Decarbonisation pathways

Full study results

Part 1 - European economy
Part 2 - European power sector

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Decarbonisation pathways

Part 1 - European economy

EU electrification and decarbonisation scenario modelling

May 2018

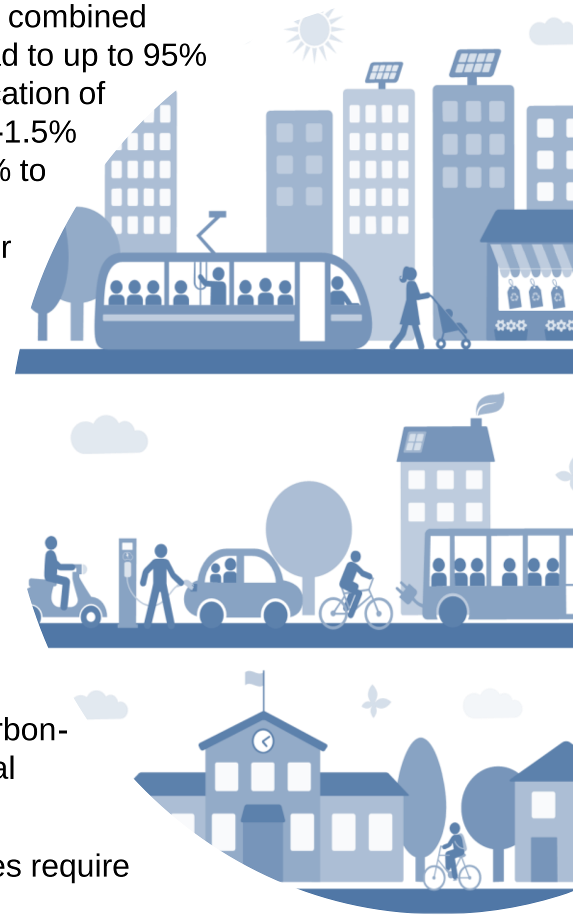
Introduction and methodology

Why this study?

- Delivering on the Paris Agreement requires an increase of the EU's contribution to the fight against climate change
- The European electricity sector believes that cost-effective decarbonisation is crucial if Europe is to remain competitive in the global market place, and we are committed to leading this transition
- In its new vision published earlier this year, the power sector made a pledge to become carbon neutral well before mid-century, taking into account different starting points and commercial availability of key transition technologies, and sees electrification as a way to accelerate decarbonisation in other sectors of the economy in a cost-effective way
- With a view to achieving this vision and to making a meaningful contribution to the EU's climate ambition, Eurelectric has developed a set of EU decarbonisation and electrification scenarios towards 2050 for the main energy-using sectors
- The power sector will support these efforts and the second phase of this project will analyse in detail the decarbonisation pathways of the power sector and their associated costs, driving towards carbon-neutrality well before 2050, further supporting the results obtained during phase one

Key messages

- The potential for electrification is substantial across energy-using sectors and will underpin deep decarbonisation of the economy. Deep decarbonization is by implication an electrification journey. Electrification is the most direct, effective and efficient way of reaching the decarbonization objectives
- Significant changes, such as fast removal of barriers to adoption of electric technologies combined with technological progress, ambitious policies changes and global coordination, can lead to up to 95% emissions reduction by 2050. Scenarios are underpinned by 38% to 60% direct electrification of the economy (as a share of total final energy consumption) which is achievable with a 1-1.5% year on year growth of the EU direct electricity consumption, while TFC reduces by 0.6% to 1.3% each year. The first driver is climate protection which also brings societal and environmental benefits stemming from electrification such as noise reduction or better air quality. Further technology breakthroughs could lead to even higher electrification rates
- Electrification, both direct and indirect, has a critical role to play for achieving multiple EU policy targets. Energy efficiency measures and other carbon-neutral solutions will complement electrification to deliver on these ambitions
  - Electricity will play a leading role in transport where up to 63% of total final energy consumption will be electric in our most ambitious scenario
  - In buildings, energy efficiency is a key driver of emission reductions; district heating and cooling are expected to keep on playing critical roles in some geographies, while 45% to 63% of buildings energy consumption could be electric in 2050 driven by adoption of electric heat pumps
  - A series of industrial processes can technically be electrified with up to 50% direct electrification in 2050 and the relative competitiveness of electricity against other carbon-neutral fuels will be the critical driver for this shift. Hydrogen and other carbon-neutral alternatives will also play a role and drive indirect electrification
- Different starting points in terms of energy mix, economic situation and industrial activities require different pathways and level of efforts across EU countries



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Our analysis builds on a granular multi-factor approach

The study is based on a multi factor approach including:

- Total cost of ownership in the short to medium term,
- Relative cost competitiveness of decarbonization technologies,
- Market developments,
- Technological developments,
- Regulatory aspects at national and EU level,
- Political ambition,
- Societal benefits and barriers/incentives on the consumer side

The analysis focuses on the role of electricity to accelerate decarbonization in transport, buildings and industry, with a view to:

Advancing Europe's competitiveness, economic growth and job creation, esp. in the industry sector, through efficient and reliable energy solutions

Promoting a sustainable and healthy society for European citizens, through carbon neutral energy and enhanced cities' air quality, esp. through electrified transportation

Securing long-term affordable, reliable and flexible energy supply to key European sectors and countries

In addition to electrification, decarbonization strategies will always include a combination of multiple levers, technologies and solutions, e.g.,

Energy efficiency,
Green gas,
Hydrogen,
Additional use of RES,
CCS for industrial processes

Total final energy consumption and electricity demand are computed based on granular inputs and modelling at the country and sub-sector level (>50 sub-sectors considered across the 4 sectors prioritized: power, transport, buildings, industry)

Outputs from this multi-factor analysis were syndicated through a very comprehensive stakeholder engagement with all eurelectric members as well as with external stakeholders through:

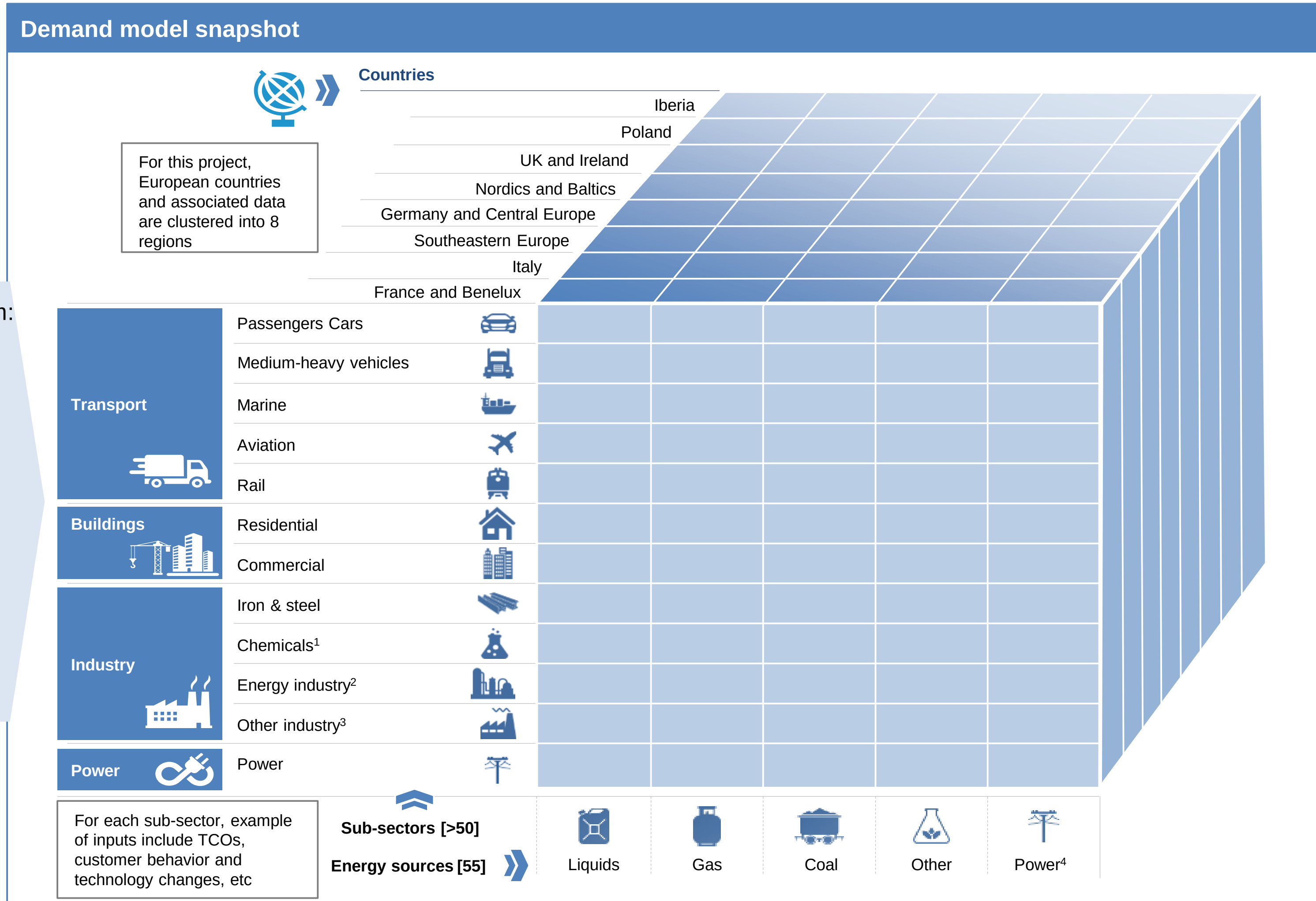
Workshops and discussions with relevant stakeholders by sector and industry

Planned event in Brussels to discuss the key findings of the study

Detailed inputs collected bottom-up contribute to the robustness of the demand forecasts of energy and electricity

Bottom-up inputs from:

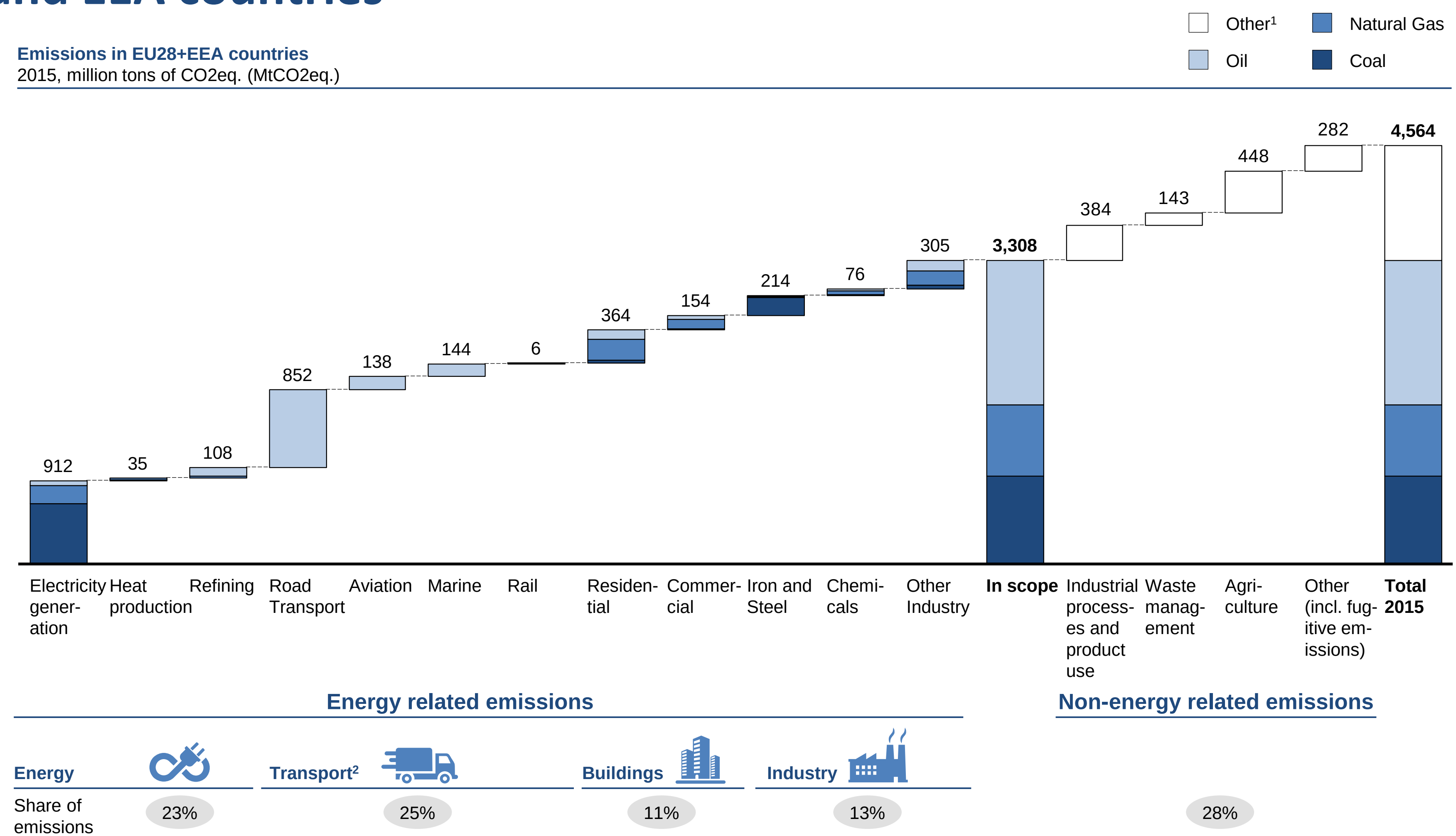
- National associations and their members
- Eurelectric committees and working groups
- External stakeholders from different perspectives: NGOs, industry associations, etc



1. Organic, Ammonia, Other; 2. Oil & Gas, Own use, Other 3. Construction, Food & Agriculture, Manufacturing, Materials, Mining, Non-Energy, Other; 4. Separate global granular model

SOURCE: Energy Insights, a McKinsey Solution – Global Energy Perspective

Our project focuses on all energy related emissions for all EU28 and EEA countries



1. E.g. methane emissions from land-fills or agriculture and GHG emissions from waste burning
2. Includes international aviation and marine for consistency purposes

SOURCE: Energy Insights, EuroStat, EU inventory, team analysis

EU decarbonization and electrification scenarios

eurelectric designed 3 deep EU decarbonization scenarios

	2015 - Baseline	2050 scenarios: Scenario 1	Scenario 2	Scenario 3
EU economy decarbonization achieved vs. 1990[1,2]	~22%	~80%	~90%	~95%

Driving towards full EU economy decarbonization

1 Emissions out of scope are expected to contribute proportionally to the decarbonization effort required in each scenario
2 Decarbonization will be different by sector depending on relative costs and available technologies, industry contributing least with below 80% of emission reduction in all scenarios

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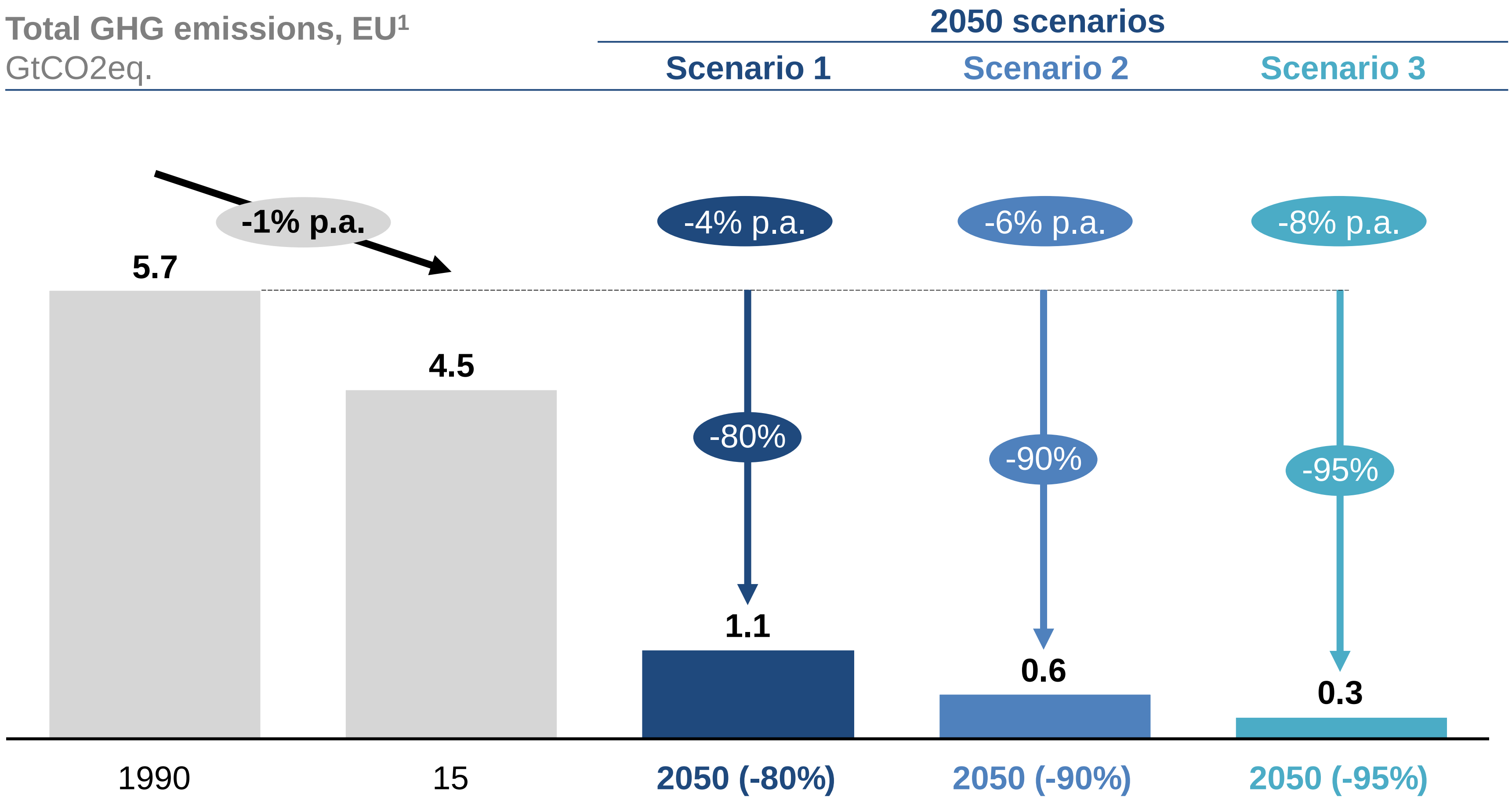
The 3 scenarios deliver unprecedented but necessary reductions in CO2 emissions

-x% p.a. Required annual emission reduction rate between 2015-2050 to achieve target



SOURCE: Energy Insights, EuroStat

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Current total direct electrification rates in Europe, across transport, industry and buildings, are 20-22%

Electrification[1] in 2015	France and Benelux	Germany and Central Europe	Iberia	Italy	Nordics and Baltics	Poland	Southeastern Europe	UK and Ireland	Europe (total)
Transport	**1%**	**2%**	**1%**	**2%**	**1%**	**1%**	**0%**	**1%**	**1%**
Aviation	0%	0%	0%	0%	0%	0%	0%	0%	**0%**
Marine	0%	0%	0%	0%	0%	0%	0%	0%	**0%**
Rail	81%	75%	73%	95%	59%	69%	36%	35%	**70%**
Road Transport	0%	0%	0%	0%	0%	0%	0%	0%	**0%**
Buildings	**38%**	**29%**	**52%**	**28%**	**47%**	**24%**	**35%**	**33%**	**34%**
Commercial	52%	38%	66%	51%	59%	50%	64%	49%	**50%**
Residential	30%	23%	42%	18%	41%	13%	25%	26%	**26%**
Industry	**29%**	**34%**	**35%**	**36%**	**41%**	**25%**	**30%**	**35%**	**33%**
Iron & Steel	18%	28%	54%	37%	45%	31%	36%	21%	**32%**
Other Industry	33%	36%	33%	36%	40%	24%	32%	34%	**35%**
Chemicals	24%	31%	33%	36%	42%	28%	17%	47%	**30%**
Total	**22%**	**22%**	**24%**	**21%**	**32%**	**18%**	**20%**	**21%**	**22%**

Note: aggregated electrification rates are weighted based on TFC, by country, sector and sub-sector

1 Direct electrification defined as share of electricity consumption within Total Final Energy Consumption
Source: 2015 IEA energy tables

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Electrification is pushing the frontiers of EU decarbonization

	Introduction of new technologies		Infrastructure development
Transportation	▪ **Several e-truck models commercialized in 2018 for a variety of purposes** (i.e., freight transport, garbage-collection vehicles) led by multiples manufacturers such as Volvo, Mercedes, DAF and Tesla ▪ First **electric vessels** are developing for freight transport in the Netherlands and e-ferries in Norway	▪ Avinor announced plans for **fully electric short-haul flights** by 2040 ▪ Airbus, Rolls-Royce, and Siemens team up for the development of **electric airplanes for short-haul**, aimed for the mid 2030s ▪ Nearly **doubling of investment in autonomous & electric vehicles** (8.4$B in 2014 to 15.2$B in 2016) world wide	▪ Tesla has installed more than **2,750 supercharger positions in the EU**; In the meantime, wireless charging for EVs has been standardized across Europe in 2017 ▪ Sweden built **first ever electrified road for charging vehicles as they drive** (2km stretch)
Buildings	▪ Nerdalize in the Netherlands is **heating residential water** using the heat generated from their cloud computing services	▪ Drammen **district heating in Norway provides 85% of hot water** needed for the city. With low cost of hydro-based electricity, it is cheaper to run a heat pump than a gas or electric boiler	▪ Hydeploy Consortium is aiming to blending up to **20% hydrogen with the UK gas moving towards further indirect electrification**
Industry	▪ Pilot projects for the **electrification of cement production** in Sweden ▪ **Electrification of steel production** using hydrogen (HYBRIT project) in Sweden	▪ VoltaChem and TNO are developing technologies that focus on the **conversion of renewable energy to heat, hydrogen and chemicals**	▪ Power-to-X alliance in Germany is investing up to 1.1B euros to facilitate **production of green hydrogen and synthetic methane**

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Scenarios are based on a combination of factors, including ambition, technology development, customer behavior and regulation

Today

Scenario 1	Accelerate current technological trends, policies and customers' uptake
Scenario 2	Shift policies significantly to remove barriers and promote decarbonization and electrification
Scenario 3	Drive early technological breakthrough and deployment at scale through global coordination

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Key drivers and pre-requisites of the 3 scenarios

Main electrification drivers and key incremental changes between scenarios

	Scenario 1	Scenario 2	Scenario 3
Ambition	▪ The EU takes bold steps to implement what it promised to deliver under the Paris Agreement: 80% emissions reduction versus 1990	▪ EU opts for a more ambitious implementation of the Paris Agreement in the context of increased international coordination and ambitious review process: 90% emissions reduction	▪ EU decides to fully decarbonize its economy by 2050 in a context of concerted efforts with decarbonization policies around the world which ensure a level playing field

