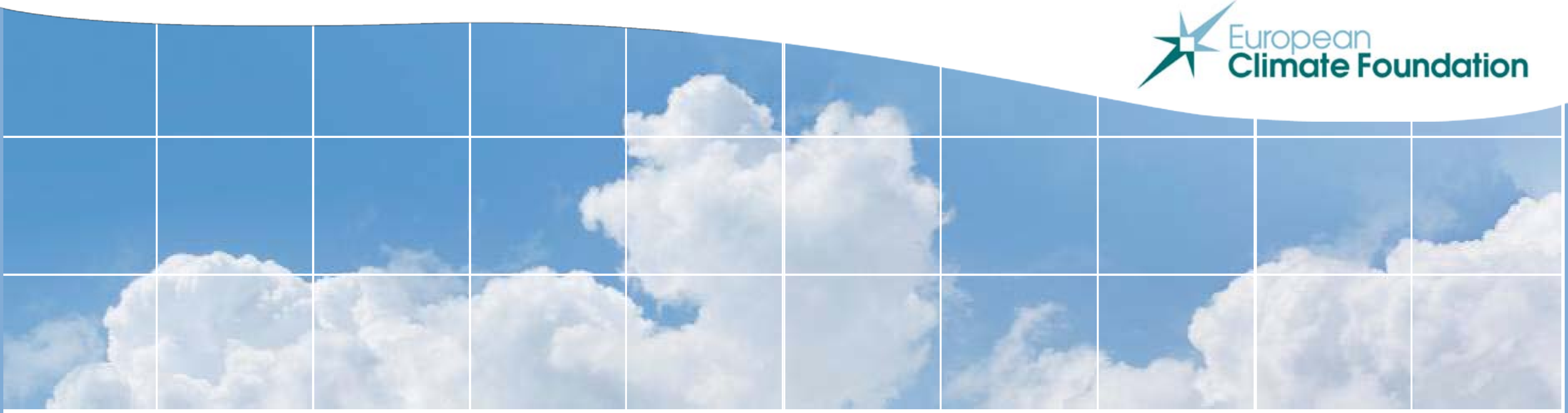

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Roadmap 2050: A practical guide to a prosperous, low-carbon Europe

Harvard Energy Policy Group
Cambridge, MA
21 May 2010

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Roadmap 2050 project team

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ECF (Philanthropic European climate foundation)	▪ Overall sponsor and funder ▪ Final report will be ECF branded
McKinsey & Company (Strategic consultancy)	▪ Overall content leadership, project management, data collection, analysis ▪ Reach out to industries, workshop facilitation
ECN (Energy research center)	▪ Support on assumptions for technologies (lead on nuclear) ▪ Policy development and recommendations based on analytics
KEMA (Technical grid consultancy)	▪ Grid design and investments, production capacity and costs associated with providing a plausible, secure electricity system for each of the pathways
Imperial College London	▪ In-depth modeling of system balancing requirements, reliability, optimization of transmission and back-up investment
The Centre (Political consultancy)	▪ Manage contact to EU-commission and parliament and ensure alignment with their needs. Participate in outreach to member states
Office for Metropolitan Architecture – R. Koolhaas	▪ Provide creative participation in the development of narrative. Provide conceptual framing and visual communication
ESC (Energy Strategy Centre)	▪ Design the report launch communication strategy ▪ Manage the launch of the report including holding presentations, meetings
RAP (Regulatory Assistance Project)	▪ Provide technical and policy input from their global experience
Oxford Economics (Macro-economic consultancy)	▪ Provide analysis of macro-economic impacts of decarbonization scenarios

Key stakeholders are involved by providing input and reviewing results

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	Core Working Group participants
Utilities	CEZ GROUP, edp, RWE, Enel, e·on, IBERDROLA, VATTENFALL
Transmission System Operators	ENERGINET/DK, nationalgrid, tennet, Terna, entsoe
Manufacturers	acciona, Siemens, Vestas
NGOs	E3G, GERMANWATCH, WWF

