European
Climate Foundation

Roadmap 2050: a practical guide to a prosperous, low-carbon Europe

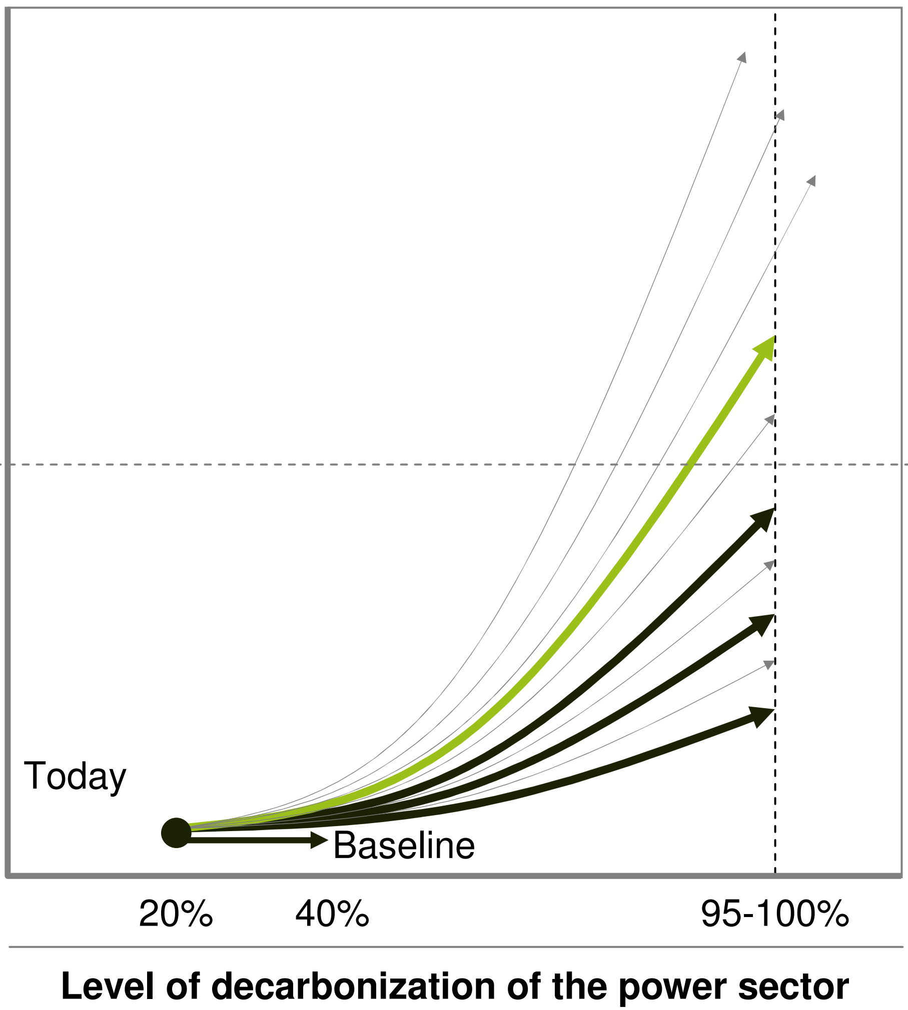
Volume I: technical and economic assessment

Report exhibits

April, 2010

Including other regions and technologies

Focus on EU-27 and existing technologies



Pathways containing, e.g., tidal, nuclear fusion, algae and power from Iceland or Russia are not assessed

A 100% renewable scenario that includes CSP[1] from North Africa and EGS[2] is assessed technically

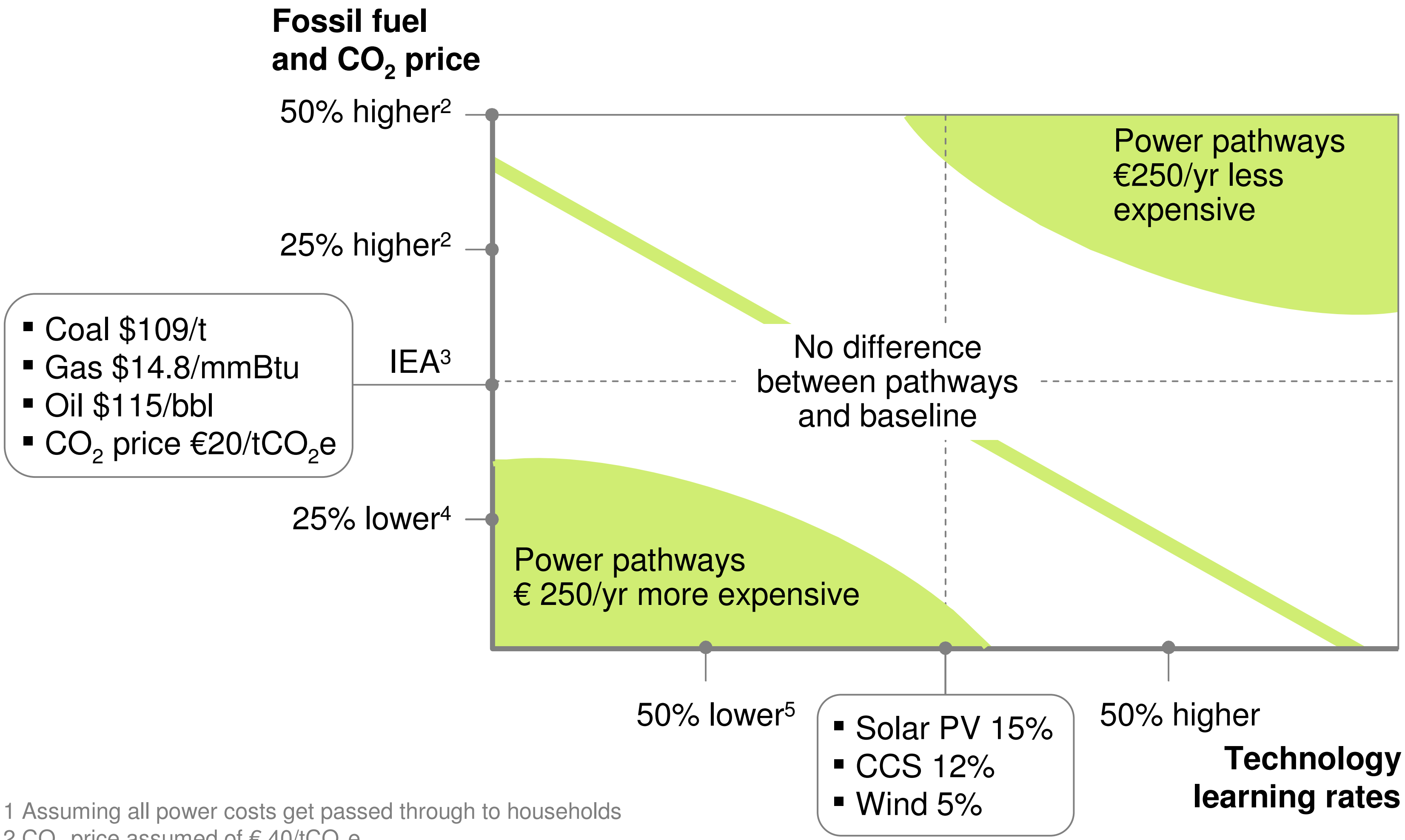
Three pathways with varying shares of renewable, nuclear and CCS[3] are assessed both technically and economically

1 Concentrated Solar Power (thermal, not photo voltaic)
2 Enhanced Geothermal Systems
3 Carbon Capture and Storage

EXHIBIT 1

The cost of the decarbonized pathways and the baseline are likely to differ less than € 250 per year per household

Cost impact of the decarbonized power pathways per year per household[1]



1 Assuming all power costs get passed through to households
2 CO_2 price assumed of € 40/tCO_2e
3 IEA WEO 2009 '450 Scenario' assumptions for 2030, kept constant up to 2050
4 No carbon price
5 For all technologies. Learning rate is defined as capex improvement per doubling of cumulative installed capacity

EXHIBIT 2

Energy and power intensity reduce by 1% to 1.5% per year

Mtoe per € of sector value added[1]

Service
Industry
Residential & Transport

Sub-sectors	Energy intensity 2010	Energy intensity 2050	Energy intensity CAGR[2]	Power intensity 2010	Power intensity 2050	Power intensity CAGR[2]
Basic metals	1,080	585	-1.5	274	189	-1.0
Industry overall	118	70	-1.3	39	28	-0.8
Electronic engineering	66	37	-1.4	37	24	-1.1
Mechanical engineering	65	50	-0.6	N/A	N/A	N/A
Construction	55	33	-1.3	20	13	-1.1
Retail trade	37	23	-1.2	28	20	-0.9
Wholesale trade	34	21	-1.2	15	11	-0.9
Transport	33	21	-1.2	N/A	N/A	N/A
Residential	33	18	-1.6	10	6	-1.1
Services overall	20	11	-1.5	10	7	-1.1
Finance	12	7	-1.3	6	4	-1.0
Business Services	10	6	-1.2	6	4	-0.8

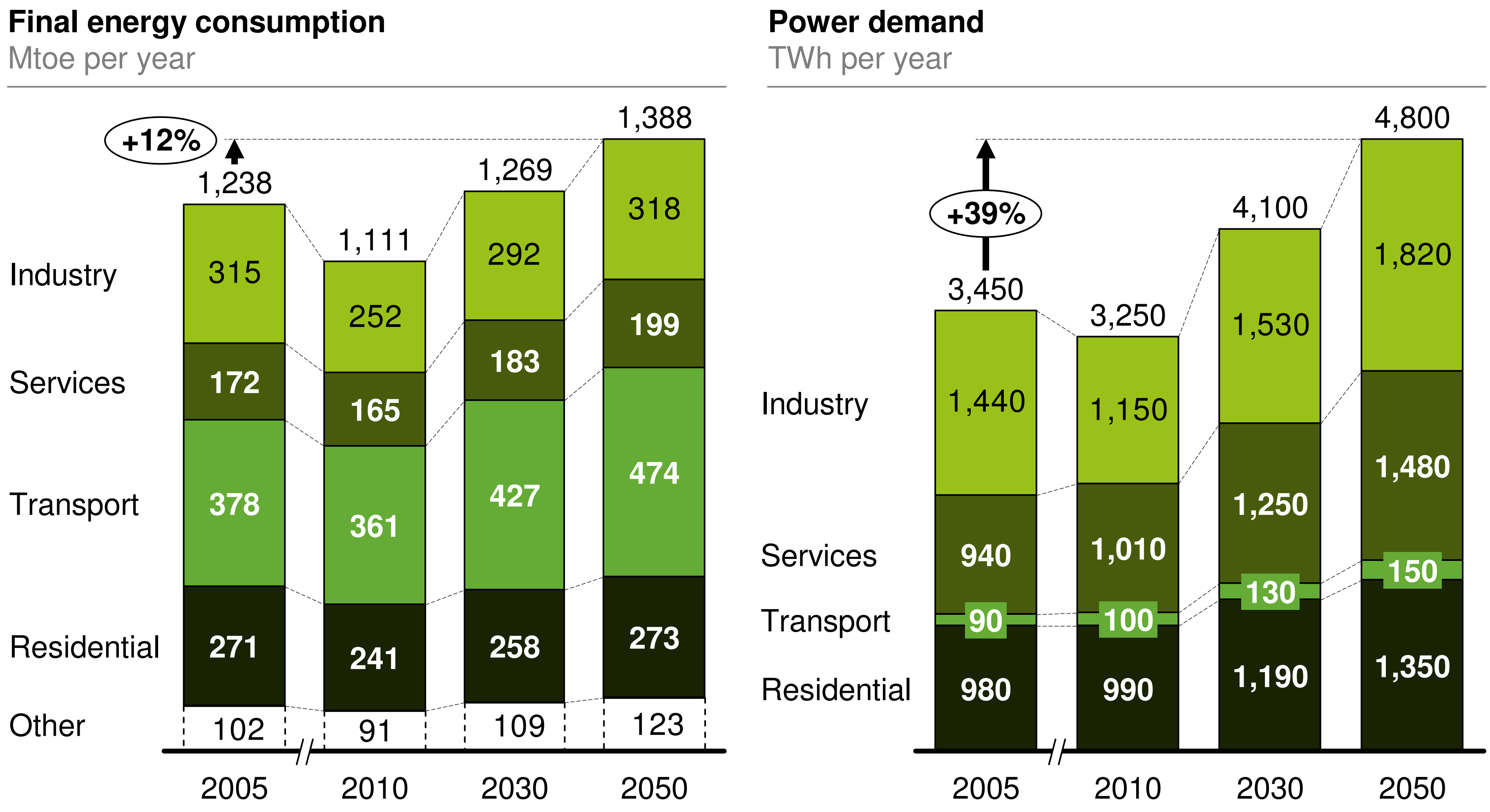
1 Value added is GDP for the whole economy; value added in industry; value added in services; GDP for transport; and households income for residential
2 Compounded Annual Growth Rate

SOURCE: IEA WEO 2009; team analysis

EXHIBIT 3

Power demand grows by ~40% over 45 years in the baseline

EU-27, Norway and Switzerland energy and power demand



SOURCE: IEA WEO 2009; team analysis

EXHIBIT 4

Learning rates are applied to estimate future capex

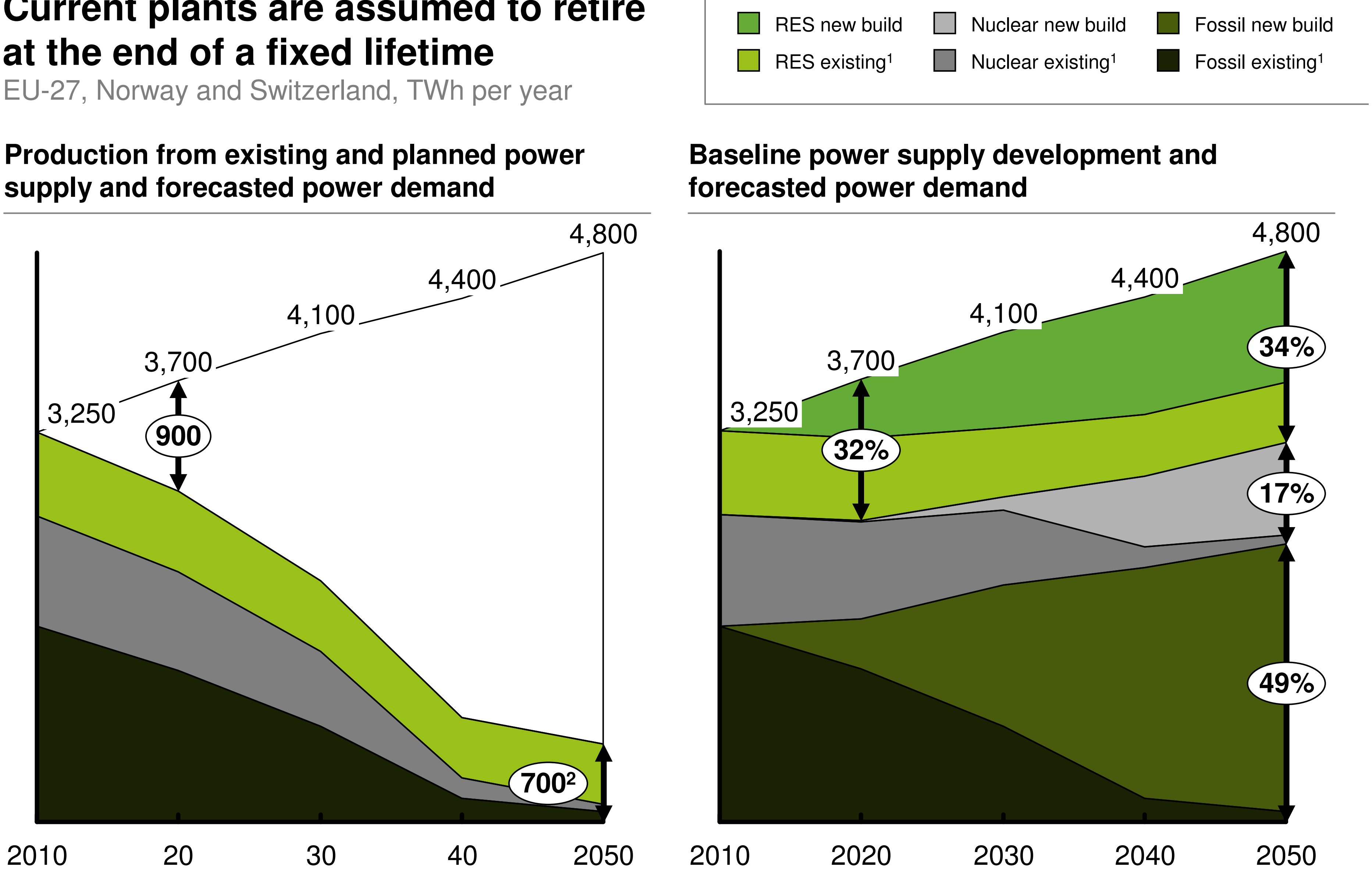
Type of generation	Generation technologies	Learning rate[1] Percent	Yearly Reductions Percent	Capex 2010 €/KW	60% RES / 20% nuclear / 20% CCS	
					Capex 2030 €/KW	Capex 2050 €/KW
Fossil	▪ Coal Conventional		0.5	1,400-1,600	1,250-1,450	1,150-1,350
	▪ Gas Conventional		0.5	700-800	650-750	600-700
	▪ Coal CCS[2]	12		2,700-2,900 [3]	2,000-2,200	1,750-1,950
	▪ Gas CCS[2]	12		1,500-1,600 [3]	1,000-1,200	900-1,100
	▪ Coal CCS[2] retrofit	12		1,250-1,450 [3]	600-800	500-700
	▪ Gas CCS[2] retrofit	12		750-950 [3]	350-550	300-500
	▪ Oil		0.5	750-850	700-800	600-700
Nuclear	▪ Nuclear[4]	3-5		2,700-3,300	2,700-3,300	2,600-3,200
RES						
Intermittent	▪ Wind Onshore	5		1,000-1,300	900-1,200	900-1,200
	▪ Wind Offshore	5		3,000-3,600	2,000-2,400	1,900-2,300
	▪ Solar PV	15		2,400-2,700	1,000-1,400	800-1,200
Non-Intermittent	▪ Solar CSP	HC[5]		4,000-6,000	2,900-3,500	2,200-2,600
	▪ Biomass dedicated		1.0	2,300-2,600	1,600-1,900	1,300-1,600
	▪ Geothermal		1.0	2,700-3,300	2,000-2,400	1,800-2,200
	▪ Hydro		0.5	1,800-2,200	1,750-2,000	1,500-1,900

1 Percent cost reduction with every doubling of accumulated installed capacity
2 Learning rate of 12% applies to CCS part; Learning of coal/gas plant identical to coal/gas
3 starts in 2020, additional capex to conventional plants for retrofits
4 France starts with lower capex of 2750 €/kWe; LR on Gen II and Gen III separated
5 Hardcoded input based on workshop including storage