Technology development	▪ Technology development is driven by acceleration of current trends and learning curves
	▪ Low-carbon technologies available today increase their market share and are deployed across the EU economy
		▪ Early technology development and deployment: mature technologies experience steep cost reductions towards 2030 and new technologies that are coming to the market today are commercially deployed at a large scale across the economy after 2040
		▪ Some industrial processes are redesigned to reduce their emissions while more complex industrial processes remain challenging to decarbonize and electrify
			▪ Major technology breakthroughs:
			  ▪ Early and major shift in cost reduction of currently non-mature technologies driven by high adoption of electric solutions, innovation, Research and Development
			  ▪ Breakthrough technologies at an early stage of innovation today are commercialized at broad scale before 2040

Consumer behavior	▪ End user awareness and appetite for clean technologies increase but cost/convenience remain important limiting factors ▪ Taxes and levies hamper consumers' switch to electric solutions	▪ Clean technologies progressively become mainstream and increasingly competitive for consumers ▪ Electricity is relatively competitive against other energy carriers, driving partial adoption in industry, while overall competitiveness of the EU industry is safeguarded	▪ Fast and massive adoption of clean technologies by consumers across the world, driven by high competitiveness of electricity vs. other energy carriers; especially, early and fast adoption of electric solutions as they are readily available
Regulation	▪ Over time, policies -including CO2 emissions related policies and pricing- start driving market forces towards deployment of mature and maturing clean technologies and technology switch	▪ Regulation on CO2-GHG emissions, environment, fossil fuels and infrastructure tightens ▪ Major shifts in policies, tariffs and taxes, driving earlier shift and removing current barriers to electrification	▪ Implementation of regulations and mechanisms envisioned for scenario 2 now happens on a global scale ▪ Much earlier implementation of this regulation (vs. scenario 2) is needed to deliver on full decarbonization objectives by 2050

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Direct electrification results by scenario

		2015 Baseline	2050 Scenario 1	2050 Scenario 2	2050 Scenario 3
Total EU economy	EU economy decarbonization vs 1990	22%	80%	90%	95%
	Direct electrification rate	22%	38%	48%	60%
Total transport	Direct electrification rate	**1%**	29%	43%	63%
Total buildings	Direct electrification rate	**34%**	45%	54%	63%
Total industries	Direct electrification rate	**33%**	38%	44%	50%

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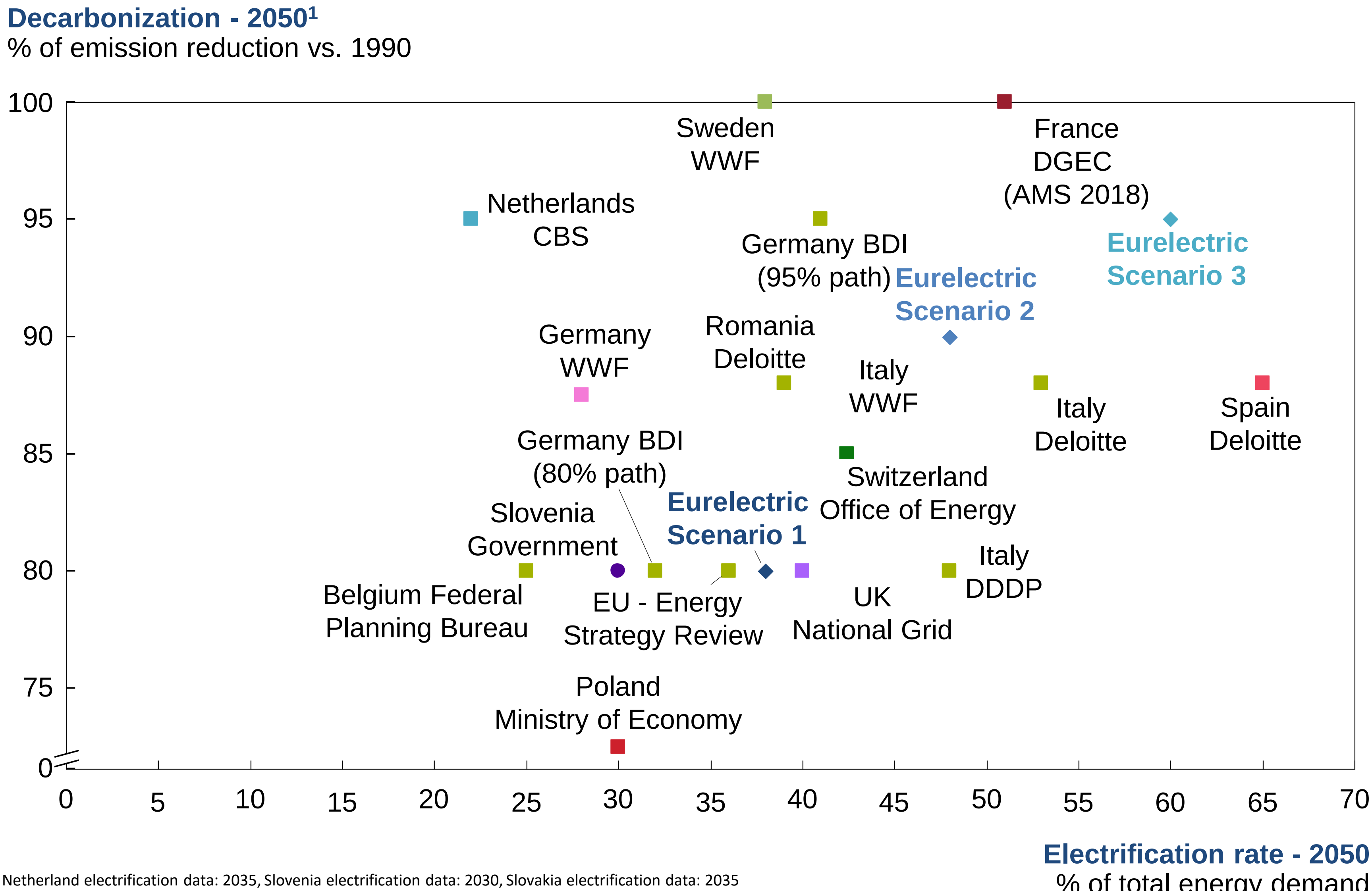
eurelectric scenarios against European benchmark



- Netherland electrification data: 2035, Slovenia electrification data: 2030, Slovakia electrification data: 2035
- Spain, Germany, Italy decarbonization rate is 80 – 95%

1 Decarbonization could be achieved through a combination of factors, including electrification but also energy efficiency and alternative carbon-neutral fuels, e.g., H2, biofuels, etc

SOURCE: National reports (Utility, Government) , NGO, Independent research agencies and think tanks

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Energy efficiency drives down final energy consumption significantly, while yearly direct electricity consumption increases by 1.0 to 1.5%

Scenario 1
Scenario 2
Scenario 3

Total Final Energy Consumption (TFC[1])

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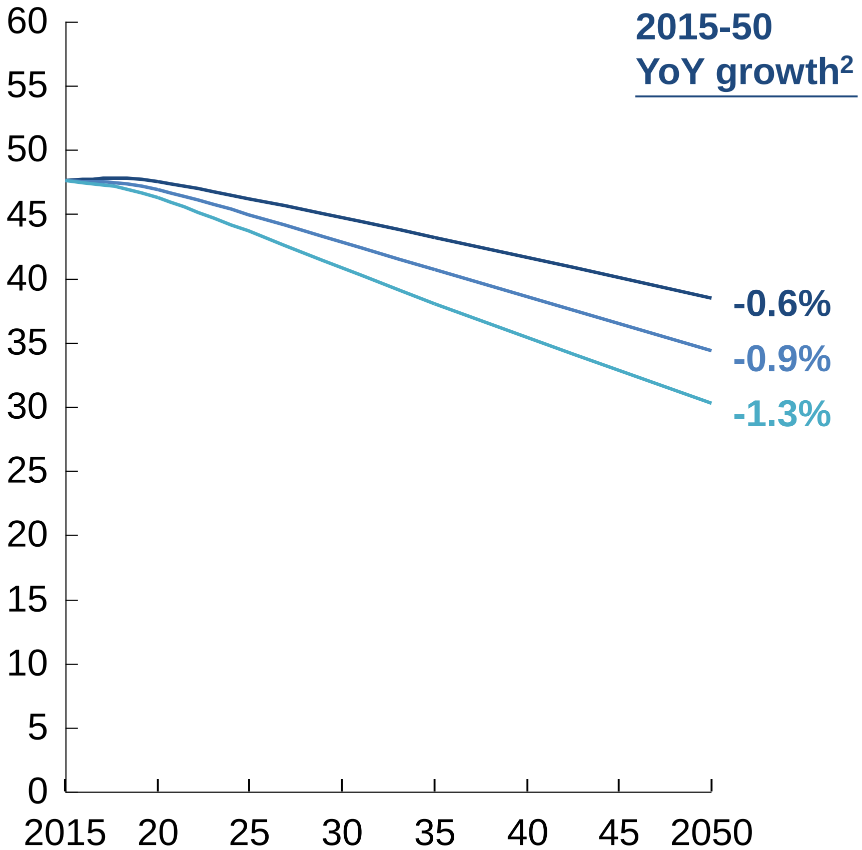
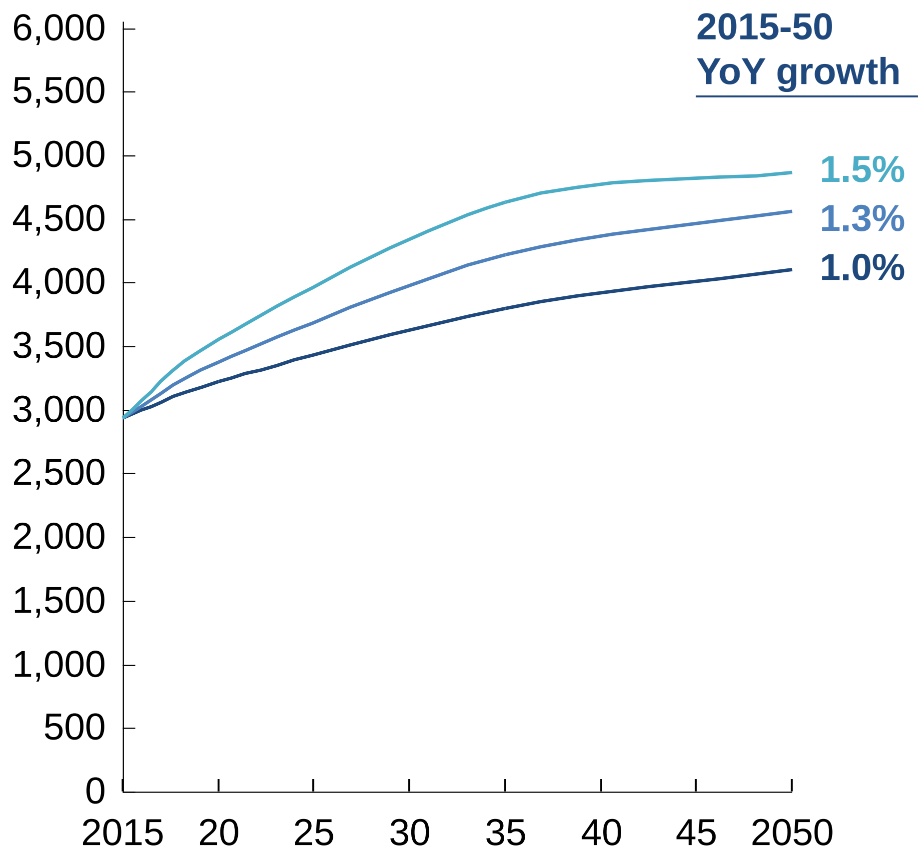


Direct electricity consumption in TFC[1]

TWh



1 Includes 32 countries in scope: EU28 + EEA; ENTSOE report additionally includes Turkey and other Eastern European countries adding up to a total of ~3,300 TWh
2 Annual YoY TFC reduction adjusted to total GDP growth (as a proxy for increase in energy productivity) varies between 2% and 2.8% depending on scenarios

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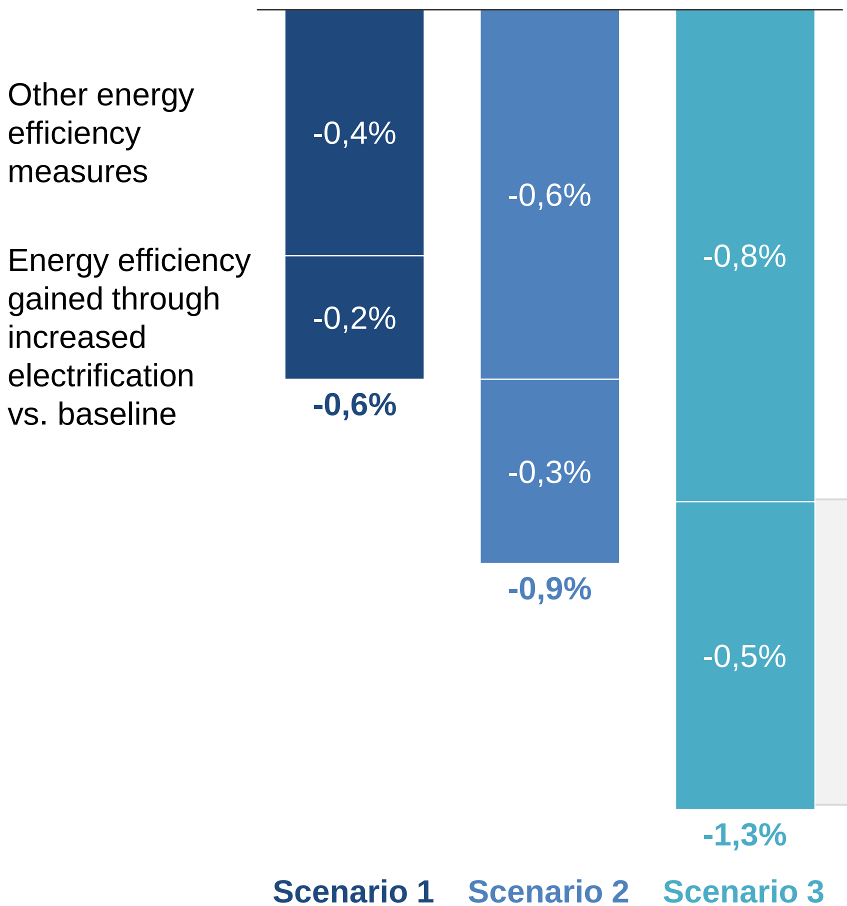
Deploying electric solutions is strongly contributing to the total energy efficiency gains

Drivers of energy efficiency gains

2015-2050 YoY reduction in TFC



Illustrations by sector

Transport

- In passenger cars, EVs consume 25% of ICE vehicles' energy consumption
- For trucks, e-trucks consume ~50% of their diesel equivalents' own energy consumption

Buildings

- In space heating, heat pumps' coefficient of performance (COP[1]) is 4-5x higher than the COP for typical gas boilers
- In cooking, the energy intensity of electric solutions is 10% lower than for gas and down to 1/5 of the energy intensity of charcoal and wood

Industry

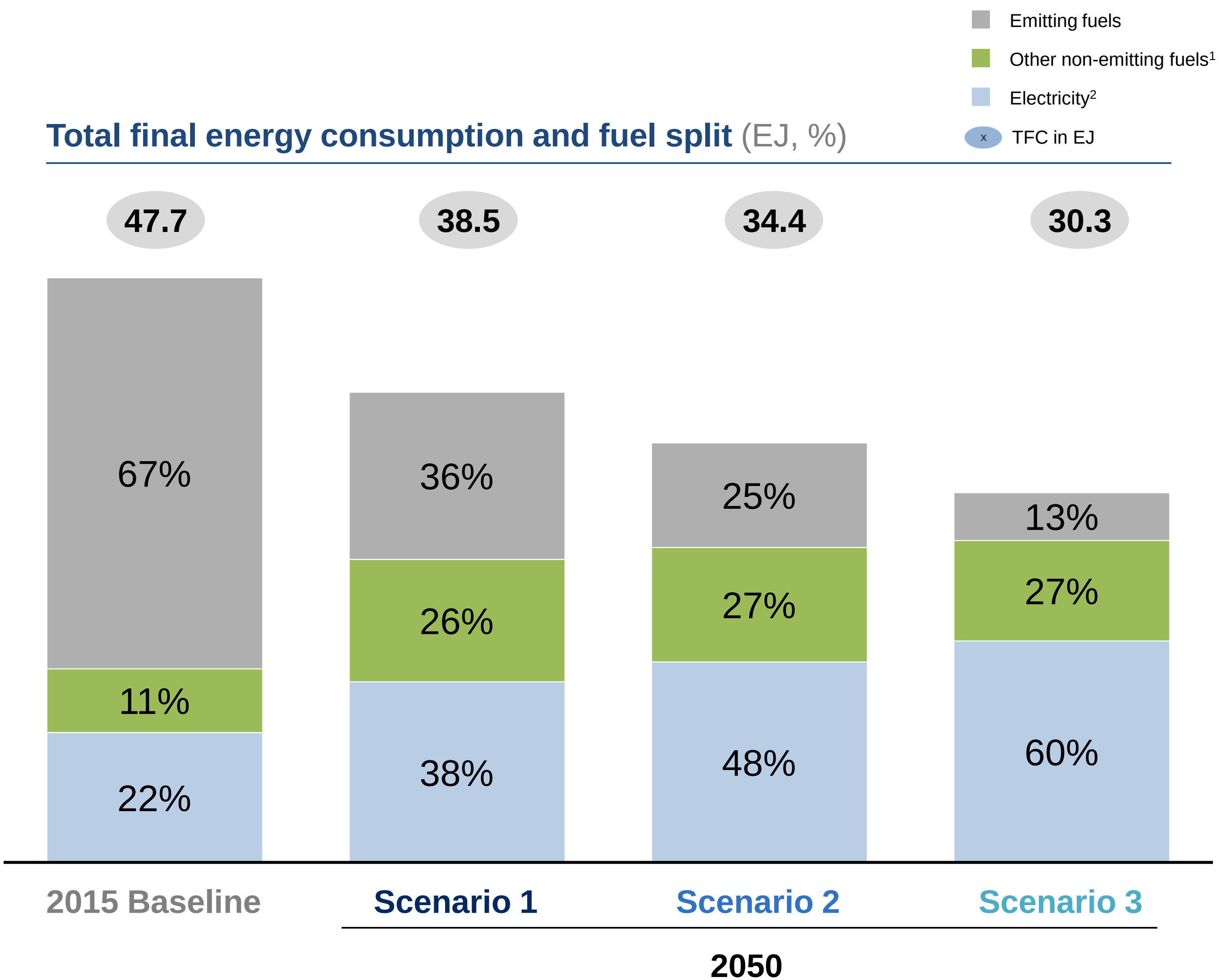
- For steel, electric arc furnace route using recycled steel is 5-6x less energy intense than traditional coal-based (blast furnace) production routes
- In other industry, electric solutions (e.g., heat pumps, hybrid boilers) can be between 100-300% more energy efficient for low temperature grades then their gas equivalents

1 Coefficient of performance (COP) = ratio of heat delivered vs energy needed as input

A strong electricity uptake in total final energy consumption

Electrification will be driven by economic drivers, technological advances and further support from enabling regulation. Other carbon-neutral technologies, starting with increased energy efficiency, will develop in parallel and contribute to reach the decarbonization targets.

