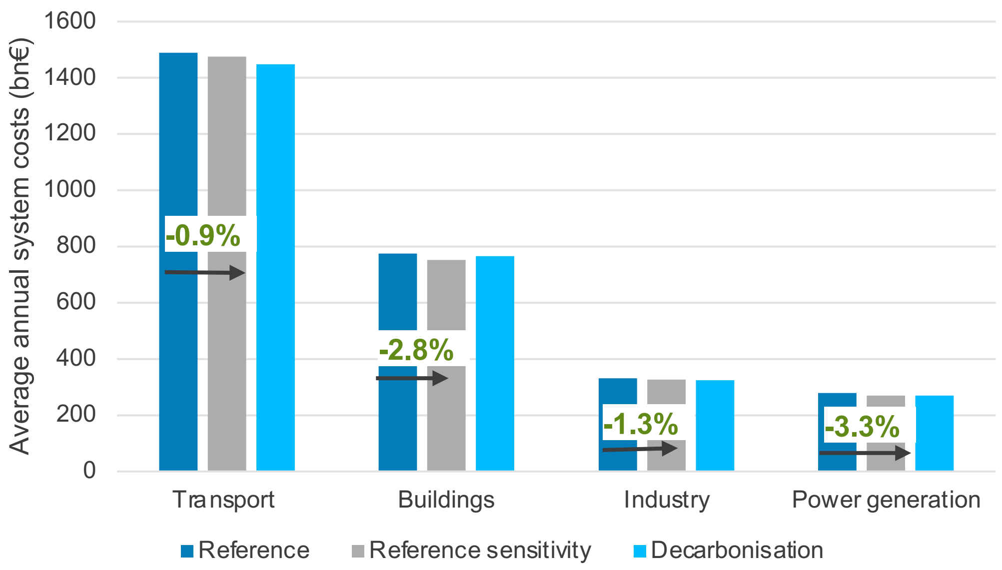


- **Average annual investments over the period 2030 and 2050 decrease by 12% in the Decarbonisation scenario** compared to the Reference scenario as investments in the transport and power sector decrease thanks to the reduction in RES and battery costs. Investments in the buildings and industry sectors are similar given the climate ambitions remain the same as well as the costs.

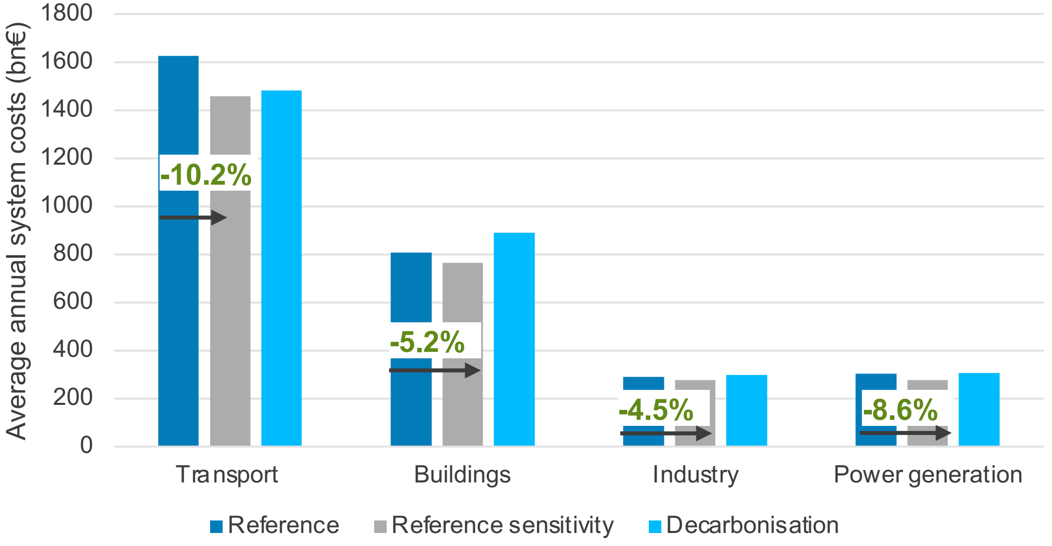
Transport and power system costs are lower in the Reference sensitivity thanks to reduced technology costs while buildings and industry benefit from reduced electricity costs

- By construction, system costs for all sectors are lower in the Reference sensitivity scenario than in the Reference scenario over the period 2021-2050.
- Between 2031 and 2050, the decrease is the highest in the transport and power sectors (respectively 10.2% and 8.6%) as the Reference sensitivity assumes lower RES and batteries costs than in the Reference scenario. Buildings and industry system costs also see a decrease thanks the reduced electricity costs that will feed into the fuel costs of those sectors.