EXHIBIT 5

Current plants are assumed to retire at the end of a fixed lifetime

EU-27, Norway and Switzerland, TWh per year

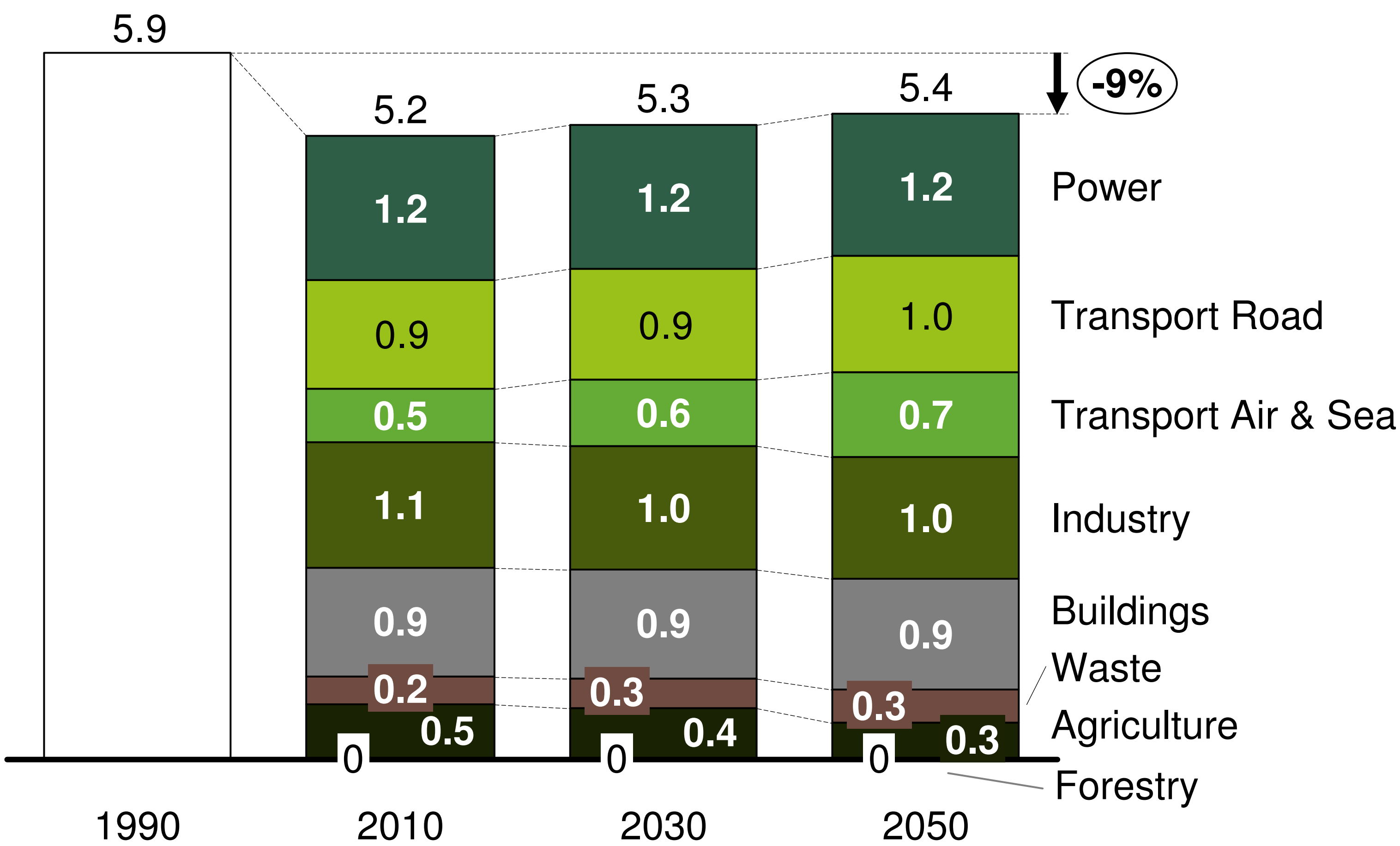


1 Existing capacity includes plants under construction
2 RES capacity remaining in 2050 is entirely made of hydropower plants

EXHIBIT 6

Emissions are assumed to grow slightly in the baseline after a drop before 2010

EU-27 total GHG emissions, $GtCO_2e$ per year



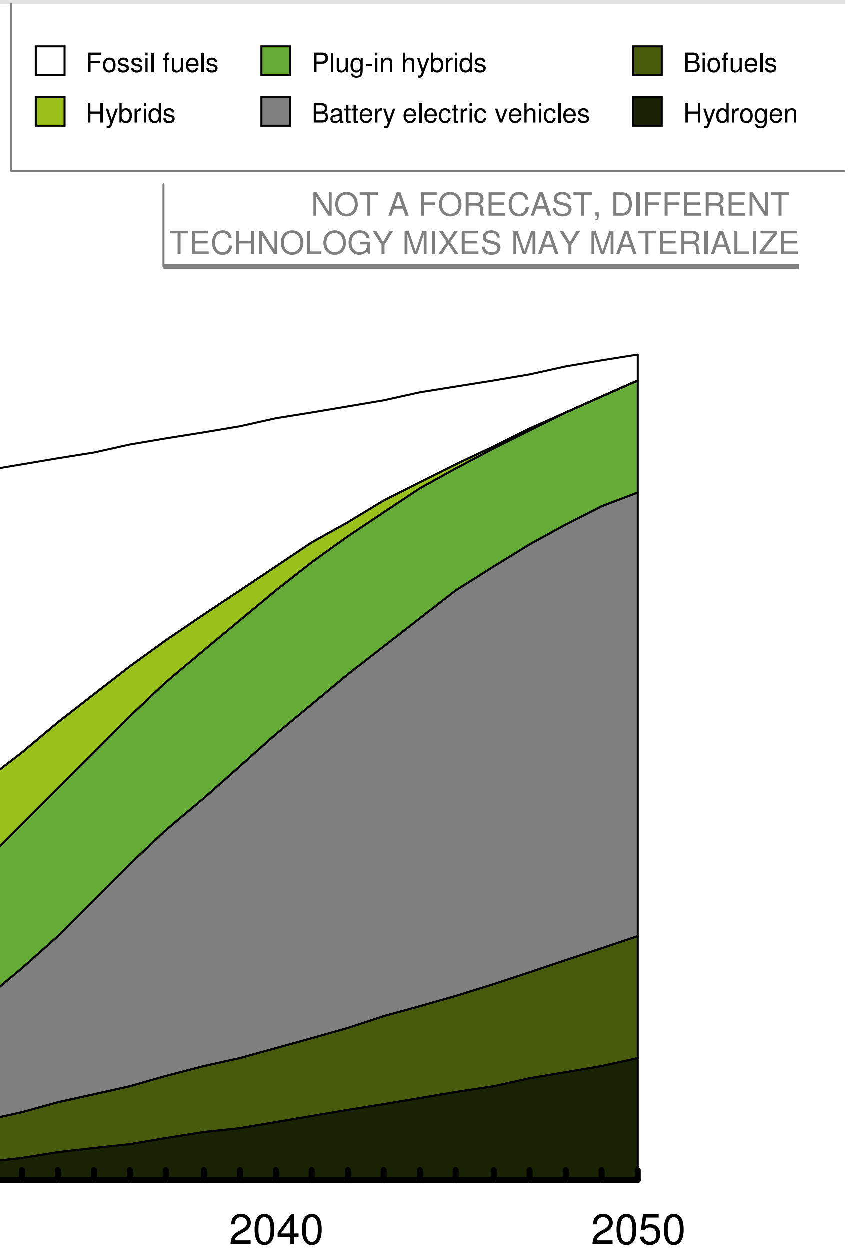
SOURCE: McKinsey Global GHG Abatement Cost Curve; IEA WEO 2009; WRI (CAIT 2009) Oxford Economics for GDP 2030-50; team analysis

EXHIBIT 7

The decarbonized pathways assume a mix of electric vehicles, biofuels and fuel cell vehicles

Billions of Km driven[1] by type of energy sources

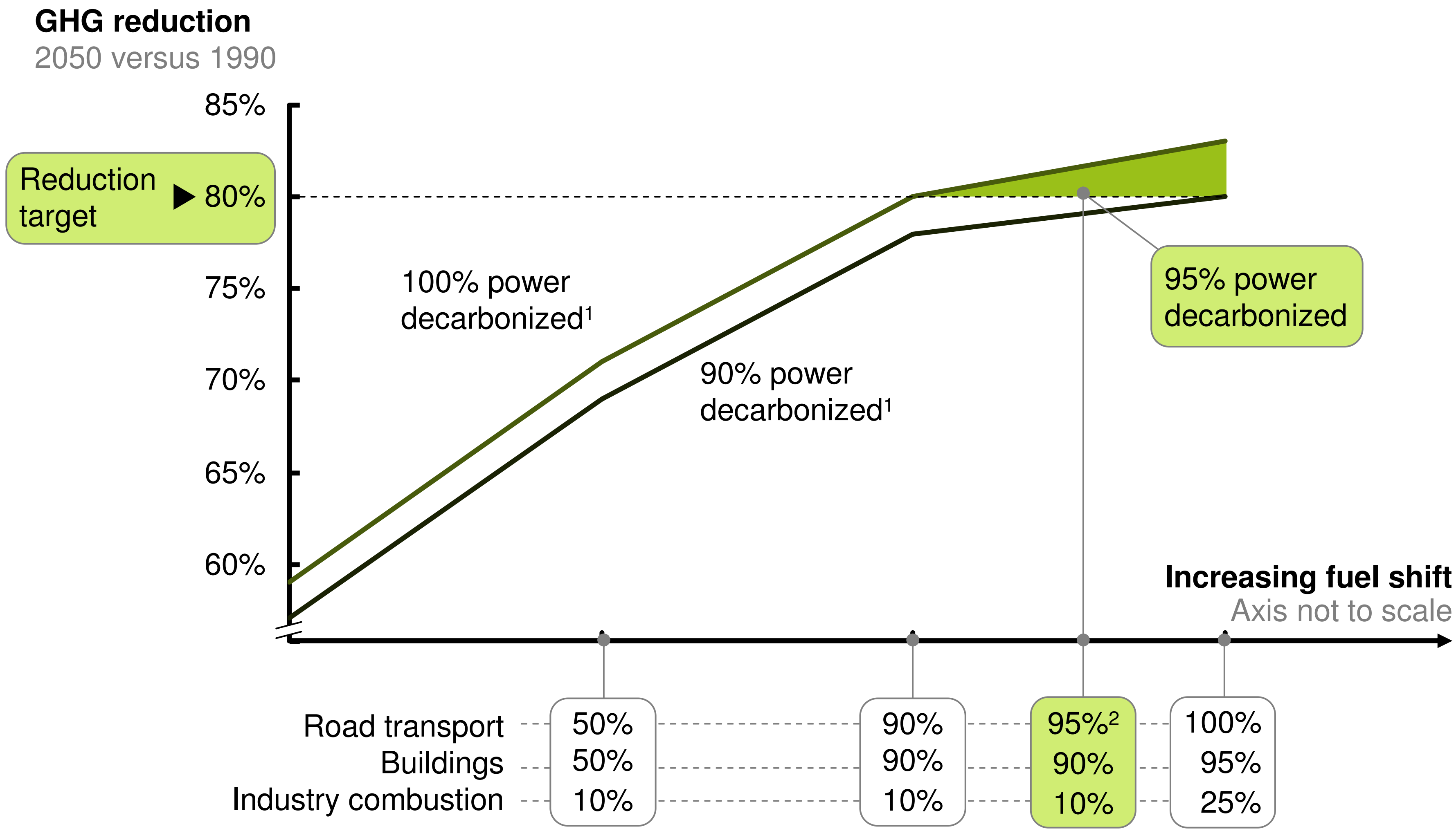
NOT A FORECAST, DIFFERENT TECHNOLOGY MIXES MAY MATERIALIZE



1 Kilometers for heavy trucks normalized with a factor 4 higher fuel consumption per km

EXHIBIT 8

The power sector needs to be decarbonized between 90 and 100%



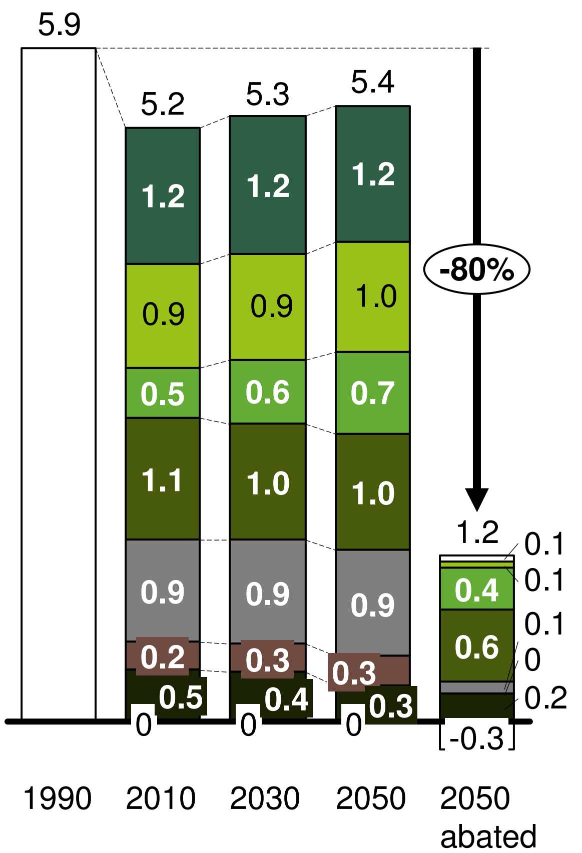
1 Decarbonization of power relative to baseline with carbon intensity of 250 tCO_2/TWh, 90% reduction would reduce this to 25 tCO_2/TWh

2 Assumptions: For light- and medium-duty vehicles – 100% electrification (partially plug-in hybrids), for heavy-duty vehicles use of 45% biofuels, 45% hydrogen fuel cells, for air and sea transport use of 30% biofuels, 70% fossil fuels (after 40% efficiency improvement)

80% decarbonization overall means nearly full decarbonization in power, road transport and buildings

$GtCO_2e$ per year

EU-27 total GHG emissions



Sector	Total abatement	Abatement within sector[1, 2]	Abatement from fuel shift
Power	95% to 100%	> 95%	
Road transport	95%	20%	75% (electric vehicles, biofuels and fuel cells)
Air & Sea transport	50%	30%	20% (biofuels)
Industry	40%	35% (efficiency, CCS[3])	5% (heat pumps)
Buildings	95%	45% (efficiency)	50% (heat pumps)
Waste	100%	100%	
Agriculture	20%	20%	
Forestry	-0.25 GtCO2e	Carbon sinks	

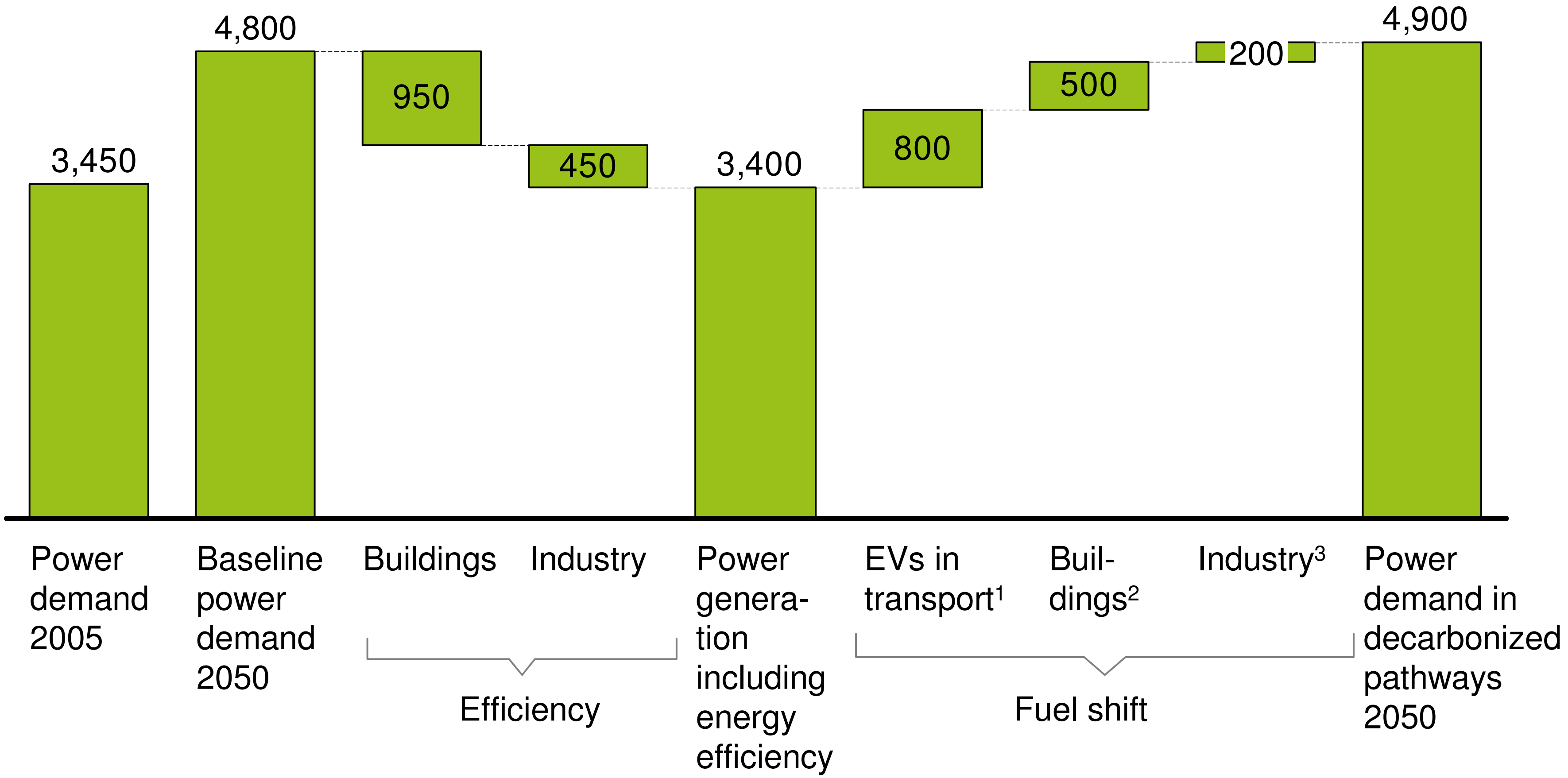
1 Abatement estimates within sector up to 2030 based on the McKinsey Global GHG Abatement Cost Curve
2 Large efficiency improvements are already included in the baseline based on the IEA WEO 2009 (up to 2030), especially for industry
3 CCS applied to 50% of large industry (cement, chemistry, iron and steel, petroleum and gas); not applied to other smaller industries

SOURCE: McKinsey Global GHG Abatement Cost Curve; IEA WEO 2009; US EPA; EEA; Team analysis

EXHIBIT 10

Power demand will go down due to higher efficiency and up due to additional demand from transport and building heating