Total final energy consumption and fuel split (EJ, %)



1 Includes non-emitting primary fuels/sources such as geothermal, solar thermal, and biomass but also secondary fuels such as biofuels, synthetic fuels, hydrogen and others
2 Direct electricity consumption

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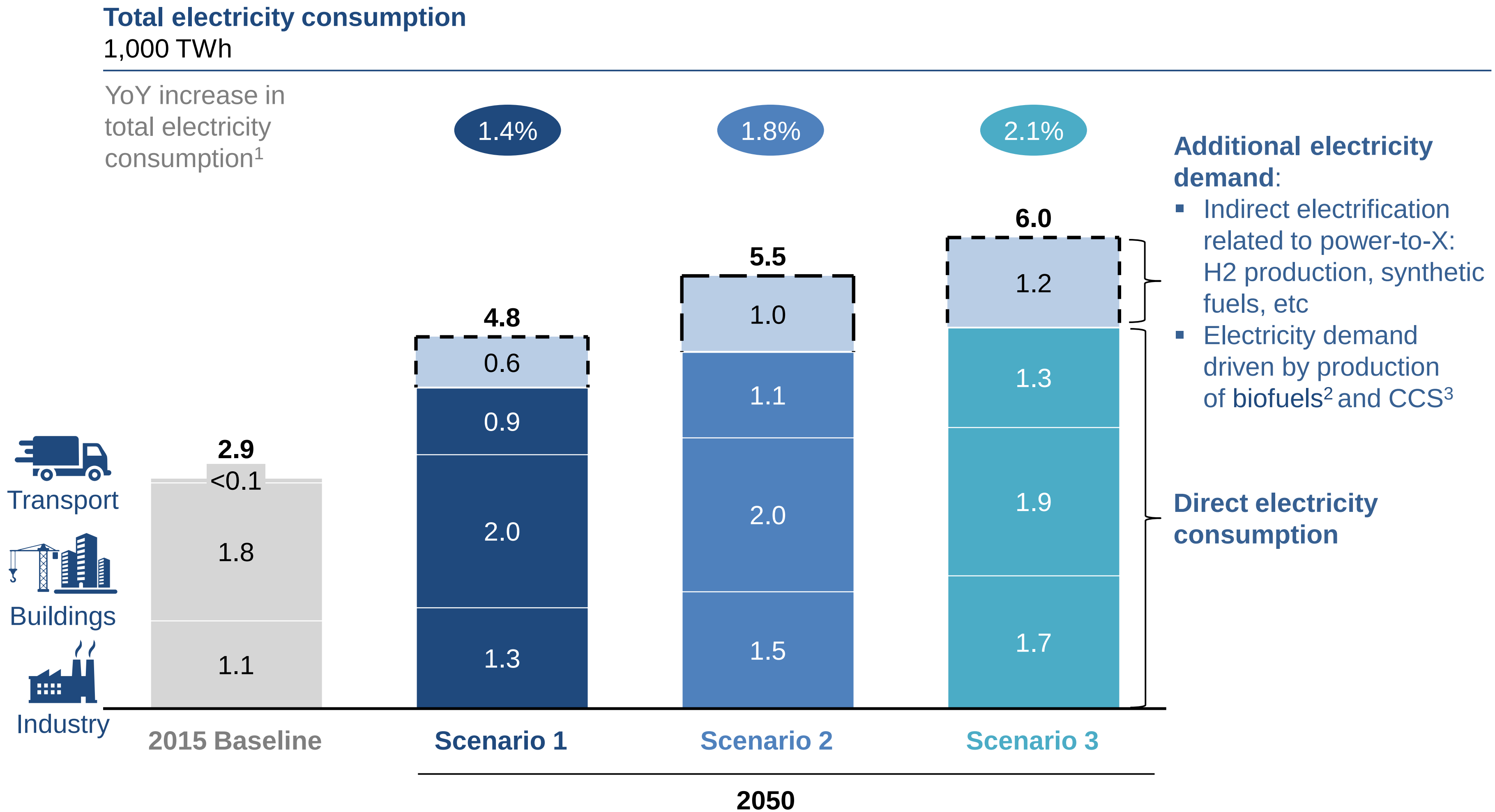
Total electricity demand is expected to increase beyond envisioned direct electrification

Total electricity demand

	Definition	YoY increase in total electricity consumption in TFC: Scenario 1	Scenario 2	Scenario 3
Direct electricity demand	Direct use of electricity as an energy carrier (e.g. power consumed by households, road transportation, etc.)	1.0%	1.3%	1.5%
+ Indirect electricity demand for power-to-X	Power demand to produce hydrogen (via electrolysis), gas and other synthetic fuels which can then be used to decarbonize certain industry processes or as a fuel for transports	0.3%	0.4%	0.5%
+ Additional electricity demand for other decarbonization	Power required for CCS[1] and to produce other clean fuels/feedstock (e.g. biofuels)	0.1%	0.1%	0.1%

1 Total CO2 abated through CCS: <200 Mt Co2; CCS may require technology improvement as well as increasing acceptability, e.g., for underground storage

Strong electricity uptake in all sectors, with strongest increase in transport



1 Includes both direct and indirect electrification (power-to-X) as well as electricity demand driven by production of CCS and biofuels
2 Biofuels require feedstock as well as additional energy (either in form of thermal energy or power) for their production – see glossary
3 Total CO2 abated through CCS: <200 Mt Co2; CCS may require technology improvement as well as increasing acceptability, e.g., for underground storage

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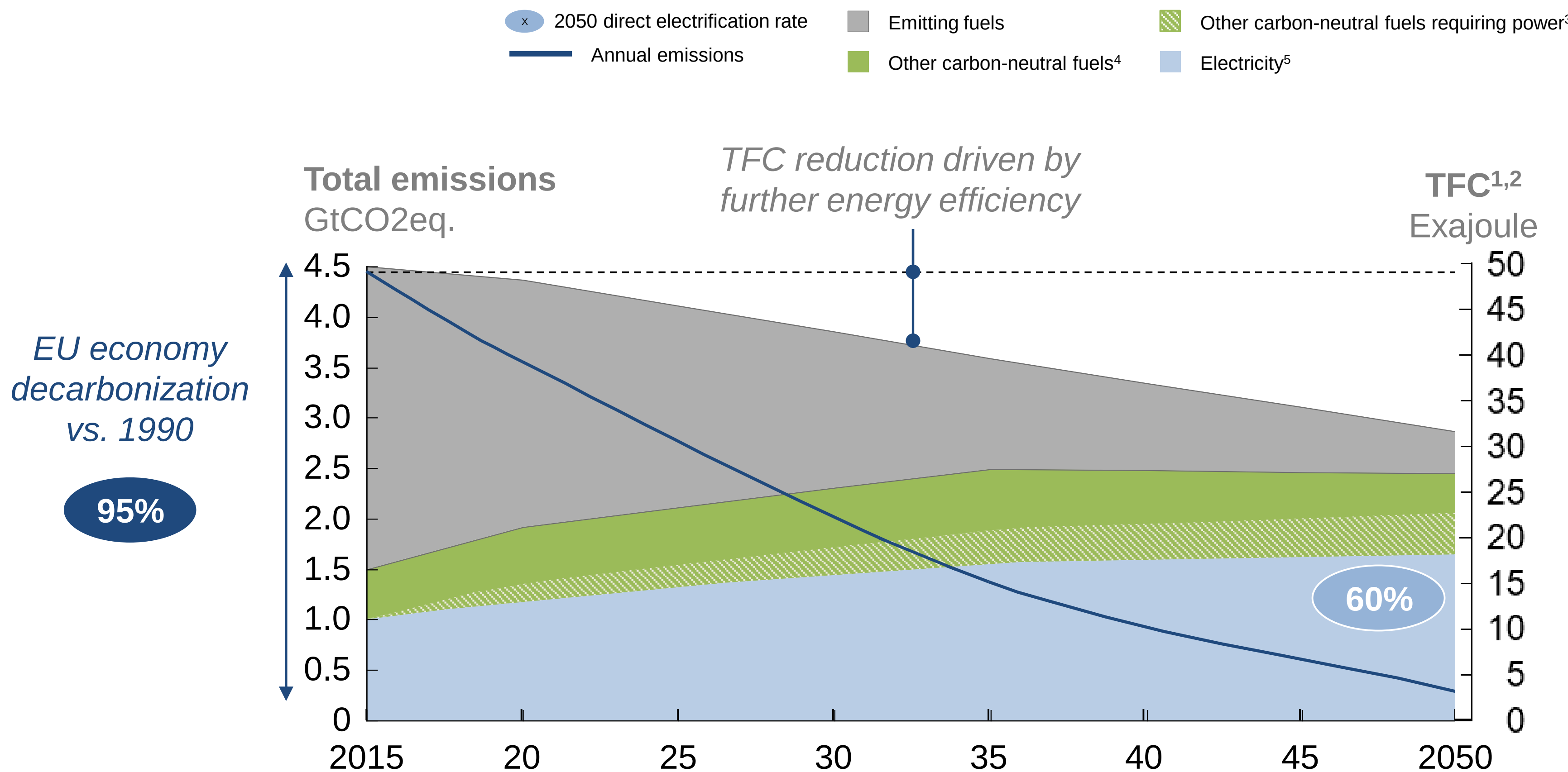
95% decarbonization through strong electrification, energy efficiency, and support from other non-emitting fuels

Impact of electrification on Total Final Energy Consumption (TFC) and EU economy emissions



1 Includes 32 countries in scope: EU28 + EEA; ENTSOE report additionally includes Turkey and other Eastern European countries adding up to a total of ~3,300 TWh
2 Electricity consumption from transformation sectors not included; 3 Includes non-emitting fuels that trigger indirect electrification through power-to-X (H2, synth fuels) as well as non-emitting fuels that trigger increased electricity demand to be produced such as biofuels; 4 Includes all other non-emitting fuels/sources such as geothermal, solar thermal, and others; 5 Direct electricity consumption

Implementation of envisioned electrification and decarbonization will require to overcome some challenges, especially in scenario 3

- Expected annual energy productivity gains vary from 2% to 2.8% depending on scenario. 1/3 of this increase in energy efficiency is driven by electrification; capturing the other 2/3 of these expected energy efficiency gains would require to remove the current observed barriers to adoption and implementation of energy efficiency measures
- Ambitious decarbonization in scenario 3, especially of industry (around 80% versus 1990), might come at an extra cost versus existing emitting technologies
- Significant technology progress and breakthroughs have to materialize in the timeframe considered, such as the production of cost-competitive and clean H2 and synthetic fuels at scale
- Required ramp-up in supply chain and infrastructures for electric solutions development and deployment has to be secured to effectively support adoption of electric solutions
- Acceptability challenges, for instance for CCS, would need to be addressed

Scenarios – Regional perspectives

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Different starting points in the energy transition

2015 baseline – direct electrification rate

Nordics and Baltics: 32%
- Large amount of renewable resources and low electricity prices
- Specific policies and business initiatives driving further electrification being implemented in some Nordics countries
- Large share of district heating in buildings

UK - Ireland: 21%
- Historical importance of gas in the UK and oil in Ireland
- Low share of aviation and marine within TFC mix
- High potential for electrification of some industrial sub-sectors

Poland: 18%
- The ability to fully decarbonize the power sector will heavily depend on commercial ability of key transition technologies taking into account its highest relative investment burden related to 80% share of coal in the Polish power mix, coupled with one of the EU's lowest GDP/capita levels (68% of EU av.)
- 75% share of coal in district heating serving 53% of population
- 20% share of energy-intensive industry in the Polish gross value added employing 15% of the workforce

France - Benelux: 22%
- Large share of nuclear compared to other regions, driving current electrification rates
- High share of international marine in Netherlands and Belgium, hard to significantly electrify before 2050

Germany and CE: 22%
- Governmental push towards a more carbon-neutral economy
- High reliance on fossil fuels in electricity generation
- High retail electricity prices vs. Europe
- Nuclear phase out of Germany

Iberia: 24%
- Significant share of nuclear and renewables
- Highest share of marine in TFC vs. other regions, with challenging electrification

Italy: 21%
- Historical development of gas infrastructure (e.g. CNG)
- Significant share of renewables in generation mix

South Eastern Europe: 20%
- Significant reliance on fossil fuels
- Moderate electricity prices vs. rest of Europe

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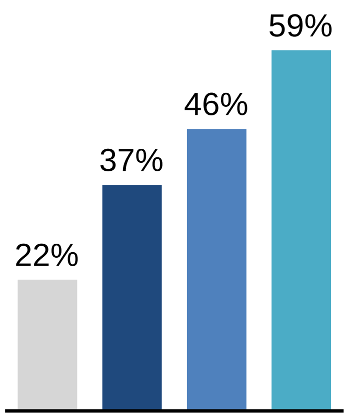
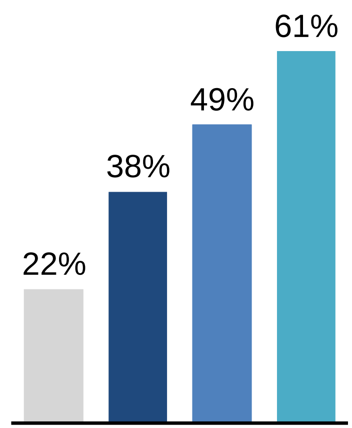
Direct electrification rates vary by region across scenarios

- 2015 baseline
- Scenario 1
- Scenario 2
- Scenario 3

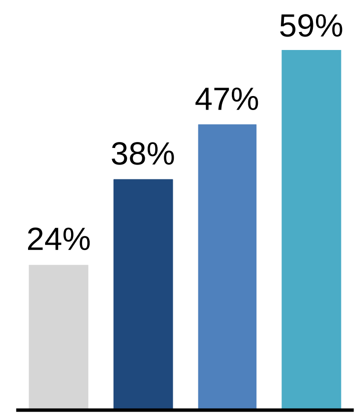
France & Benelux



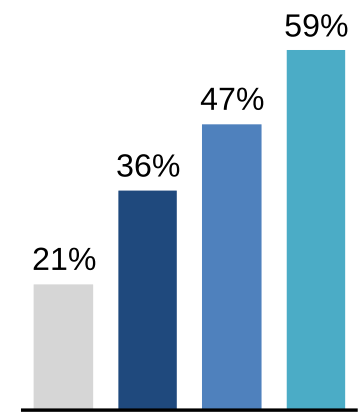
Germany & Central Europe



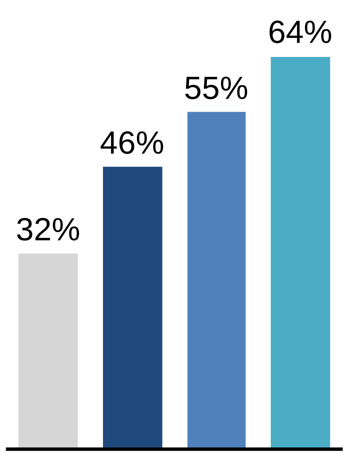
Iberia



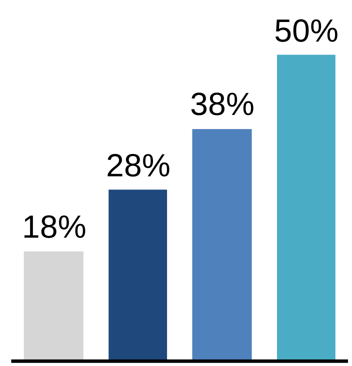
Italy



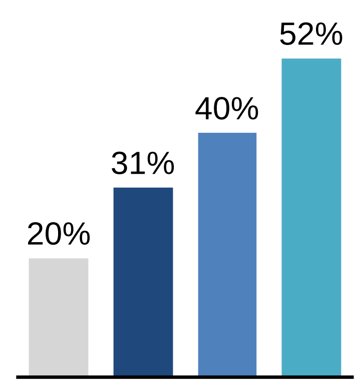
Nordics and Baltics



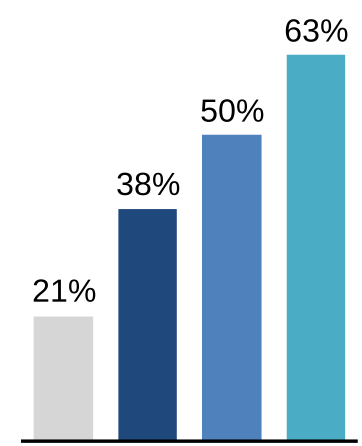
Poland



Southeastern Europe



UK & Ireland



Scenarios – Perspectives by sector – Transport

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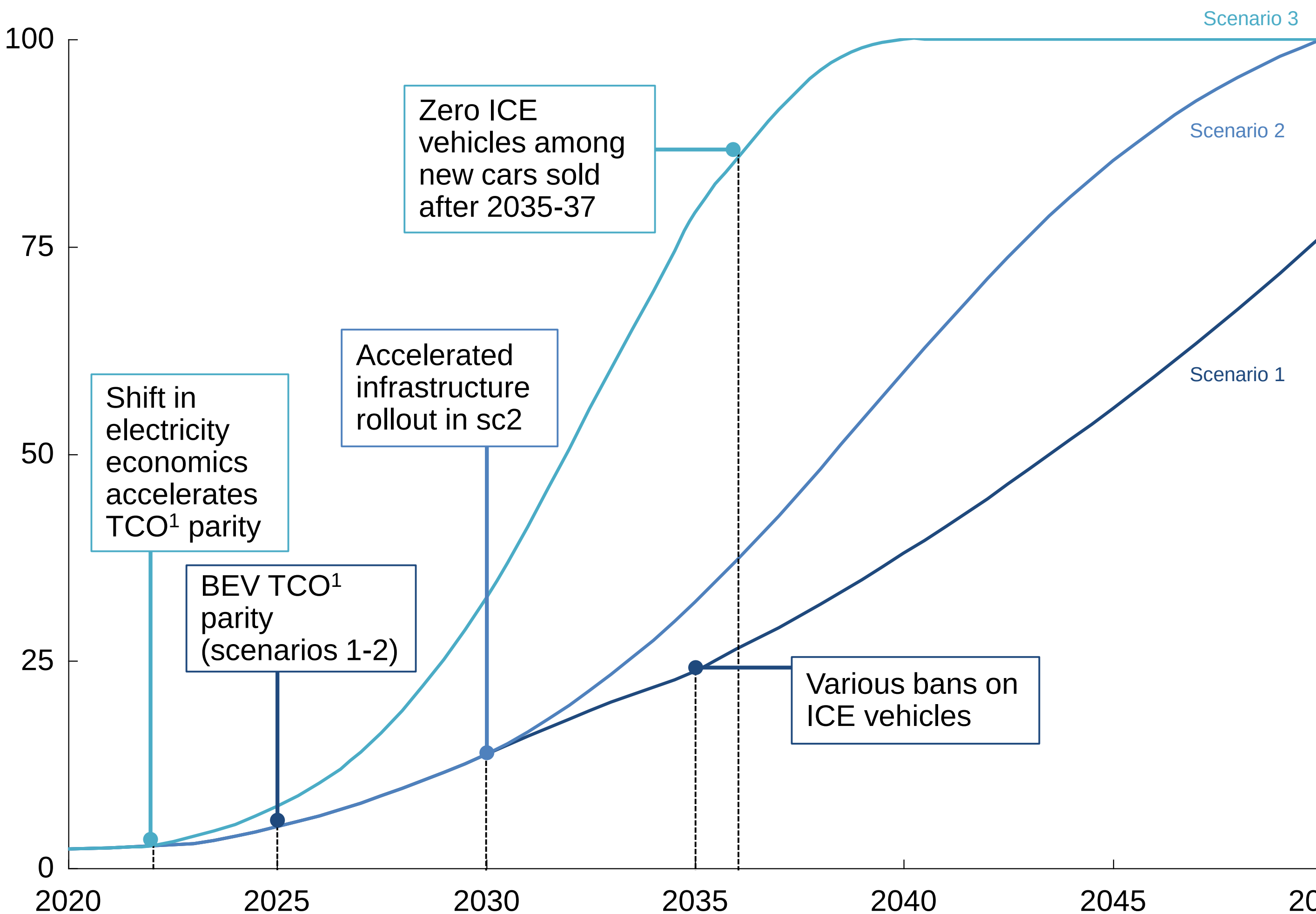
Favorable TCO[1] and regulatory push drive up-take of electric vehicles in passenger cars across our 3 scenarios

Share of battery electric vehicles (BEVs) in new sales in the EU

Percent



Key drivers of BEVs sales

- Current fleet
- Macro-economic drivers: GDP, population growth
- Scrap rates, especially of internal-combustion-engine (ICE) vehicles
- TCO of BEVs relative to other competing technologies, driven by decreasing battery cost
- Demand for shared mobility and autonomous driving
- Infrastructure deployment and innovation *(i.e. wireless charging)*
- Non-economic drivers for BEV acquisition (*i.e. regulation, environmental awareness)*

1 TCO: total cost of ownership

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Electrification of passenger cars requires a strategic charging infrastructure build-up

			2050 scenarios		
		2015 baseline	**Scenario 1**	**Scenario 2**	**Scenario 3**
Electric vehicles production and fleet	EVs in fleet	~0.5 million	~88 million	~100 million	~130 million
	Share of EVs in fleet	< 1%	65%	80%	96%
	Installed battery manufacturing capacity[1]	~10 GWh	~700 GWh	~840 GWh	~840 GWh
Electricity consumption	Km driven by EVs per year	10 billion	2.5 trillion	2.8 trillion	3.1 trillion
	Consumption by EVs per year (% of passenger cars TFC)	~1.5 TWh	~250 TWh (42% of TFC)	~260 TWh (66% of TFC)	~256 TWh (94% of TFC)
Charging infrastructure	Charging points	~0.5 million	~80 million	~85 million	~65 million
	Fast charging	1%	5%	15%	50%
	Slow charging office & public	6%	10%	30%	35%
	Slow charging home	93%	85%	55%	15%

Key drivers across scenarios

- Increasing efficiencies of products and production processes (e.g., engines energy efficiency, production learning curves)
- More systematic deployment of smart charging services
- Increasing adoption of shared mobility, reducing total fleet size while increasing VKT per vehicle
- Development of autonomous driving, shifting consumers' behavior and charging from mostly slow-charging at home to fast charging stations

1 Assumption: EV Battery density is 40 Wh/kg

Resulting electrification by sub-sector (1/2)

		2015 Baseline	2050 Scenario 1	2050 Scenario 2	2050 Scenario 3
Passenger cars	Direct electrification rate	0%	42%	66%	94%
	Share in new sales	1%	75%	100%	100%
	Share in fleet	<1%	65%	80%	96%
Trucks	Direct electrification rate	0%	24%	29%	48%
Buses	Direct electrification rate	0%	29%	39%	58%

Resulting electrification by sub-sector (2/2)

		2015 Baseline	2050 Scenario 1	2050 Scenario 2	2050 Scenario 3
Aviation	Direct electrification rate	**0%**	0%	2%	5%
Marine	Direct electrification rate	**0%**	2%	6%	11%
Rail	Direct electrification rate	**70%**	73%	80%	93%
Total transport	Direct electrification rate	**1%**	29%	43%	63%
Total transport	Total electricity demand as part of TFC[1]	**1%**	34%	48%	67%

1 Includes direct electrification, indirect electrification and electricity demand driven by production of CCS and biofuels

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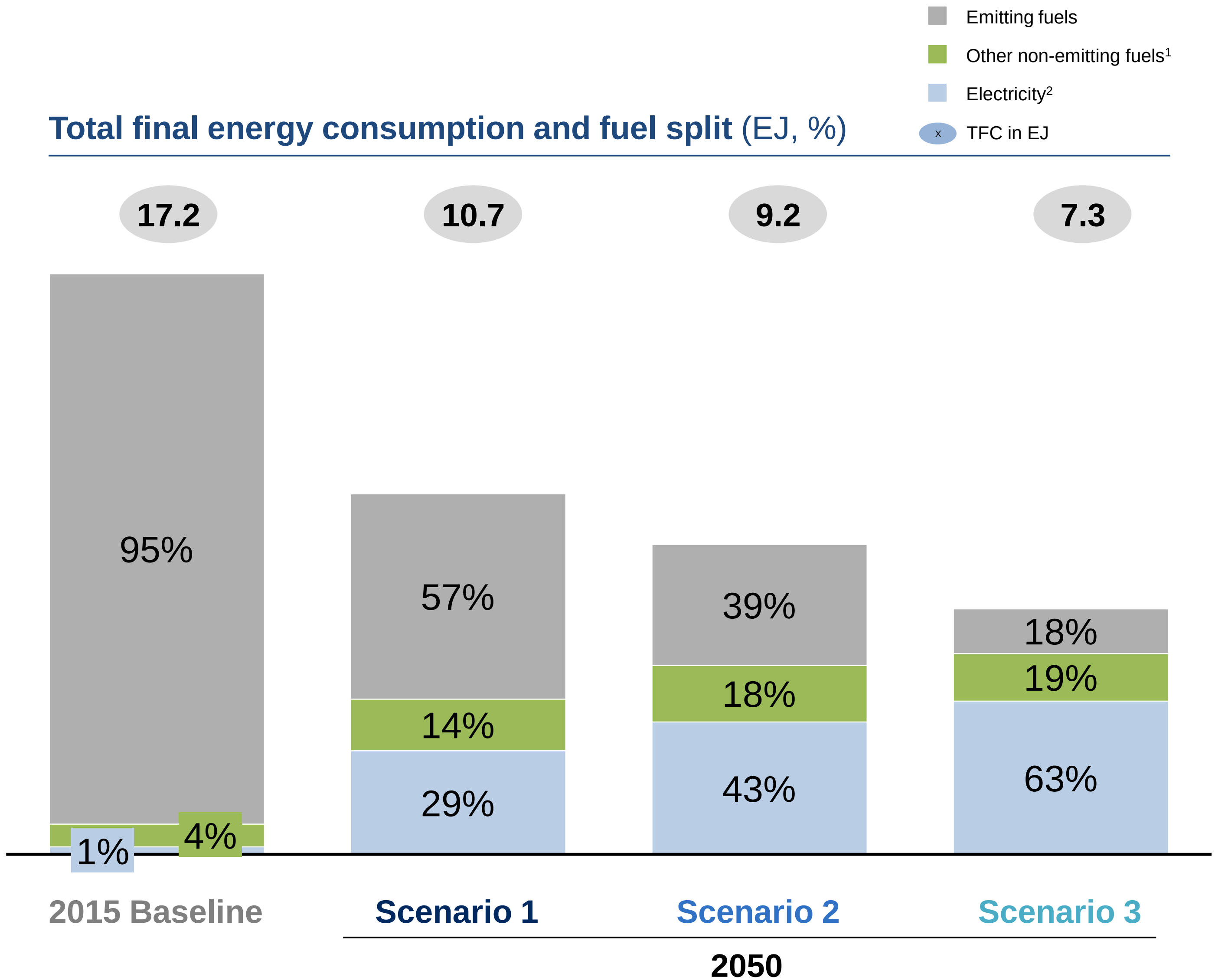
Transport total final energy consumption - breakdown by scenario

