Decarbonization pathways

European power sector

EU electrification and decarbonization scenarios

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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

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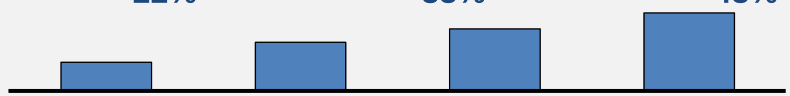
Direct electrification results by scenario

		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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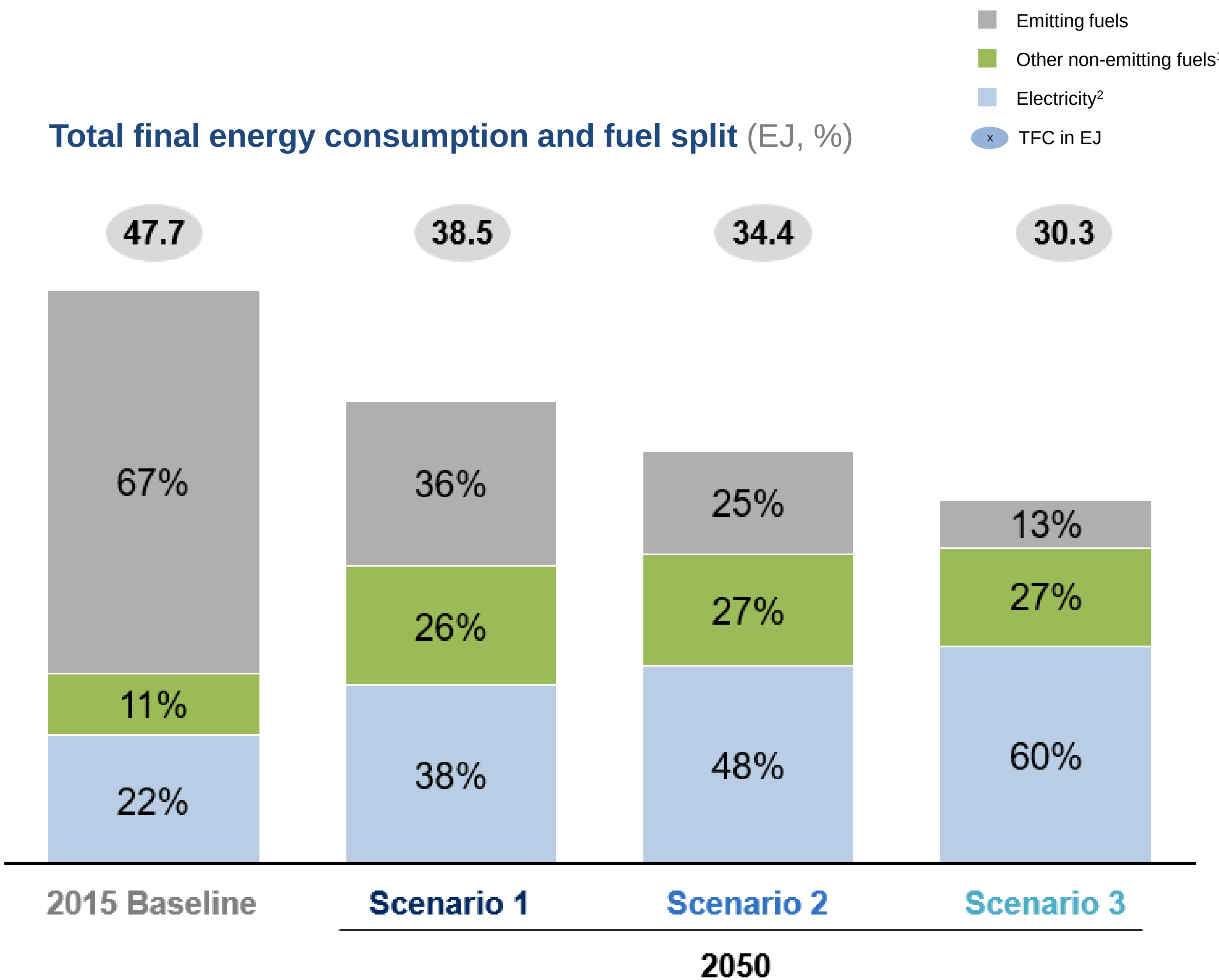
A strong electricity uptake in total final energy consumption

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.



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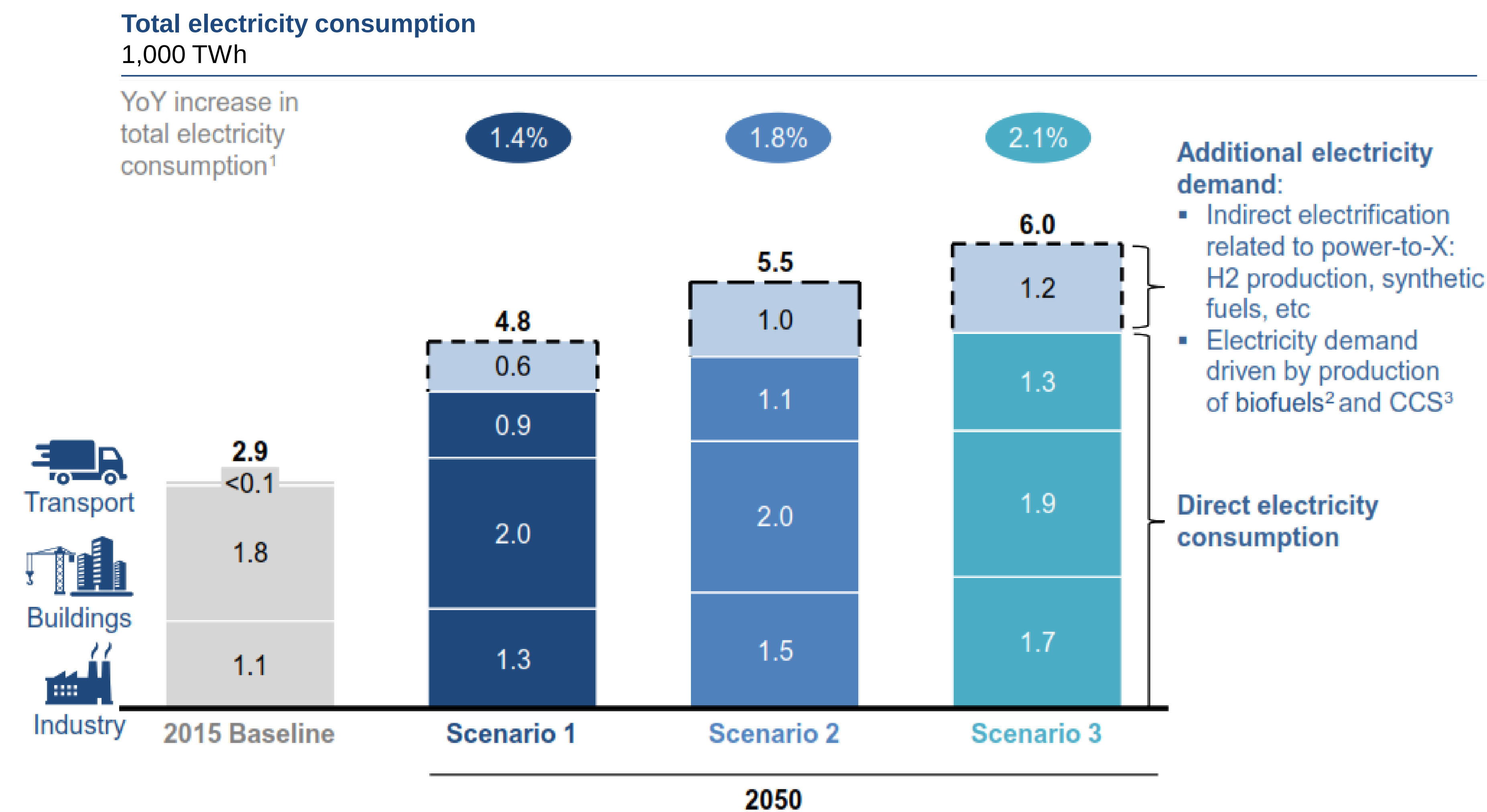
Strong electricity uptake in all sectors, with strongest increase in transport