EU-27, Norway and Switzerland power demand, TWh per year

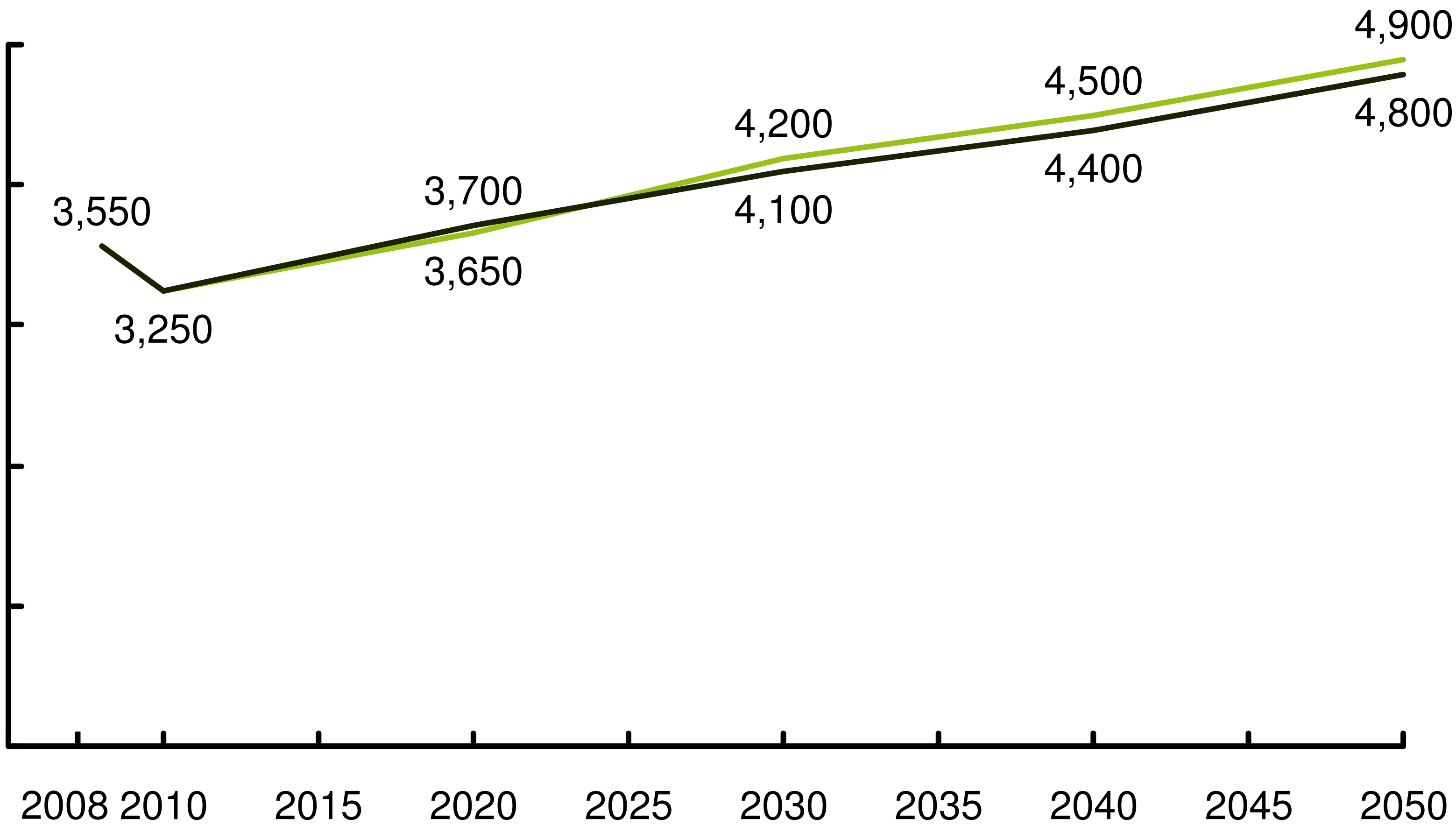


1 Electrification of 100% LDVs and MDVs (partially plug-in hybrids); HDVs remain emitting ~10% while switching largely to biofuel or hydrogen fuel cells
2 90% of remaining primary energy demand converted to electricity (heating/cooling from heat pumps, assumed 4 times as efficient as primary fuel)
3 10% of remaining primary energy demand for combustion converted to electricity (heating from heat pumps, assumed 2.5 times as efficient as primary fuel)

EXHIBIT 11

Power demand in the baseline and the decarbonized pathways develop similarly

EU-27, Norway and Switzerland power demand, TWh per year



A balanced mix of production technologies has been assumed

In percentage of production

	Coal	Coal CCS	Coal CCS retrofit [1]	Gas	Gas CCS	Gas CCS retrofit	Nu-clear	Wind: On-shore	Wind: Off-shore	Solar: PV	Solar: CSP	Bio-mass	Geo-thermal	Large Hydro
80% RES 10% CCS 10% nuclear	0	3	2	0	5	0	10	15	15	19	5	12	2	12
60% RES 20% CCS 20% nuclear	0	7	3	0	10	0	20	11	10	12	5	8	2	12
40% RES 30% CCS 30% nuclear	0	7	3	0	10	0	20	11	10	12	5	8	2	12
Baseline: 34% RES 49% coal/gas 17% nuclear	21	0	0	28	0	0	17	9	2	1	1	8	1	12

1 Only on “CCS ready” plants

EXHIBIT 13

Significant capacities are required in solar, wind and back-up plants

GW installed in 2050

	Fossil fuels	Solar PV	Wind onshore	Wind offshore	Other[1]	Back-up plants
80% RES 10% CCS 10% nuclear	80	815	245	190	420	270
60% RES 20% CCS 20% nuclear	155	555	165	130	455	240
40% RES 30% CCS 30% nuclear	240	195	140	25	490	190
Baseline: 34% RES 49% coal/gas 17% nuclear	410	35	140	25	380	120

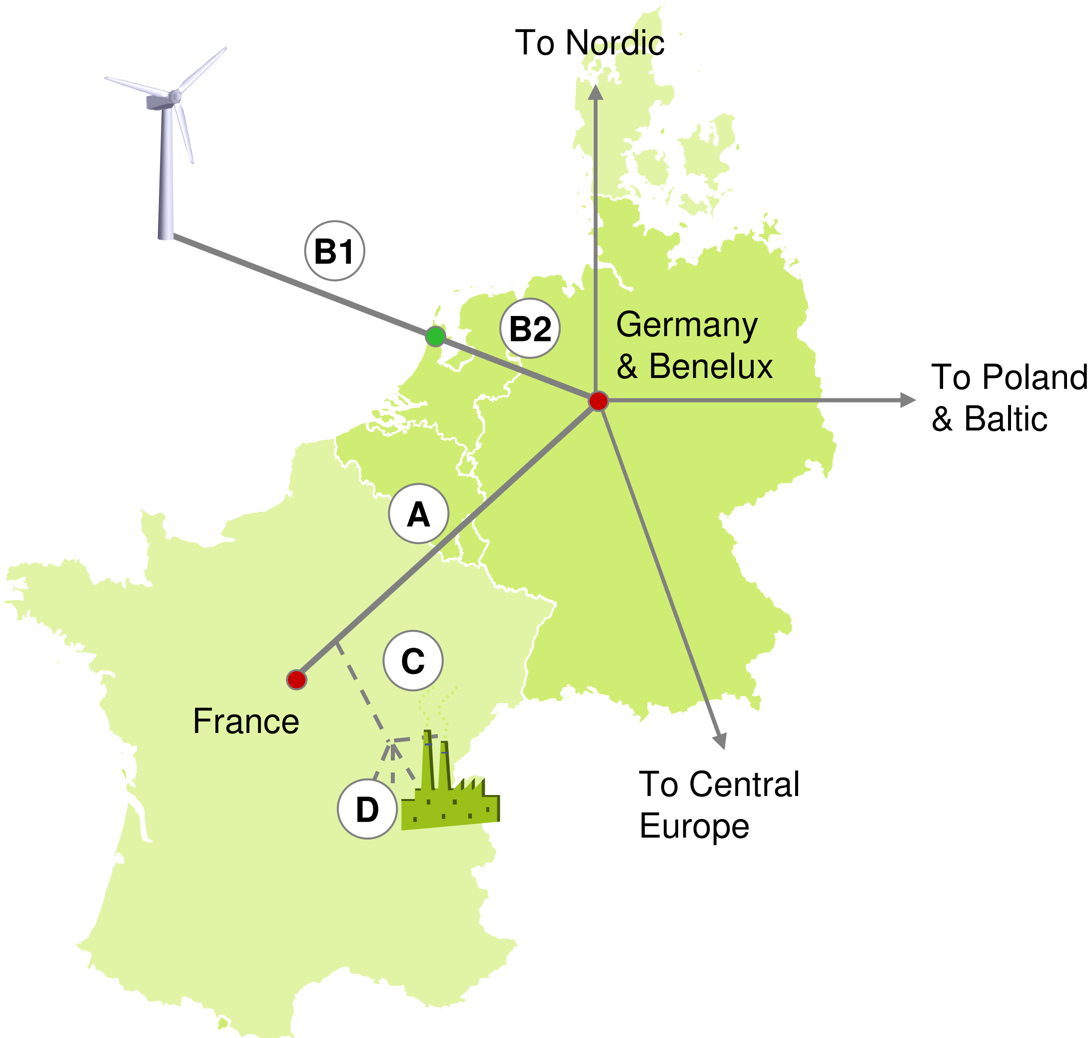
1 Includes nuclear, hydro, biomass, geothermal, solar CSP

EXHIBIT 14

Both inter- and intra-regional transmission requirements are quantified

Example for Germany & Benelux

- Centre of gravity
- Shore landing point



(A) Transmission between centers of gravity of regions[1]
Included in the grid cost, with required capacity determined based on the grid modeling

(B1) Transmission of offshore wind parks to shore
Included in wind generation capex

(B2) Transmission from shore landing point to centre of gravity
Included in grid cost. Estimated using average cost and length. Number of links required based on installed offshore wind capacity.

(C) Transmission within region
Not explicitly modeled but largely covered through (A)

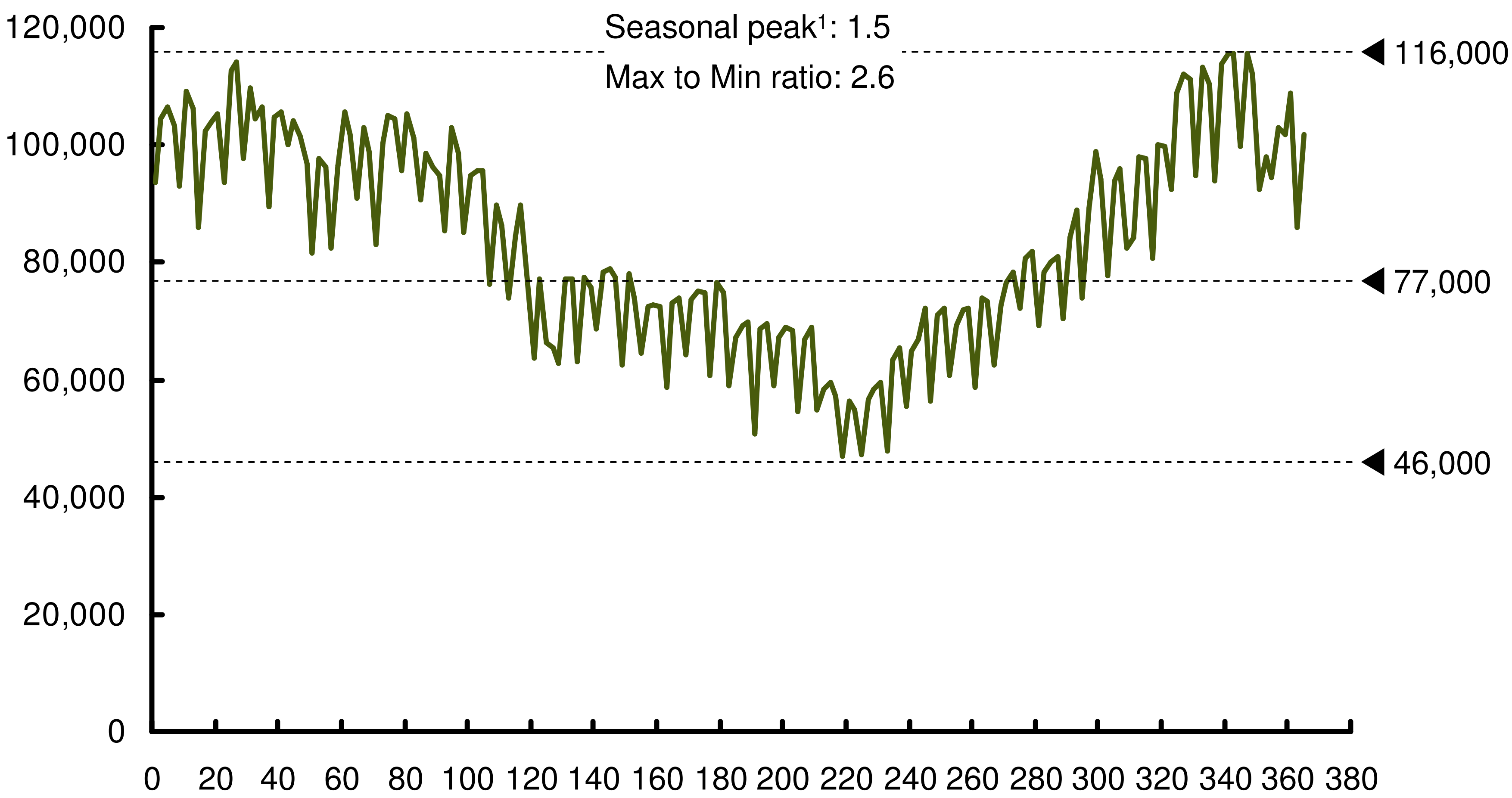
(D) Transmission and distribution grid reinforcements to end-user
Not included

1 This assumes a firm capacity capability from centre of gravity to centre of gravity that would allow for the dispersion of power along the way implicitly covering intra-regional reinforcements

EXHIBIT 15

Load curve for France, adjusted for increased winter peak for heat pumps

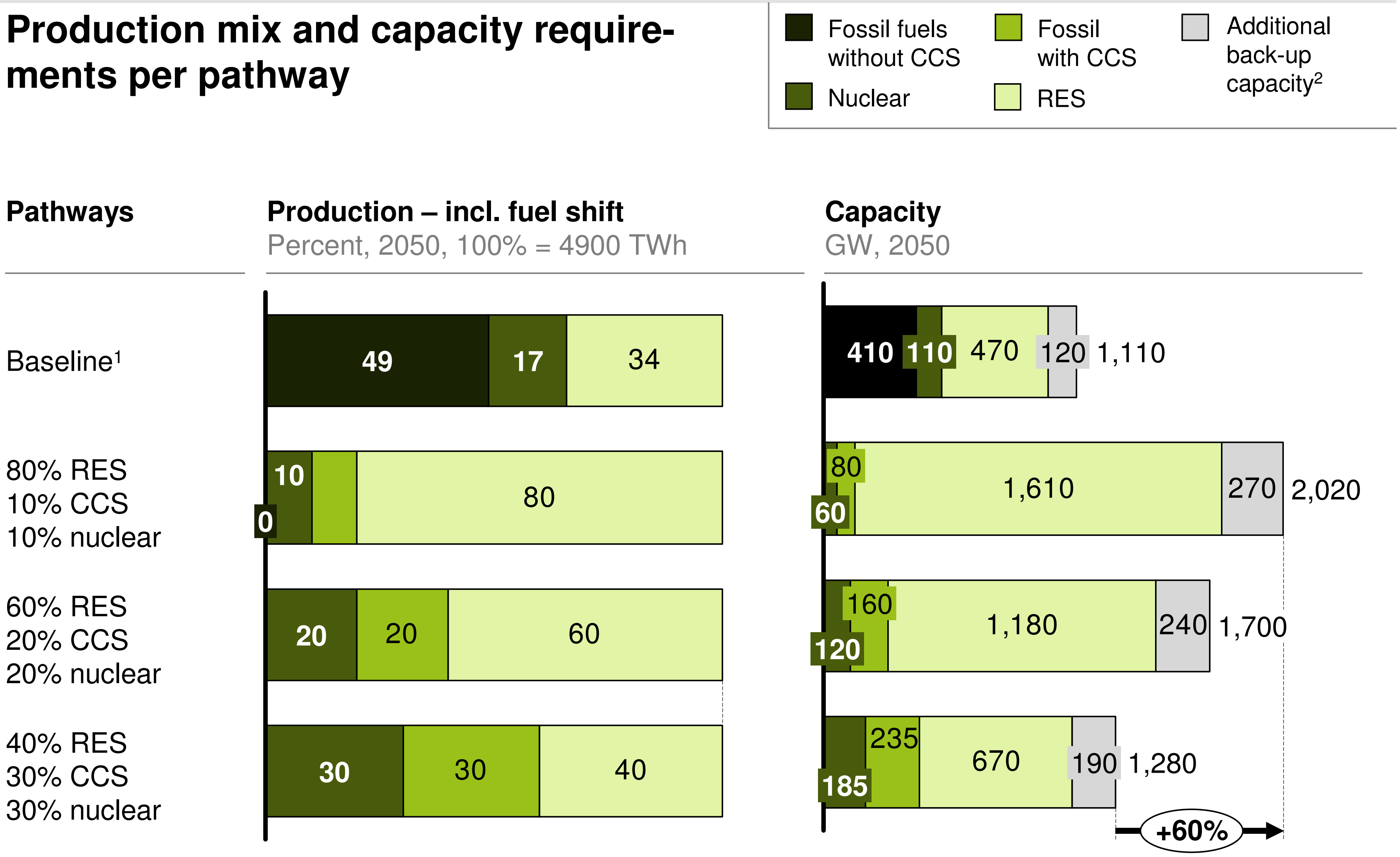
2050, GW



1 Seasonal peak defined as winter demand peak divided by summer demand peak

EXHIBIT 16

Production mix and capacity requirements per pathway



1 Supply of 4800 TWh, technology split by PRIMES, forecast updated with IEA WEO 2009 and Oxford economics

2 Additional back-up capacity to meet peak demand. Assumed to be OCGT in the costing, but could be any equivalent. 20% DR case shown.