In transport, EV TCO will drive adoption of electric solutions, except in sub-sectors where limitations in energy density (e.g. aviation, heavy-duty) would drive towards other solutions; some of them have to be developed (e.g., H2) while other cleaner technologies (e.g., CNG) could be adopted transitionally



1 Includes non-emitting secondary fuels such as biomethane, biodiesel, bioethanol, hydrogen and others
2 Direct electricity consumption

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Scenarios – Perspectives by sector – Buildings

Resulting electrification by sub-sector – Commercial

		2015 Baseline	2050 Scenario 1	2050 Scenario 2	2050 Scenario 3
Space heating	Direct electrification rate	**16%**	25%	43%	53%
Water heating	Direct electrification rate	**15%**	25%	43%	53%
Cooking	Direct electrification rate	**20%**	75%	90%	95%

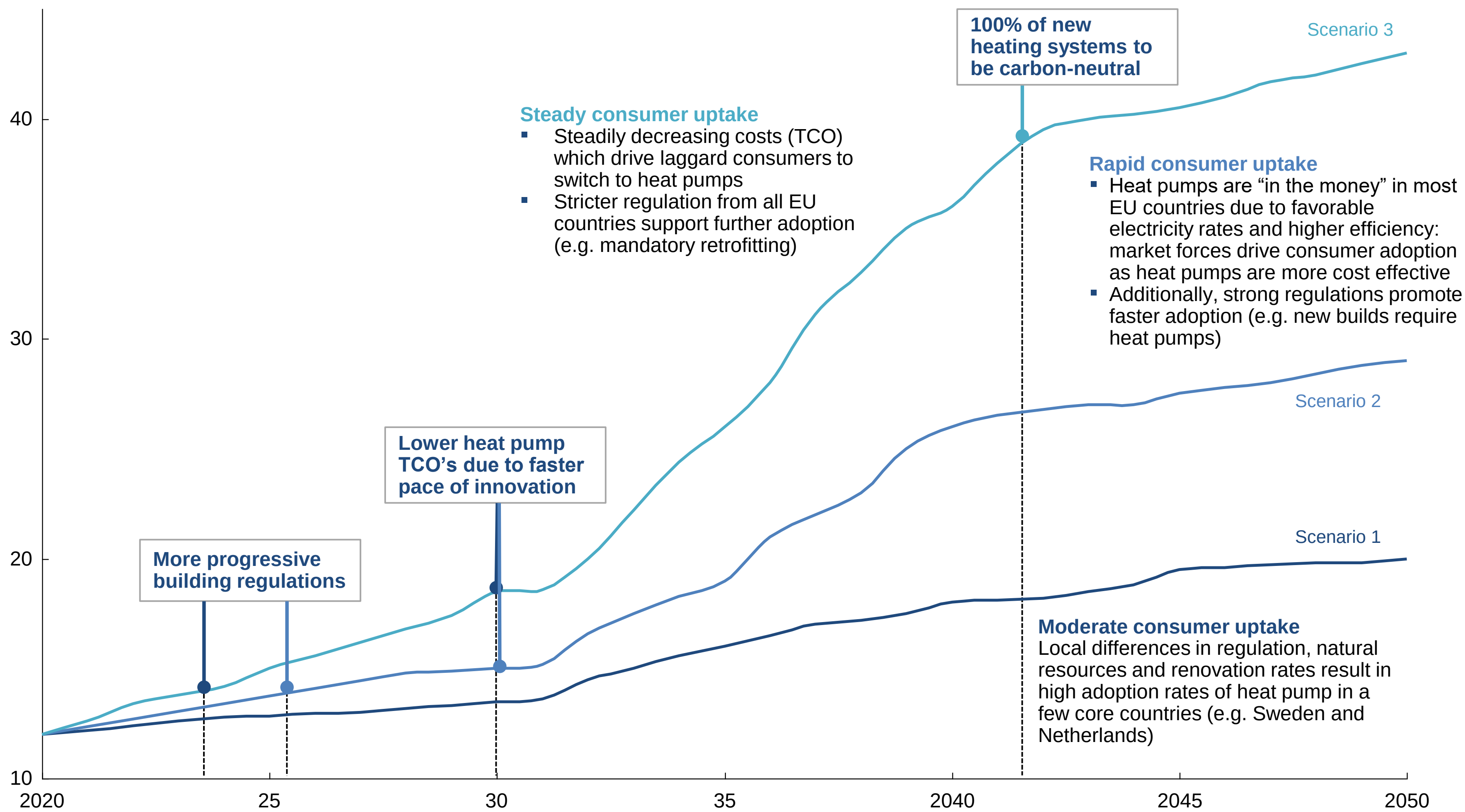
Resulting electrification by sub-sector – Residential

		2015 Baseline	2050 Scenario 1	2050 Scenario 2	2050 Scenario 3
Space heating	Direct electrification rate	**8%**	21%	32%	44%
Water heating	Direct electrification rate	**11%**	22%	32%	44%
Cooking	Direct electrification rate	**26%**	75%	90%	95%
Total buildings	Direct electrification rate	**34%**	45%	54%	63%
	Total electricity demand as part of TFC[1]	**34%**	45%	56%	64%

1 Includes direct electrification, indirect electrification and electricity demand driven by production of CCS and biofuels

Changes in heat pump economics are driving adoption of electrification in space heating for buildings

Heat pump market share of space heating
Percent of total TFC electrified



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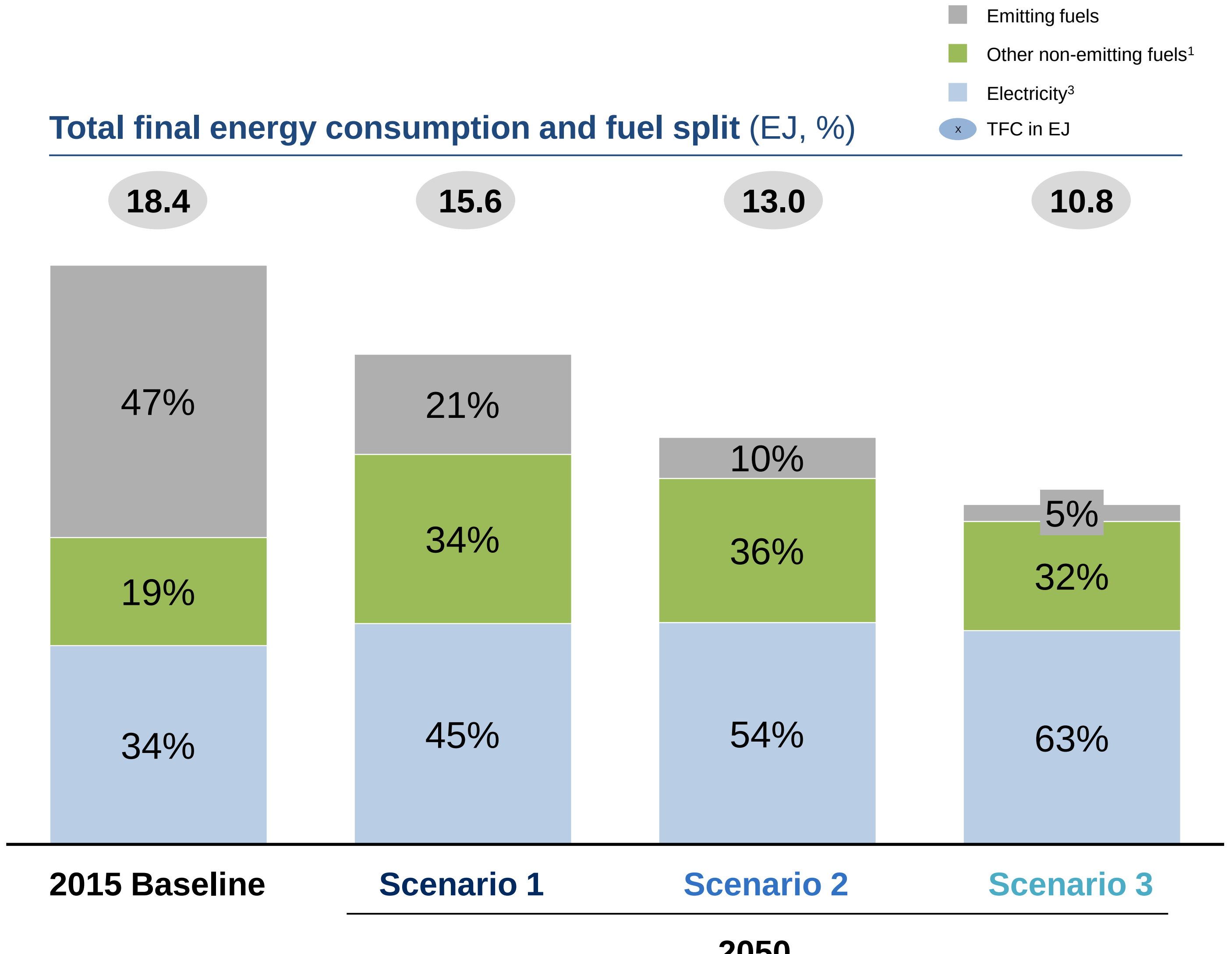
Buildings[2] total final energy consumption - breakdown by scenario

In buildings, innovations in heat pumps (TCO, volume needed) drive increasing adoption of electric solutions; role of district heating remains critical, while biogas and H2 can emerge as a complementary way to decarbonize the sector



1 Includes non-emitting primary fuels/sources such as geothermal, solar thermal, and biomass but also secondary fuels such as biofuels, synthetic fuels, hydrogen, heat and others
2 Buildings includes all end uses (i.e. space and water heating, cooking, appliances, space cooling and lighting)
3 Direct electricity consumption

Scenarios – Perspectives by sector – Industry

Electrification is expected to play a major role, as part of the 'menu' of options that could address the industry CO_2 emission

Demand side measures

Lower the demand for virgin products by increasing reuse and recycling of the materials, or by replacing it by another material

Energy efficiency

Adapting the production equipment to lower energy use per production volume

Electrification of heat

Replace fossil fuel for heating with electricity in e.g., ethylene production

Hydrogen as fuel or feedstock

Replace the feedstock or fuel with carbon neutral hydrogen e.g., in ammonia production

Biomass as fuel or feedstock

Replace the feedstock or fuel with sustainably produced biomass to reduce CO_2 emissions, e.g., use bio-based feedstock in chemicals production

CCS / CCU

Capture the CO_2 emitted and store (CCS) or use (CCU)

Other innovation

- Innovative processes e.g., electrochemical production process
- Non-fossil fuel feedstock change e.g., change in cement feedstock

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Direct electrification is mostly relevant for the cement and ethylene sectors as well as for industries supplied by fuel

- $\color{green}\checkmark$ Applied at industrial scale sites
- $\color{orange}\checkmark$ Technology (to be applied) in pilot site
- $\checkmark$ (Applied) research phase

		Electrification of heat	Hydrogen as a feedstock	Biomass as fuel or feedstock	CCS[2]	Other innovations[3]
Feedstock and fuel	Cement	$\checkmark$		$\color{green}\checkmark$	$\color{orange}\checkmark$	$\checkmark$ $\color{green}\checkmark$ $\color{orange}\checkmark$ Alternative feedstocks[4]
	Iron and steel		$\color{orange}\checkmark$	$\color{green}\checkmark$	$\color{orange}\checkmark$	$\checkmark$ Electrolysis for iron reduction
	Ammonia		$\color{orange}\checkmark$	$\checkmark$	$\color{green}\checkmark$	$\checkmark$ Methane pyrolysis for hydrogen production
	Ethylene	$\color{orange}\checkmark$		$\color{green}\checkmark$	$\color{orange}\checkmark$	$\checkmark$ Electrochemical processes for monomer production
Fuel	Other industry[1] (heat)	$\color{green}\checkmark$		$\color{green}\checkmark$	$\color{orange}\checkmark$	$\checkmark$ Medium temperature heat pumps

1 Includes manufacturing, construction, food and tobacco, etc.; 2 CCS may require technology improvement as well as increasing acceptability, e.g., for underground storage;
3 Not exhaustive; 4 Technological maturity depends on the type of alternative feedstock

SOURCE: Report “Energy transition – Mission impossible for the industry ?” (McKinsey, 2018)

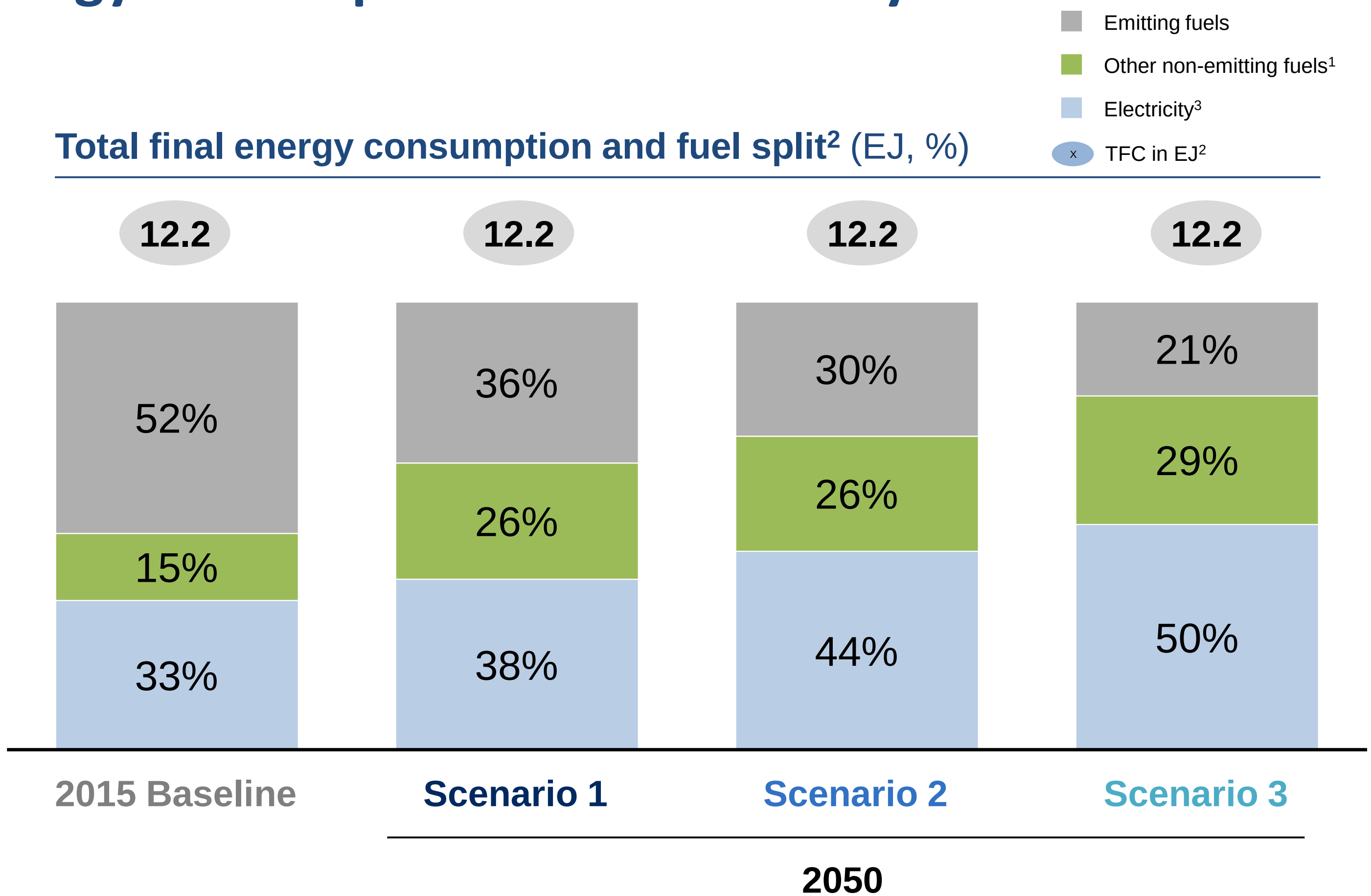
Resulting electrification by sub-sector

		2015 Baseline	2050 Scenario 1	2050 Scenario 2	2050 Scenario 3
Chemicals	Direct electrification rate	30%	35%	36%	39%
Iron & Steel	Direct electrification rate	32%	38%	39%	42%
Other industries	Direct electrification rate	35%	39%	47%	55%
Total industries	Direct electrification rate	33%	38%	44%	50%
	Total electricity demand as part of TFC[1]	33%	45%	53%	60%

1 Includes direct electrification, indirect electrification and electricity demand driven by production of CCS and biofuels

Industry final energy consumption - breakdown by scenario

In industries, a competitive electricity cost against other clean energy carriers and technology breakthroughs drive further adoption of electricity, both directly and indirectly; new solutions (e.g., H2, CCS) become available and cost-competitive as well



<u>Note</u>: In addition to being energy carriers, some fossil fuels are used as feedstock: e.g., oil is an essential raw material for the production of plastics, gas can be used to foster chemical reactions, and coal as a reductant for certain processes in metal production. The usage of these fuels as feedstock is also expected to decarbonize partially as industry processes evolve and replace these emitting feedstocks with non-emitting alternatives, e.g. biofuels and hydrogen, accounting for 21% to 27% of total feedstock by 2050.

1 Includes non-emitting primary fuels/sources such as geothermal, solar thermal, and biomass but also secondary fuels such as biofuels, synthetic fuels, hydrogen, heat and others
2 Excluding additional TFC from indirect electrification (e.g. hydrogen production, CCS, biofuel production, etc.), 3 Direct electricity consumption

Decarbonisation pathways

Part 2 -European power sector

EU electrification and decarbonisation scenario modelling
November 2018

Introduction and methodology

Context and objectives of this study

Focus for this report

Context

The EU has committed to at least 40% emissions reduction below 1990 level by 2030, and has further set an aspiration of 80-95% reduction by 2050. To achieve this, all sectors must contribute.

Cost-effective decarbonization is crucial if Europe is to remain competitive in the global market place and are committed to leading this transition.

In its new vision published earlier this year, the **electricity sector made a pledge to become carbon neutral well before mid-century**, taking into account different starting points and commercial availability of key transition technologies. **Competitive electrification is a way to accelerate decarbonization in other sectors** of the economy.

Objectives

With a view to achieving this vision and to making a meaningful contribution to the EU's climate ambition **eurelectric has in the first phase of this project developed three EU decarbonization and electrification scenarios towards 2050** for the main energy-using sectors.

In the second phase of this project we have analysed in detail the **decarbonization pathways to drive the power sector** towards **carbon-neutrality well before 2050** at the lowest possible cost for each of our three EU decarbonization and electrification scenarios.

The report from phase 1 of this study can be found on the Eurelectric web site:
https://www.eurelectric.org/news/decarbonisation-pathways-electrification-part/

Key messages

- Our analysis shows that the **European power sector can be fully decarbonized by 2045 in a cost-effective way**. We expect the **cost of wholesale electric supply in a fully decarbonized system to be 70 – 75 EUR/MWh** including storage, which is significantly lower than previous estimates.The transformation will require increased investment levels, but due to rapid cost declines in renewables the overall cost of carbon-neutral electricity generation has been reduced significantly in recent years.

- **The least-cost electricity system that can achieve carbon neutrality** have four key characteristics:
  - **Very high penetration of renewables and significant transmission build.** Renewables, including hydro and sustainable biomass, will represent >80% of electricity supply by 2045 driven by rapid cost decline and large untapped resource potentials. High transmission build allows the benefits of renewables to be shared across Europe
  - **System reliability and flexibility needs provided by multiple sources in the power sector and from other industrial sectors**. These include hydro, nuclear power and gas, and emerging sources deployed at scale such as demand side response, battery storage, hydrogen electrolysis and power-to-X
  - **Changing role of fossil generation.** Fossil electricity supply will be gradually phased out and represent only ~5% of total supply by 2045. However, gas will still represent ~15% of total installed capacity to contribute to system reliability, especially in regions that don't have access to hydro or nuclear
  - **Decreasing costs of carbon neutral technologies and innovation to abate the last tons of CO2 emissions** (e.g. CCS, negative emissions) coming from the marginal use of the remaining thermal capacity such as negative emissions and CCS technologies

Key messages

- Achieving this ambitious objective will require the fast implementation of six enablers across society:
  - **Political commitment to deep decarbonization across all sectors** of the economy and across regions. Continued efforts to integrate the European energy system
  - **Active involvement of citizens** e.g. through demand response and prosumers and **increased social acceptance** for high renewables build out and new transmission lines
  - **Synergies with other sectors**. For example, P2X and H2 production enable decarbonization of other sectors while providing balancing capabilities to the power system. Existing gas pipeline infrastructure can be repurposed for power to gas and hydrogen transport and storage
  - **Efficient market-based investment frameworks and adequate market design** to trigger investments in a high renewables-based system. For example, resources must to a larger extent be valued based on their contribution to system reliability. Meaningful CO_2 price signals will also be required to sufficiently incentivize full decarbonization
  - **A smarter and reinforced distribution grid** that integrates new market participants (e.g. decentralized solar PV and local flexibility sources), and plays a significant role in consumer empowerment through managing local congestions and redispatch, security of supply and grid resilience issues
  - **The path and investments required to reach full decarbonization differs by country** as European regions have different existing electricity mix and resources available. To ensure just energy transition **support and dedicated EU funding will be required for Member States that face a more difficult starting point** in the electrification and energy transition journey.