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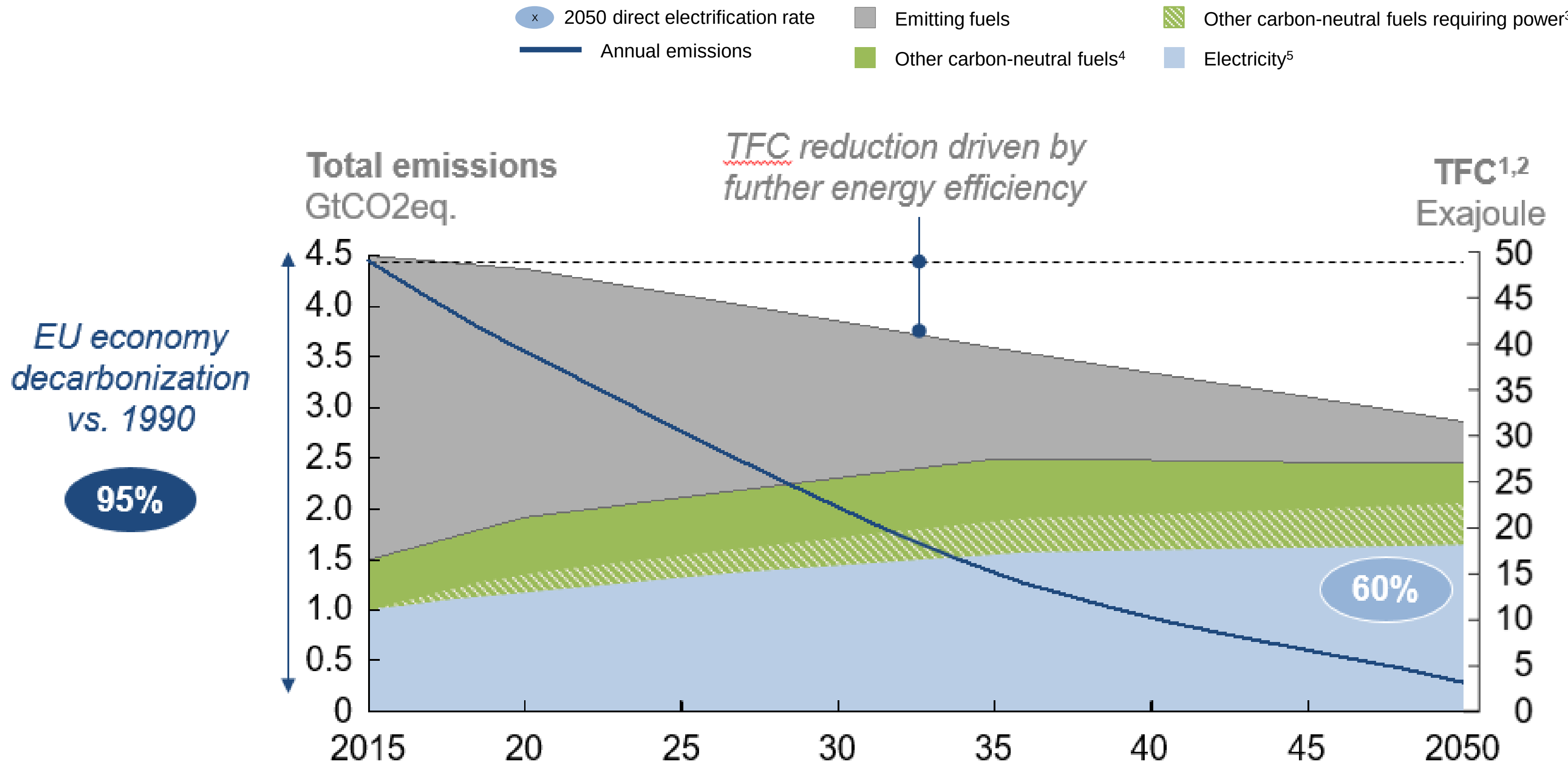
95% decarbonization through strong electrification, energy efficiency, and support from other non-emitting fuels