Annual total system costs and power generation costs, Reference vs. Reference Sensitivity and Decarbonisation scenarios, 2021-2030



Annual total system costs and power generation costs, Reference vs. Decarbonisation scenarios, 2031-2050



- Annual total energy system cost include industry, buildings and transport costs
- Industry, buildings, and transport system costs include energy capex, opex and fuel costs (including network costs)
- Power generation costs include generation capex, opex and fuel costs

A.5. Digitalisation of generation

Digitalisation will significantly improve controllability and predictive maintenance of power plants

- **A digital power plant is a generation plant which relies on digital applications to connect plants and their operation through data analysis and automation processes:**
  - IIot (Industrial Internet of Things): interconnected sensors, capturing and communicating data, to enable real-time analytics of industrial processes
  - Digital infrastructure to collect and provide the required computing power to process the data

Digitalisation of operation activities

- **Digitalised natural resource availability data** (basin data, wind data) improves weather prediction and power generation management as well as production efficiency
- **Control systems and remote monitoring** to command the behaviour of devices enhance supervision and control over generation assets
- Digitalised remote power plant management allow the operation and optimisation of plants during extreme weather conditions
- Simulation to optimize asset performance

Digitalisation of maintenance activities

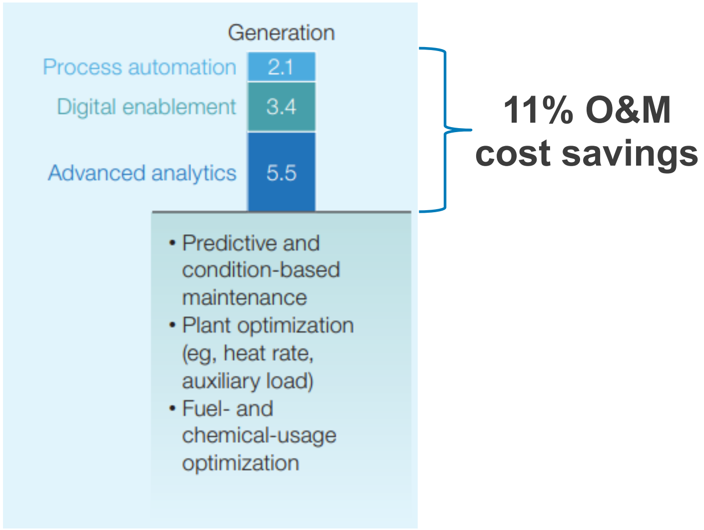
- **Prevention of emergency events** (frequency and magnitude):
  - Satellite and digitalised basin data allow early detection of land slide risks
- **Prevention of costly failures** using advanced analytics for **predictive maintenance**
  - Monitoring of geologic stability of civil work foundations (Ground Penetrating Radar)
- Supervision systems to avoid sending workers on the field

Through improved performance and system costs savings, digitalisation can contribute to further decarbonisation

The benefits of digitalisation of power plants are wide ranging and include:

- **Enables further decentralisation** via distributed energy resources
- **Improves productivity** thanks to enhanced forecasting which enables adaptative behaviours of physical assets. IRENA (2019) references an example of a GE wind turbine's output in Japan enhanced by 5% thanks to AI.
- **Decreases O&M costs (by about 11% according to McKinsey 2018) through e.g.**
  - Predictive maintenance allows the minimization of plant maintenance shutdowns leading to operating costs savings in some cases up to 50%.
  - Automation of processes, remote control of assets
  - Data analytics make possible to identify non-optimal performance and engage into corrective operations resulting in maintenance and lost production savings. .
- **Decreases energy system cost** through enhanced forecasting enables to better estimate energy output, but also transmission capacity (which depend on meteorological conditions)
- **Extend assets lifetime,** as tailormade operations and maintenance plans result in longer lifetime of physical assets

Operations and maintenance cost saving for power generation (%)