EXHIBIT 17

Transmission flows and back-up generation capacity requirements

2050, GW

Pathways	DR	Additional transmission[1]	Back-up and balancing	RES curtailment[2] %
Baseline[1]	0%	2	120	
Requirements on top of the baseline				
80% RES 10% CCS 10% nuclear	0%	165	255	3
	20%	125	150	2
60% RES 20% CCS 20% nuclear	0%	100	205	2
	20%	85	120	1
40% RES 30% CCS 30% nuclear	0%	55	150	2
	20%	50	70	2

1 Requirements by 2050 additional to existing lines
2 In percentage of total renewable energy production

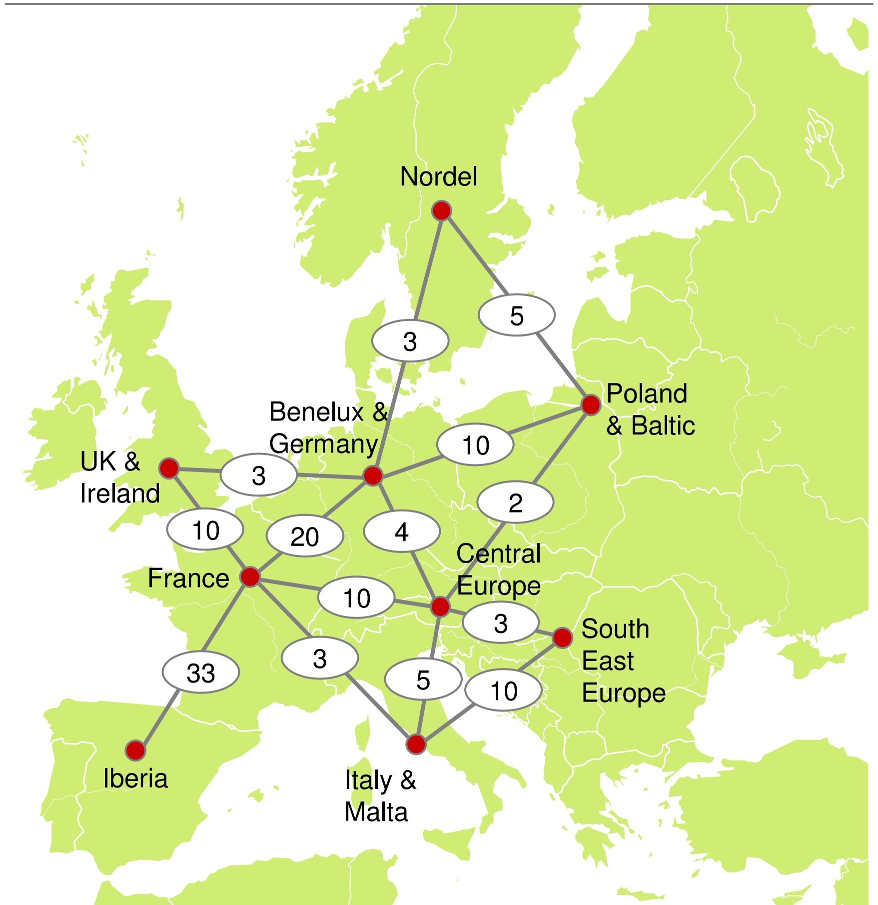
EXHIBIT 18

Grid expansion requirement example: threefold increase required for the 60% RES pathway

Centre of gravity

60% RES, 20% DR

Total net transfer capacity requirements
GW (existing + additional)

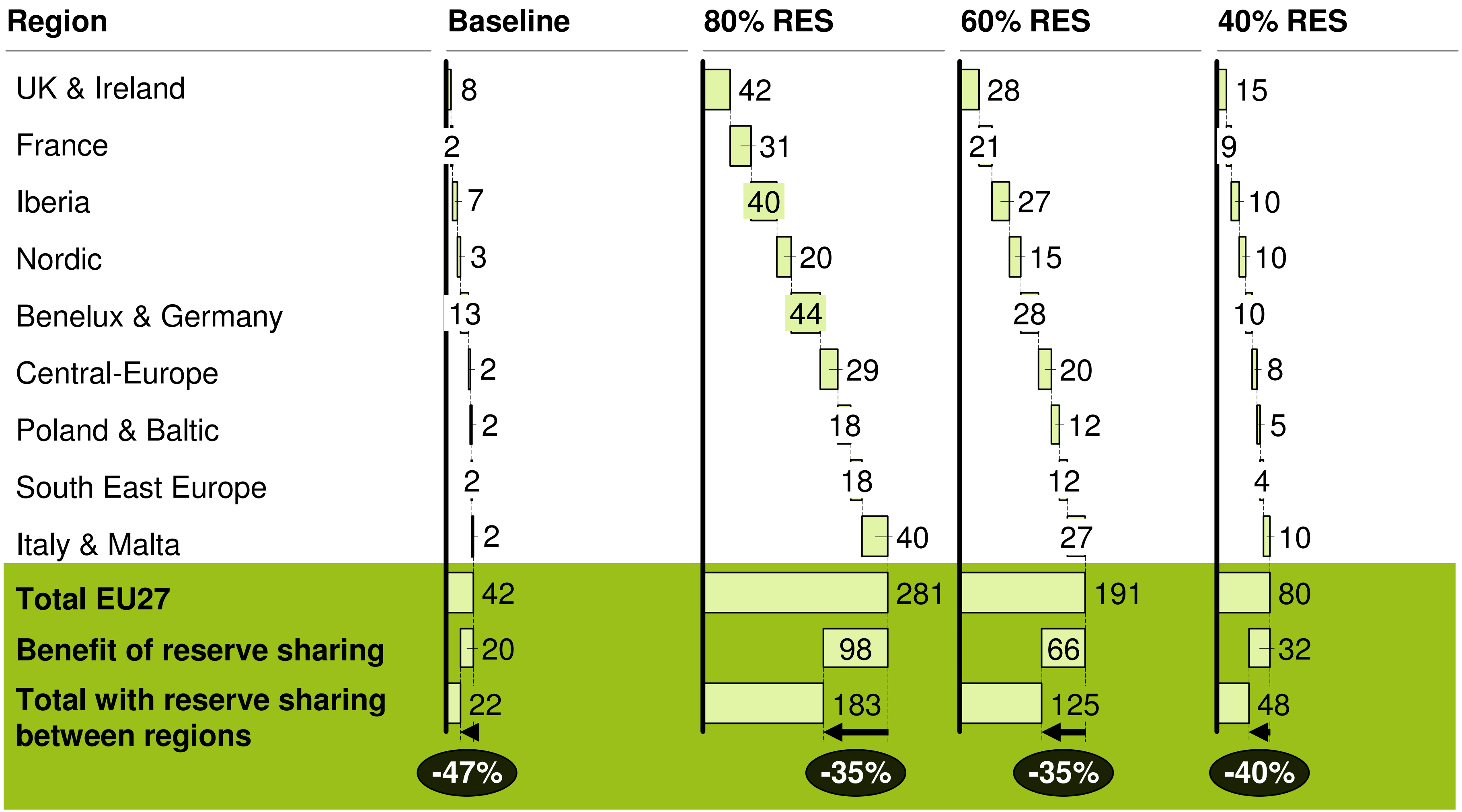


Interconnection	Capacity additional + (existing), GW	Annual utilization %
▪ UK&Ireland-France	8 + (2)	75
▪ UK&Ireland-Nordel	0 + (0)	0
▪ UK&Ireland-Benelux & Germany	3 + (0)	83
▪ France-Iberia	32 + (1)	83
▪ France-Benelux & Germany	14 + (6)	78
▪ France-Central-Europe	7 + (3)	93
▪ France-Italy&Malta	0 + (3)	92
▪ Nordel-Benelux & Germany	0 + (3)	75
▪ Nordel-Poland&Baltic	4 + (1)	60
▪ Benelux & Germany-Central-EU	0 + (4)	74
▪ Benelux & Germany-Poland&Baltic	9 + (1)	81
▪ Central-Europe-Poland & Baltic	0 + (2)	77
▪ Central-South East EU	1 + (2)	80
▪ Central-Europe-Italy	0 + (5)	58
▪ South East EU-Italy	9 + (1)	79
Total	**87 + (34)**	

EXHIBIT 19

Reserve sharing across EU-27 reduces total reserve requirements by ~40%

Maximal reserve requirements[1], GW



1 Reserve refers to reserve required at four hour ahead of real-time. This is required to manage the larger changes in generation (due to plant outages and expected uncertainty in intermittent output) expected over that four hour period that could require starting additional (or switching off) generation

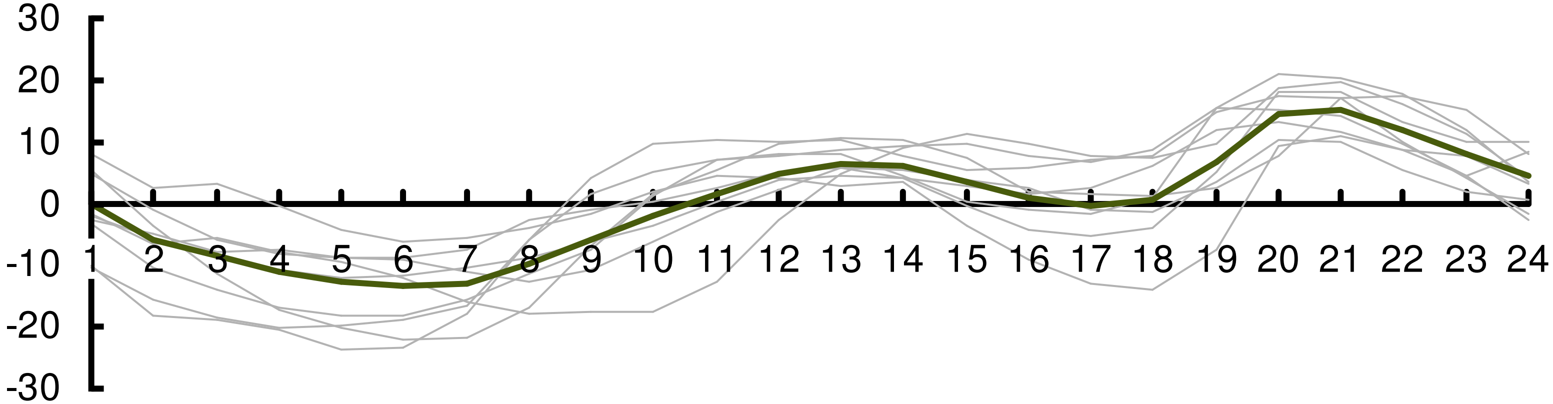
EXHIBIT 20

Increased transmission cancels out both daily and seasonal fluctuations

Percent

Individual regions
Total EU-27

Example: Regional demand variation from average per hour during one day



Regional demand variation from average over the year

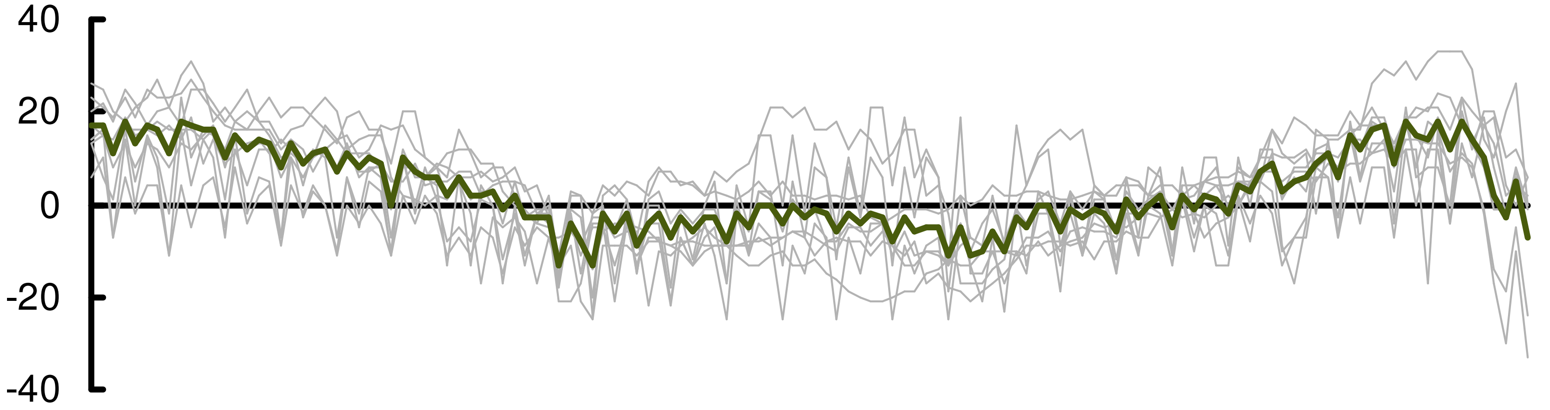
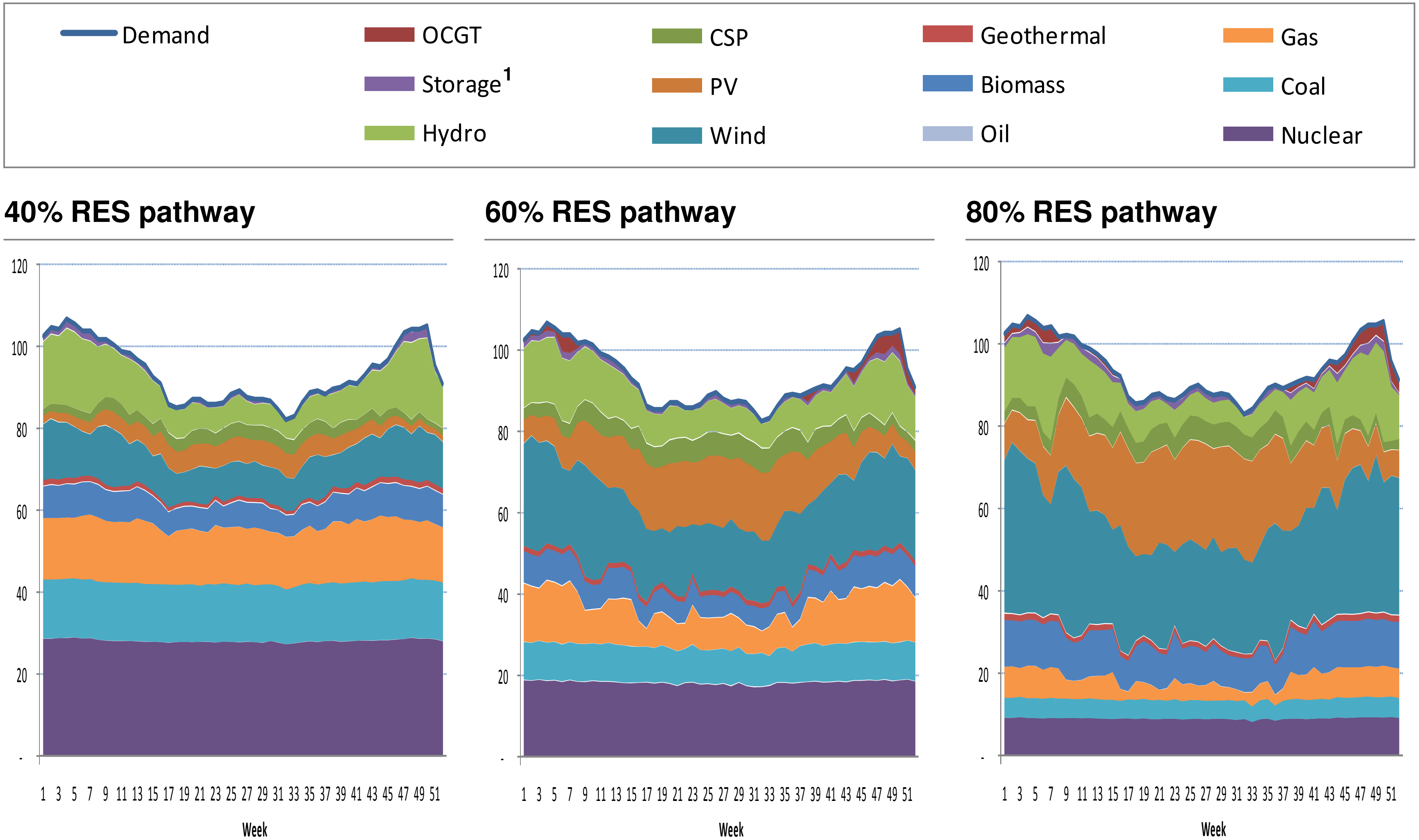


EXHIBIT 21

A combination of solar and wind is more stable than wind alone

Yearly energy balance, 20% DR, TWh per week



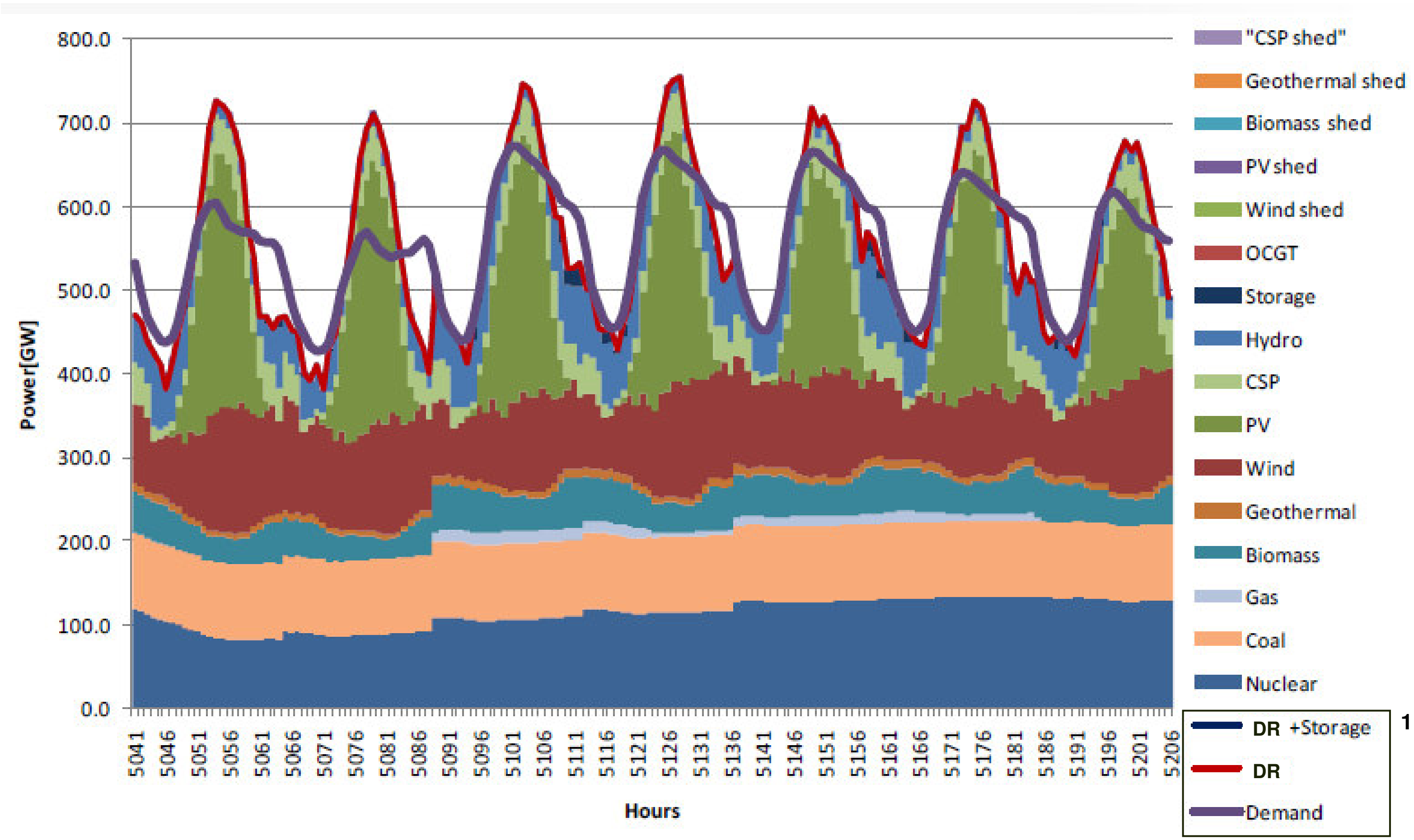
1 Storage included in the model relates to the existing hydro storage available across the regions

EXHIBIT 22

Demand management helps to make demand follow supply, maximizing the utilization of RES