Further outreach

Plus 40 more companies, NGOs and research institutes

NUON, EWEA, First Solar, DESERTEC FOUNDATION, Q.CELLS, SCHOTT solar

SOURCE: Team analysis

80% by 2050 only possible with *zero-carbon power supply*

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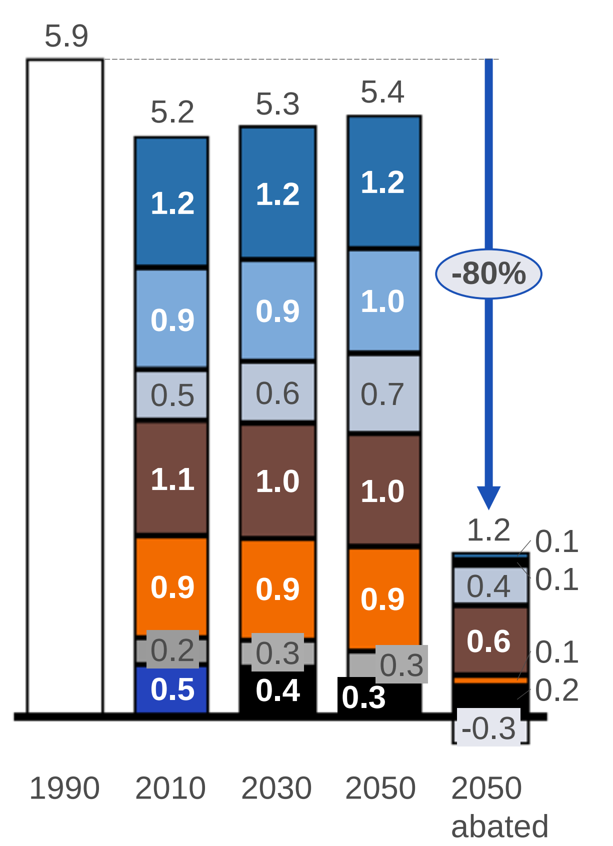
EU-27 total GHG emissions
$GtCO_2e$ per year



Sector	Abatement	Within sector[1, 2]	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% (CCS[3])	5% (heat pumps)
Buildings	**95%**	45% (efficiency and new builds)	50% (heat pumps)
Waste	**100%**	100%	
Agriculture	**20%**	20%	
Forestry	**-0.25 $GtCO_2e$**	Carbon sinks	

1 Based on the McKinsey Global GHG Abatement Cost Curve
2 Large efficiency improvements already included in the baseline
3 CCS applied to 50% of industry (cement, chemistry, iron and steel, petroleum and gas, not applied to other industries)

SOURCE: Team analysis

Pathways must be reliable, technically feasible, have a positive impact on the economy…& be nearly zero carbon

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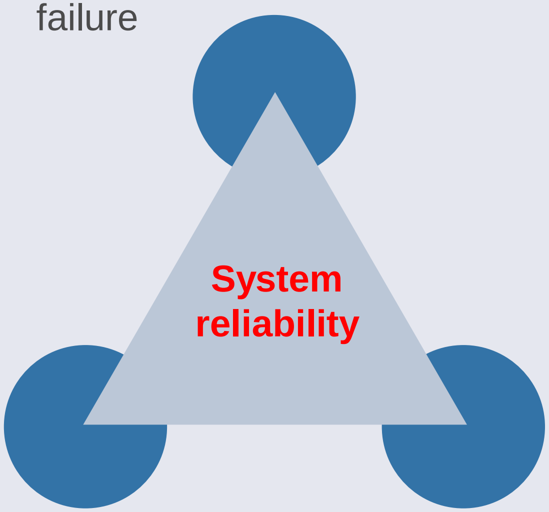
Assessment criteria

Security of energy supply and technology risk, e.g., self reliance, risk of technology failure



Economic impact, e.g., cost of electricity, GDP, capital requirements

Sustainability, e.g., greenhouse gas emissions, resource depletion

SOURCE: Team analysis

Efficiency flattens demand growth, 'fuel shift' drives it back up to the same level as 'BaU', but far less energy intensive

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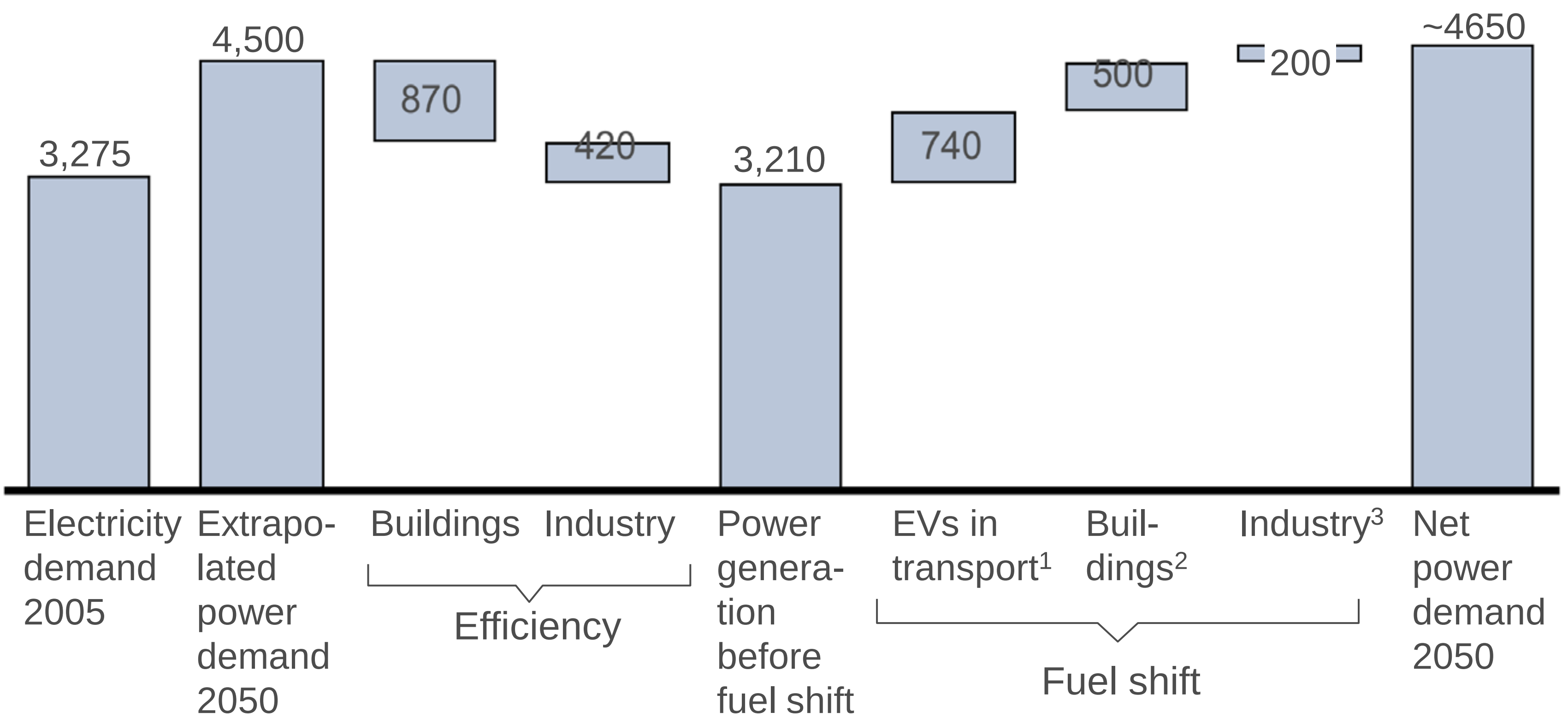
EU-27 power demand, TWh per year