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

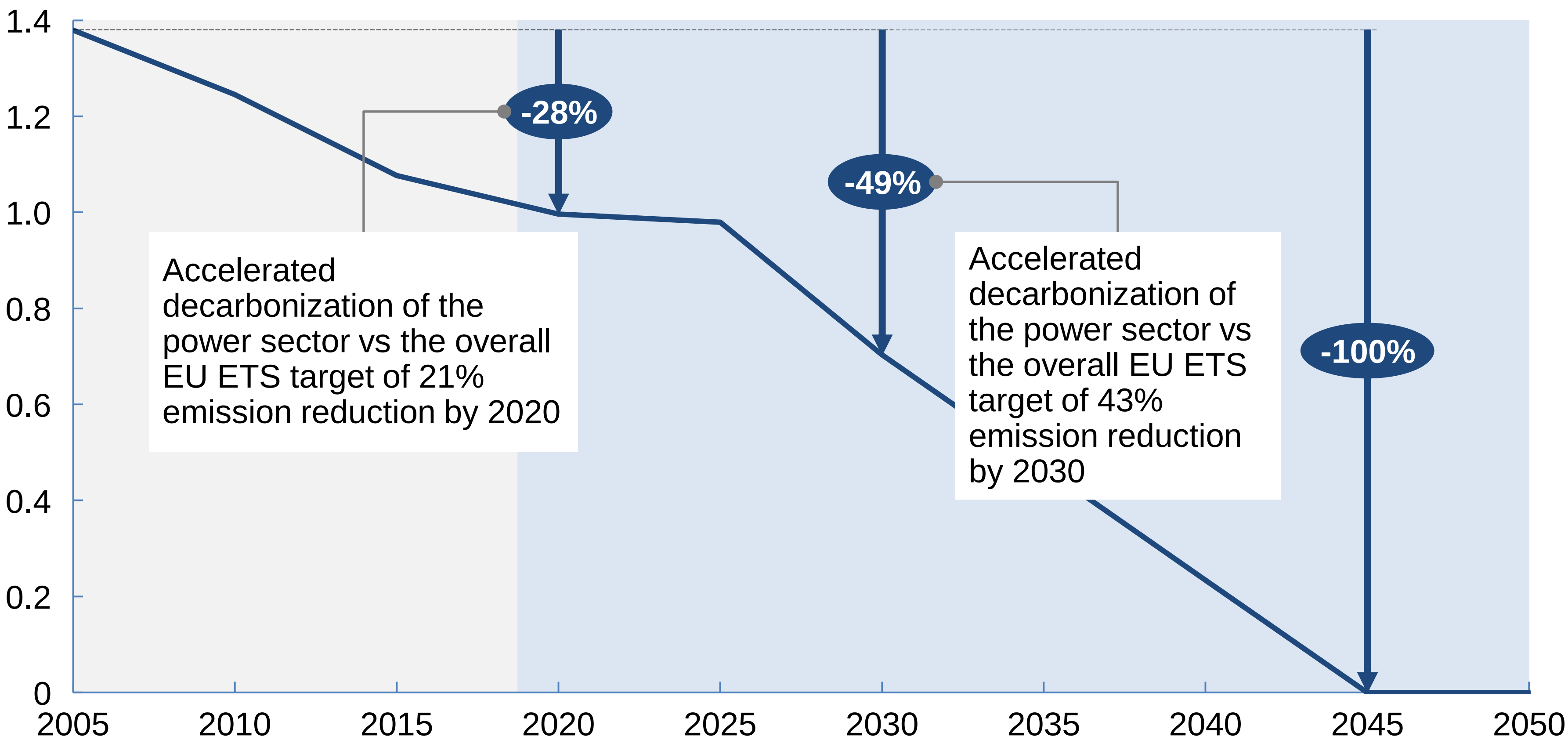


1 Includes 32 countries in scope: EU28 + EEA; ENTSOE report additionally includes Turkey and other Eastern European countries adding up to a total of ~3,300 TWh

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

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

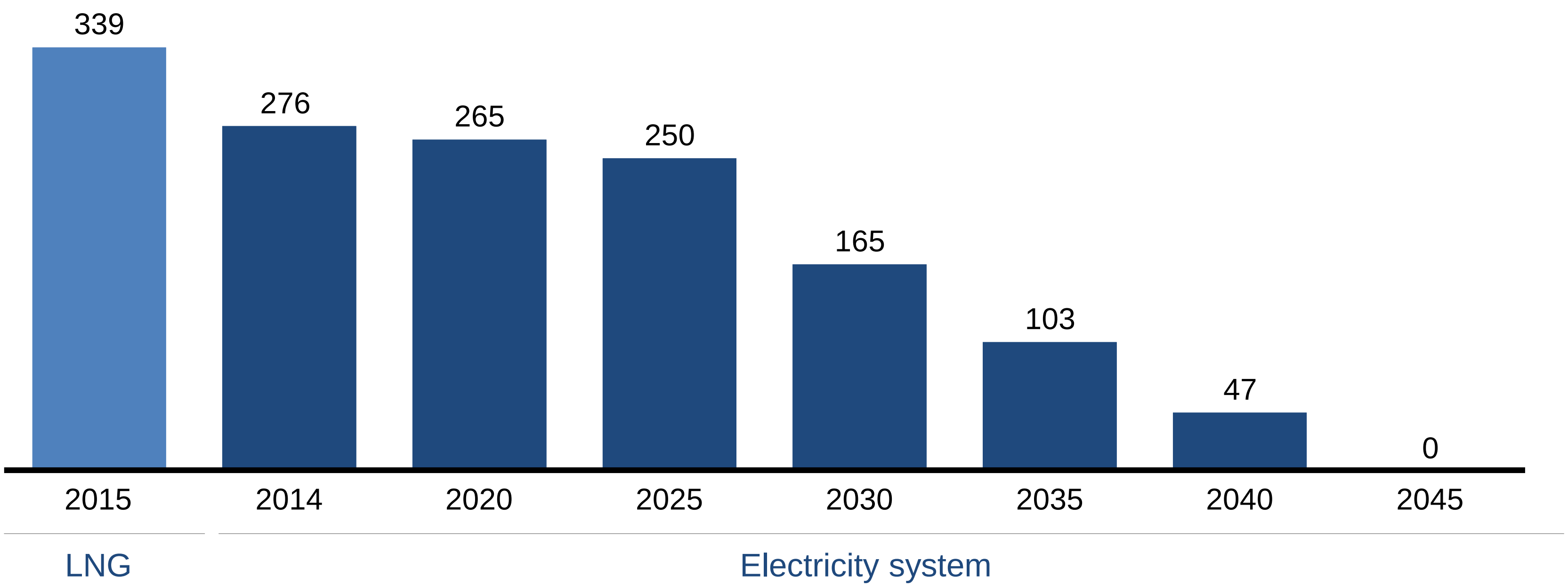
CO_2 emissions from power sector in all scenarios, GT CO_2



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

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

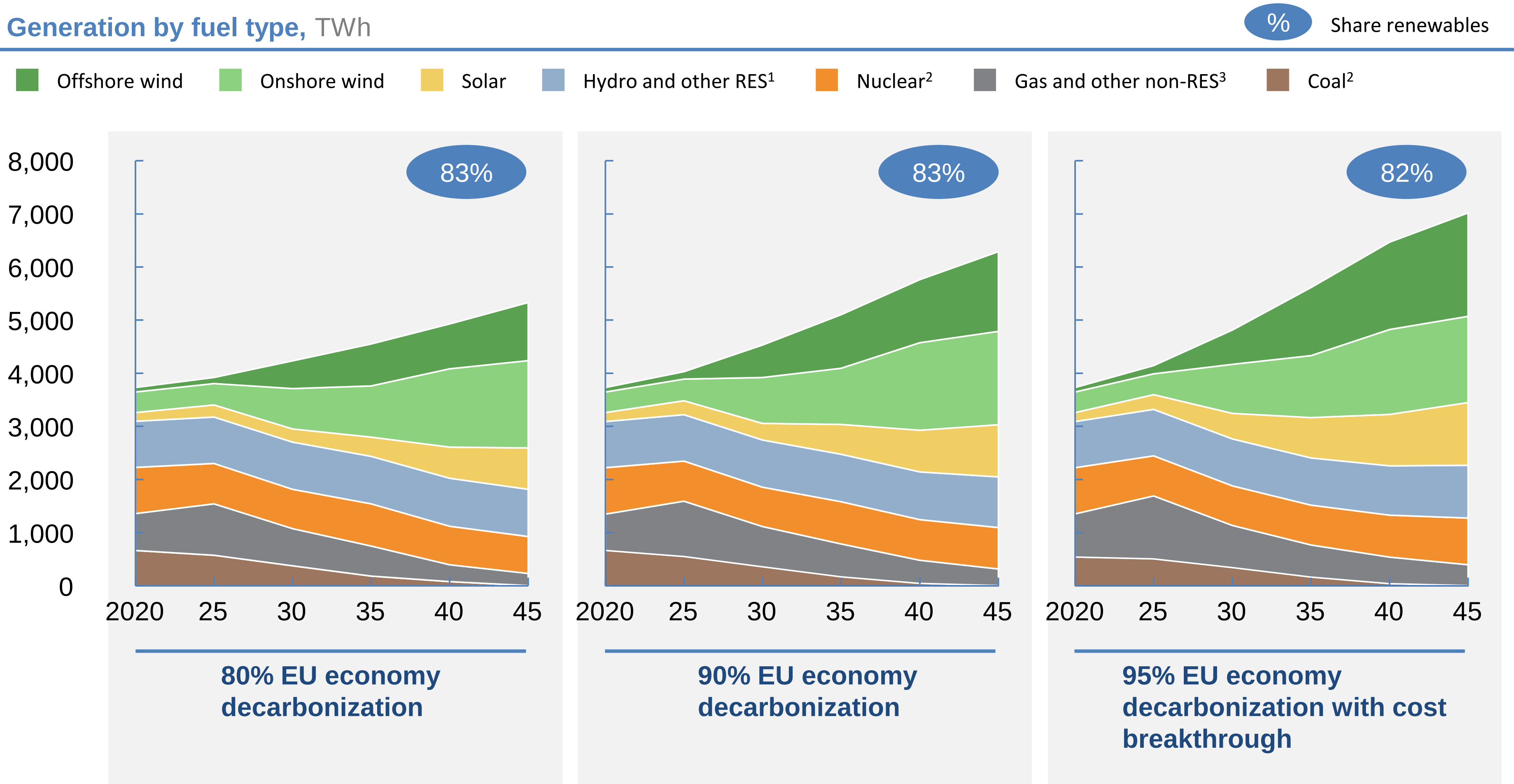
System reliability and flexibility needs provided by multiple sources in the power sector and from other industrial sectors. These include hydro, nuclear power and gas, and emerging sources deployed at scale such as demand side response, battery storage, hydrogen electrolysis and power-to-X