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Our analysis builds on a granular multi-factor approach

The analysis focuses on what is required for the power sector to become carbon neutral well before 2050 with a view to

- Promote a sustainable and healthy society for European citizens, through carbon neutral electricity and enhanced cities' air quality, esp. through electrified transportation
- Secure long-term affordable, reliable and flexible electricity supply to all Europeans

The study is based on least cost optimization model that identifies the European power system that minimizes costs and achieves carbon neutrality well before 2050. We optimize along several dimensions including generation and capacity mix and sources of system flexibility incl. demand side response and storage

In addition we test these results against market-related and political realities, e.g. national renewable targets, government nuclear decommissioning plans, and generation capacity under construction

Outputs from this multi-factor analysis were syndicated through a very comprehensive stakeholder engagement with all eurelectric members as well as with external stakeholders through workshops and discussions with relevant stakeholders by sector and industry

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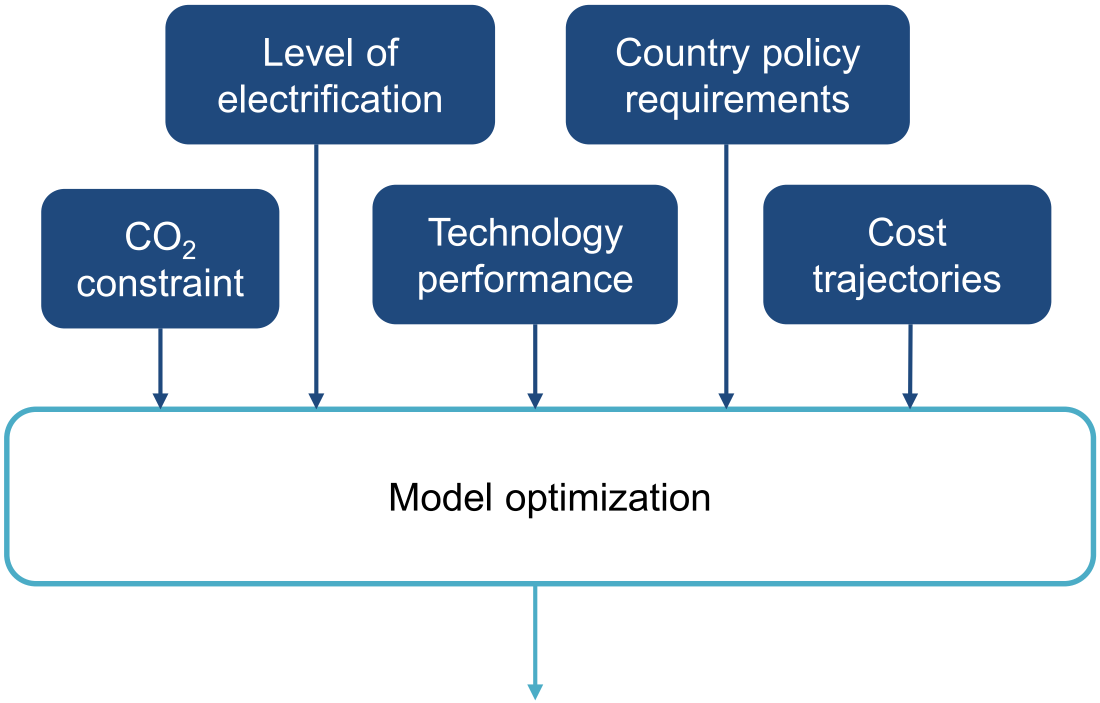
Our study is based on a rigorous modelling exercise

- The model determines which **power sector investments and operating decisions minimize costs** while meeting the target of full carbon neutrality
- We model solutions for 8 European regions

Inputs vary by scenario



Outputs

Least cost system decarbonization for each scenario modelled, including capacity and generation mix, sources of flexibility, cost and investment required

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We have modelled 3 deep decarbonization scenarios based on electrification of key economic sectors

	2015 – Baseline	2050 scenarios: Scenario 1	Scenario 2	Scenario 3
EU economy decarbonization achieved vs. 1990[1,2]	~22%	~80%	~90%	~95%
Direct electrification rate	~22%	~38%	~48%	~60%
Indirect electrification rate	~0%	~4%	~5%	~5%

Cost breakthrough scenario in which we are driving towards full EU economy decarbonization. Assumes accelerated cost decline for renewables, nuclear, CCS and storage

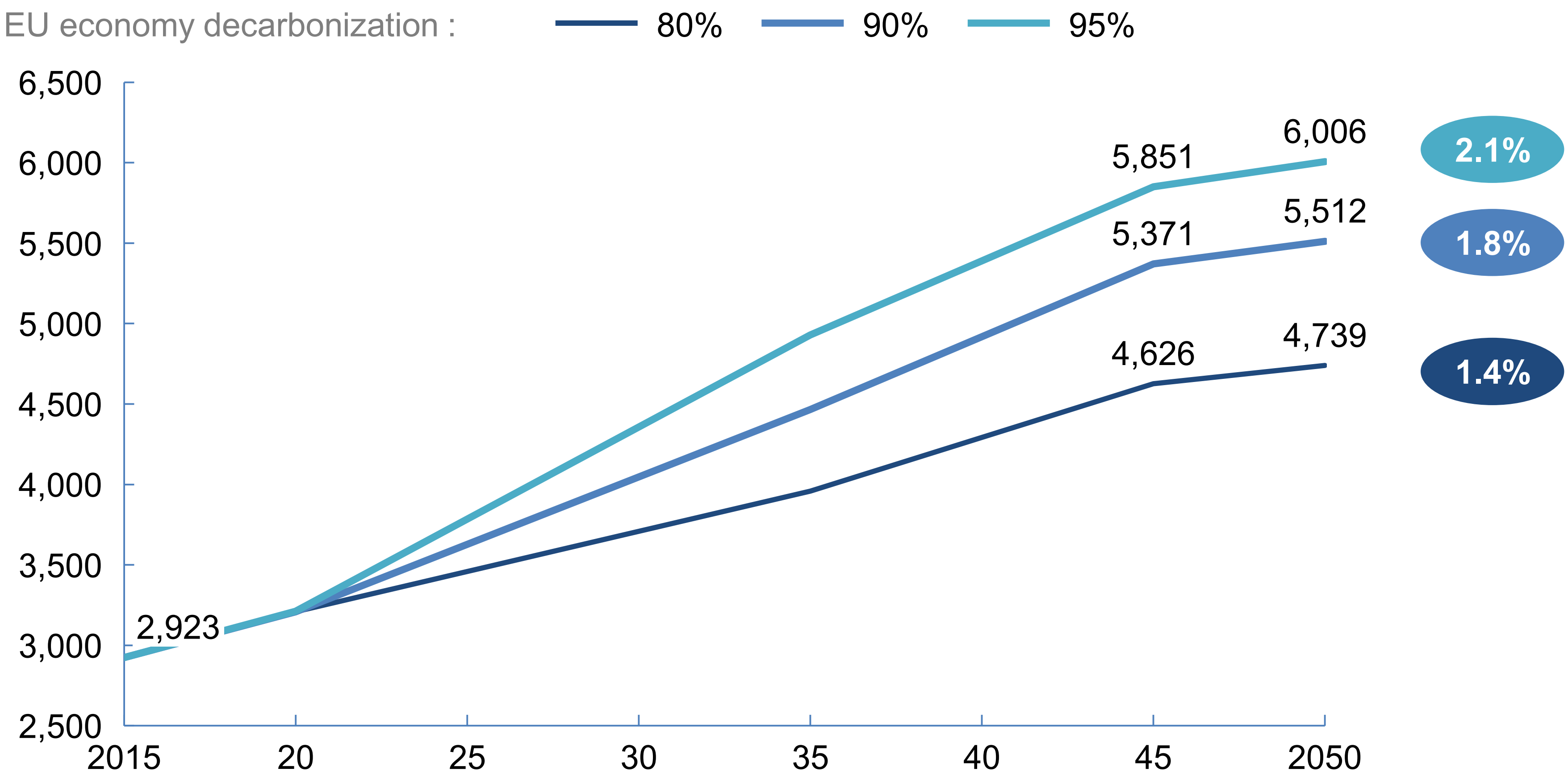
1 Emissions out of scope are expected to contribute proportionally to the decarbonization effort required in each scenario

2 Decarbonization will be different by sector depending on relative costs and available technologies, industry contributing least with below 80% of emission reduction in all scenarios

We consider three levels of final electricity demand which correspond to different levels of EU economy decarbonization

Electricity demand[1], TWh

CAGR[2] 2015 – 2050



1 Including indirect electricity demand for P2X and H2 production used in other sectors
2 Compounded annual growth rate

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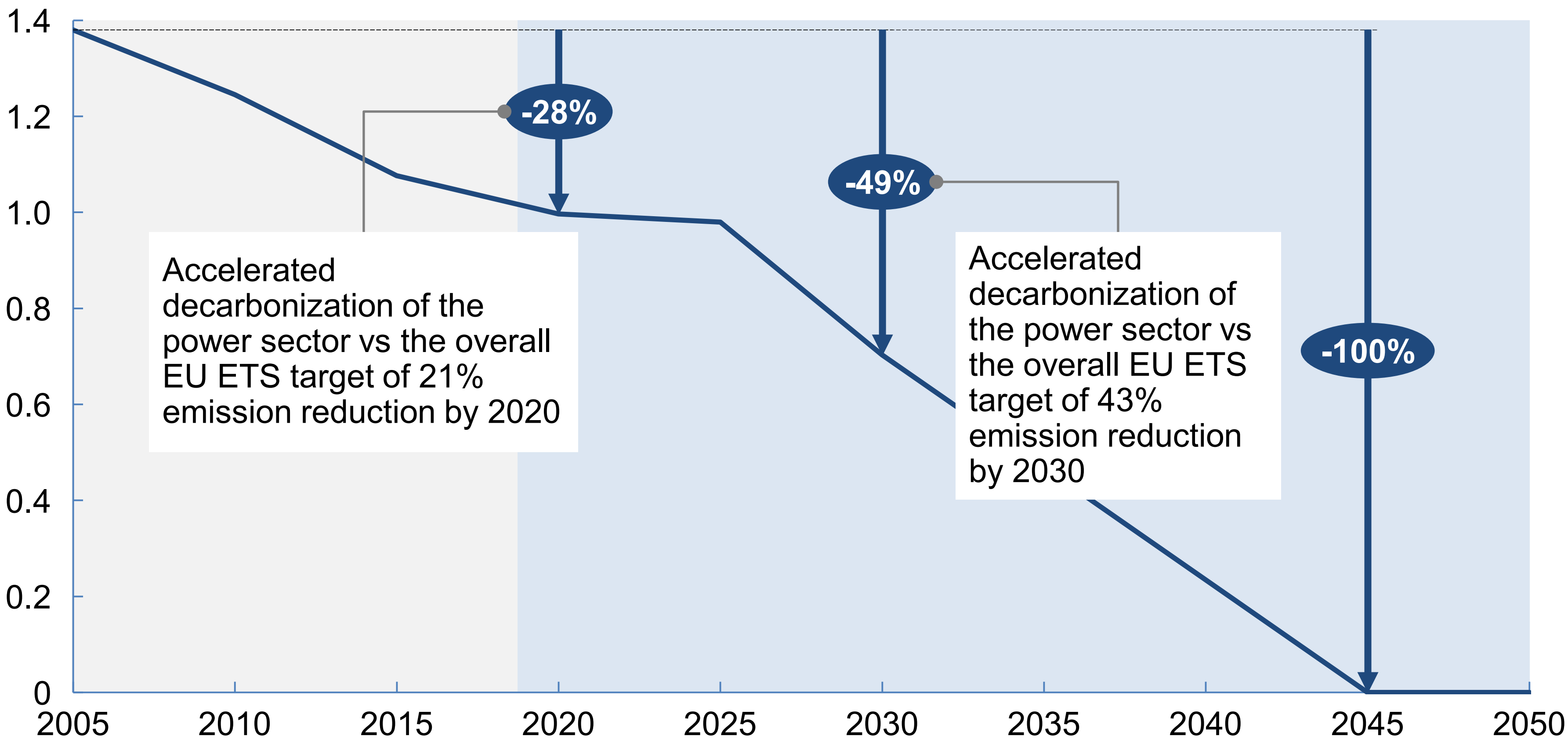
In all three scenarios, the European power sector is carbon neutral by 2045

CO_2 emissions from power sector in all scenarios, GT CO_2



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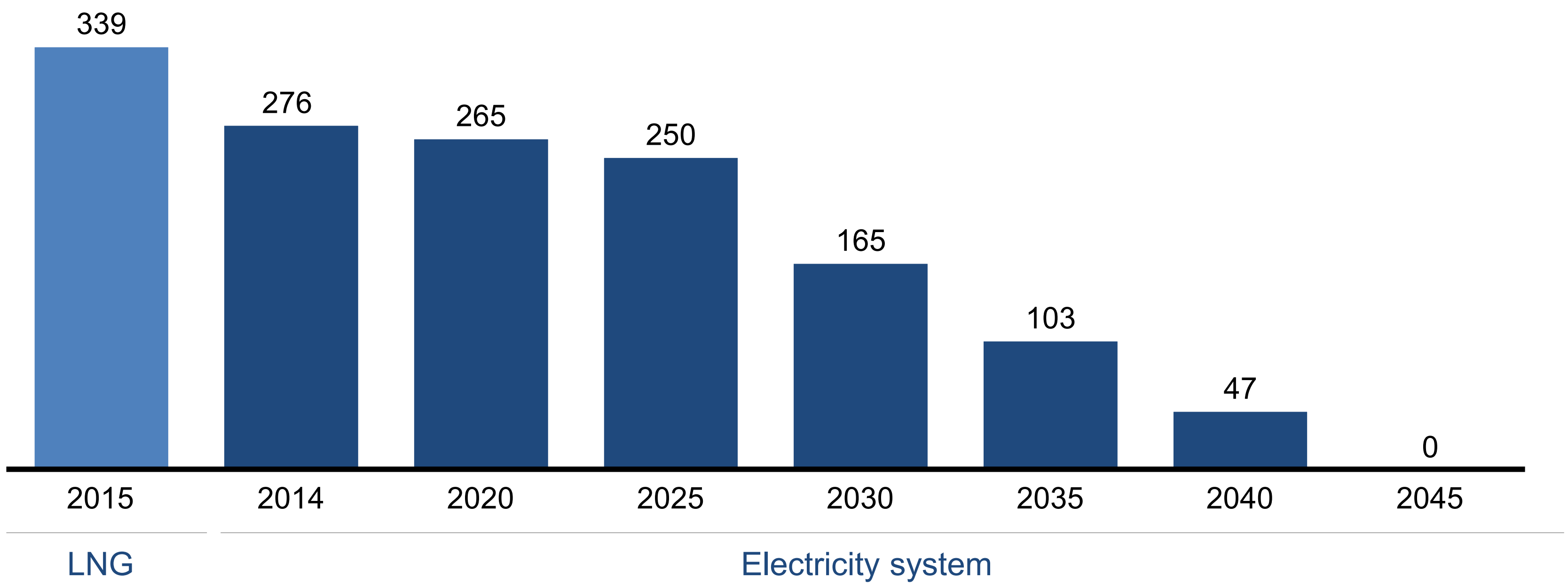
Electricity will continue to be the energy carrier with lowest carbon content per MWh going forward

Carbon intensity of electricity supply, g/KWh

80% EU economy decarbonization



90% scenario	276	265	243	155	92	40	0
95% scenario	276	265	237	145	84	36	0

SOURCE: EC 2015 Fuel Quality Directive; EEA

Power sector decarbonization scenarios

By 2045 we envision a carbon neutral power sector that makes a significant contribution to decarbonization of the EU economy

High penetration of renewables and transmission build will be the main driving force of the European energy transition. Renewables will represent >80% of electricity supply driven by large untapped potential and rapidly declining cost

System reliability and flexibility needs provided by multiple sources in the power sector and from other industrial sectors. These include hydro, nuclear power and gas, and emerging sources deployed at scale such as demand side response, battery storage, hydrogen electrolysis and power-to-X

Changing role of fossil generation. Fossil electricity supply will be gradually phased out and represent only ~5% of total supply by 2045. However, gas will still represent ~15% of total installed capacity to contribute to system reliability, especially in regions that don't have access to hydro or nuclear

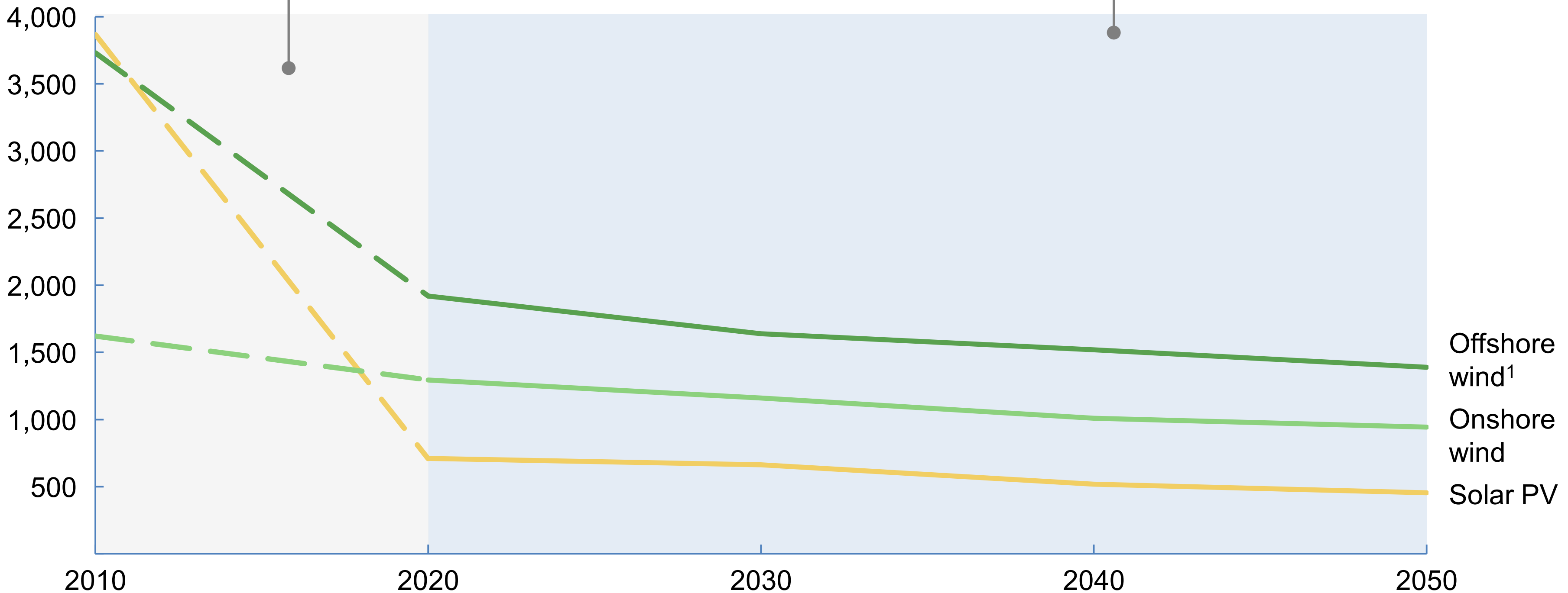
Decreasing costs of carbon neutral technologies and innovation to abate the last tons of CO2 emissions (e.g. CCS, negative emissions) coming from the marginal use of the remaining thermal capacity such as negative emissions and CCS technologies

Renewables have seen massive cost reductions over the past decade and decline is expected to continue

Capex by technology, EUR/KW

Smarter regulations and technology development have driven **significant cost reductions and efficiency improvements in renewables** over the last years.

Cost decline is expected to continue, but at a slower pace in coming years typical based on learning curves and scale. Less optimal locations will also be used



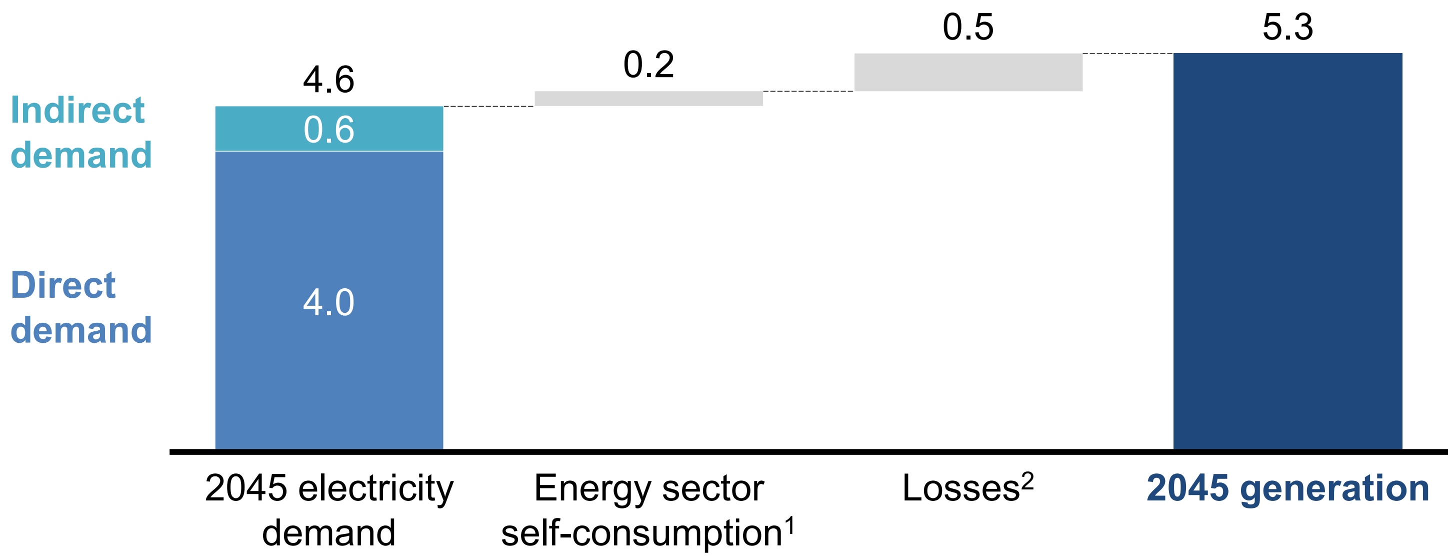
1 It refers to shallow water

SOURCE: IRENA ("Renewable Power Generation Costs in 2017") for historical data; ASSET Project ("Technology pathways in decarbonisation scenarios") ãnd Danish Energy Agency (Technology Data for Energy Plants for Electricity and District heating generation) for future projections

Total power generation is higher than end use electricity demand to account for losses and energy sector self-consumption