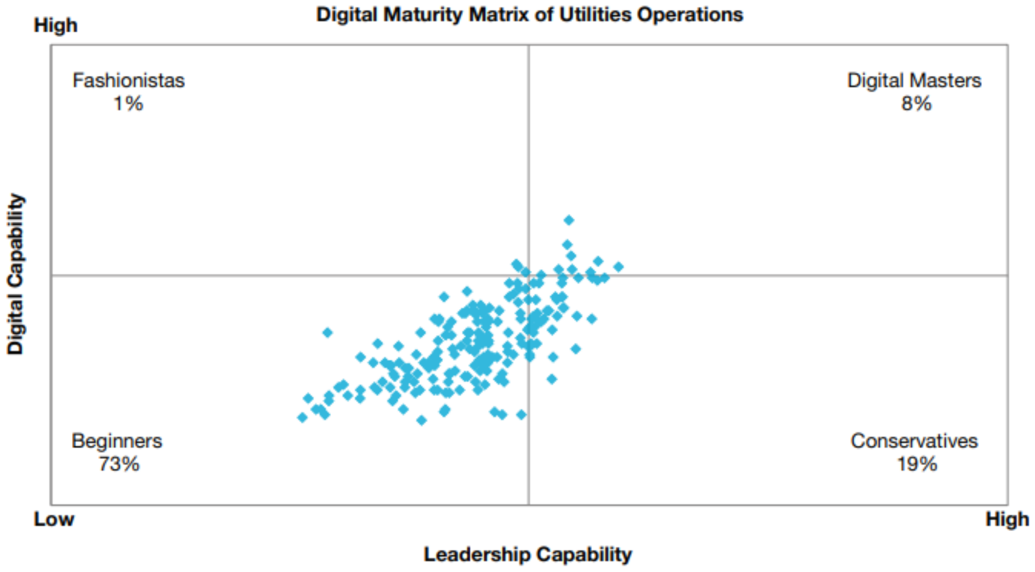
Source : McKinsey analysis

In the **Decarbonisation scenario**, digitalisation is assumed to have a impact on **efficiency of power plants, O&M costs, as well as to bring costs savings to the network and the system.**

A need for business initiatives : though many utilities adopt digitalisation, they often do not realize the full potential of it

- **A digital plant strategy is embraced by more and more utilities and Europe is leading the way**
  - Many utilities are investing in their analytics capabilities, as well as in sensing and smart grids, as well as their operations, automation and business systems.
  - This movement is led by Europe with France, Italy and Germany having more than 50% utilities with operational digital plants
- **But digitalisation has to be combined with a long-term strategy consideration to reap its full benefits**
  - Only a minority of the utilities have digitally mature production-related operations
  - For instance, in the wind sector there is much scope for greater digitalisation:
    - Most digital solutions for wind turbines are marketed as add-ons, not as part of the basic offering.
    - Wind energy buyers tend to see digitalisation as a 'nice-to-have' and not as a 'must-have'

Utilities are lagging behind in terms of digital maturity



Source: Capgemini Digital Transformation Institute, digital utility survey, February-March 2017; Framework from Leading Digital, George Westerman, Didier Bonnet, Andrew McAfee, Harvard Business Review Press, 14 Oct. 2014.

Note 1: The results come from a worldwide survey conducted by Capgemini
Note 2: The study considers both fossil-fuel generation plants and renewable assets

Technological innovations will unlock further potential for digitalisation

Examples of potential technology innovations for utilities:

- IIot will provide more and more precise and useful data
  - Ex: Micro Electro Mechanical System (MEMS) are sensors installed on wind turbines to pick up and listen to the sounds emitted in order to identify any blade anomalies.
- Remote monitoring will help to maximize harnessing of renewable energy source
  - Ex: Solar trackers are devices orienting the solar panels towards the sun to follow the sun's path to maximize energy capture.
- Digital supervision systems will facilitate and accelerate plants inspection
  - Ex: Drones combined with AI is a way to automate plants surveillance
- Advanced analytics will improve maintenance scheduling
  - Ex: Digital twins are virtual versions of a physical asset, they enable detection of non-optimal performance without physical access to the asset and alert on maintenance needs.