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

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

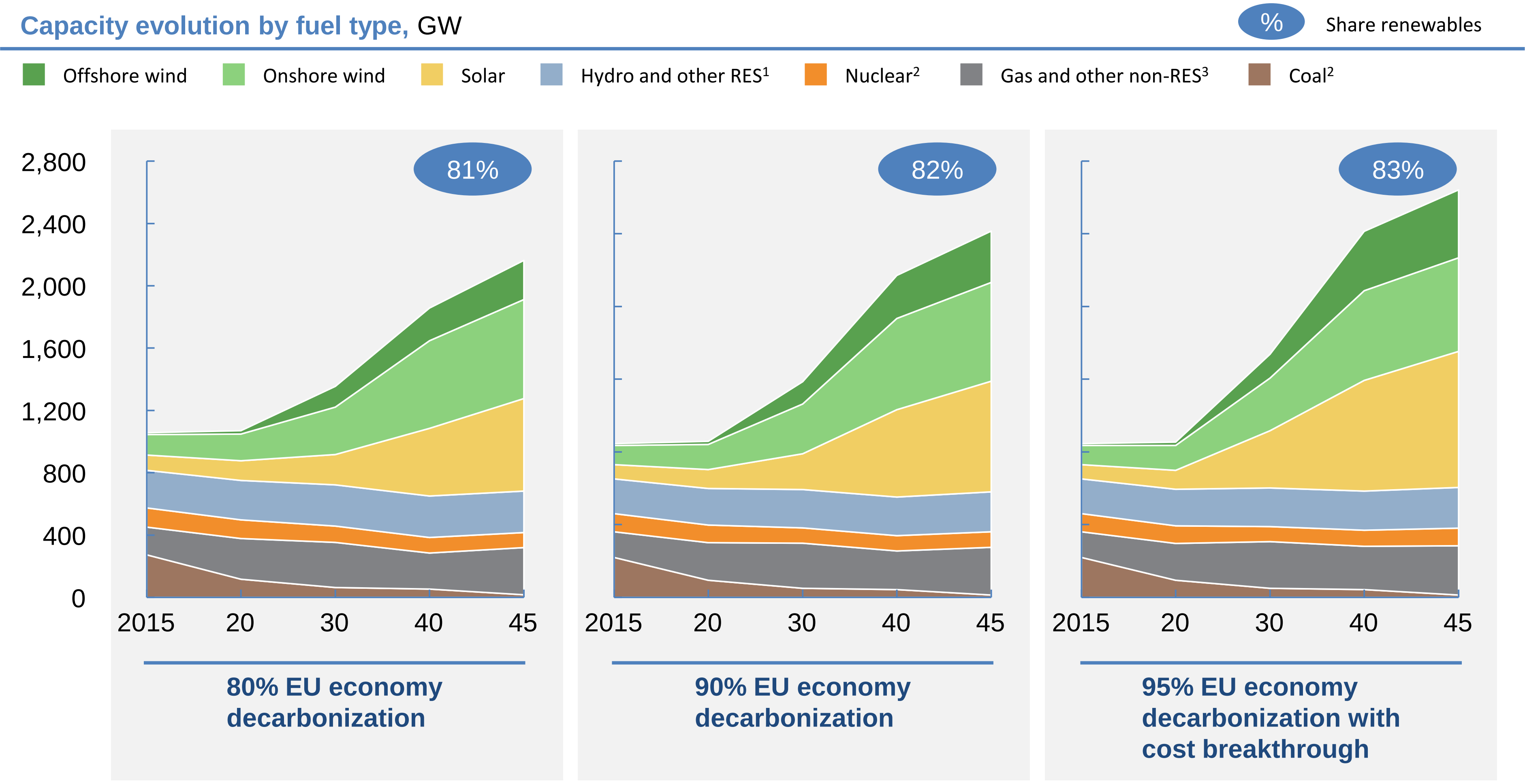
Generation by fuel type, TWh



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

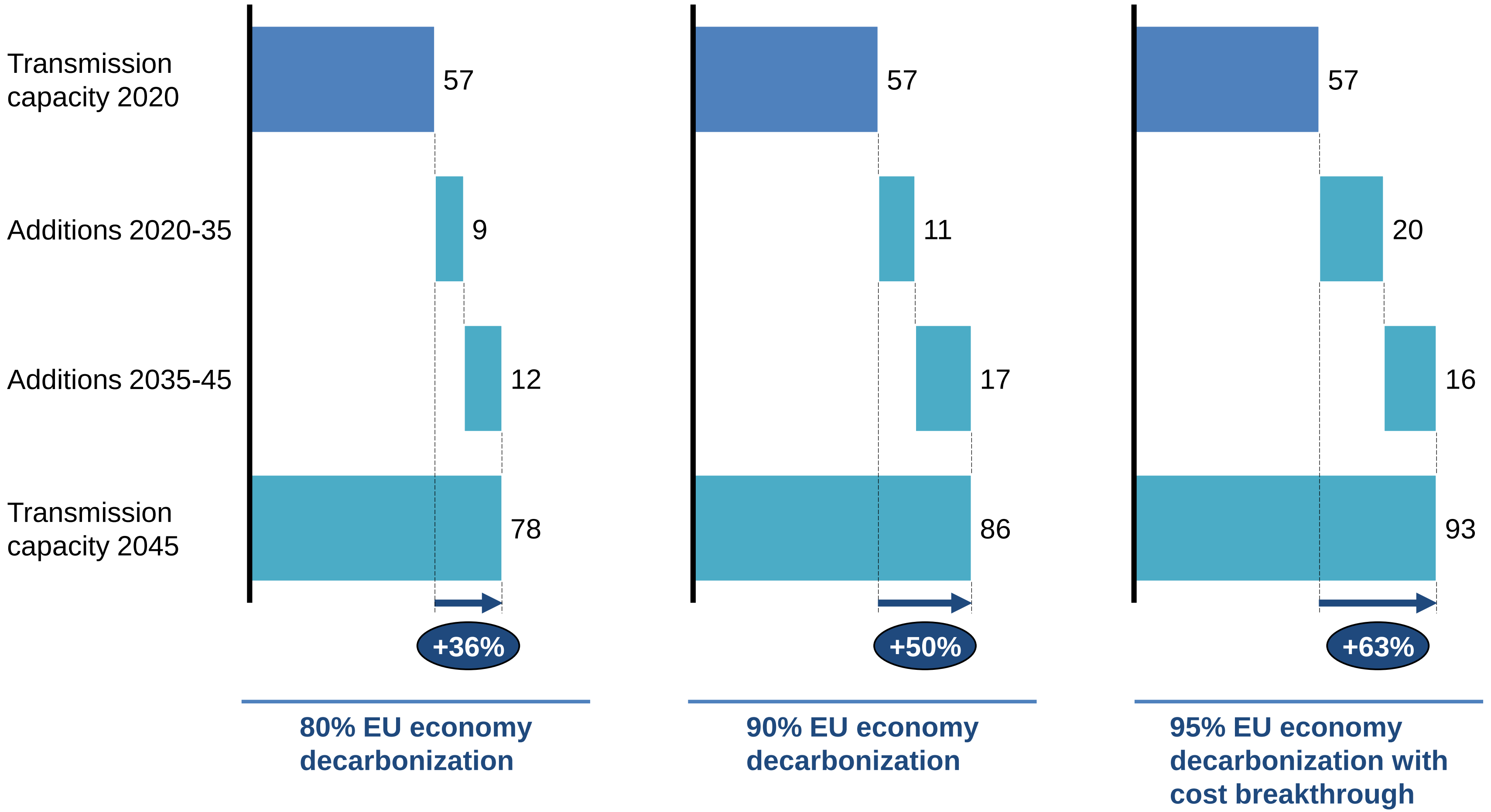