Electricity demand and generation, 1000 TWh

80% EU economy decarbonization

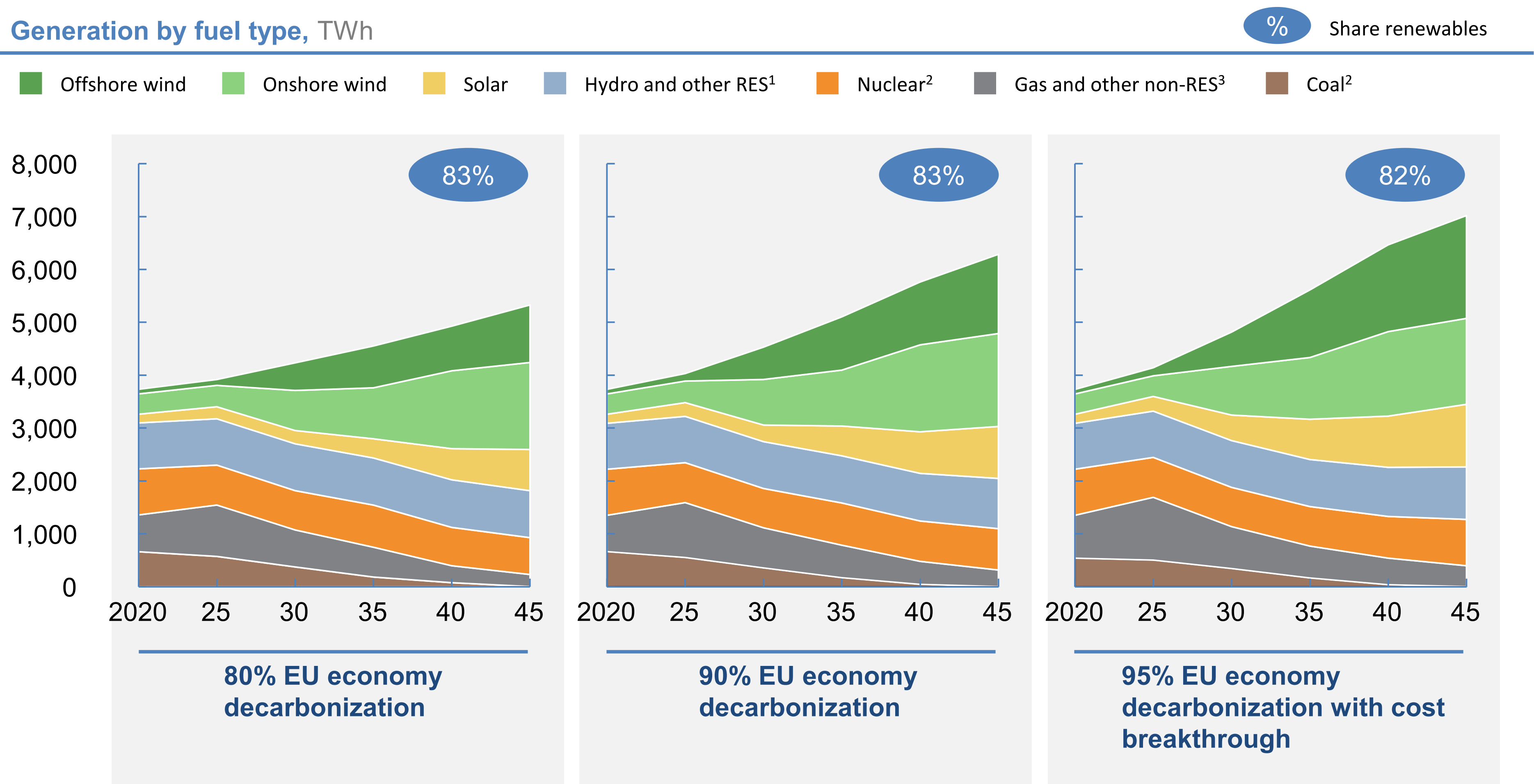


	2045 electricity demand	Energy sector self-consumption[1]	Losses[2]	2045 generation
90%	**5.4**	0.2	0.7	**6.3**
95%	**5.9**	0.2	0.9	**7.0**

1 Includes power sector self consumption (electricity, CHP, heat plants), consumption in oil and gas extraction, in petroleum refineries and in coal mines
2 Includes grid and battery storage losses

In the least-cost, carbon neutral electricity system the bulk of electricity is provided by renewables and nuclear

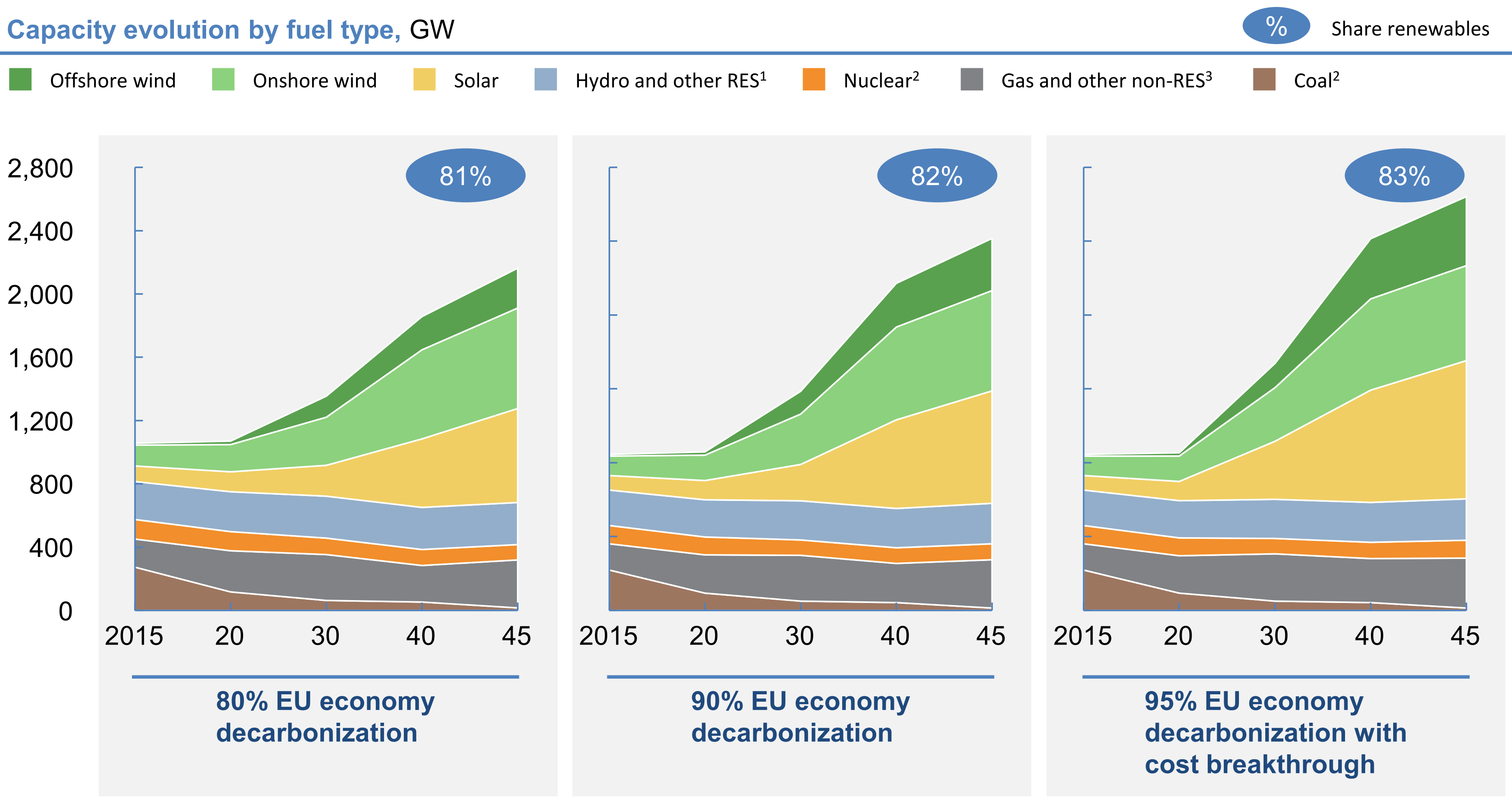
Generation by fuel type, TWh



1 Includes also small amounts of geothermal, biomass and biogas
2 National policies on nuclear and coal phase out have been reflected
3 Up to 15% of gas capacity with CCS and other non-renewables

Renewables account for ~80% of total installed capacity by 2045, while coal is phased out over the period

Capacity evolution by fuel type, GW



1 Includes also small amounts of geothermal, biomass and biogas

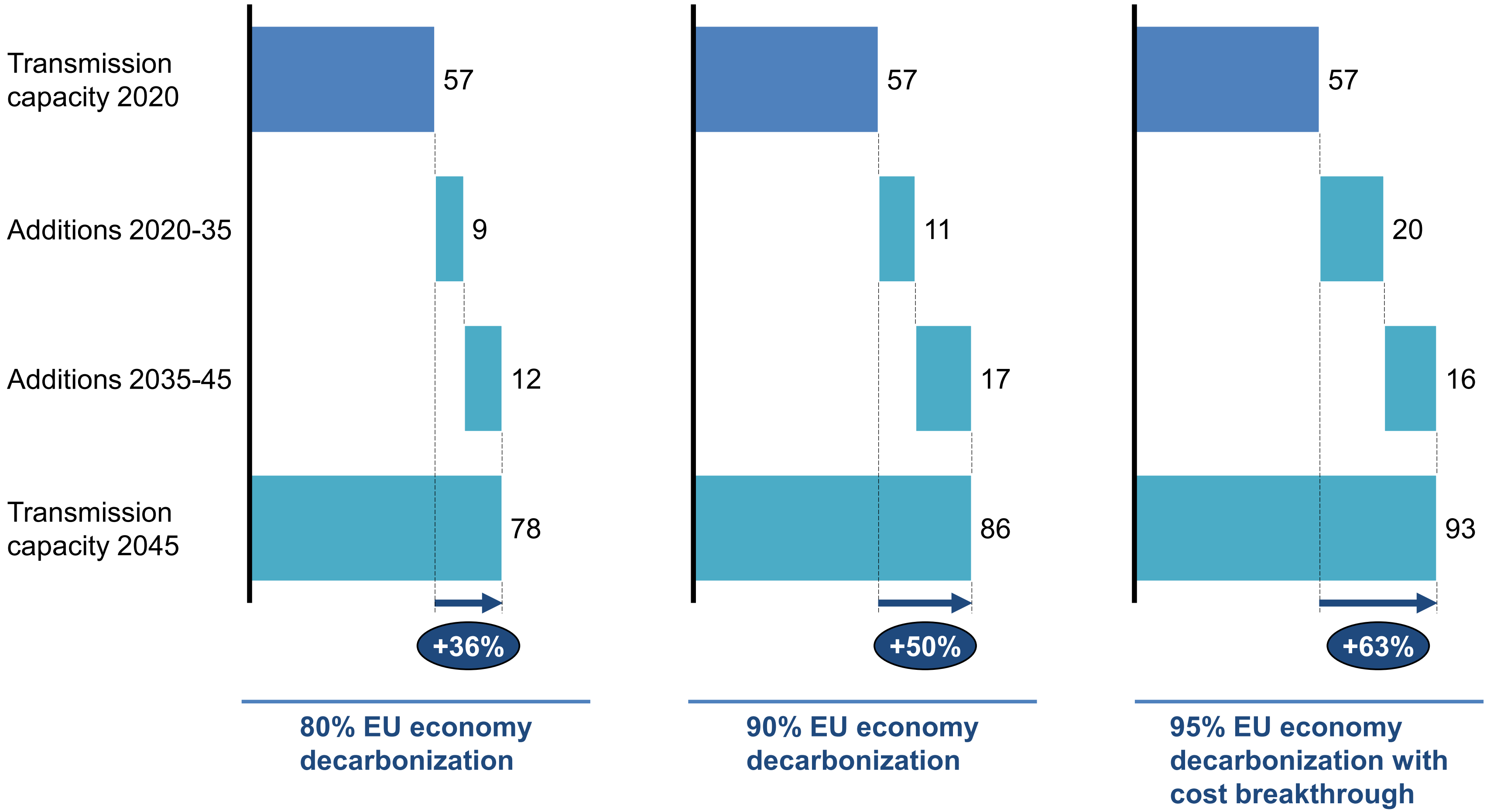
2 National policies on nuclear and coal phase out have been reflected

3 Up to 15% of gas capacity with CCS and other non-renewables

SOURCE: 2015 capacity from Enerdata

Transmission between regions enable a low cost energy transition as the benefit of renewables can be shared across Europe

Transmission capacity between regions, GW

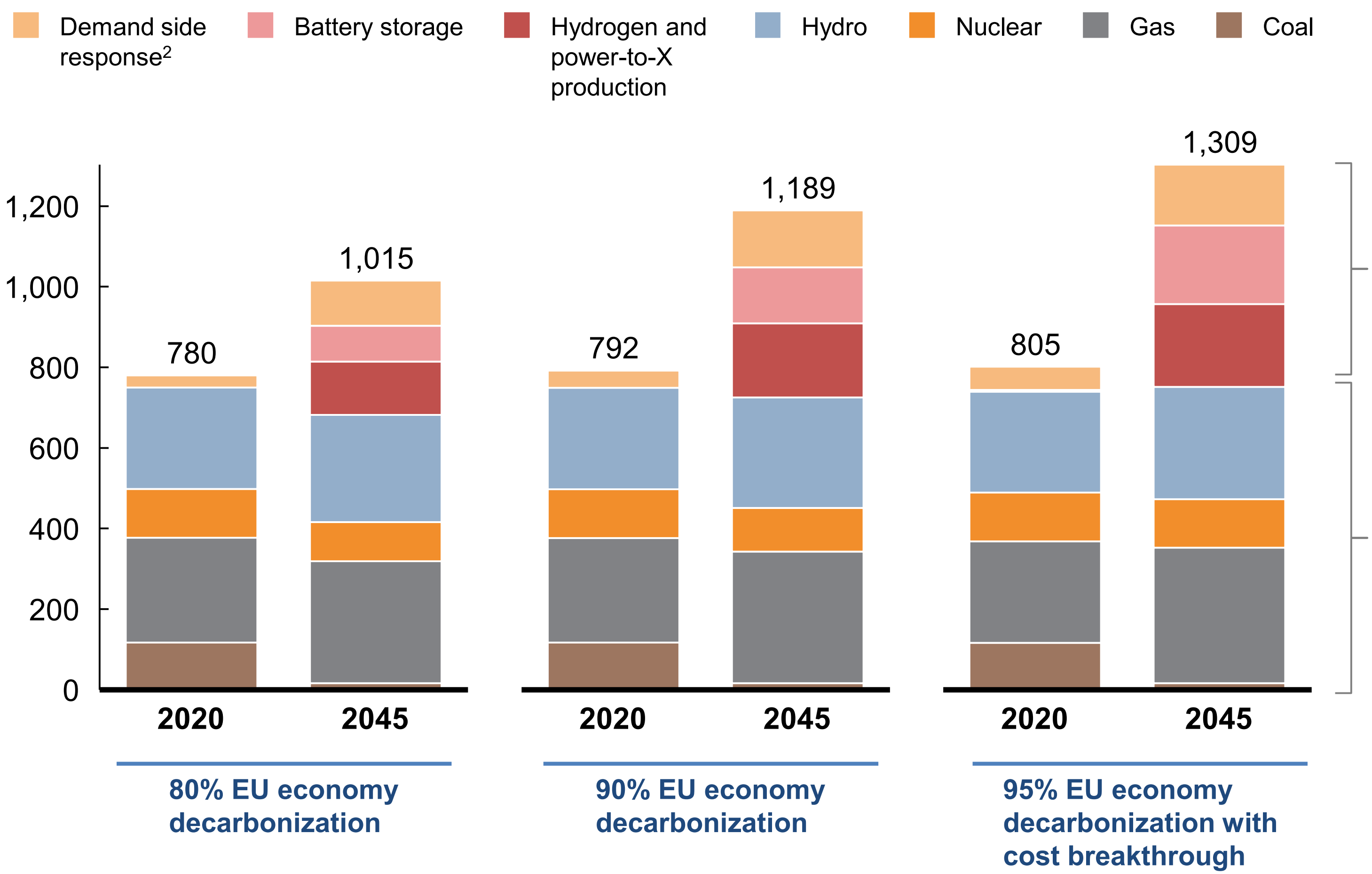


A system-wide shift from dispatchable generation to renewables will require new sources of system reliability and flexibility

- A shift from dispatchable generation to renewables **require new sources of balancing to respond to variability in renewables production**
- **Renewables production varies hour to hour and across seasons** due to changes in weather conditions. It also **varies by region, due to differences in resources available** and climate conditions
- Different sources of reliability and flexibility can **serve different system needs**. For example
  - **Hourly demand peaks** can be met by **hydro**, **demand-side response and dispatch of battery storage**
  - **Seasonal supply variations** can be bridged by varied **production of P2X and H2, nuclear and hydro**
  - **Regional supply peaks** can be met by **higher exports** through an interregional transmission system
- Sources can also **compete with each other** and will require well designed flexibility markets

System flexibility is provided by several sources of dispatchable resources serving as back-up for days with low renewable generation

Dispatchable resources[1], GW



New sources of flexibility

- Enable better utilization of other generators
- Significant increase in capacity expected

Traditional sources of flexibility

- Similar capacity needed in a high renewables, higher demand system as today
- Provide electricity when renewables production is low and ability to leverage DSR has been exhausted
- Hydro plays a unique role and can improve the overall dispatch and system economics

1 District heating that is coupled with power sector is not included in this analysis
2 DSR flexibility is provided by hour to hour load shifting in transportation, buildings and heating

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ILLUSTRATIVE

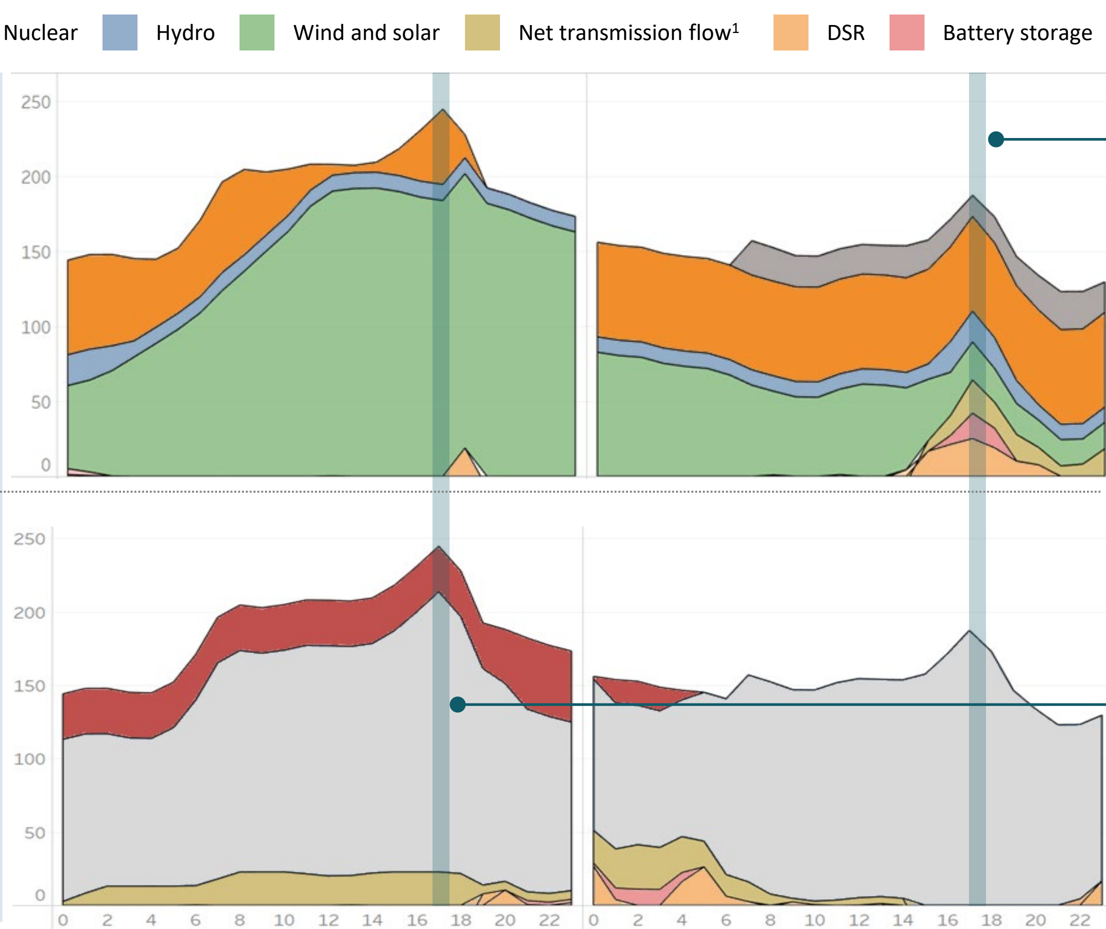
Example: The system uses a variety of flexible resources to match supply and demand when renewable production is low

Unconstrained day: 14th Dec, 2045

Constrained day: 18th Dec, 2045

Generation GWh

Demand GWh



- Most constrained hour for reliability is **defined by very low renewable output**
- **Remaining thermal capacity maintains system reliability** when renewables are low
- **Dispatchable resources all contribute** in the most constrained hour
- Dec 14th demand higher than Dec 18th, but existence of higher renewables result in no thermal dispatch. **Surplus electricity is used for P2X and exports to other regions**

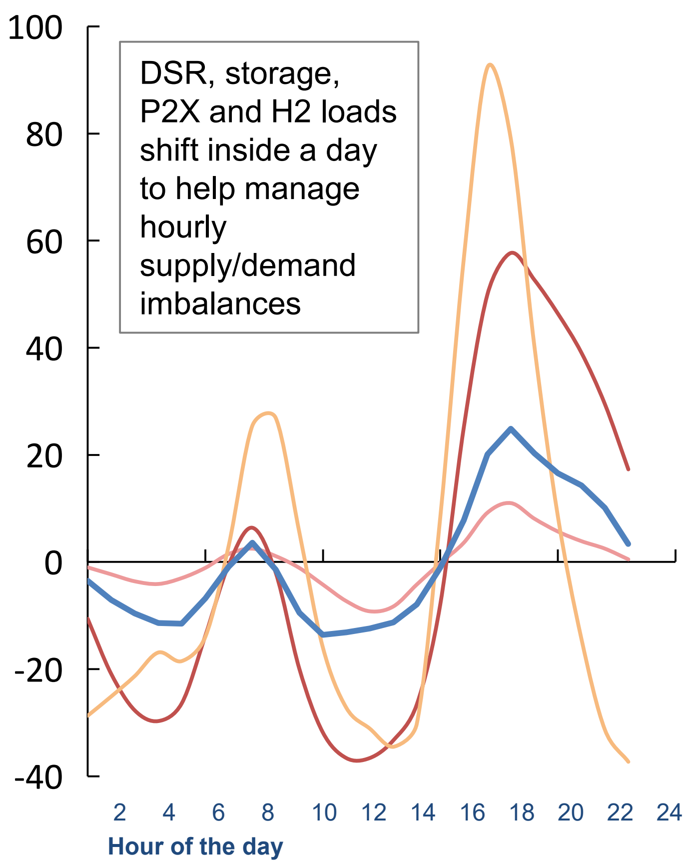
1 Imports/exports

Short-term and seasonal system balancing are supported by several competing sources