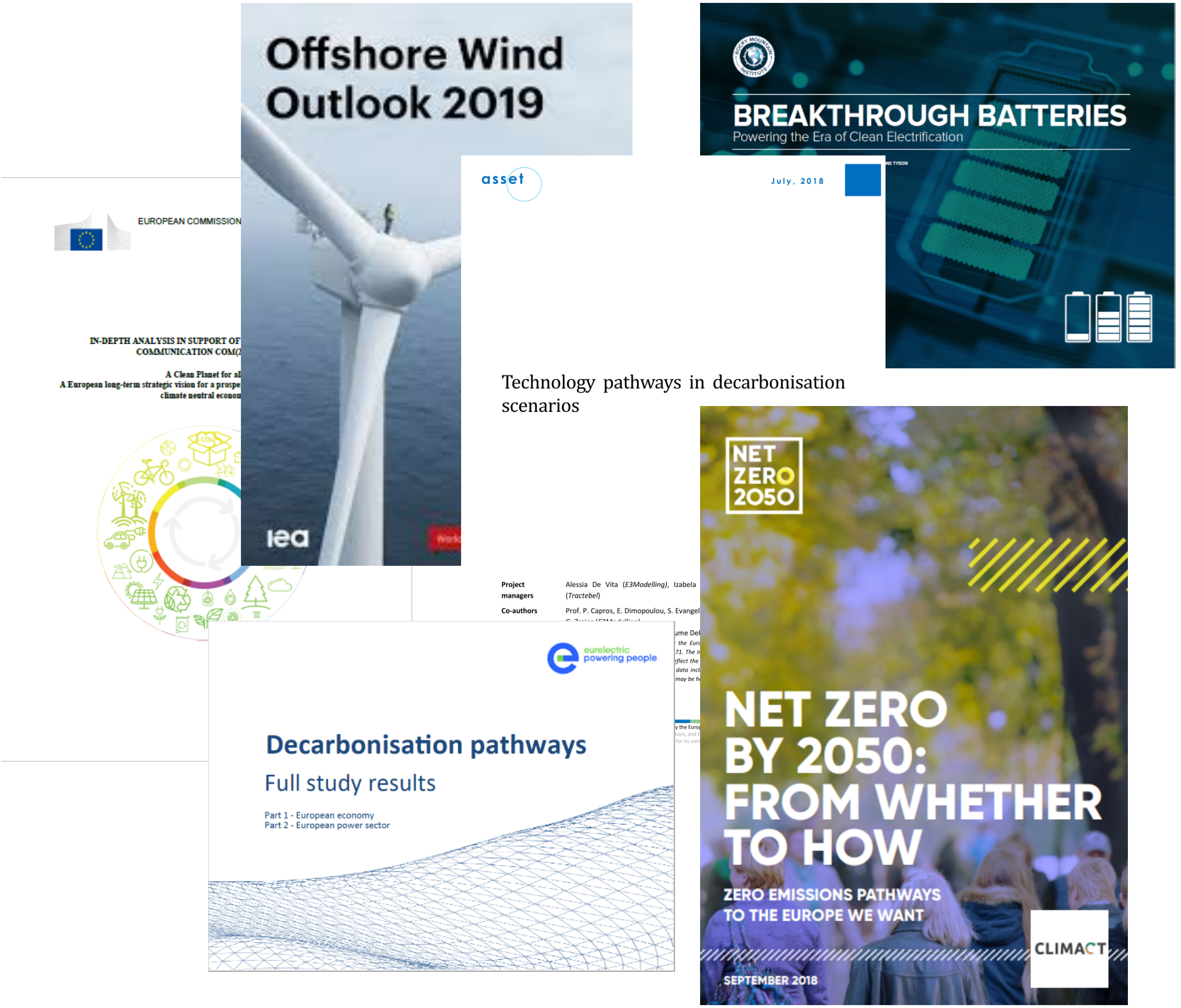
Key enablers of technical innovations:

- A **relevant European regulatory framework** in the field of digitalisation, on subjects such as artificial intelligence, machine learning and blockchain
- **A strong start-up ecosystem to support collective innovation**
  - As an example, in 2017, Enel called for startups and innovative SMEs to participate in their challenge "Innovate renewable energy!" which consisted in proposing technological innovative solutions in exchange of financial and technical support to develop them

A.6. Literature review

We have reviewed various studies to further increase 2030 ambitions to reach 2050 net zero objective (1/2)

- **6 Decarbonisation roadmaps for 2050**
  - Countries beyond this geographic scope are modelled at an aggregate level.
- **7 Sector-specific publications**
  - Industry
  - Agriculture
  - Batteries
  - Flexibility value of the power sector
- **9 studies on clean energy costs**
  - RES technology costs
  - EV batteries technology costs
- **5 Key EC publications**
  - Technology cost assessments
  - Impact assessments of the climate policies



We have reviewed various studies to further increase 2030 ambitions to reach 2050 net zero objective (2/2)