Capacity evolution by fuel type, GW



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

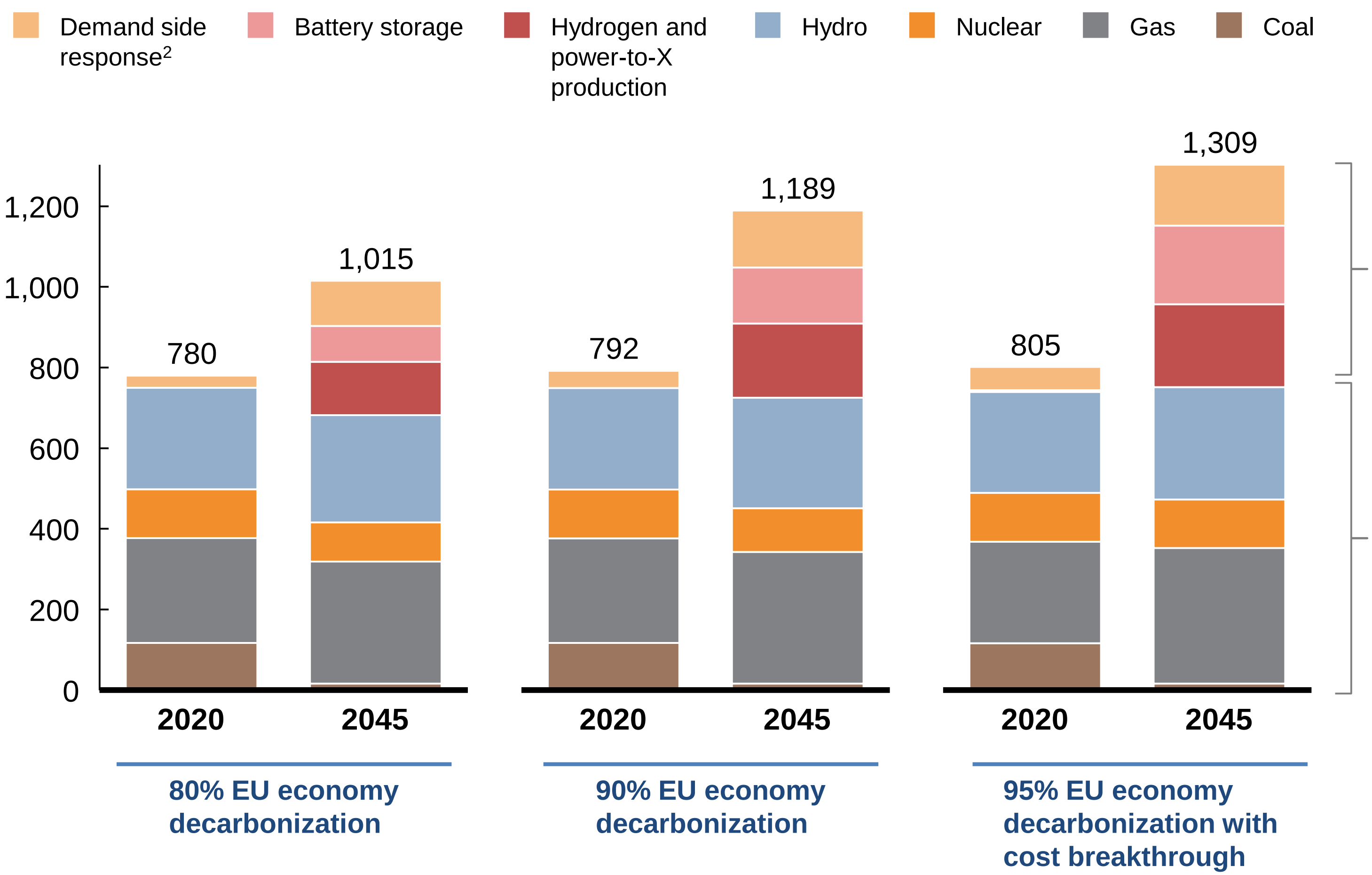


A system-wide shift from dispatchable generation to renewables will require new sources of system reliability and flexibility