1 Assumption: electrification of 100% LDVs and MDVs (partially plug-in hybrids); HDVs remain emitting ~10% while switching largely to biofuel or hydrogen fuel cells

2 Assumption: 90% of remaining primary energy demand converted to electricity usage in buildings for heating/cooling from heat pumps; assumed to be 4 times as efficient as primary fuel usage

3 Assumption: 10% fuel switch of remaining combustion primary energy demand converted to electricity in industry for heating from heat pumps; assumed to be 2.5 times as efficient as primary fuel usage

SOURCE: Team analysis

Most of the non-hydro capacity will be retired by 2040

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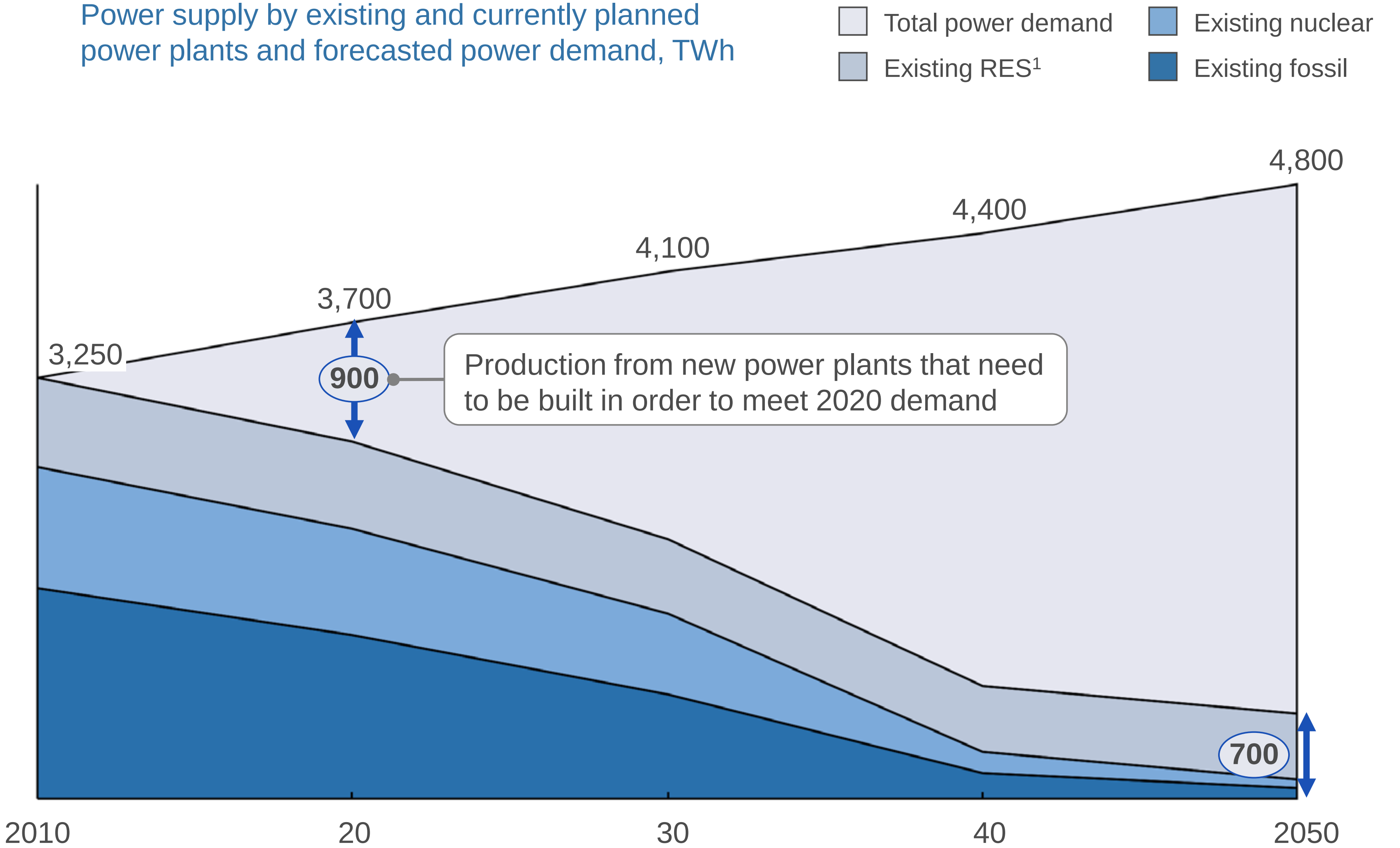
Power supply by existing and currently planned power plants and forecasted power demand, TWh