2050 decarbonisation roadmaps

- E3G study (Jul 2018) “The EU’s climate strategy needs a new assessment of ambition”
- ECF (Sep 2018) “Net zero by 2050: from whether to how”
- IRENA (Feb 2018) “Renewable energy prospects for the European Union”
- EUC Artelys (Nov 2017) “Cleaner, smarter, cheaper”
- Eurelectric (May 2018) “Decarbonisation pathways”
- ISI Frauenhofer (2014) “Study evaluating current energy efficiency policy framework in the EU”

Clean energy technology costs

- IRENA (2019) “Renewable power generation costs in 2018”
- BNEF (2019) “Global trends in RES investment 2019”
- IEA-NEA (2015) “Projected costs of generating electricity”
- BEIS (2016” Electricity generation costs”
- IRENA (2016) “The power to change: solar and wind cost reduction potential”
- IEA (2018) “World energy outlook 2018”
- IEA (2019) “Offshore wind outlook 2019”
- BNEF (2019) “A behind scenes take on Lithium-ion battery”
- ICCT (2019) “Update on electric vehicle costs in the United States through 2030”

EC publications

- EC (2014) “Energy technology reference indicator projections for 2010-2050” (ETRI)
- EC (Nov 2016) “Impact assessment accompanying the proposal for revising the Renewable Energy Directive”
- EC (Mar 2018) “Non-paper on complementary economic modelling undertaken by DG ENER regarding different energy policy scenarios”
- ASSET (Jul 2018) “Technology pathways in decarbonisation scenarios”
- EC (Nov 2018) “A clean planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy”

Sector specific

- Material economics (2019) “Industrial transformation 2050 – pathways to net-zero emissions from EU heavy industry”
- IES (2019) “Industrial transformation 2050 – towards an industrial strategy for a climate neutral Europe”
- IEEP (2019) “Net-zero agriculture in 2050: how to get there”
- RMI (2019) “Breakthtough batteries – powering the era of clean electrification”
- COWI (2016) “Impact assessment study on downstream flexibility, price flexibility, demand response and smart metering”
- ADEME (2015) “Un mix électrique 100% renouvelable ? Analyses et optimisations”
- RTE (2017) “Réseaux électriques intelligents”

Literature points to neutral carbon economy in 2050 as necessary and achievable if key drivers are activated

International action drivers
- Limit global warming to 1.5°C
- Paris agreement and further increasing commitment at global level
- EU pioneer role and future competitivity in the transition to carbon-neutral economy
- Opportunities for international cooperation

EC regulation drivers
- Revised EU-ETS directive
- ICE norms
- BAT standards for industry and power plants
- Residential energy efficiency and heat pumps
- Agriculture and alimentary regulation to increase
- LULUCF directive

European and national Policy drivers
- Promoting transport electrification
- Promotion multimodal and collaborative transport
- Promoting demand-side participation
- Promoting clean air action
- Commitment to phase-out of coal-based generation
- Potential benefits for economy, environment and health

Technology drivers
- Falling clean energy costs (RES generation, batteries)
- Higher energy efficiency potential
- Increasing batteries penetration
- Automation and digitalisation
- Carbon storage

Business drivers
- Demand-side participation
- Circular economy business models
- Focus on lower levels of production with higher added value
- Electrification of industrial processes
- CO2 prices
- Digitalisation/internet

Between 2016 and 2018, the EC increased its 2030 targets accounting for the reduction of technology costs and latest EC regulation policies

EUCO27 / EUCO30 scenarios for impact assessment of RES and EE targets in 2030
Technology costs assumptions based on ETRI (2014)

2030 impact assessment (March 2018)
WIP reduced technology costs assumptions

New 2050 Roadmap (Nov 2018)
Reduced technology cost assumptions based on latest trends (ASSET project)
Accounting for recent regulation

Impact assessment (mid 2020)

2016 | **2018** | **2019**

2030 indicators	GHG **-40.8%** RES **27%** EE **30%**	GHG **-45.8%** RES **33%** EE **33%**	GHG **-48%** RES **33%** EE **33%**
Average cost over 2021-2030	System cost: **€1951.8 bn/year** Investment: **€379 bn/year**	System cost: **€1972.3 bn/year** Investment: **€488 bn/year**	Investment: **€396 bn/year**

More ambitious targets for 2030 are expected to be achieved with a limited increase of total cost and investment over 2021-2030, but large investments are projected for 2031-2050

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