- 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

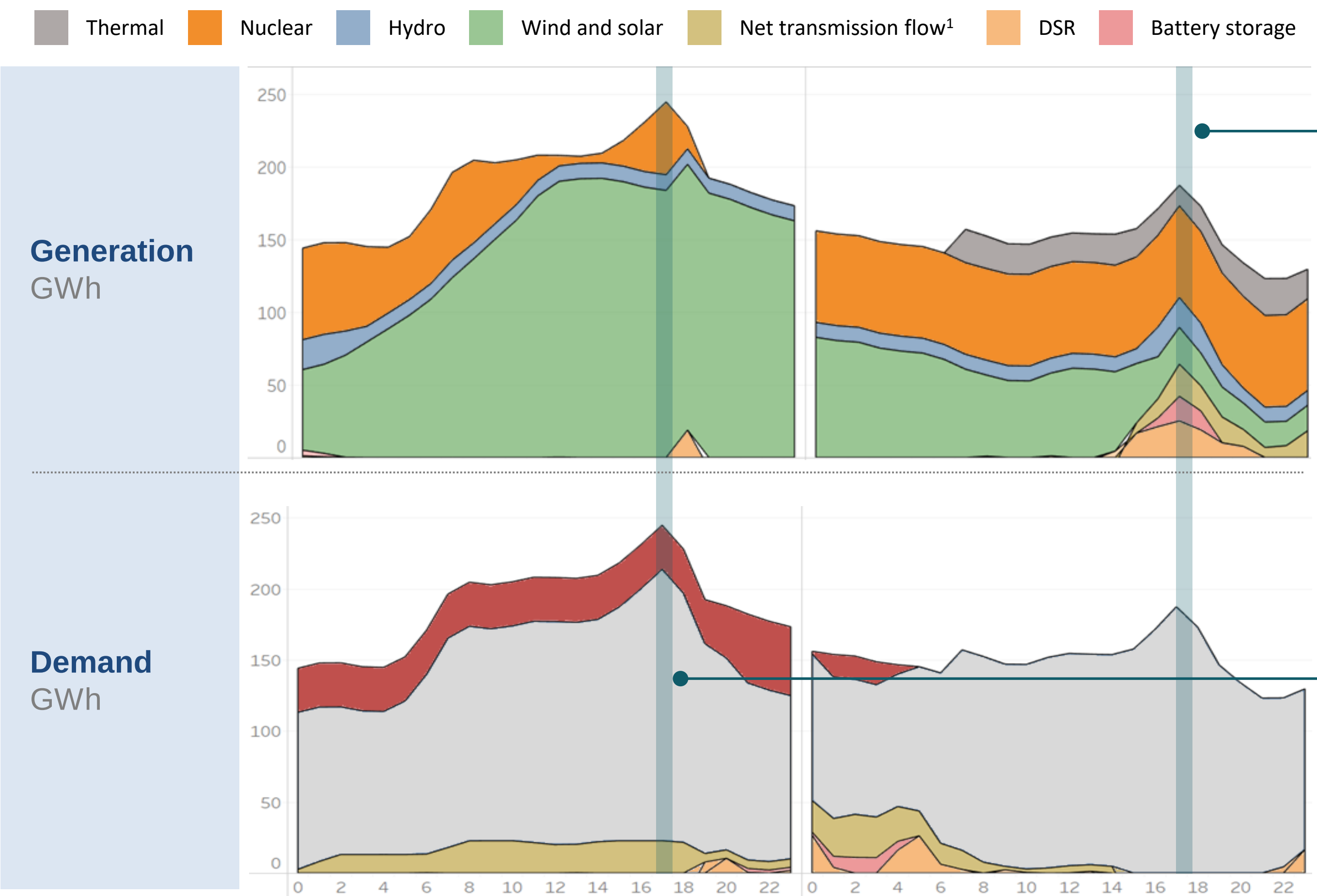
1 District heating that is coupled with power sector is not included in this analysis
2 DSR flexibility is provided by hour to hour load shifting in transportation, buildings and heating

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



- 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

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

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

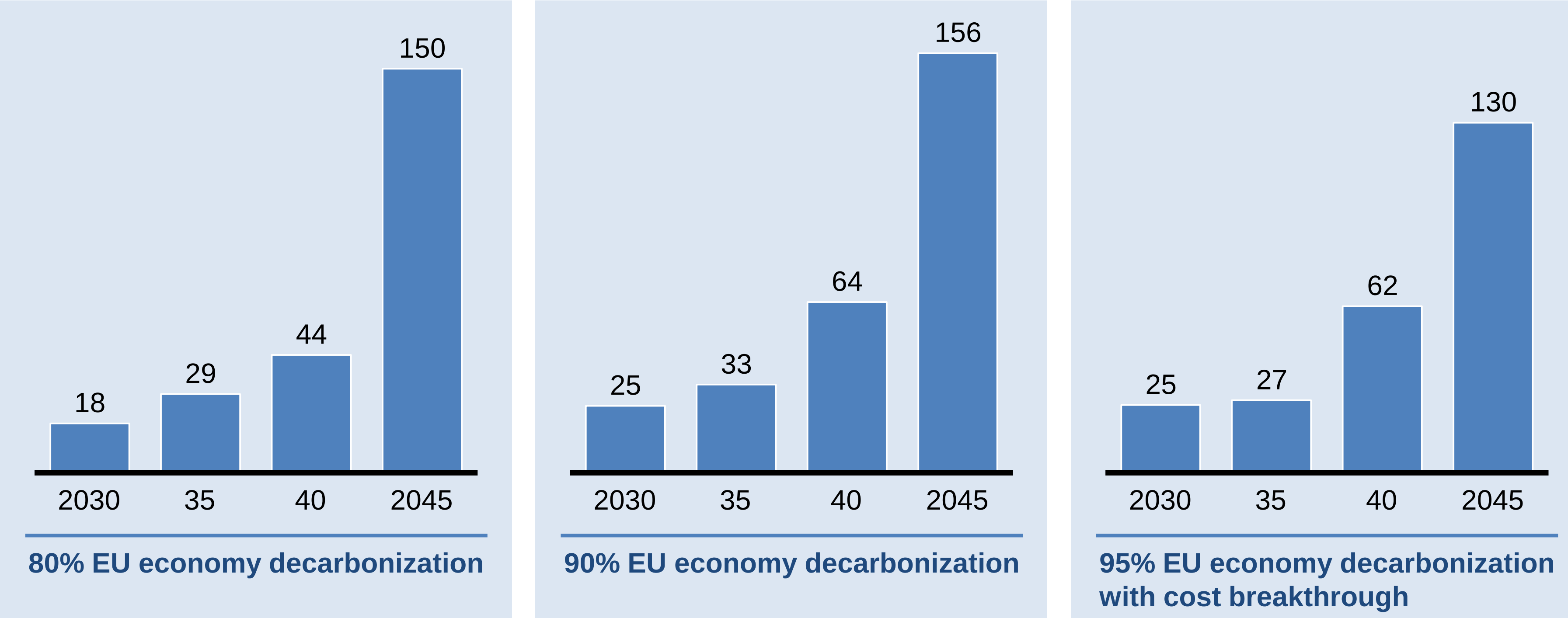
- Hydrogen and green gas produced with clean electricity can be reinjected to the grid, but this process currently involves high efficiency losses. However, the added benefit of providing flexibility to the power system must also be taken into account