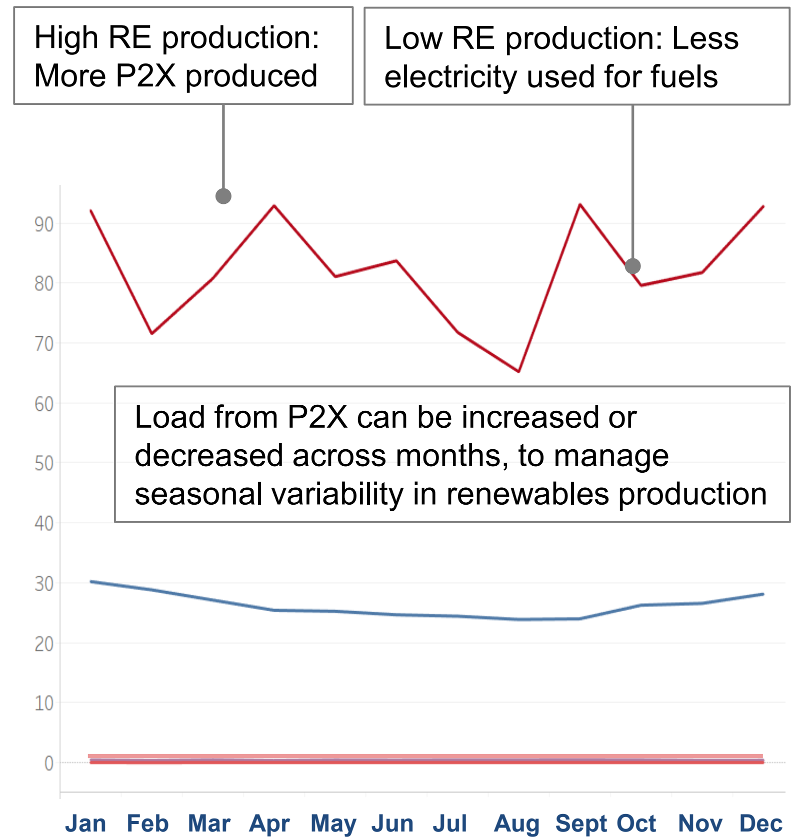
Carbon neutral flexibility is provided intra-day (hourly) to match short term variations in intermittent production

Power-to-X, hydrogen production, and hydropower are also able support to seasonal balancing

Daily balancing[2], 2045, GW



Seasonal balancing[3], 2045, TWh



1 Production of H2 and Power-to-X required for decarbonization outside of the electric sector
2 Difference from system average load / output by type of resource
3 Variation in load shown for P2X/H2; variation in production shown for hydropower

P2X and H2 production is driven by demand from other sectors and would be lower if based solely power sector economics

External demand for P2X and H2 is important but not essential for the system

- To meet 80%, 90% and 95% decarbonization targets **we assume demand for P2X and H2 in other sectors.** Production of these fuels account for 14 – 19% of total electricity demand and is an **important balancing resource for the system**
- In a sensitivity check on the 95% scenario where we remove all external demand for P2X and H2 we find significantly **lower production of these fuels when only based on power sector economics.** Non-availability of these fuels would imply that other decarbonization options would be needed for other sectors to reach 80 – 95% reduction
- A **high renewables system would still be viable**, but would use other sources of flexibility such as batteries

Key differences in a power system with no external demand for P2X and H2

~10% **lower electricity demand** by 2045 due to lower demand for P2X and H2

~30% lower offshore wind generation and **~20%** lower solar generation due to lower electricity demand

~75% **lower P2X and H2 production** vs when defined by demand from other sectors

~50% **higher battery capacity** replacing P2X and H2 for short-duration balancing

Demand side response can be leveraged for short term balancing and will play a larger role in the future power system

Transport

- Demand from **electrified light duty vehicles in aggregate is very flexible.** However, flexibility may be reduced by increased ride sharing and automation
- **Medium duty vehicles also have some flexibility**, but have higher utilization and less flexibility for day-time charging in particular

Buildings

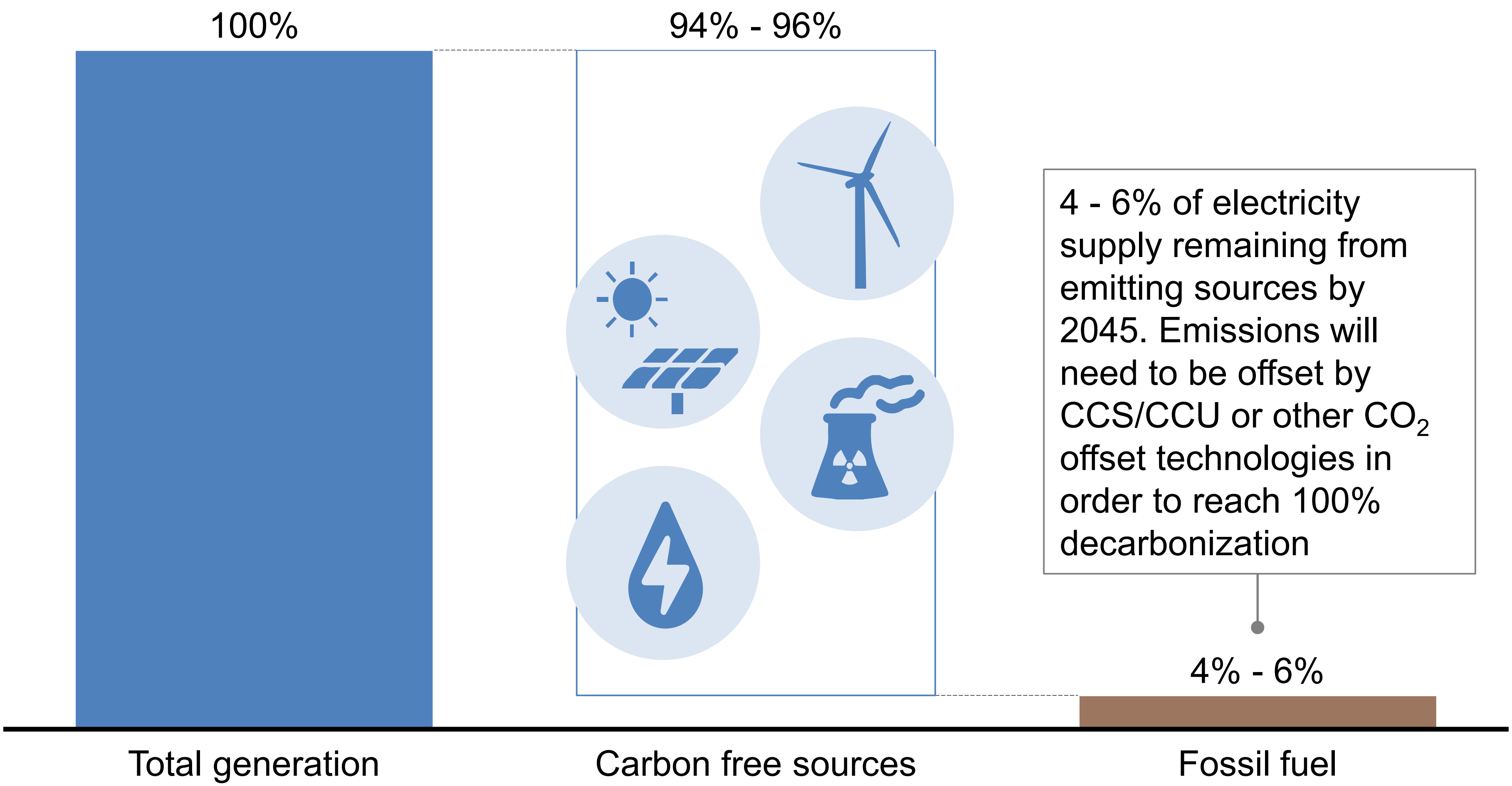
- **Space heating/cooling and water heating** use a thermal mass inside a building or in a heating network to shift demand either forward or backward in time

Industry

- **Industry process loads are diverse in their ability to provide demand-side flexibility**. Some loads provide almost no room for shifting (e.g., mechanical manufacturing activities), while others are highly flexible (e.g., commodity heating with low temperature sensitivity)

At least 120-150GW of DSR flexibility in the system by 2045

By 2045, 95% of emissions are abated through a transition to carbon neutral electricity supply



Achieving 100% decarbonization will still require innovation and accelerated maturation of abatement technologies

CCS/CCU

- CCS can be a solution to abate emissions from centralized fossil generation that is operating at sufficient utilization to justify the high upfront costs required for these installations
- While CCS is still an immature and expensive technology, there are potential synergies in technology development and scale advantages as it is also likely to be needed for other sectors where no other solution is feasible (e.g. abating process emissions in cement production)

Direct air capture[1]

- DAC is still a very immature technology with high variable cost and will likely require further research and development before it is ready for commercial scale deployment
- Due to lower upfront costs, DAC can be a solution to abate emissions from emitting fossil generation with too low utilization to justify CCS installation

Dedicated H2/green gas

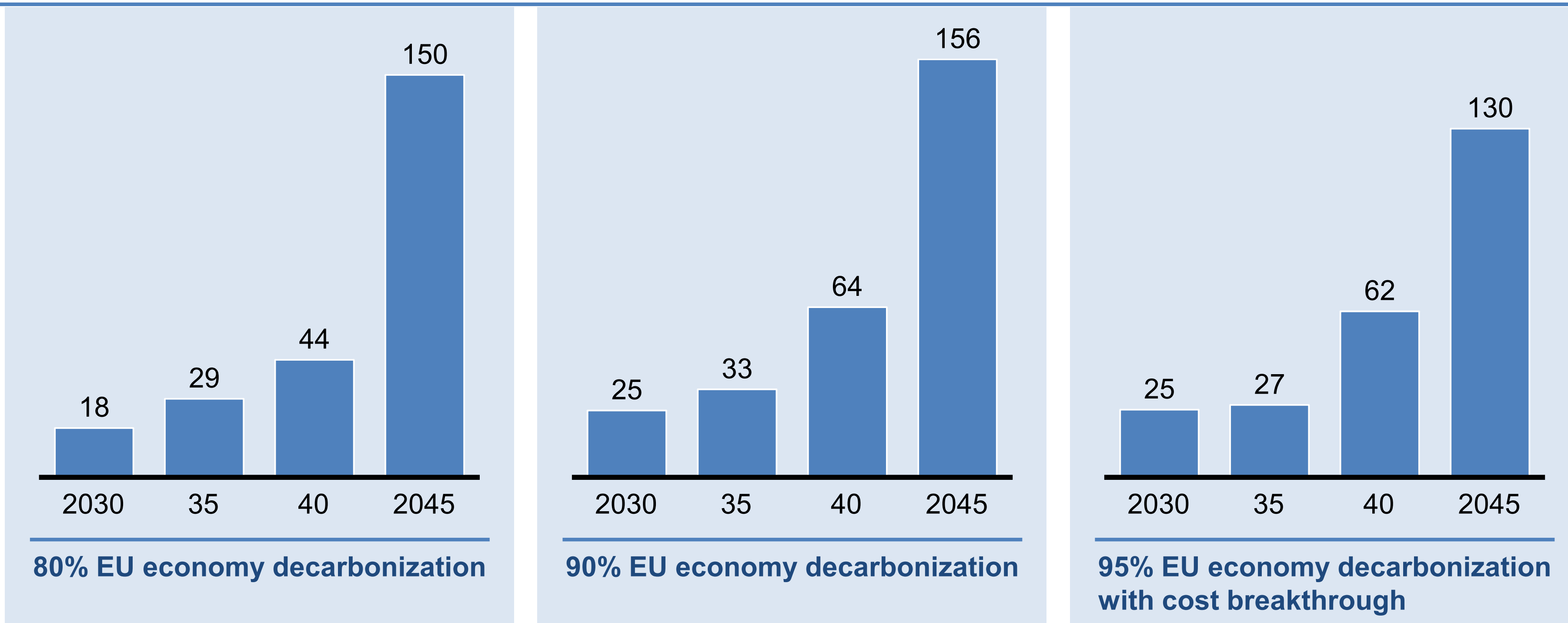
- Hydrogen and green gas produced with clean electricity can be reinjected to the grid, but this process currently involves high efficiency losses. However, the added benefit of providing flexibility to the power system must also be taken into account

In addition, further development of carbon free electricity sources, e.g. tidal and floating offshore wind could provide an alternative solution to decarbonizing the last percentage points of emissions

1 DAC is a technology that processes atmospheric air, removes CO_2 and purifies it

Most emissions can be abated at a cost of 18 – 64 €/ton, but the last tons of emissions are significantly more expensive to abate

Marginal abatement cost of CO_2[1,2], EUR/ton

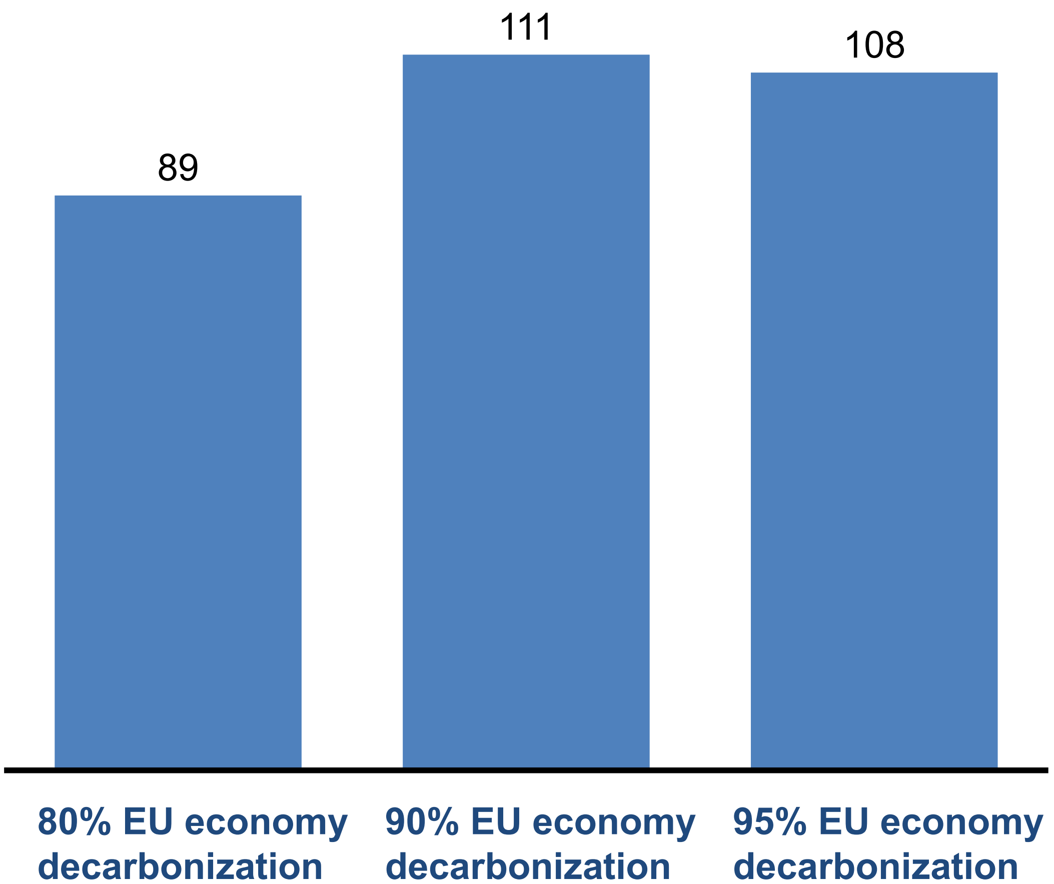


The marginal abatement cost of the *final* ton of CO_2 is difficult to estimate at it is closely tied to the cost of immature technologies, e.g. CCS. Foreseeing future cost trajectories for such technologies in a 2050 perspective is difficult. As a consequence, there is high uncertainty around what marginal abatement cost could actually be in 2045.

1 CO_2 abatement cost applies to the power sector only and is not representative of the price required to decarbonize other sectors of the economy which is likely to be higher
2 Real cost linked to 2016 price levels

Significant investments will be required to decarbonize the power sector, but will also enable decarbonization of other sectors

Average annual capital investment cost 2020 - 2045[1], EUR bn

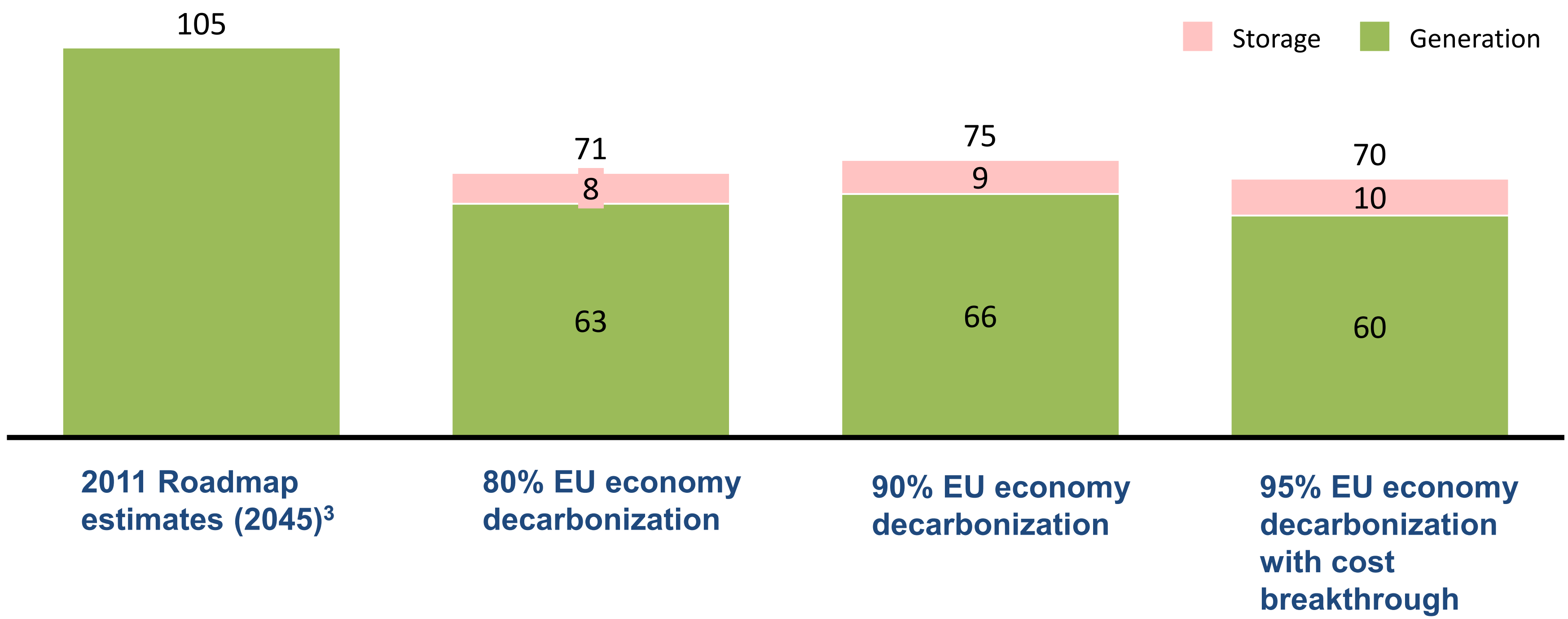


- Reaching 80 – 95% EU economy decarbonization will require a **significant ramp-up of investments** to accomplish
  1) large **increase in generating capacity to meet electricity demand growth** that is unprecedented in recent times
  2) **shift of the current generation stack** to carbon neutral electricity sources
- These investments will **compensate for investments needed to decarbonize other sectors** and are not for the power sector alone

1 Real cost linked to 2016 price level

Due to cost declines of renewables, decarbonization of the power sector now comes at a reduced cost

Cost of wholesale electric supply, 2045[1,2], EUR/MWh

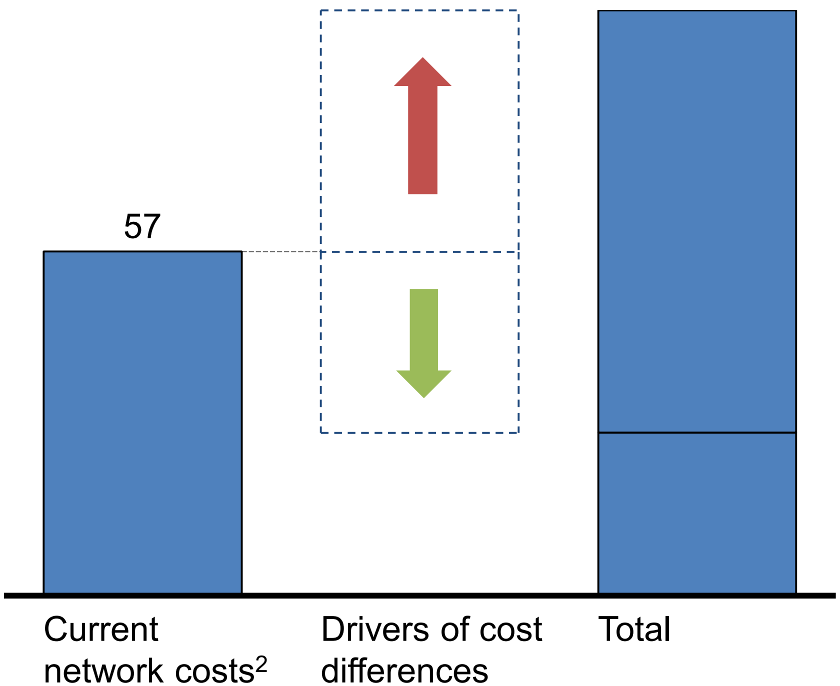


A carbon neutral power supply by 2045 can be accomplished with generation costs of 70 – 75 EUR/MWh. Due to rapid cost declines and more options for flexibility in the system, the overall cost of decarbonization has decreased significantly since previous estimates and the pathway is now achievable

1 Levelized cost approach approximates in-year revenue required to match cost; includes operating costs (e.g., fuel, variable O&M); additionally, capital expenditures (e.g., wind farms, battery storage, or CCS-retrofits) are amortized over the economic lifetime of the asset
2 Real cost linked to 2016 price level
3 Generation includes Fixed Costs, and Variable and Fuel costs; Tax on fuels and ETS auction payments included for comparison against net zero carbon scenarios

Future grid costs will be impacted by different drivers

Network costs, EUR/MWh



Drivers of cost differences[1]	**Potential Impact**
• Grid expansion costs (T&D), driven by relative peak load increases	↑
• Grid modernization - remote monitoring and controls to reduce downtime, labor and improve knowledge of network flows	↓ ↑
• Digitization	↓
• Scale effects – higher load, better utilization of many feeders	↓
• Power-to-gas load siting – At gen sites: 5-15% increase in relative peak – On bulk network: 20-40% increase in relative peak	↓ ↑