WEEK 32 – SUNNY WEEK

60% RES, 20% DR

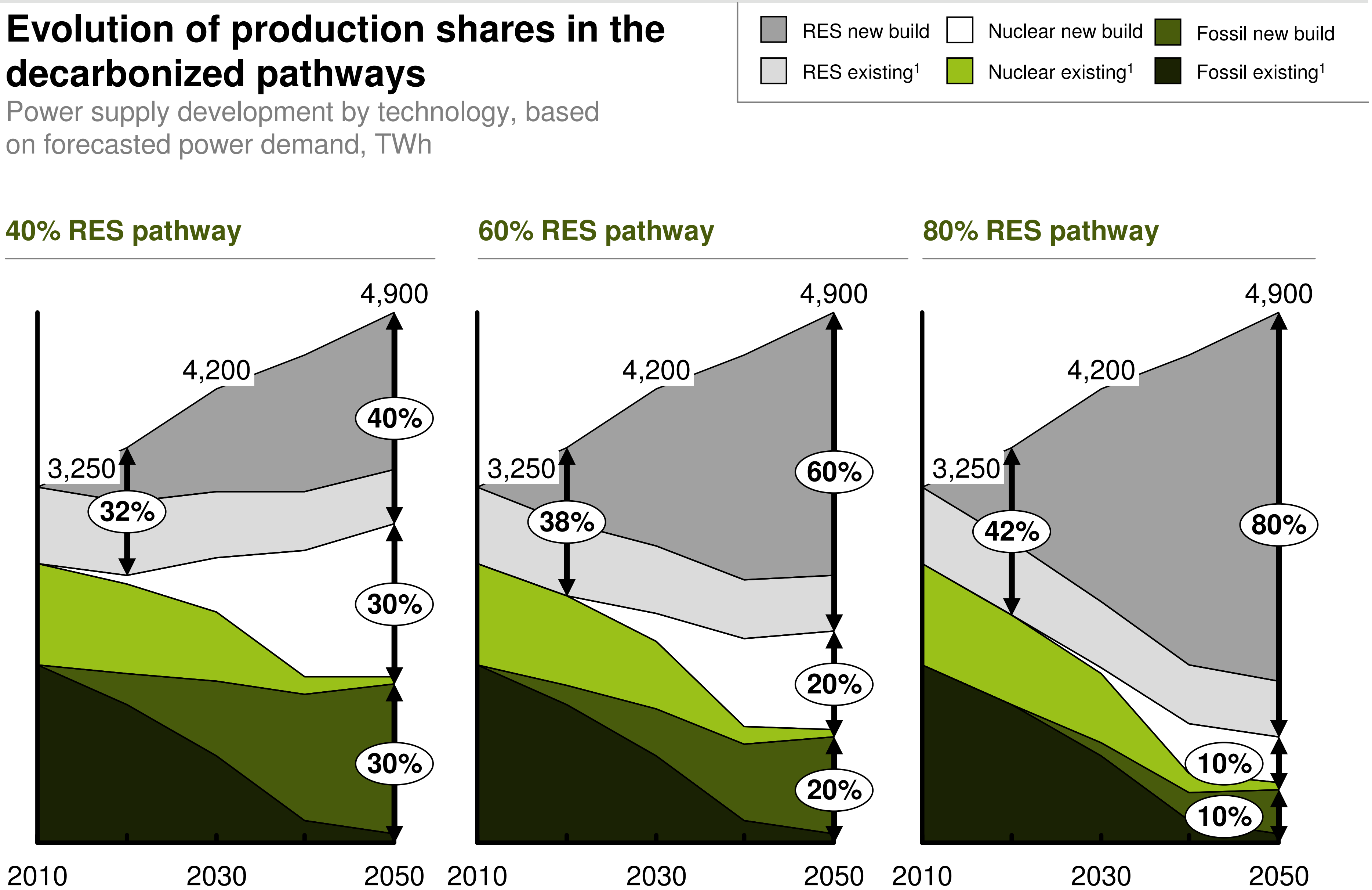


1 The graph shows how the original demand line (purple) is shifted to a higher level (red line) by DR to capture the higher PV production

EXHIBIT 23

Evolution of production shares in the decarbonized pathways

Power supply development by technology, based on forecasted power demand, TWh



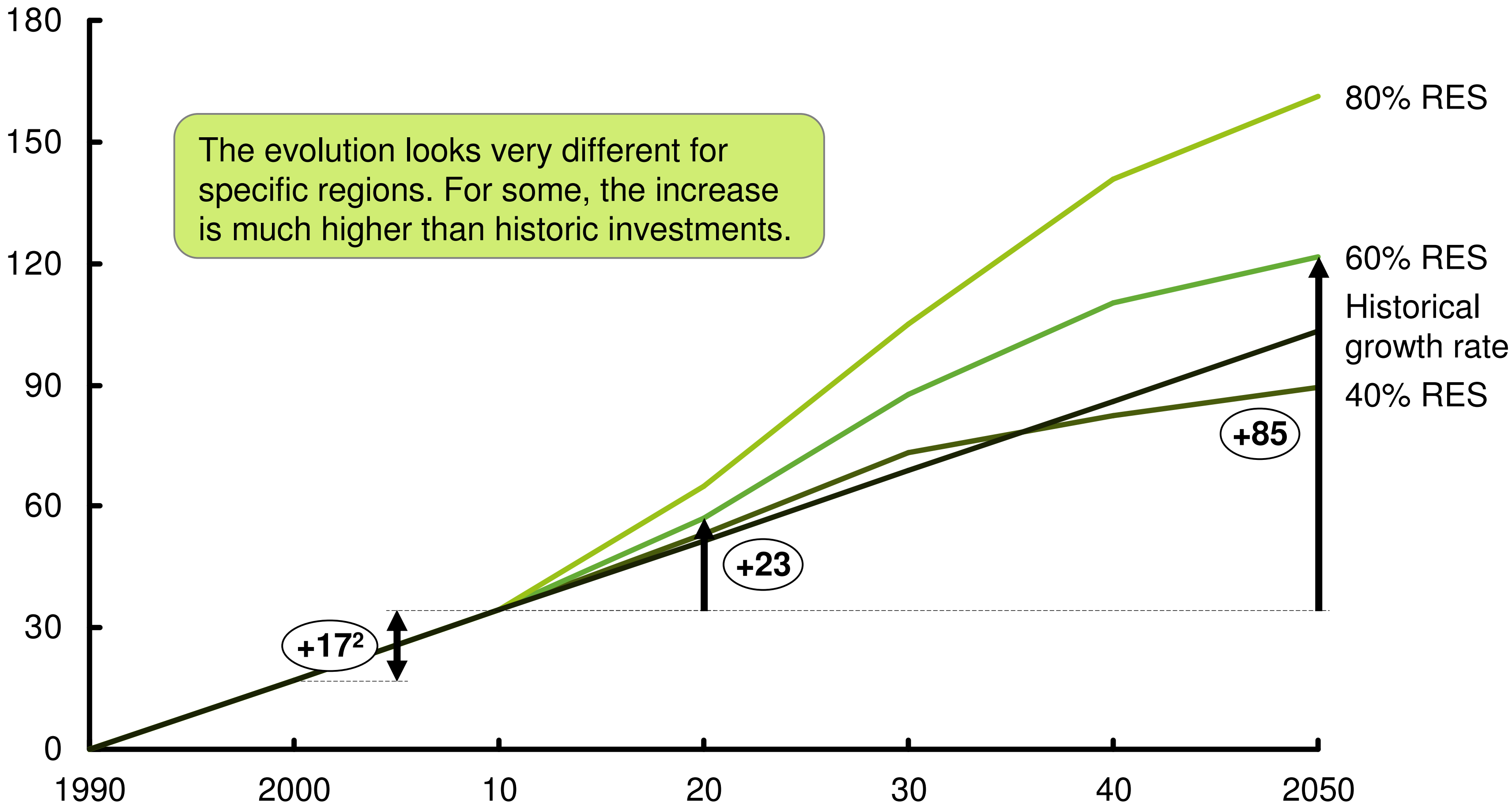
1 Existing capacity includes new builds until 2010

EXHIBIT 24

The rate of grid investments compares to historic investments at the European level

20% DR

GW, EU-27, Norway and Switzerland[1,2]



1 Development of grid is driven by the penetration of intermittent power sources (solar PV, wind onshore and wind offshore)

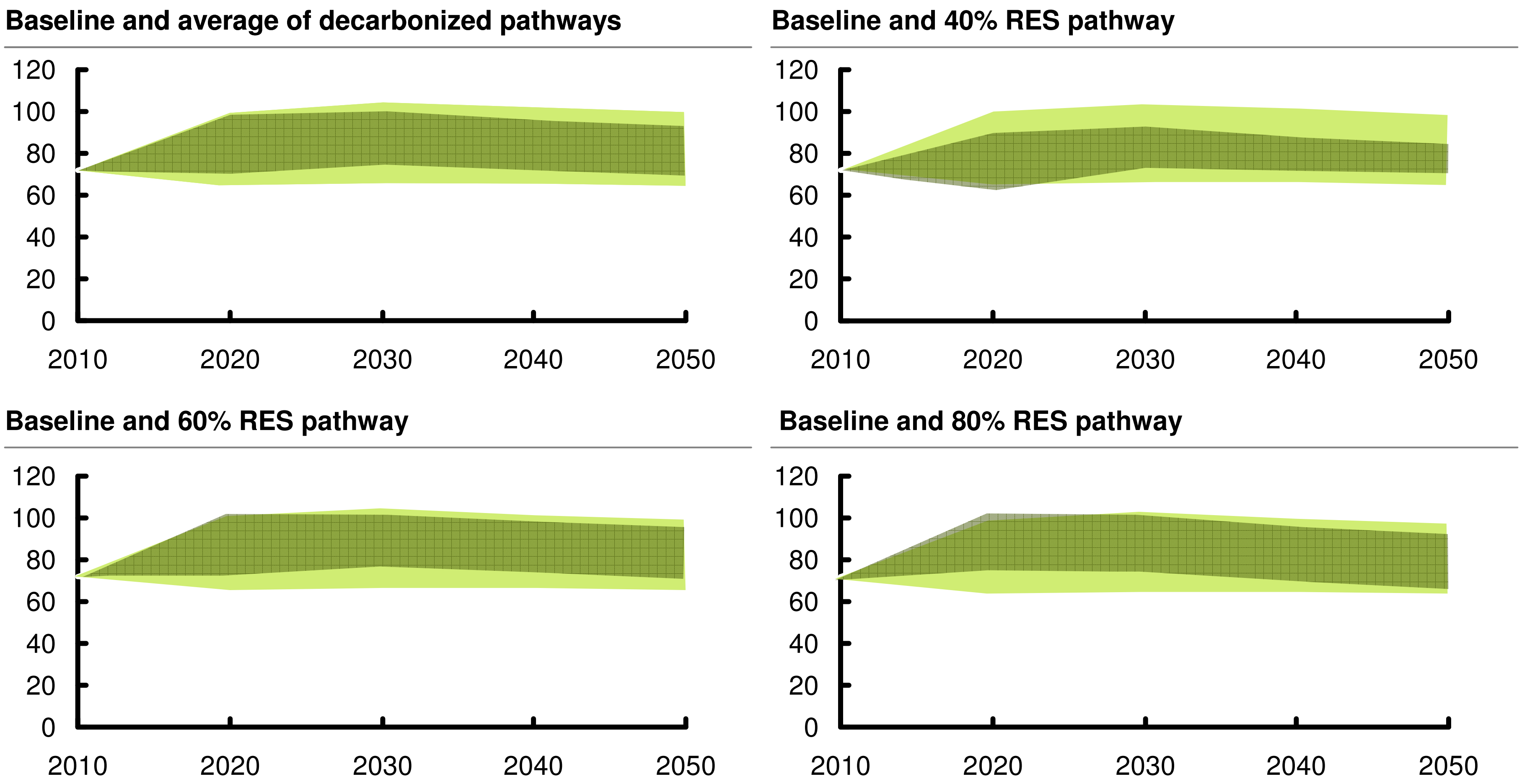
2 This assumes a linear build up of grid capacity in thousand GW km between 1990 and 2010, starting at zero, although some grid has been built even before 1990, i.e. UK-France and much of the Central European interconnections

EXHIBIT 25

The higher RES pathways have higher cost of electricity in the early years

Ranges of the levelized cost of electricity of new builds[1], € per MWh (real terms)

Baseline
Decarbonized pathways



1 Based on a WACC of 7% (real after tax), computed by technology and weighted across technologies based on their production; including grid. LCoE ranges are based on: Carbon price from €0 to 35 per tCO_2e; Fossil fuel prices: IEA projections +/- 25%; Learning rates: default values +/- 25%

EXHIBIT 26

A doubling of capital spent would be required over the next 15 years

Annual capex development per pathway, € billions per year

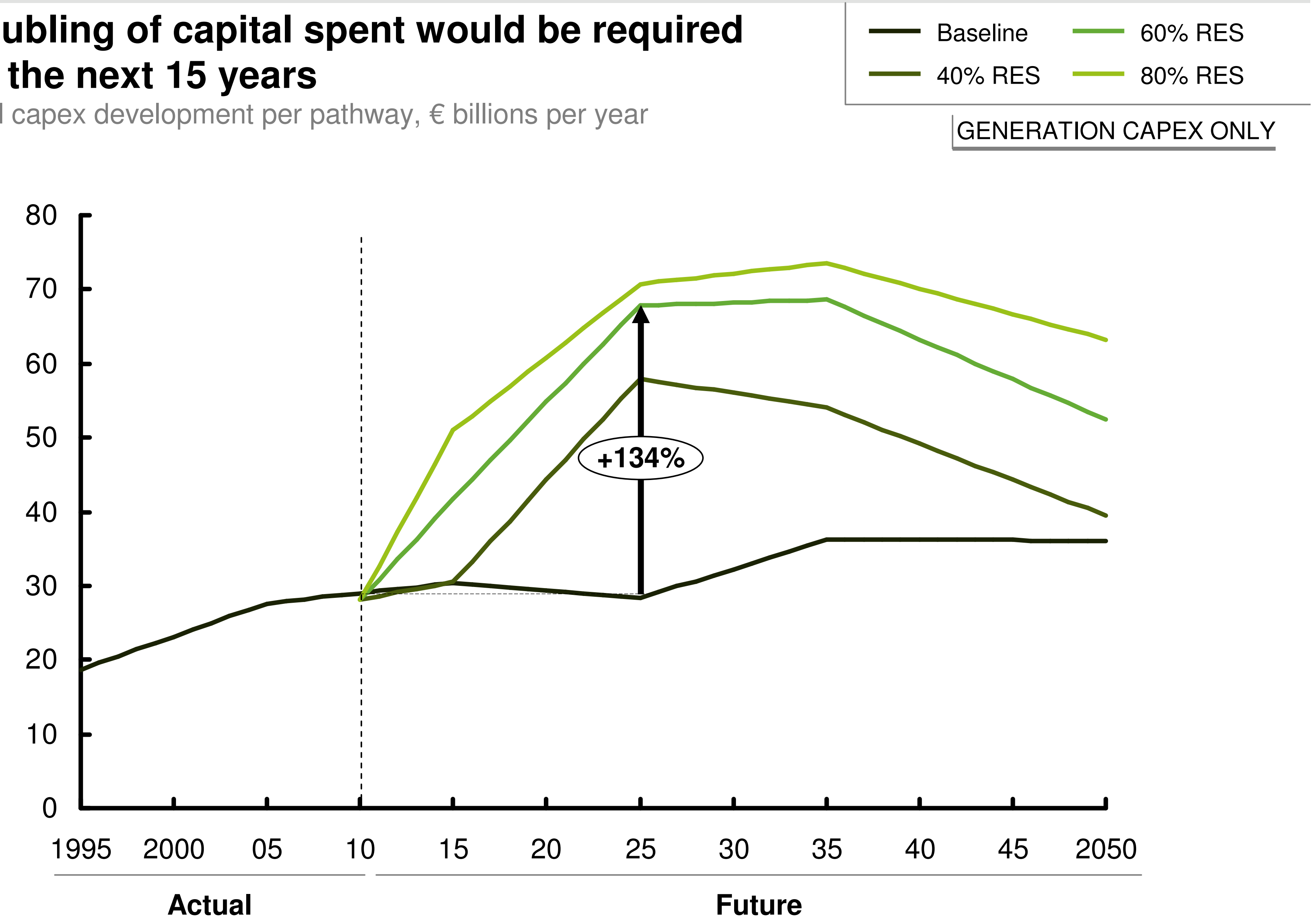


EXHIBIT 27

Transmission and back-up related capex both increase with a higher share of intermittent RES

Cumulative capex from 2010 to 2050, € billion (real terms)

Pathways	DR	Transmission capex of additional capacity: Inter-regional[1]	Transmission capex of additional capacity: Offshore wind farms	Back-up generation capex[2]
Baseline[1]	0%	2	8	32
80% RES 10% CCS 10% nuclear	0%	139	43	131
	20%	105	43	95
60% RES 20% CCS 20% nuclear	0%	84	31	114
	20%	71	31	84
40% RES 30% CCS 30% nuclear	0%	44	9	93
	20%	44	9	67