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

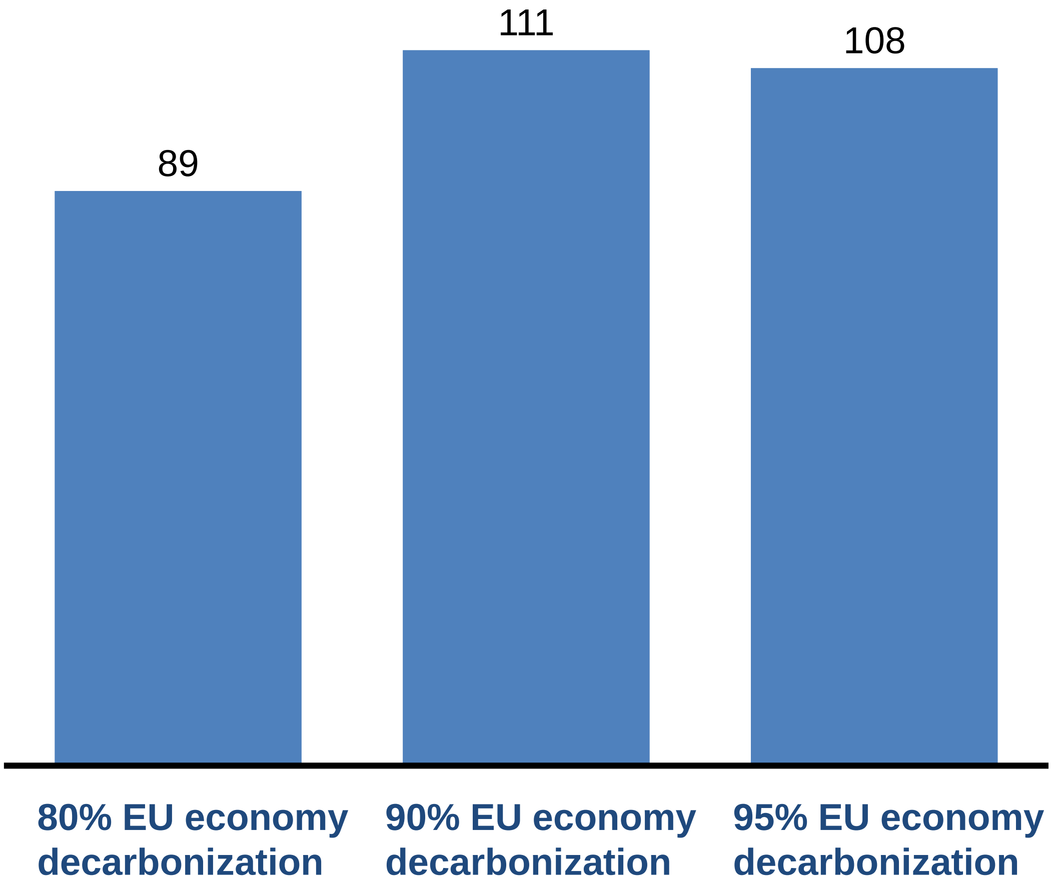


The marginal abatement cost of the *final* ton of CO_2 is difficult to estimate at it is closely tied to the cost of immature technologies, e.g. CCS. Foreseeing future cost trajectories for such technologies in a 2050 perspective is difficult. As a consequence, there is high uncertainty around what marginal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

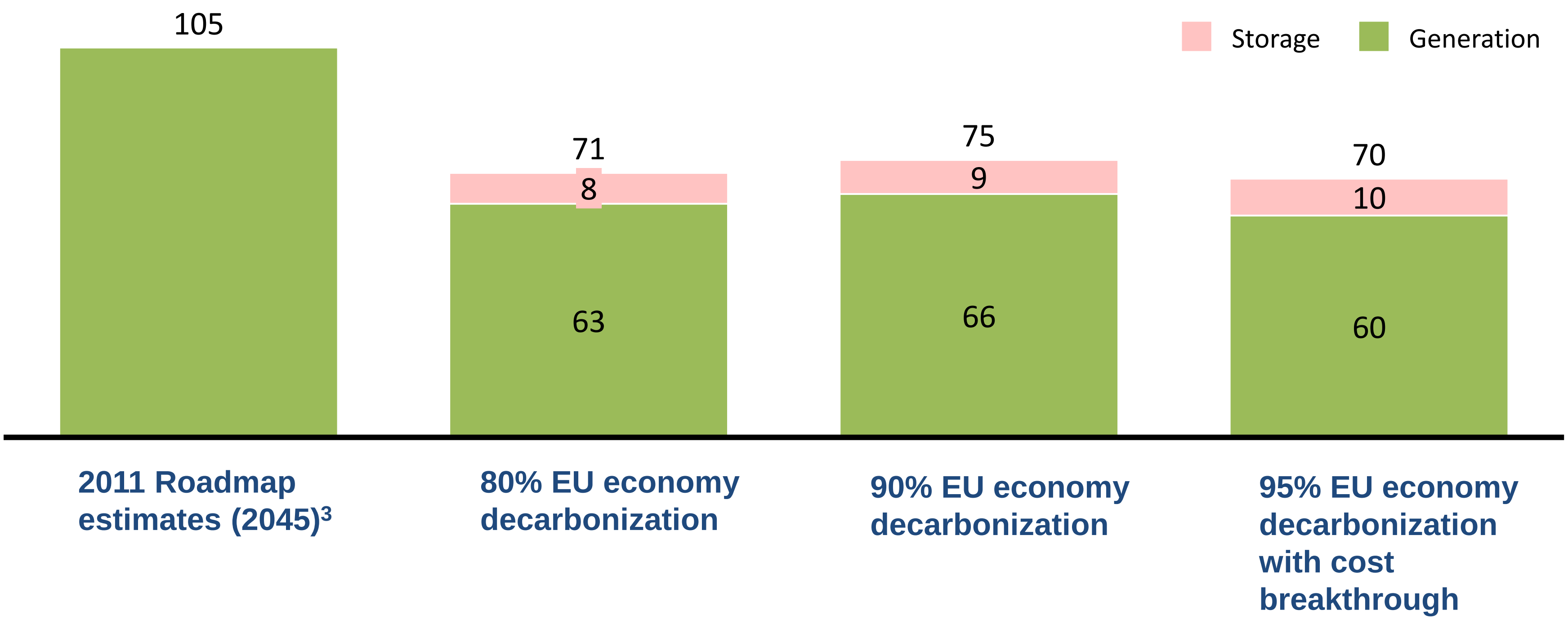


1 Real cost linked to 2016 price level

- 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

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

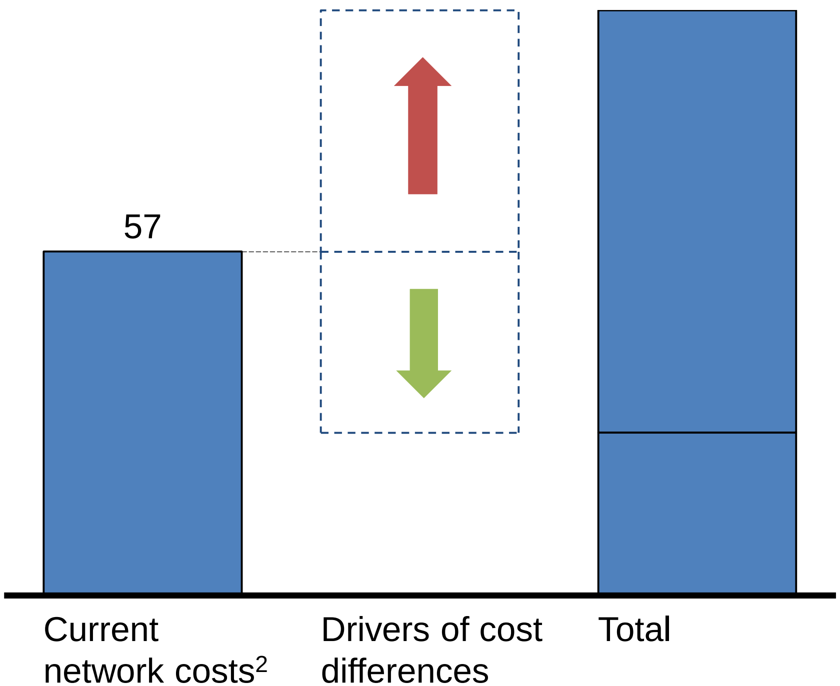
1 Levelized cost approach approximates in-year revenue required to match cost; includes operating costs (e.g., fuel, variable O&M); additionally, capital expenditures (e.g., wind farms, battery storage, or CCS-retrofits) are amortized over the economic lifetime of the asset