1 Existing RES mainly hydro; remains in operation until 2050

SOURCE: McKinsey Power Generation Model; team analysis

The pathways cover a wide range of technology mixes

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Decarbonization pathways

40% RES[1] 30% Nuclear 30% CCS	▪ RES share close to currently legally committed by the EU and the IEA baseline ▪ Sensitivities on a high nuclear share and a high thermal / CCS share are included
60% RES 20% Nuclear 20% CCS	▪ RES mix based on current deployment (minimum), aim for a broad mix of technologies and theoretical deployment (maximum) ▪ Equal shares for nuclear and thermal / CCS
80% RES 10% Nuclear 10% CCS	(same as above)
100% RES	▪ Based on 80% pathway – Conventional and nuclear replaced by CSP from Africa (15%) and enhanced geothermal (5%) – Same shares for RES as the 80% pathway

Additional sensitivities

- Fuel prices (coal, gas, uranium)
- Cost of capital
- Learning rates
- Grid solutions
- Electricity demand

1 Renewable energy sources

SOURCE: Team analysis

Power generation technologies that are at least in late stage development are included

Power generation technologies included in the pathways

Type of generation		Generation technologies
RES	Non-intermittent	Large hydro Geothermal Biomass dedicated Solar CSP with storage
	Intermittent	Wind onshore Wind offshore Solar PV Hydro run of river
Fossil		Coal conventional Coal CCS Coal CCS retrofit Gas conventional Gas CCS Gas CCS retrofit Oil
Nuclear		Nuclear III

Regional clustering of EU-27 countries (including Switzerland and Norway)

Nordic
- Denmark
- Finland
- Sweden
- (Norway)

Poland and Baltic
- Estonia
- Latvia
- Lithuania
- Poland

Benelux and Germany
- Belgium
- Germany
- Luxembourg
- Netherlands

South East Europe
- Bulgaria
- Cyprus
- Greece
- Hungary
- Romania

UK and Ireland

France

Italy & Malta

Iberia
- Portugal
- Spain

Central Europe
- Austria
- Czech Republic
- Slovakia
- Slovenia
- (Switzerland)