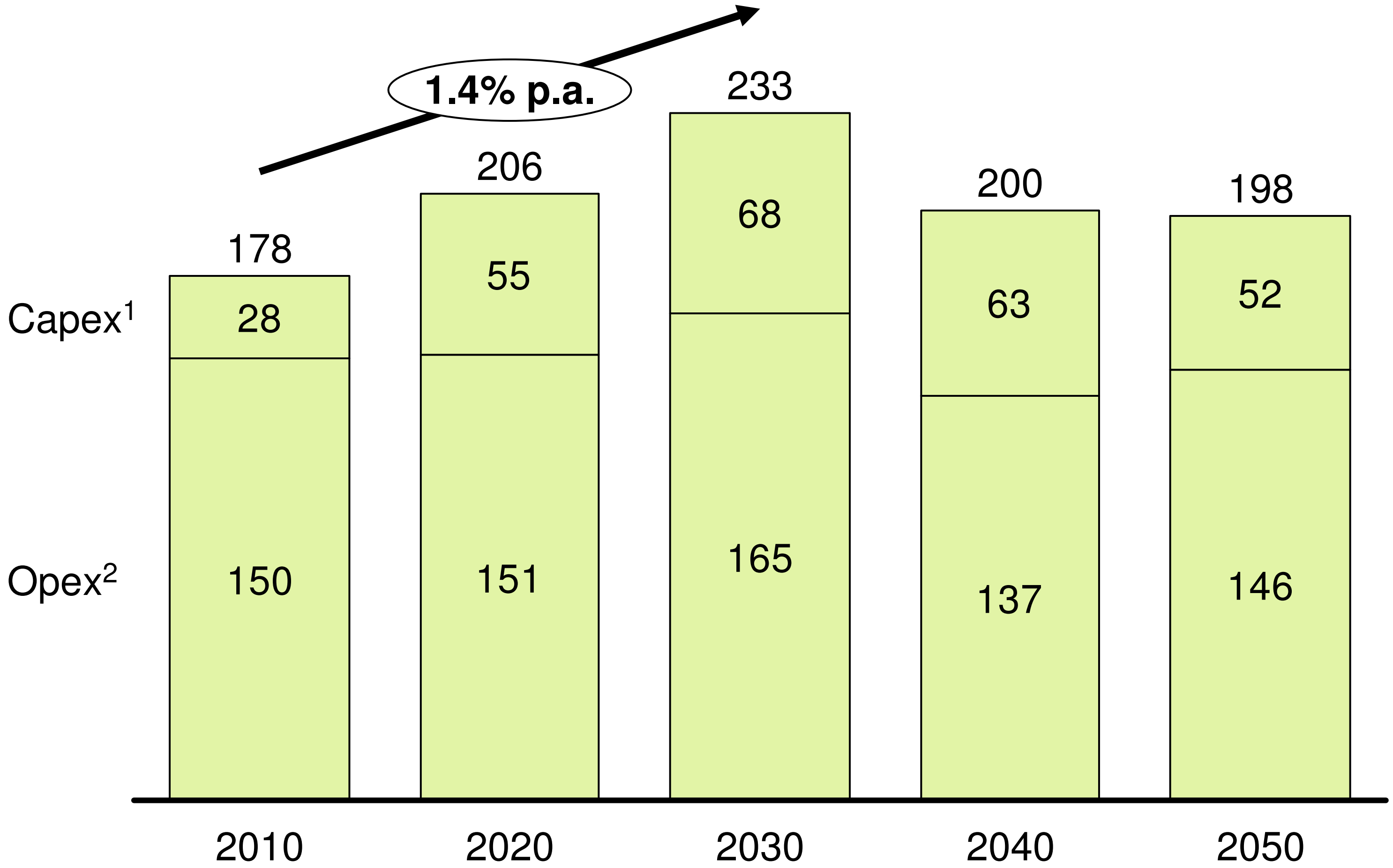
1 Based on an average transmission mix with 73% AC and 27% HVDC (comparable to the Tradewind report) at a cost of € 1,000 MW per km
2 The cost of additional capacity is assumed to be 350,000 € per MW based on OCGTs, but could be any equivalent

EXHIBIT 28

Total power costs increase up to 2030 due to increasing fuel prices and capital investments

60% RES PATHWAY

Total annual capex and opex, € billion per year



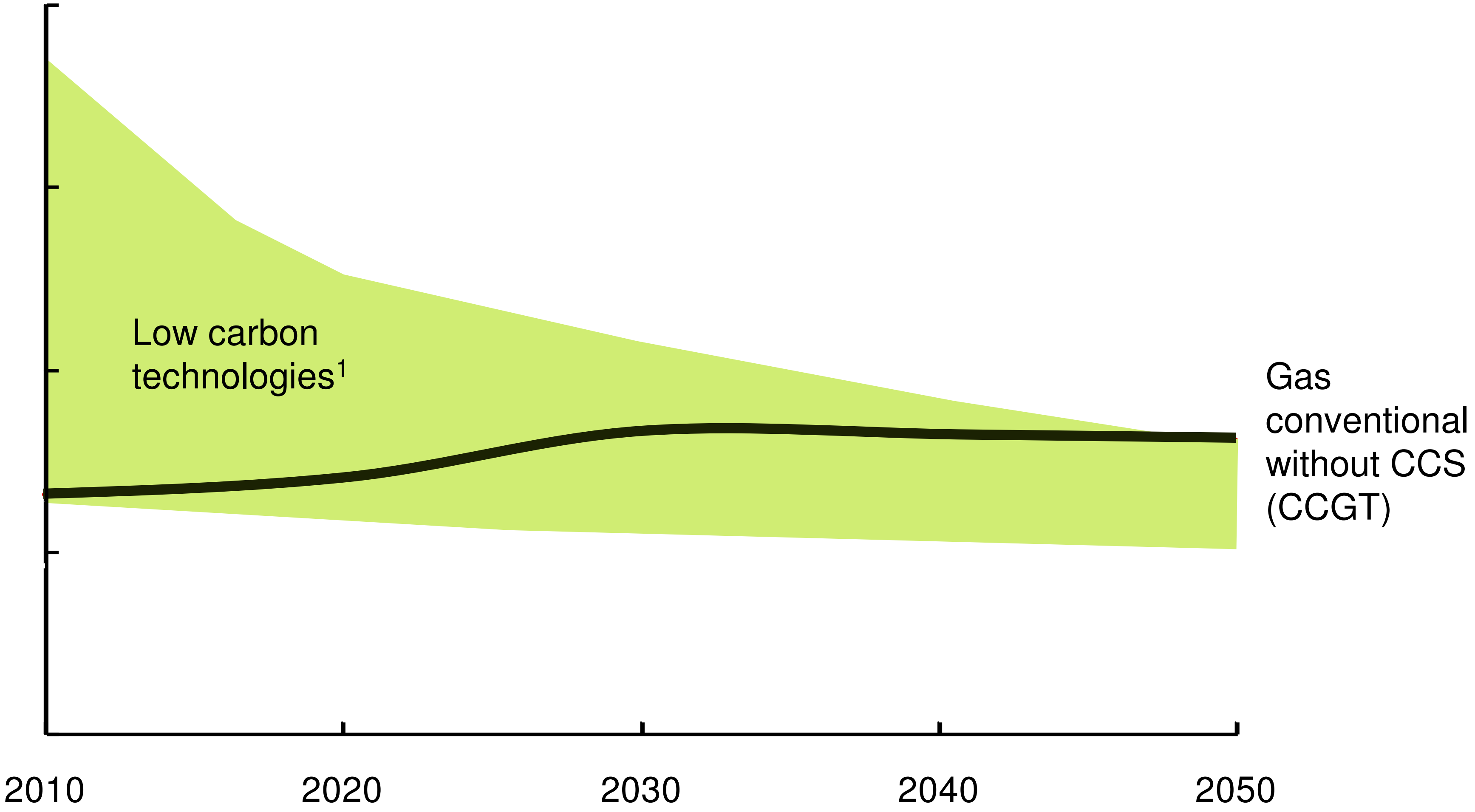
1 Capex is for new builds for generation as well as grid and back-up capacity

2 Opex covers operational expenses for the entire generation fleet

EXHIBIT 29

Low carbon technology costs decrease while gas plant costs increase

LCoE evolution of gas conventional compared to low carbon technologies, € per MWh (real terms)
Example based on the 60% RES / 20% nuclear / 20% CCS pathway, Iberia

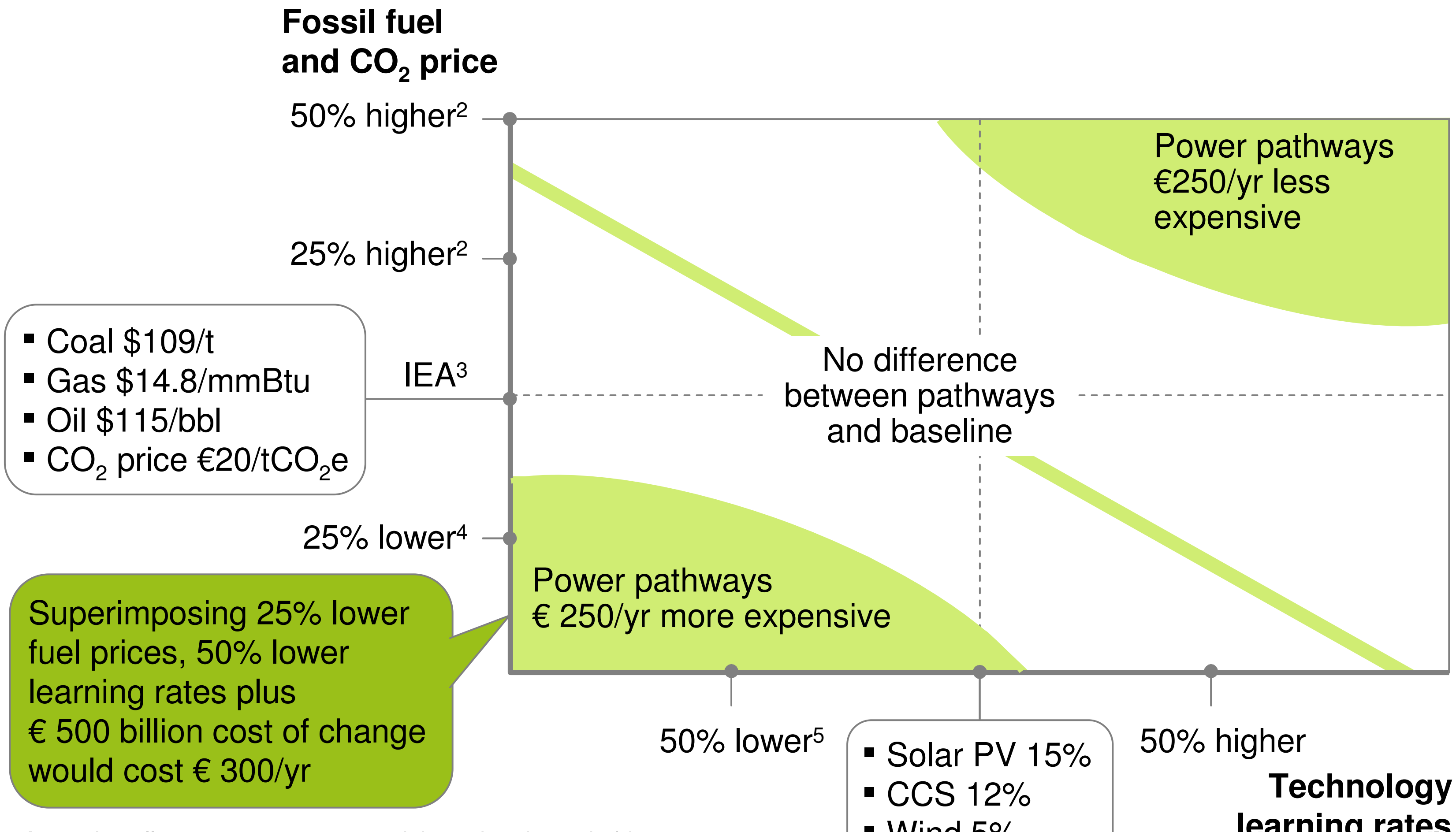


1 Technologies included: Coal CCS, Nuclear, Wind onshore and offshore, Solar PV, Solar CSP and biomass dedicated

EXHIBIT 30

The cost of the decarbonized pathways and the baseline are likely to differ less than € 250 per year per household

Cost impact of the decarbonized power pathways per year per household[1]

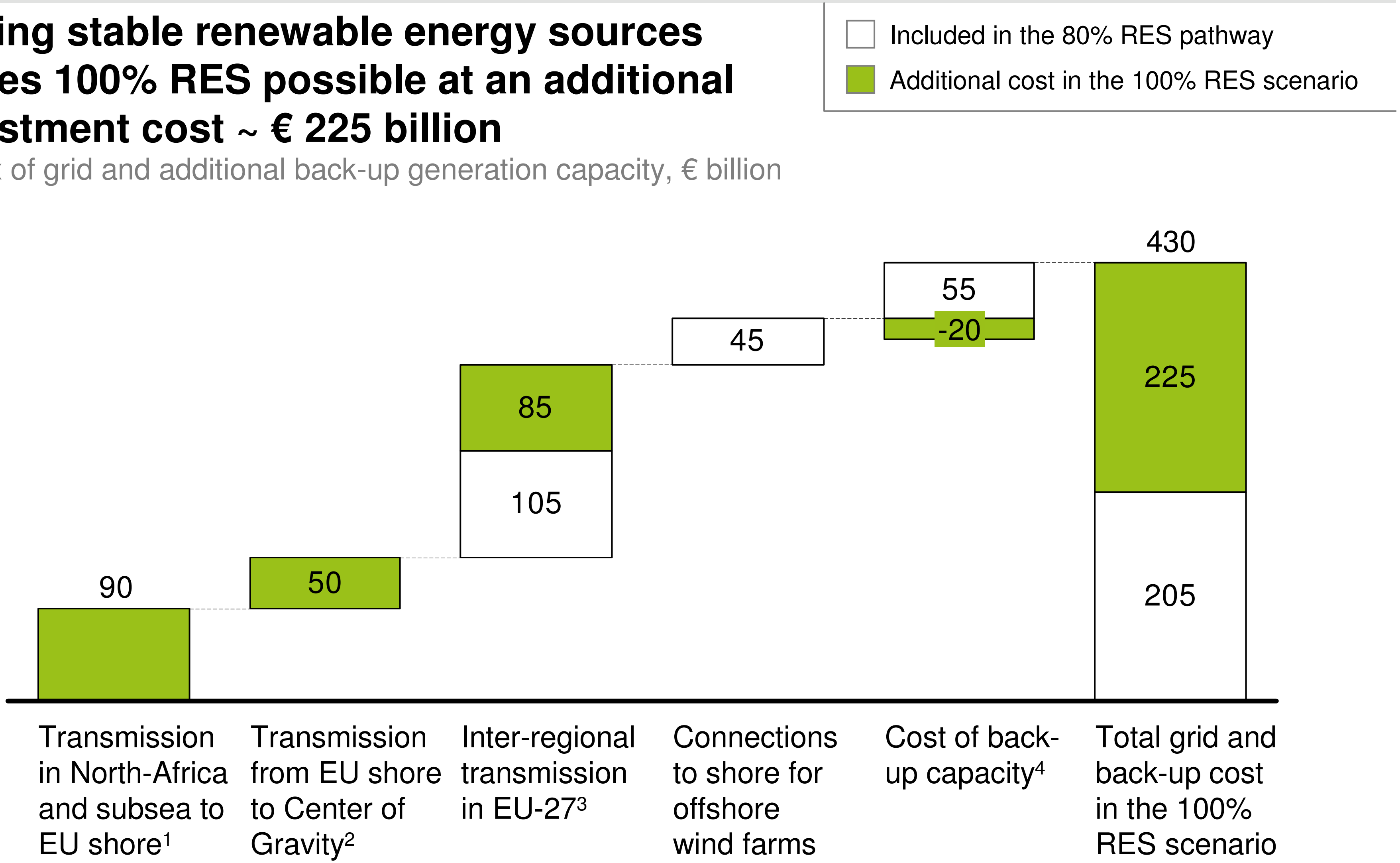


1 Assuming all power costs get passed through to households
2 CO_2 price assumed of € 40/tCO_2e
3 IEA WEO 2009 '450 Scenario' assumptions for 2030, kept constant up to 2050
4 No carbon price
5 For all technologies. Learning rate is defined as capex improvement per doubling of cumulative installed capacity

EXHIBIT 31

Adding stable renewable energy sources makes 100% RES possible at an additional investment cost ~ € 225 billion

Capex of grid and additional back-up generation capacity, € billion

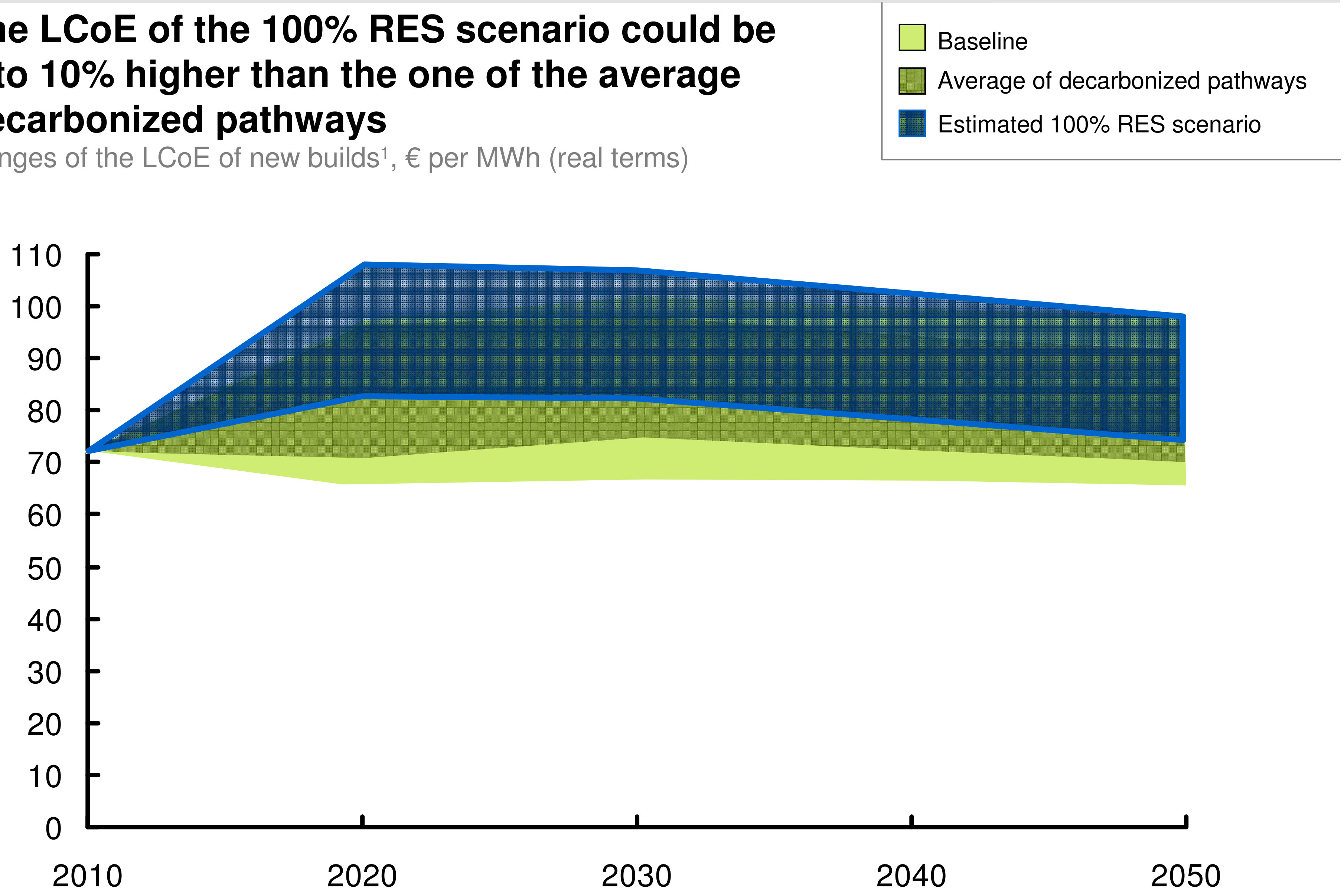


1 North African onshore transmission requirements and subsea connections to the European continent, all HVDC
2 All HVDC transmission with 20% cable and 80% overhead line
3 Requirements in transmission reinforcements to spread the electricity across the various regions from the Centers of Gravity in Southern Europe
4 With higher transmission in Europe, back-up requirements with demand response are lower in the 100% RES pathway, with 75 GW, compared to 95 GW in the 80% RES pathway

EXHIBIT 32

The LCoE of the 100% RES scenario could be 5 to 10% higher than the one of the average decarbonized pathways

Ranges of the LCoE of new builds[1], € per MWh (real terms)