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

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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

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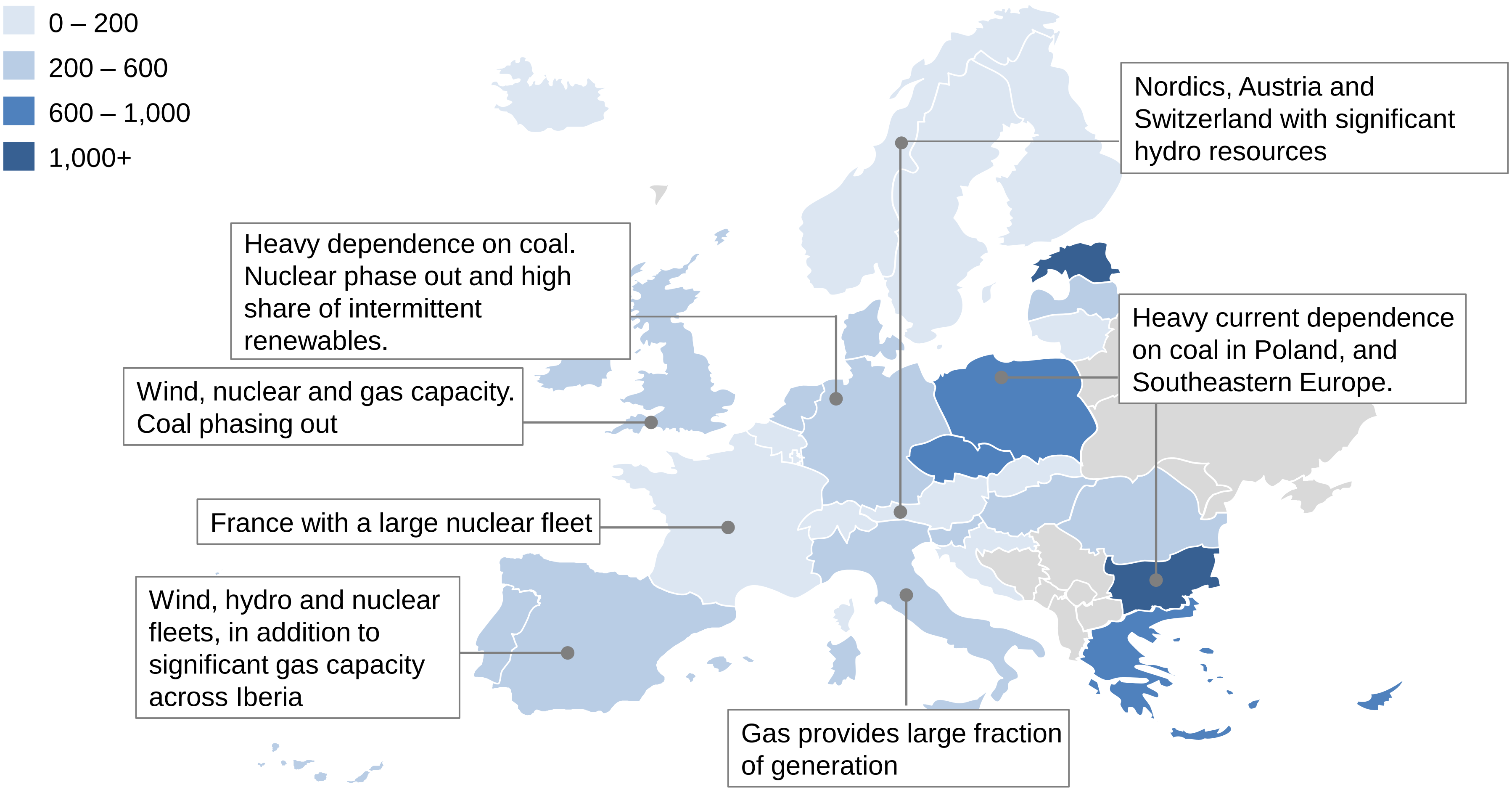
European countries have different starting points in the energy transition

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

Back up slides

Appendix 1: Back-up for generation table

Values in TWh

Resource	80% EU economy decarbonization						90% EU economy decarbonization						95% EU economy decarbonization with cost breakthrough					
	2020	2025	2030	2035	2040	2045	2020	2025	2030	2035	2040	2045	2020	2025	2030	2035	2040	2045
Offshore wind	87	111	522	791	844	1,088	87	142	611	1,007	1,188	1,498	86	153	649	1,278	1,641	1,945
Onshore wind	384	404	758	964	1,473	1,646	384	408	862	1,058	1,645	1,758	384	390	920	1,168	1,598	1,625
Solar	165	228	251	363	589	779	171	260	314	563	786	1,003	171	278	483	761	969	1,204
Hydro-power[1]	869	876	886	891	900	888	869	876	886	892	901	913	868	875	885	890	929	942
Nuclear[2]	871	755	743	797	725	697	871	755	743	798	763	782	871	755	742	747	788	876
Gas & Gas CCS	696	972	700	564	321	228	688	1,039	760	616	436	330	813	1,188	794	604	504	425
Coal & Coal CCS	661	572	373	182	75	2	662	551	354	169	43	2	538	502	342	164	36	2
Total	3,732	3,918	4,233	4,552	4,927	5,328	3,732	4,031	4,530	5,103	5,762	6,286	3,732	4,141	4,815	5,612	6,465	7,019

1 Includes also small amounts of geothermal, biomass and biogas

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

Appendix 2: Back-up for capacity table

Values in GW

Resource	2015	2020	2030	2040	2045	2015	2020	2030	2040	2045	2015	2020	2030	2040	2045
Offshore wind	11	22	133	210	252	11	22	154	296	353	11	22	164	407	467
Onshore wind	132	172	304	563	635	132	172	341	628	679	132	172	363	618	643
Solar	98	126	195	433	594	98	130	246	600	776	98	130	393	760	951
Hydro-power[1]	240	252	265	266	269	240	252	265	266	272	240	252	265	270	276
Nuclear[2]	124	121	104	101	97	124	121	104	106	108	124	121	104	110	121
Gas & Gas CCS	273	260	290	231	303	273	259	310	265	329	273	253	320	298	343
Coal & Coal CCS	178	117	63	53	16	178	117	63	53	16	178	117	63	53	16
Total	1,056	1,070	1,354	1,857	2,163	1,056	1,073	1,483	2,214	2,534	1,056	1,067	1,672	2,516	2,817
	80% EU economy decarbonization					90% EU economy decarbonization					95% EU economy decarbonization with cost breakthrough				

1 Includes also small amounts of geothermal, biomass and biogas

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