SOURCE: Team analysis

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

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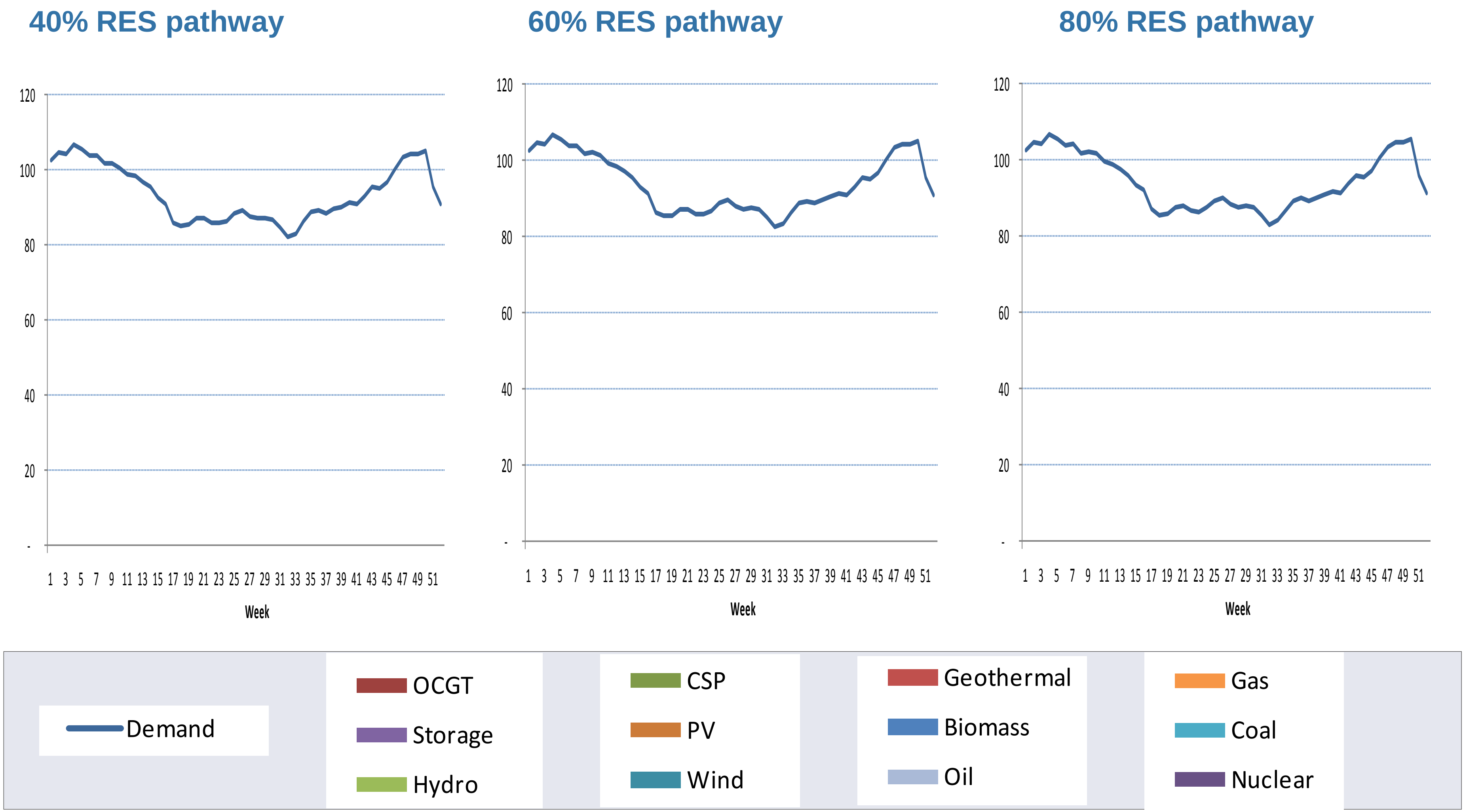
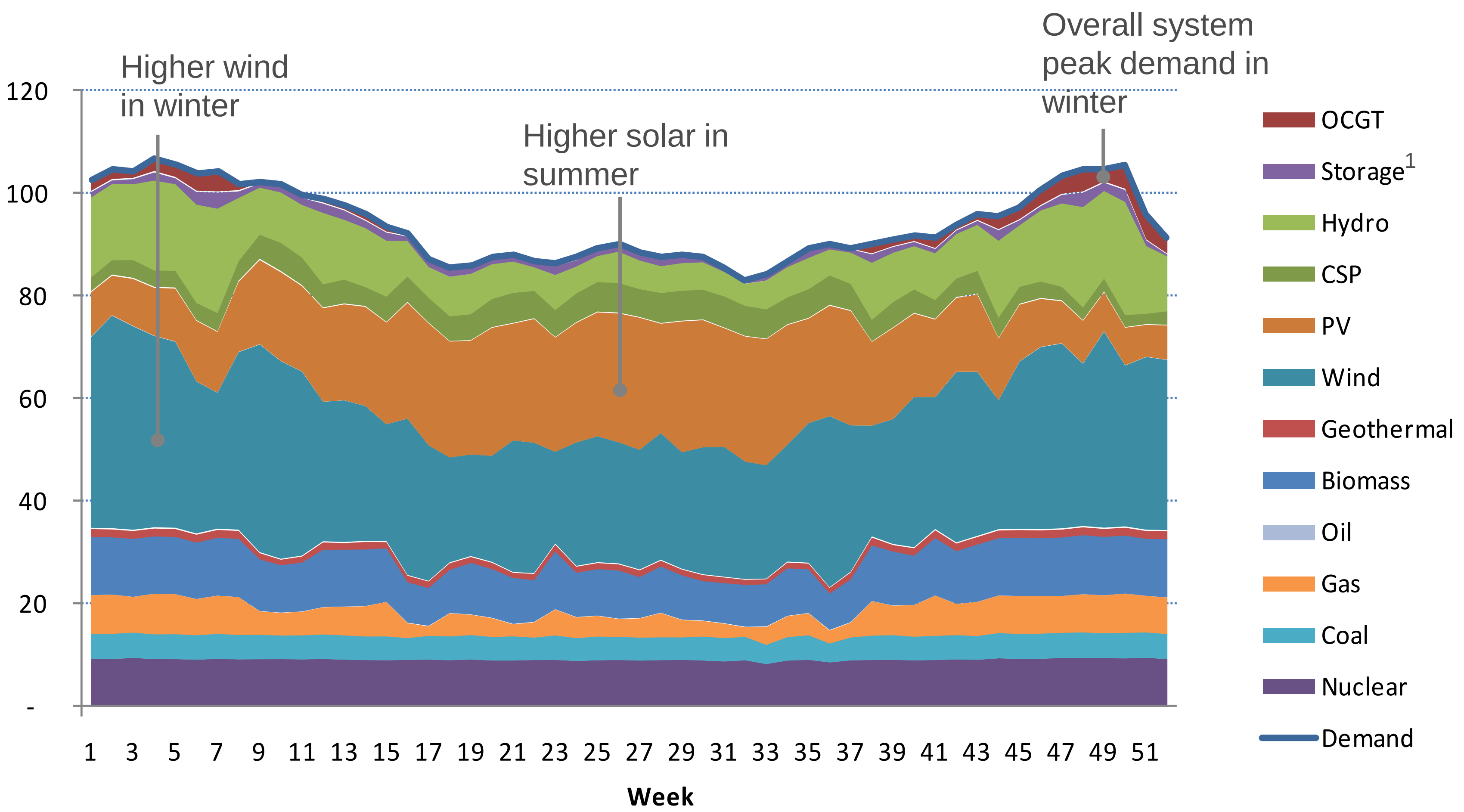
Yearly energy balance, 20% DR, TWh per week