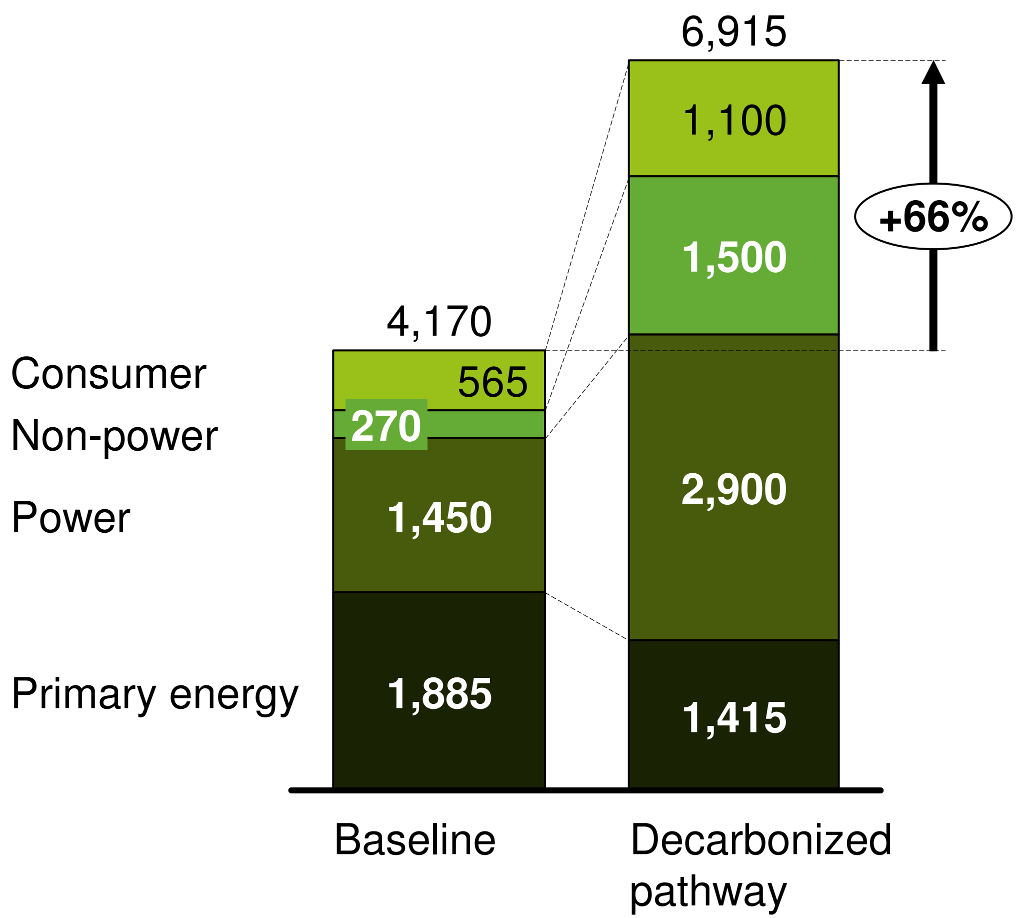


1 Based on a WACC of 7% (real after tax), computed by technology and weighted across technologies based on their production; including grid. LCoE ranges are based on: Carbon price from €0 to 35 per tCO_2e; Fossil fuel prices: IEA projections +/- 25%; Learning rates: default values +/- 25%

EXHIBIT 33

The decarbonized pathways require up to 70% more capital for all energy sectors, driven by more efficiencies and a shift away from oil

Cumulative capex 2010-50, € billions



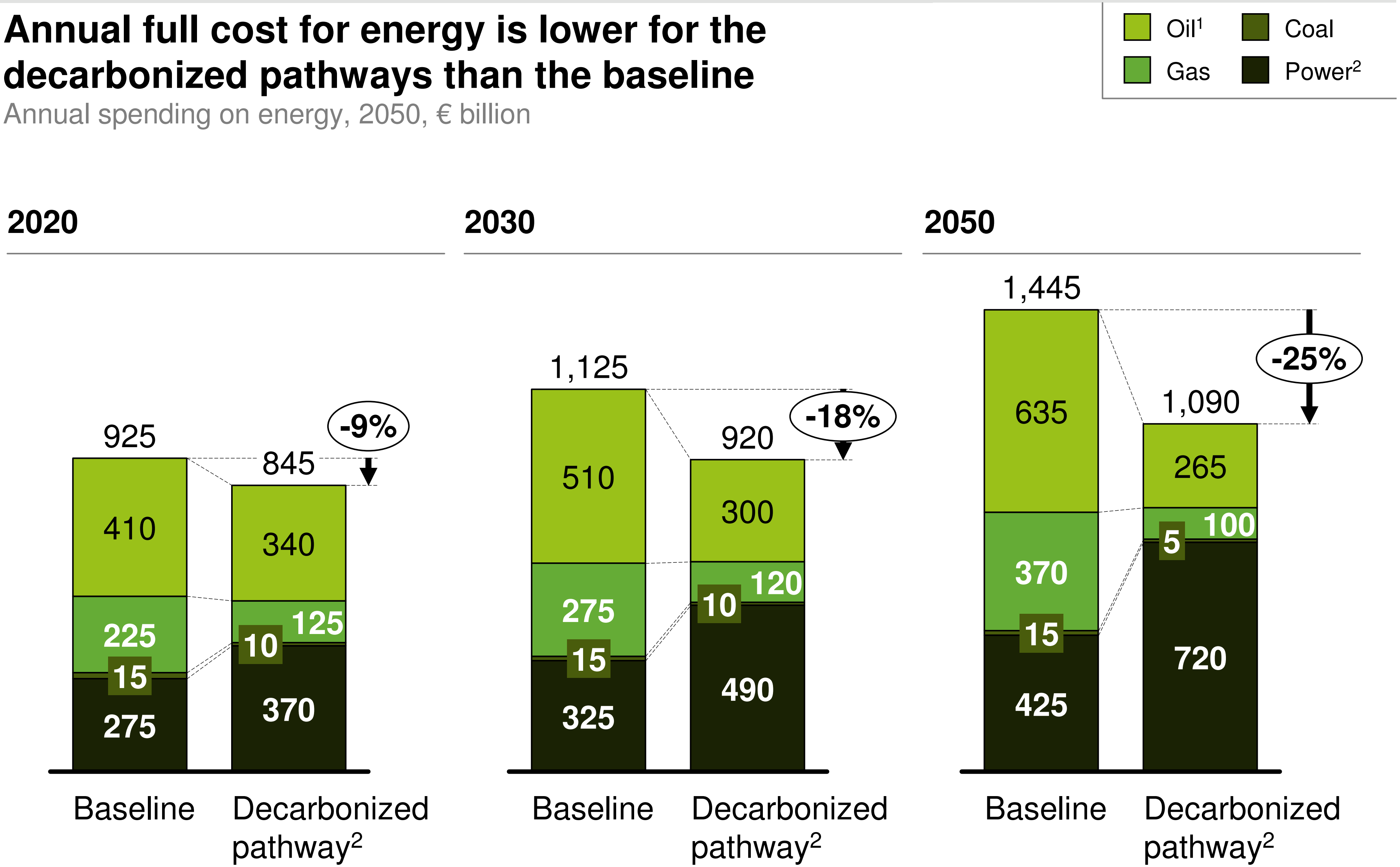
Note: Includes additional capex for EV batteries and fuel cells for vehicles (in total approximately € 500 billion)

SOURCE: IEA WEO 2009 (fossil fuel capex 2010-30, assumed constant 2030-50), McKinsey Global Cost curves, team analysis

EXHIBIT 34

Annual full cost for energy is lower for the decarbonized pathways than the baseline

Annual spending on energy, 2050, € billion



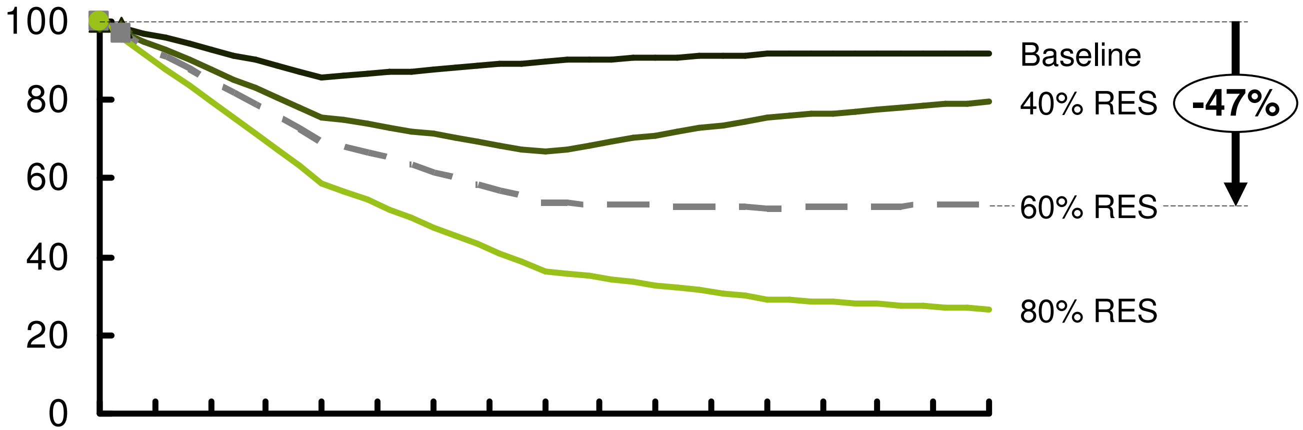
1 Includes biofuels and H2
2 Includes up to € 100 billion per year in 2050 to account for the additional capex from efficiency, EVs, heat pumps, industry CCS
3 60% RES / 20% CCS / 20% Nuclear pathway

SOURCE: IEA WEO 2009 (fossil fuel capex 2010-30, assumed constant 2030-50), McKinsey Global Cost curves, team analysis

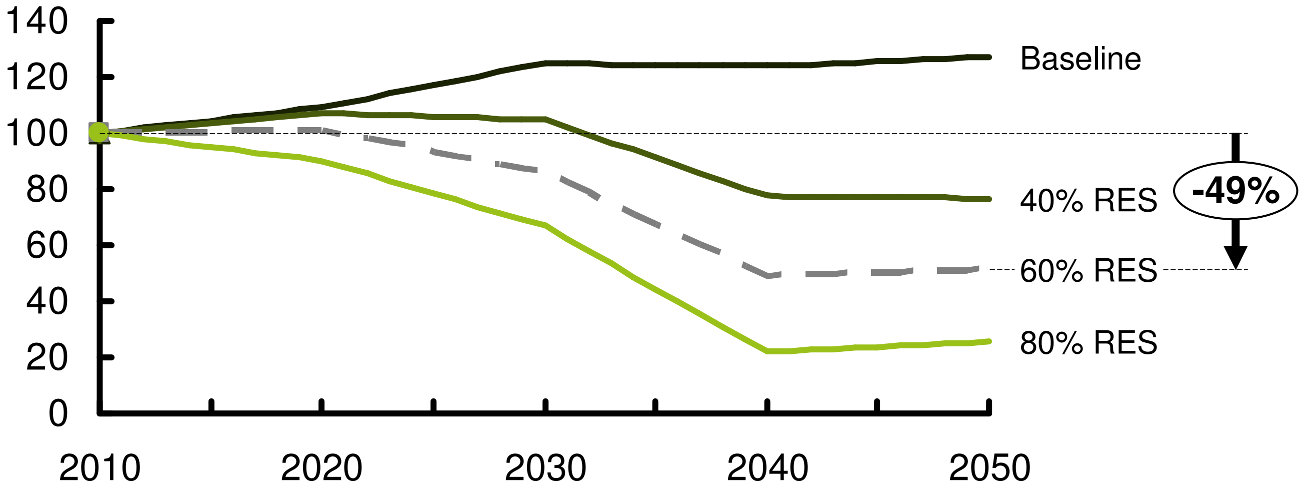
EXHIBIT 35

Coal and gas demand for power generation reduces significantly in the decarbonized pathways

Coal demand for power[1]
Indexed to 100 in 2010



Gas demand for power[2]
Indexed to 100 in 2010

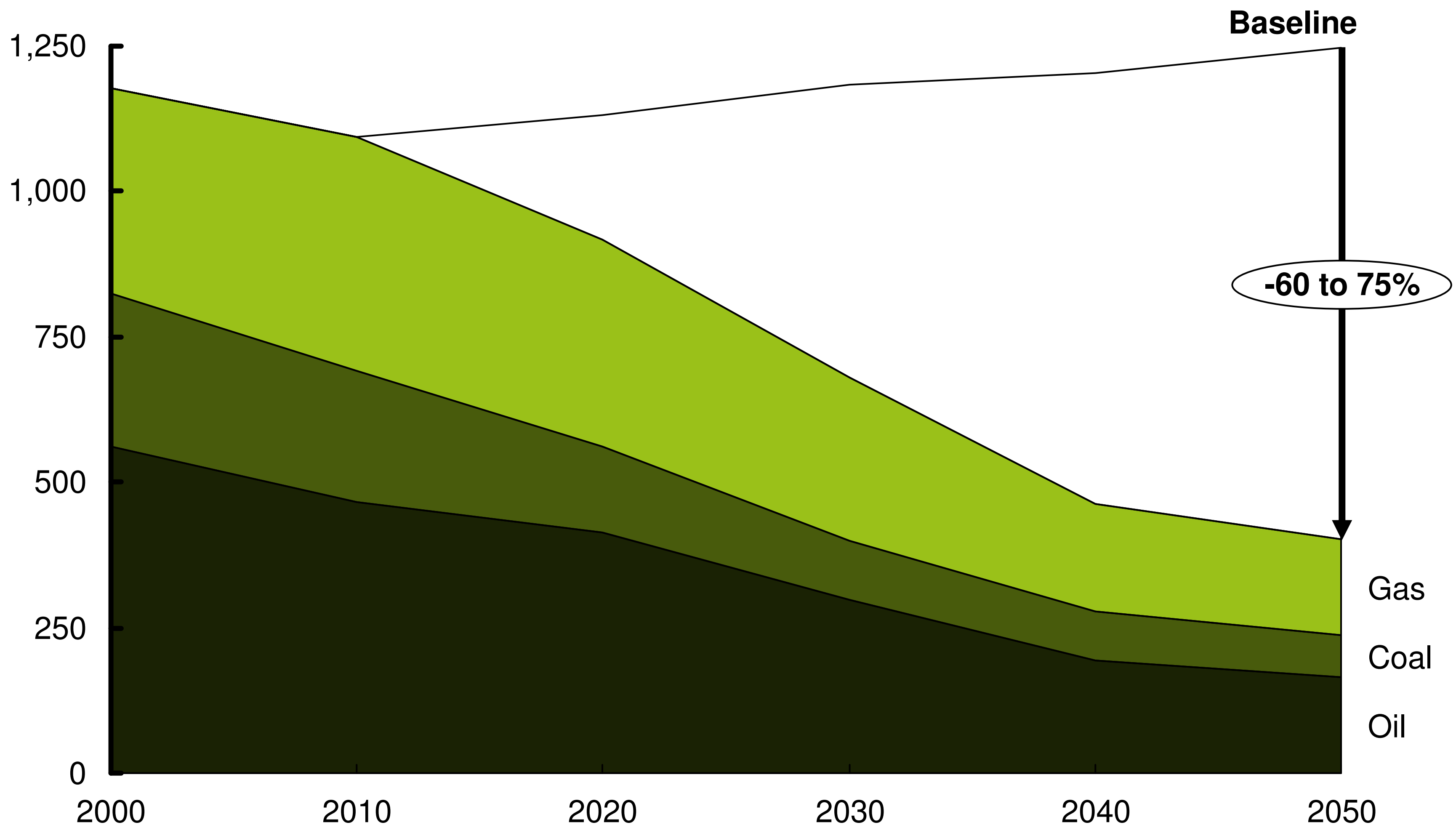


1 Coal demand in the 40% RES pathway increases after 2030 due to: increasing coal share (1 percentage point) along with the increase in power demand
2 For CCGTs only, excluding requirements for back-up and balancing plants (OCGTs)

EXHIBIT 36

Fossil fuels demand would reduce in the decarbonized pathways

Demand for fossil fuels across all demand sectors, Mtoe

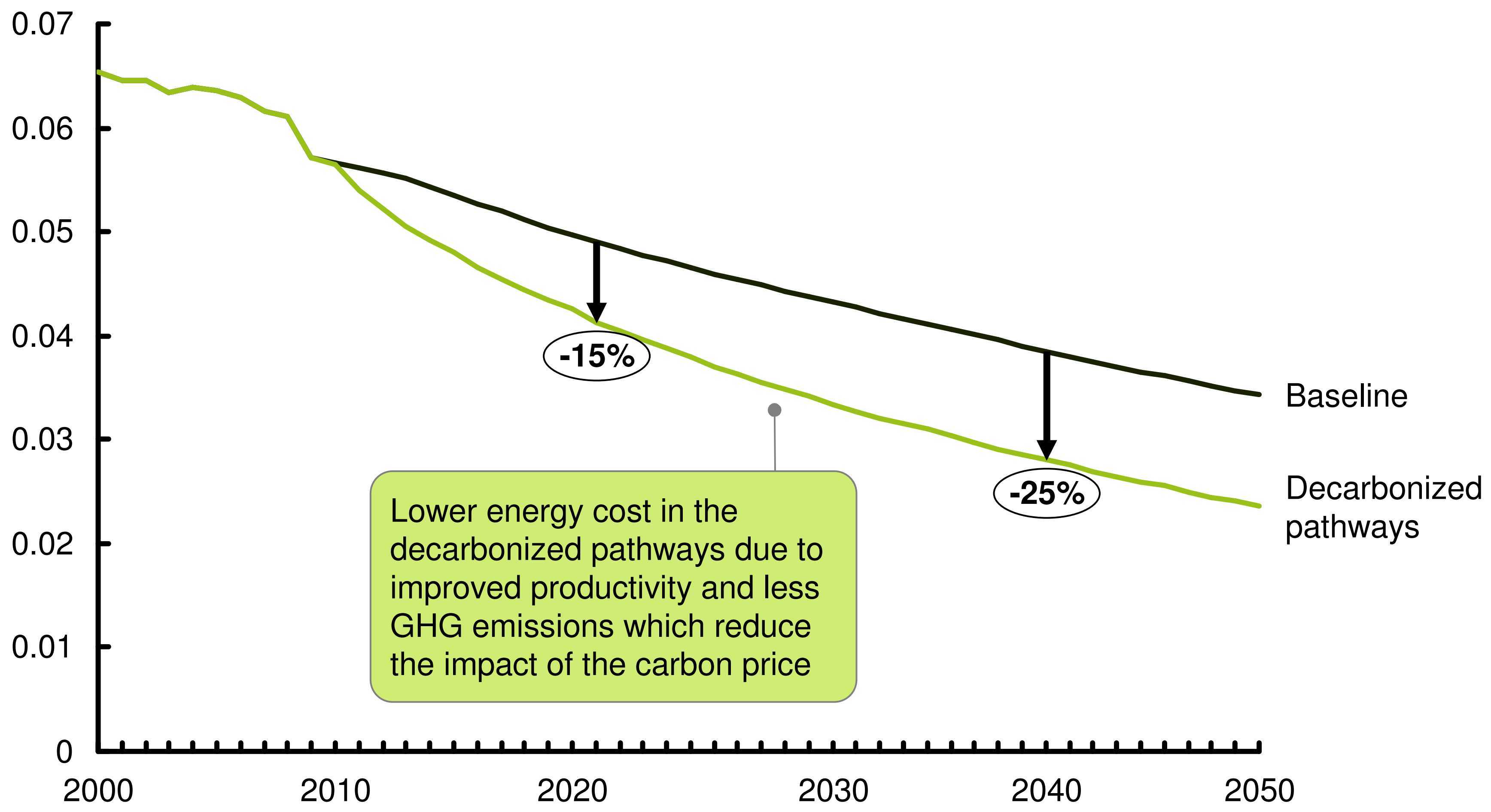


SOURCE: McKinsey Global Cost curves, team analysis

EXHIBIT 37

Energy cost decreases in the baseline, but even more so in the decarbonized pathways