Implementation details including grid planning processes, regulations, decentralization of generating assets, and security requirements will have a significant impact on network costs under the same generation scenario

1 Included in DEM as part of generation costs: Offshore wind interconnection, transmission connection of new wind/solar plants, curtailment
Included in DEM explicitly: inter-regional transmission
2 Country-level volume weighted network costs for non-household customers from 2017 Eurostat public data

Key enablers for a low cost carbon neutral power sector

A low cost, carbon neutral power sector must be supported by changing political, technological and market conditions

Political commitment to deep decarbonization across all sectors of the economy and regions. Continued efforts to integrate the European energy system

Active involvement of citizens e.g. through demand response and prosumers, and **increased social acceptance** for high renewables build out and new transmission lines

Synergies with other sectors. For example, P2X and H2 production enable decarbonization of other sectors while providing balancing capabilities to the power system. Existing gas pipeline infrastructure can be repurposed for power to gas and hydrogen transport and storage

Efficient market-based investment frameworks and adequate market design to trigger investments in a high renewables-based system. For example, resources must to a larger extent be valued based on their contribution to system reliability. Meaningful CO_2 price signals will also be required to sufficiently incentivize full decarbonization

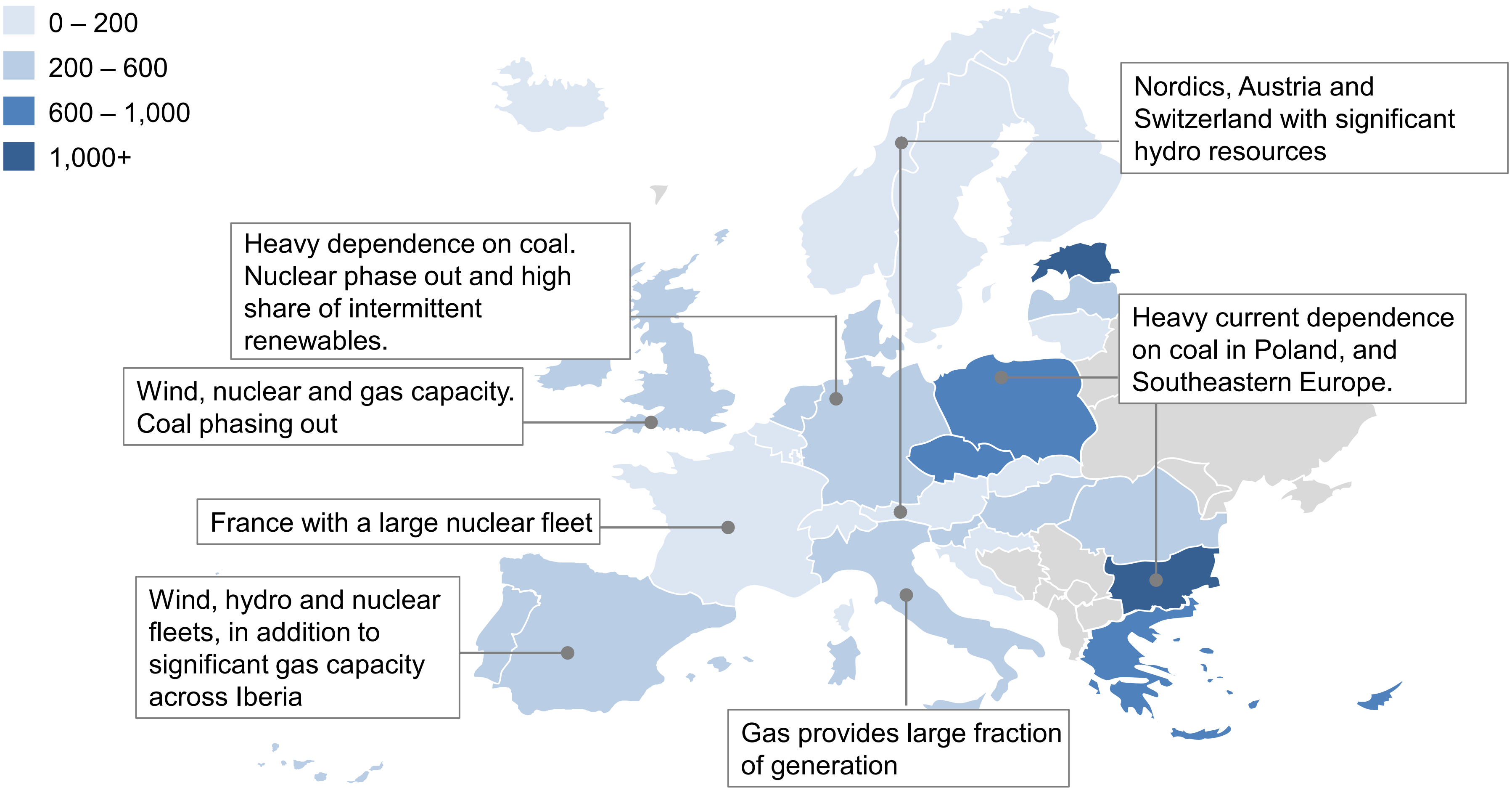
A smarter and reinforced distribution grid that integrates new market participants (e.g. decentralized solar PV and local flexibility sources), and plays a significant role in consumer empowerment through managing local congestions and redispatch, security of supply and grid resilience issues

The path and investments required to reach full decarbonization differs by country as European regions have different existing electricity mix and resources available. To ensure just energy transition **support and dedicated EU funding will be required** for Member States that face a more difficult starting point in the electrification and energy transition journey.

Different starting points

European countries have different starting points in the energy transition

2015 carbon intensity of electricity[1], kg CO_2/MWh



1 Refers to carbon intensity of domestic electricity production, i.e. does not take into account the carbon intensity of electricity mix consumed

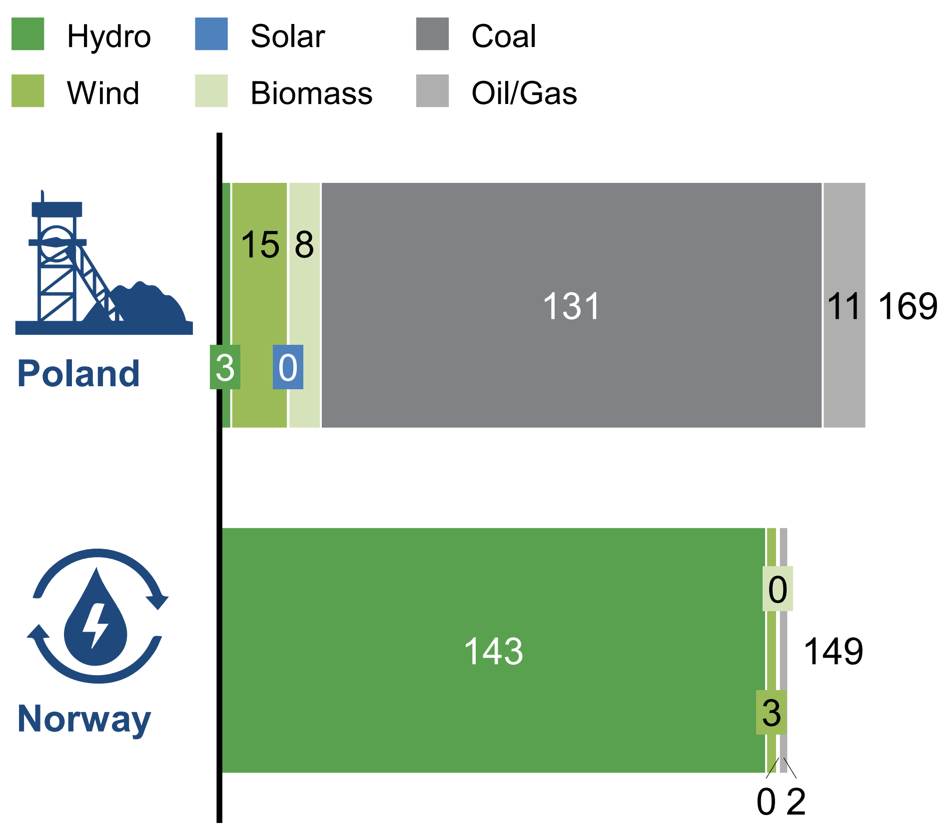
SOURCE: Eurostat and national statistics

Norway's power sector is already decarbonized while Poland relies on coal for ~80% of its electricity supply

Different starting points

- European countries have **very different starting points in the transition towards a carbon neutral power sector**
- At one end of the scale, **Norway has practically already decarbonized its power sector** and has high potential to expand its renewable capacity due to untapped wind potentials and still some hydropower resources
- At the other end of the scale, **Poland currently relies on coal for ~80% of its electricity supply** and face a more disruptive transition to achieve carbon neutrality
- Countries' starting points imply large **differences in cost and the effort and pace of transition required**

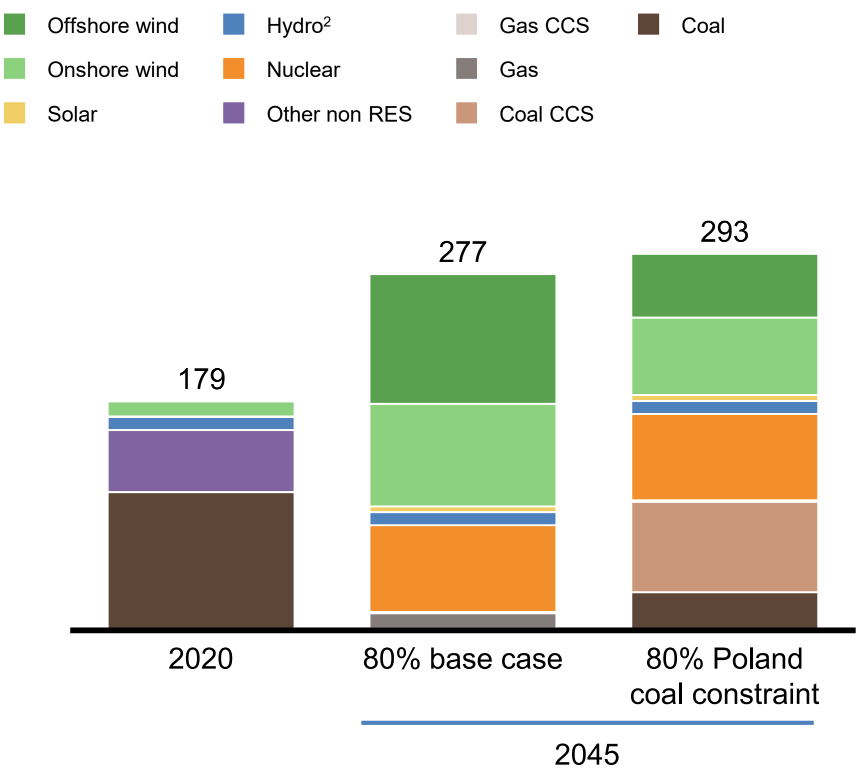
2017 generation by fuel type, TWh



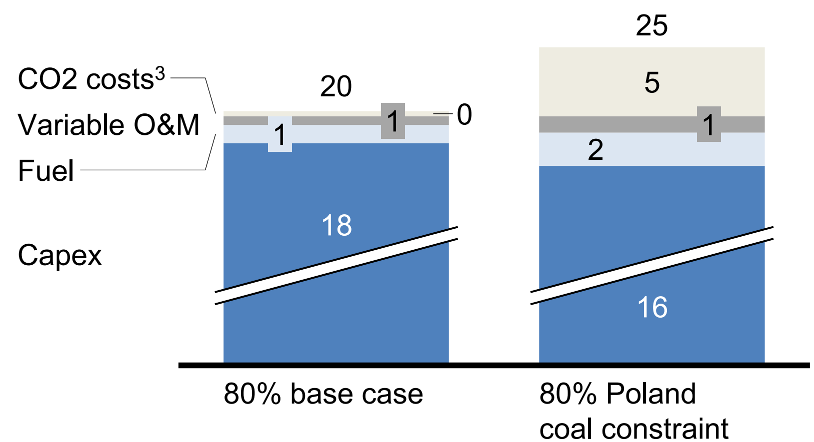
SOURCE: Enerdata

Poland's intension to keep 40% coal in the electricity mix implies lower renewables build and higher generation cost

Generation by fuel type, TWh



Annualized cost of generation[1], 2045, bn EUR



	80% base case	80% Poland coal constraint
Levelized cost of generation, 2045, EUR/MWh	73	85
Total Capex, 2020-45, bn EUR	147	128
Total CO2 costs[3], 2020-34, bn EUR	42	42
2035-45, bn EUR	26	43

Poland is currently discussing a policy to maintain 40% of coal in the energy mix by 2040. We have tested the implication of this policy through a sensitivity analysis that comply with this policy

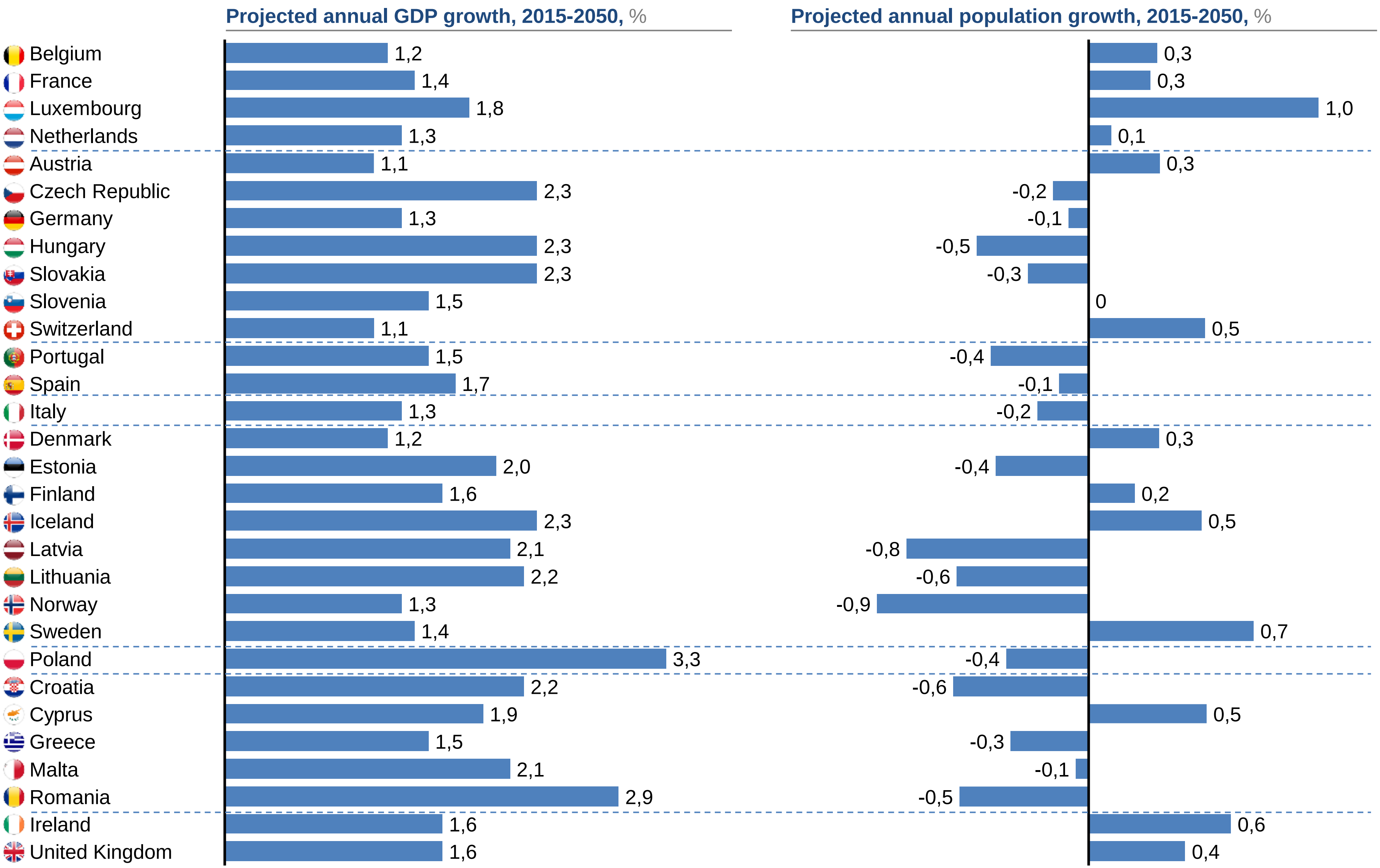
1 Does not include storage nor transmission & distribution cost

2 Includes also small amounts of geothermal, biomass and biogas

3 Estimated as the marginal cost of abatement multiplied by Poland positive emissions (over the periods); the actual CO2 cost will be highly dependent on the future market design and whether Poland can buy emissions allowances from other countries or if it needs to comply internally

Appendix

Macroeconomics differ by region but are constant across scenarios



SOURCE: McKinsey & Company Global Energy Perspective 2018; IT, ES, PT, GR, PL and CZ changed according with government publications, OECD, FMI or other national entities

Glossary (1/3)

- **Total Final Consumption:** Net amount of energy consumed by the different end-use sectors at the point of consumption (e.g. oil used for heating, electricity used for appliances, coal used for industrial processes, etc.) [in terajoules]
- **Electrification:** Share of electricity in Total Final Consumption (TFC) of Energy [Percent]
- **Direct electrification:** Direct use of electricity as an energy carrier (e.g. power consumed by households, road transportation, etc.)
- **Indirect electrification:** Power demand to produce hydrogen (via electrolysis), gas and other synthetic fuels which can then be used to decarbonize certain industry processes or as a fuel for transports. Examples of applications include steel-production (e.g. hydrogen-DRI-EAF route), chemicals industry (e.g. Ammonia production), or transport fuels (e.g. hydrogen fuel for long-haul truck transport)
- **Additional electricity demand for other decarbonization:** Production of fuels or feedstocks can require power, when these are used to replace other carbon emitting fuels or feedstocks, in an effort to decarbonize certain industrial processes or energy usages. Examples include the production of some bio fuels. (Note: electricity used to power district heating only will be considered in phase 2)

Glossary (2/3)

- **Bioenergy:** Energy content in solid (biomass), liquid (biofuel) and gaseous (biogas) fuels derived from biomass feedstocks, biogas and waste
- **Biofuels:** Liquid fuels derived from biomass or waste feedstocks, mostly ethanol and biodiesel
- **Biogas:** A mixture of methane and other gases produced by the anaerobic bacterial breakdown of organic matter such as agricultural waste, manure, municipal waste, plant material, sewage, green waste or food waste
- **Bio methane:** Biogas that has been cleaned and upgraded to natural gas standards
- **Buildings:** The buildings sector consumes energy mostly in residential, commercial and institutional buildings via space heating and cooling, water heating, lighting, appliances and cooking
- **Commercial:** Energy consumed by commercial (e.g. hotels, offices, catering, shops) and institutional buildings (e.g. schools, hospitals, offices)
- **Decarbonization:** Reduction of total cross-sectoral CO2eq. emissions (incl. land-use, agriculture, waste management) between 1990 and 2050 [Percent]
- **Efficiency factor heat pumps vs. other:** A factor of e.g. 400% considered for heat pump's efficiency relates to the relative efficiency of the average heat pump to fossil fuel boilers (i.e., a heat pump is 4x more efficient than a fossil fuel boiler)
- **Green gas:** Synonym for bio methane (see **bio methane**)

Glossary (3/3)

- **Hydrogen from methane reforming**: Hydrogen that is being produced by removing the carbon content from methane (in the context of decarbonization this carbon content is then being captured and either stored or used)
- **Hydrogen from electrolysis**: Hydrogen that is being produced via electrolysis (consumes roughly 2.5 GJ of electricity per GJ of hydrogen, efficiency of 40%) - no carbon emissions arise in the process
- **Industry:** Includes energy consumed across all industrial sectors (e.g. iron and steel, chemical and petrochemical, cement, and pulp and paper) but excludes consumption by industries for the generation of power or transformation of energy (e.g. refining)[1]
- **Power-to-X:** Power-To-X identifies technologies that transform surplus electric power (typically from renewable resources) into material energy storage, energy carriers, and energy-intensive chemical products. The term X can refer to one of the following: power-to-heat, power-to-gas, power-to-hydrogen, power-to-liquid, etc.
- **Residential:** Energy consumed by households (urban and rural)
- **Resistance heating:** Refers to direct electricity transformation into heat through the joule effect
- **Synthetic fuels:** Synthetic fuels or synfuels are liquid or sometimes gaseous fuels obtained from syngas. Syngas is a mixture of carbon monoxide or carbon dioxide and hydrogen, won via electrolysis from water
- **Transport:** Energy consumed in the transport sector by moving goods and persons irrespective of the economic sector within which the activity occurs

1 Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles (e.g. mining and construction) is reported under industry

Abbreviations

- **BEV –** Battery electric vehicle
- **CCS –** Carbon capture and storage
- **CCU** – Carbon capture and utilization
- **CE –** Central Europe
- **CNG** – Compressed natural gas
- **CO_2 –** Carbon dioxide
- **CO_2-eq –** Carbon dioxide equivalent
- **EU –** European Union
- **EU ETS** – European Union Emissions Trading Scheme
- **EV** – Electric vehicle
- **GHG –** Greenhouse gas
- **H_2** – Hydrogen
- **ICE** – Internal combustion engine
- **LNG** – Liquified natural gas
- **NG** – Natural gas
- **TCO** – Total cost of ownership
- **TFC** – Total final consumption

Abbreviations

- **CAGR –** Compound annual growth rate
- **CCS –** Carbon capture and storage
- **CCU –** Carbon capture and utilization
- **CHP –** Cogeneration or combined heat and power
- **CO2 –** Carbon dioxide
- **DAC –** Direct air capture
- **DSR –** Demand side response
- **EU –** European Union
- **EU ETS –** European Union Emissions Trading Scheme
- **H2 –** Hydrogen
- **NIMBY –** Not in my backyard
- **O&M –** Operations and maintenance
- **P2X –** Power-to-X
- **RES –** Renewable energy sources
- **Solar PV –** Solar Photovoltaic
- **T&D –** Transmission and distribution

Units and Conversion factors

- **Units**
  - **GJ** - gigajoule (1 joule x 10^9)
  - **TJ** - terajoule (1 joule x 10^{12})
  - **PJ** - petajoule (1 joule x 10^{15})
  - **EJ** - exajoule (1 joule x 10^{18})
  - **kWh -** kilowatt-hour
  - **MWh -** megawatt-hour
  - **GWh -** gigawatt-hour
  - **TWh -** terawatt-hour
  - **MtCO2 -** (1 ton of CO2 x $10^{6)}$
  - **GtCO2 -** (1 ton of CO2 x $10^{9)}$

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One last word

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