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

Increased interconnectivity across regions exploits natural counter-cyclicality of primary European RE resources

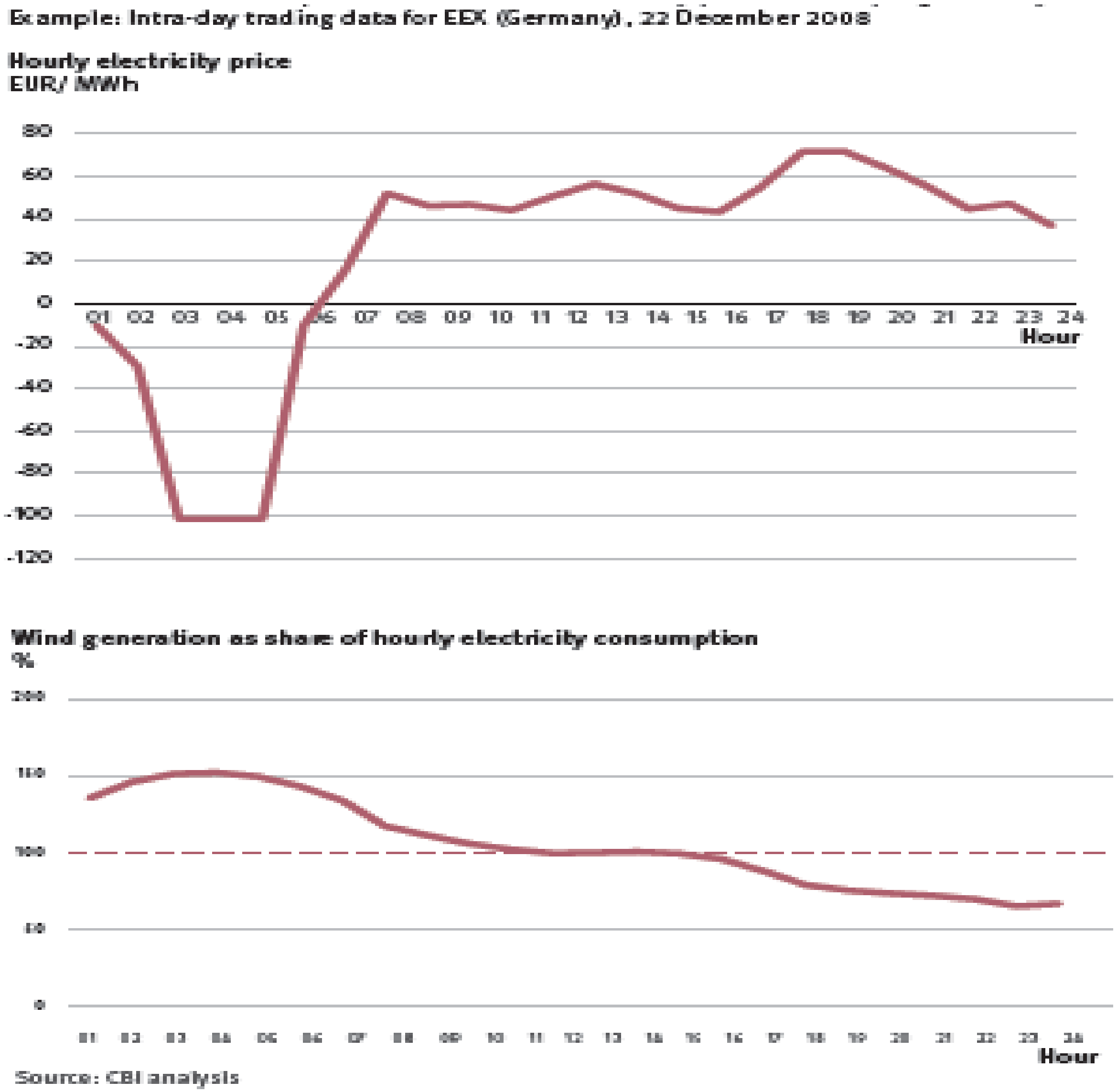
Overview of yearly energy balance, 80% RES pathway, TWh per week