Energy cost per unit of GDP output, € (real terms)

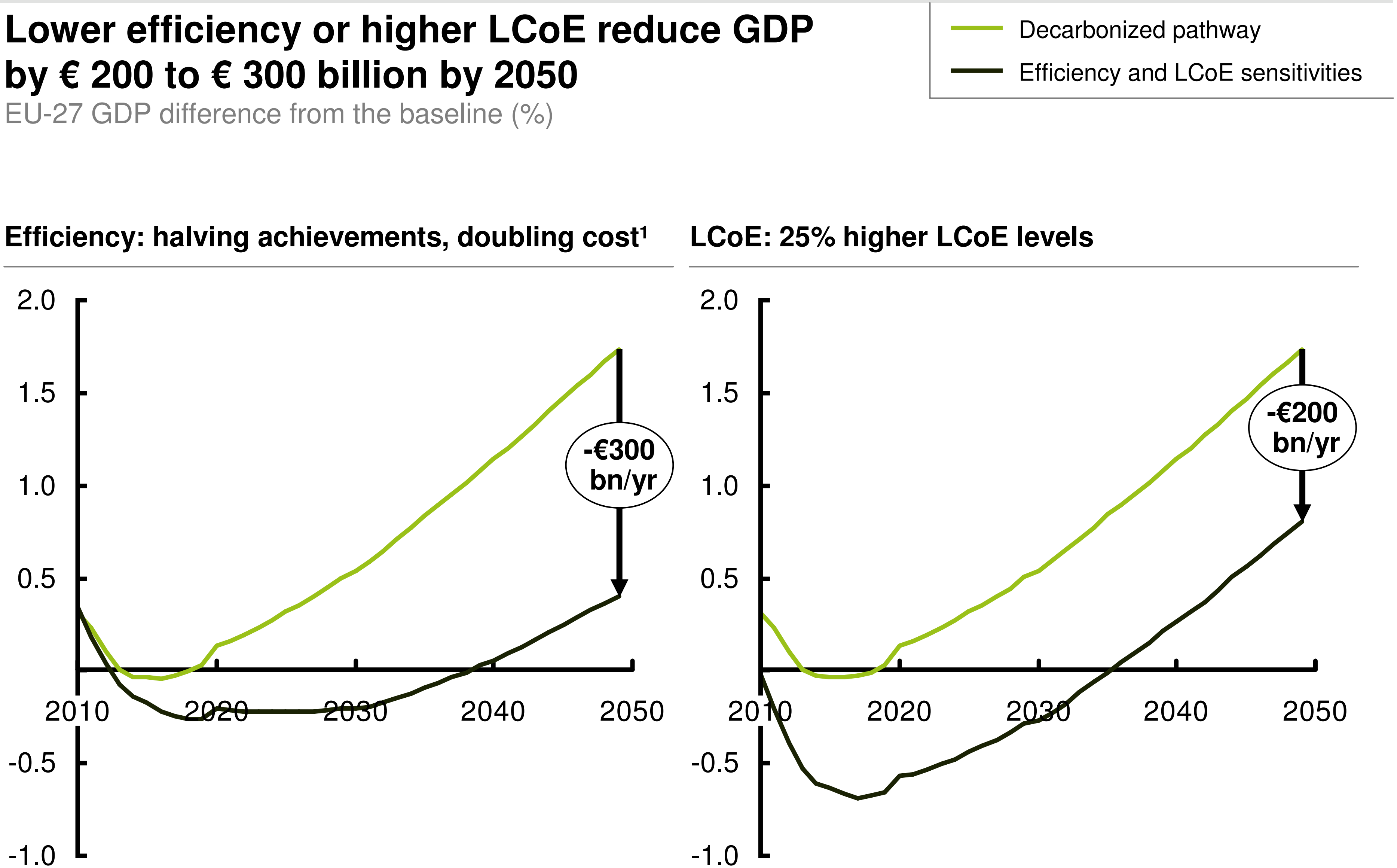


Note: Energy prices are a weighted average of prices faced by consumers weighted by the shares of consumption of different fuels

EXHIBIT 38

Lower efficiency or higher LCoE reduce GDP by € 200 to € 300 billion by 2050

EU-27 GDP difference from the baseline (%)

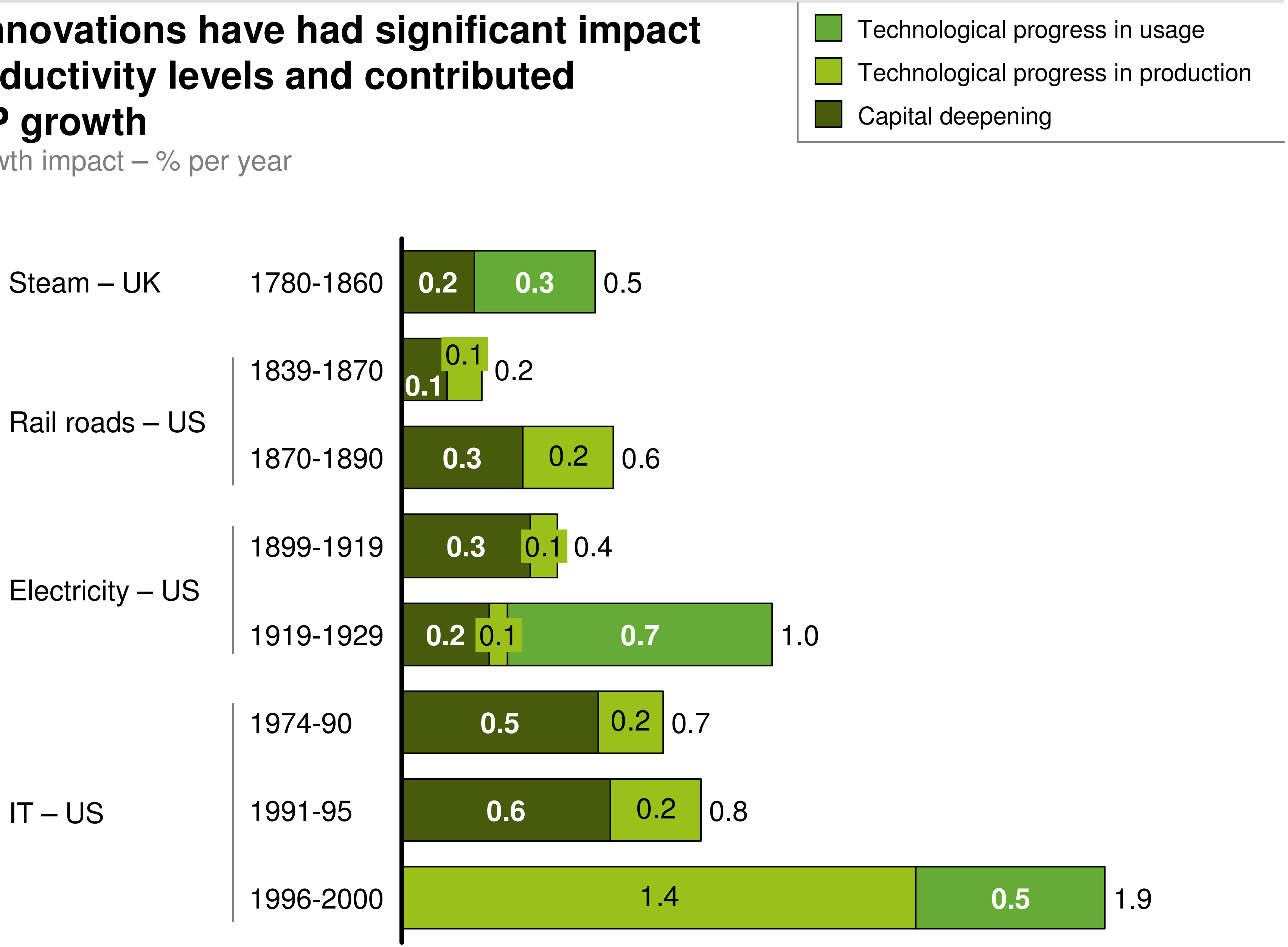


1 Doubling nominal cost of all efficiency improvements (industry, buildings and EVs); halving efficiency improvements in industry and buildings

EXHIBIT 39

Past innovations have had significant impact on productivity levels and contributed to GDP growth

GDP growth impact – % per year

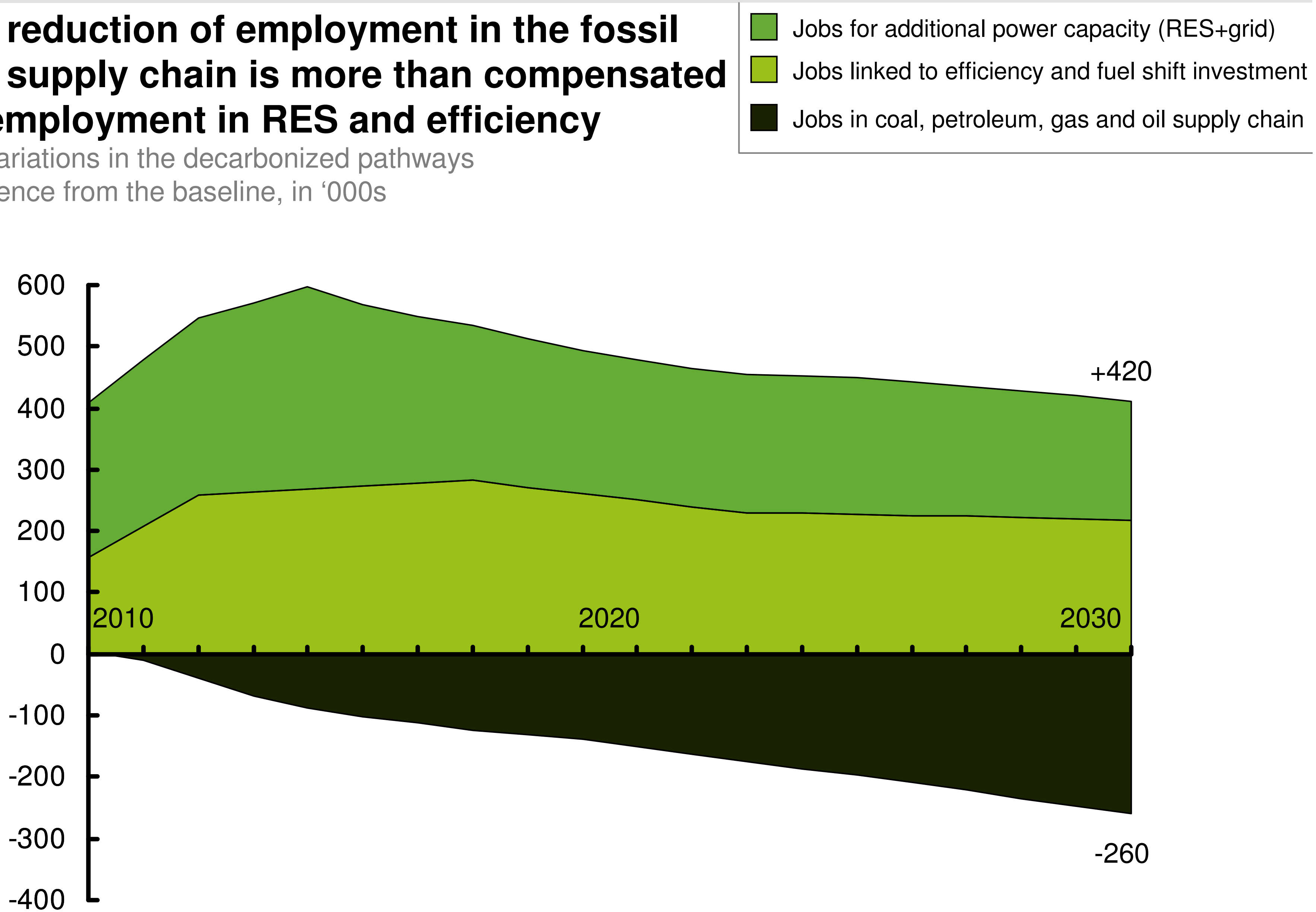


SOURCE: IMF, WEO 2001 (Chapter 3)

EXHIBIT 40

The reduction of employment in the fossil fuel supply chain is more than compensated by employment in RES and efficiency

Job variations in the decarbonized pathways
Difference from the baseline, in '000s

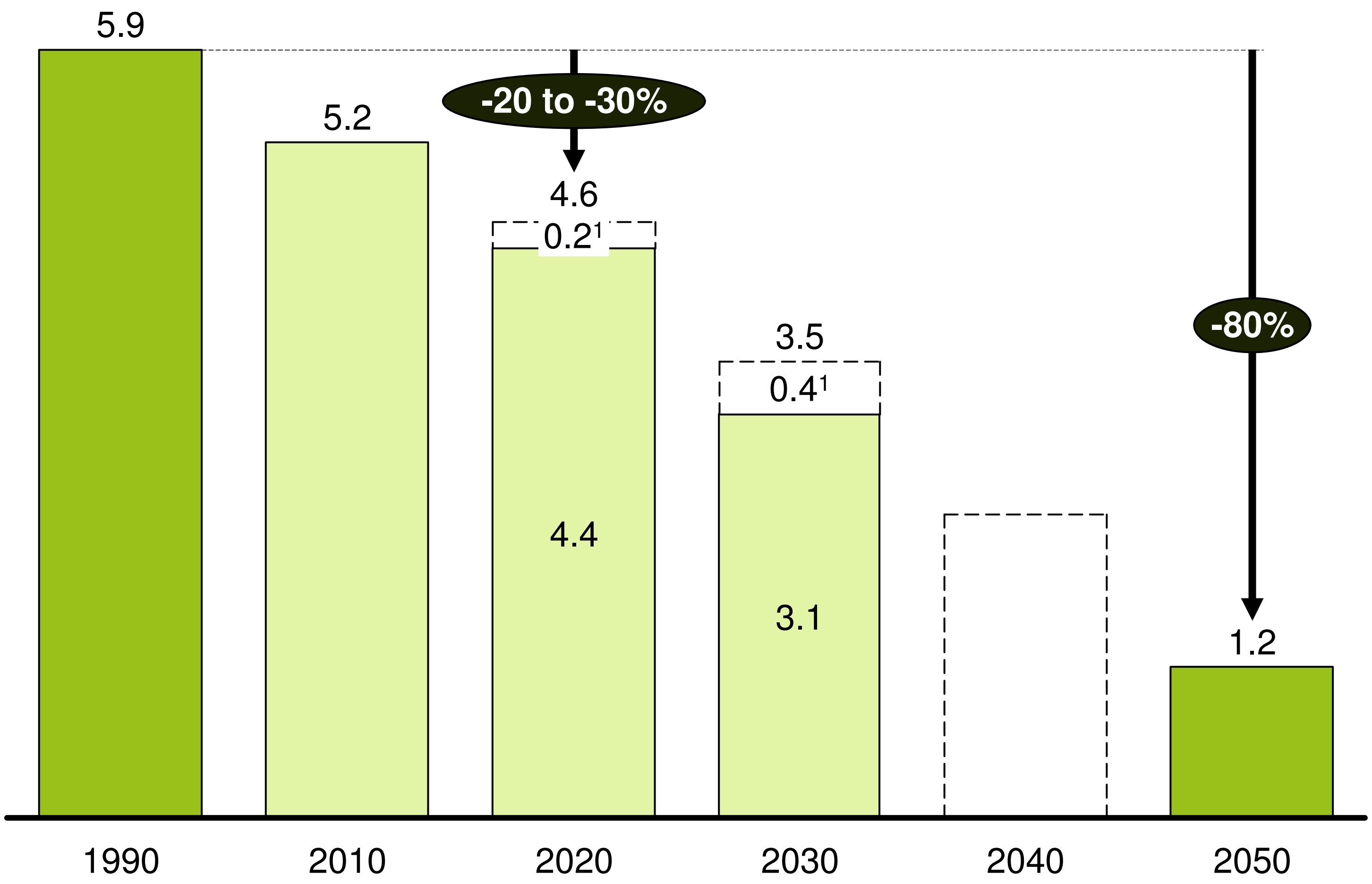


Note: Efficiency and fuel shift investment includes all efficiency levers from McKinsey cost curves (excluding what already in the baseline), further penetration of heat pumps in residential and industry and the slow penetration of EVs

EXHIBIT 41

To put the EU-27 on a path to 80% GHG reductions by 2050, a 20 to 30% reduction must be realized in 2020

EU-27 total GHG emissions in decarbonized pathway, $GtCO_2e$ per year



1 Timing of emission reductions depends on speed of implementation of abatement levers identified in the McKinsey Global GHG Abatement Cost Curve and the fuel shift towards CO_2-free electricity

SOURCE: McKinsey Global GHG Abatement Cost Curve; IEA WEO 2009; US EPA; EEA; Team analysis

EXHIBIT 42

Overview of the larger risk factors variations across pathways

Risk dimensions	40% RES, 30% nuclear, 30% CCS	60% RES, 20% nuclear, 20% CCS	80% RES, 10% nuclear, 10% CCS
Higher cost of generation • Nuclear more expensive • Lower CCS learning rate • Lower RES learning rate	CCS, nuclear capacity is 3 times that of the 80% pathway so these have the biggest impact		RES capacity is about three times that of the 40% pathways so lower learning rates have the biggest impact
Size of the transmission and back-up deployment required • Interregional transmission • Generation back-up capacity	**Capacity required, GW** ▪ 50 to 55 ▪ 75	▪ 85 to 100 ▪ 120	▪ 125 to 165 ▪ 155
Capital constraints • Competing uses drive up cost • Unavailability of capital for nuclear w/o govt support	Cumulative capital requirements, 2010-2050, € billion (share in total spent, capex + opex) ▪ 1,990 (24%)	▪ 2,550 (29%)	▪ 2,860 (33%)
Risk associated to nuclear development and production (e.g., security, waste)	Nuclear production, TWh, 2050 ▪ 1,470	▪ 980	▪ 490
Public acceptance risks	▪ Nuclear waste issue not solved ▪ CCS effectiveness and environmental risks not accepted	▪ "Energy nationalism" and NIMBY hampers interconnection and renewables policy harmonisation across Europe ▪ Biomass imports and related sustainability issues	
Risks associated with the build up of industries	▪ Nuclear/CCS industry cannot ramp up fast enough ▪ CCS storage capacity runs out	▪ RES industry cannot ramp up fast enough ▪ Smart grid roll-out and customer response slow ▪ No effective pricing mechanism installed to attract necessary investments	