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

SOURCE: Team analysis

Example: Germany



Confidence ranges for assumptions: likely outcomes are within 10-15% of each other across all pathways

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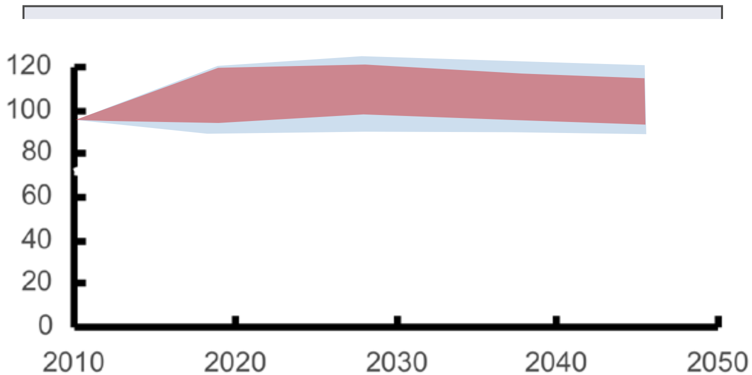
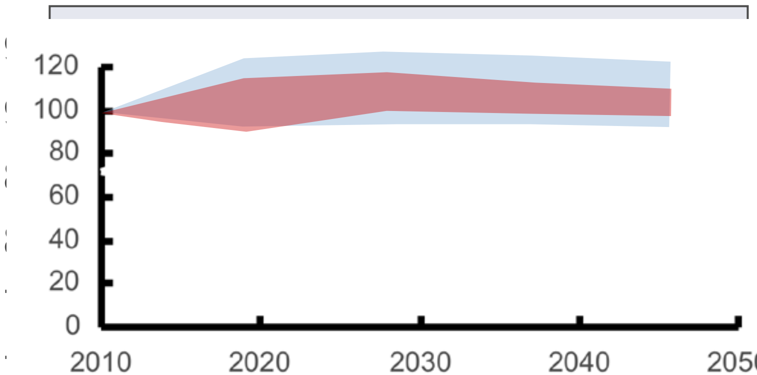
Likely ranges over time in the cost of electricity of new builds[1] EUR/MWh (real terms)

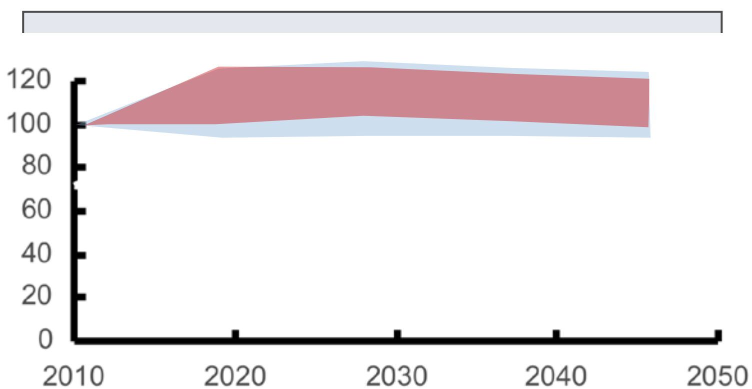
Baseline and average of decarbonized pathways

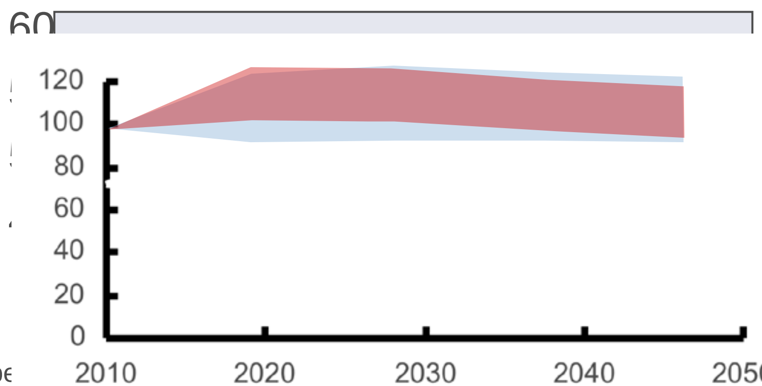


Baseline and 40% RES pathway



Baseline and 60% RES pathway





1 Based on a WACC of 7% (real after tax), computed by technology and weighted across technologies based on their production; including grid

SOURCE: Team analysis

Demand flexibility reduces grid and related investments, minimizes low-carbon resource curtailment, minimizes cost

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2050, GW

Pathways	DSM	Transmission & additional generation capacity requirements[1]: Transmission	Transmission & additional generation capacity requirements[1]: Back-up and balancing	RES curtailment[2] %
80% RES 10% CCS 10% nuclear	0%	166	255	3
	20%	127	160	2
60% RES 20% CCS 20% nuclear	0%	103	205	2
	20%	87	140	1
40% RES 30% CCS 30% nuclear	0%	56	150	2
	20%	55	110	2

SOURCE: Team analysis

Increased transmission cancels out both daily and seasonal fluctuations

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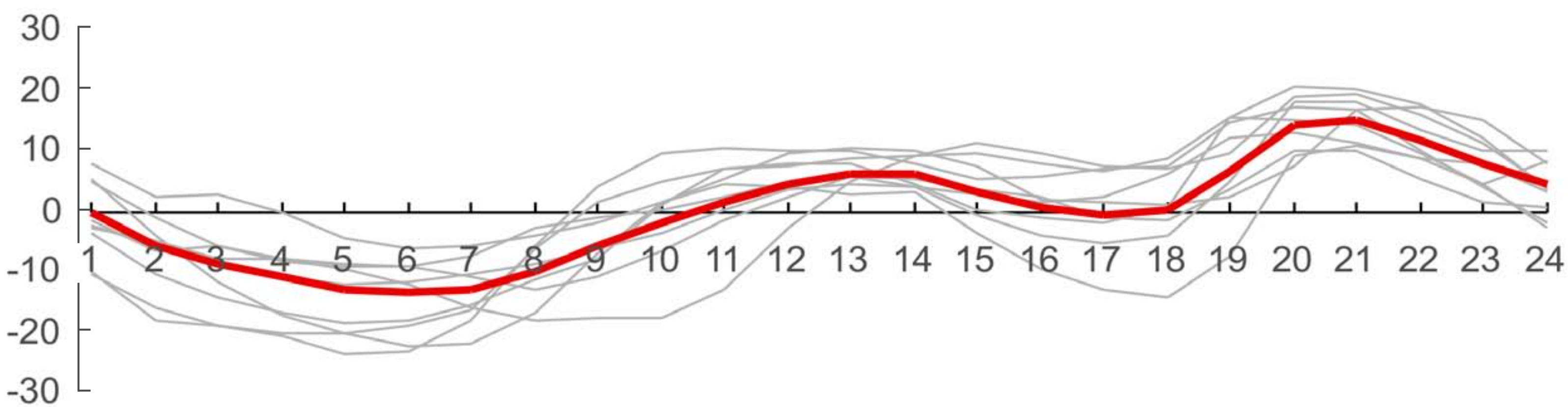
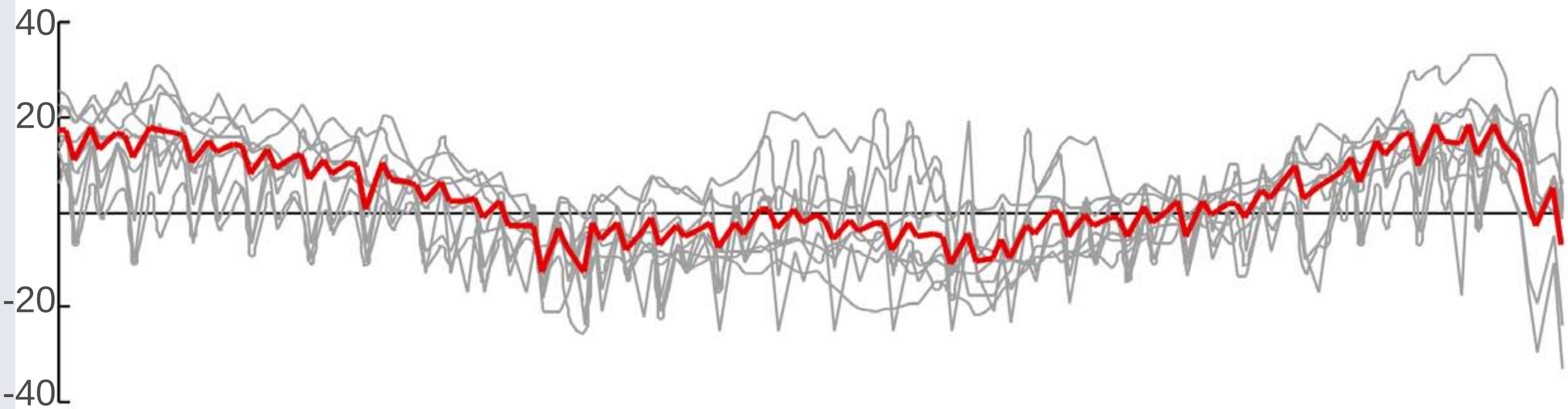
Percent

Individual regions — Total EU-27

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



Regional demand variation from average over the year



NOTE Excluding additional seasonality demand from heat pumps and extreme weather cases

SOURCE: Imperial College; KEMA analysis

Increased demand flexibility through 'smart' grid investments is a cost-effective alternative to curtailing low-carbon sources

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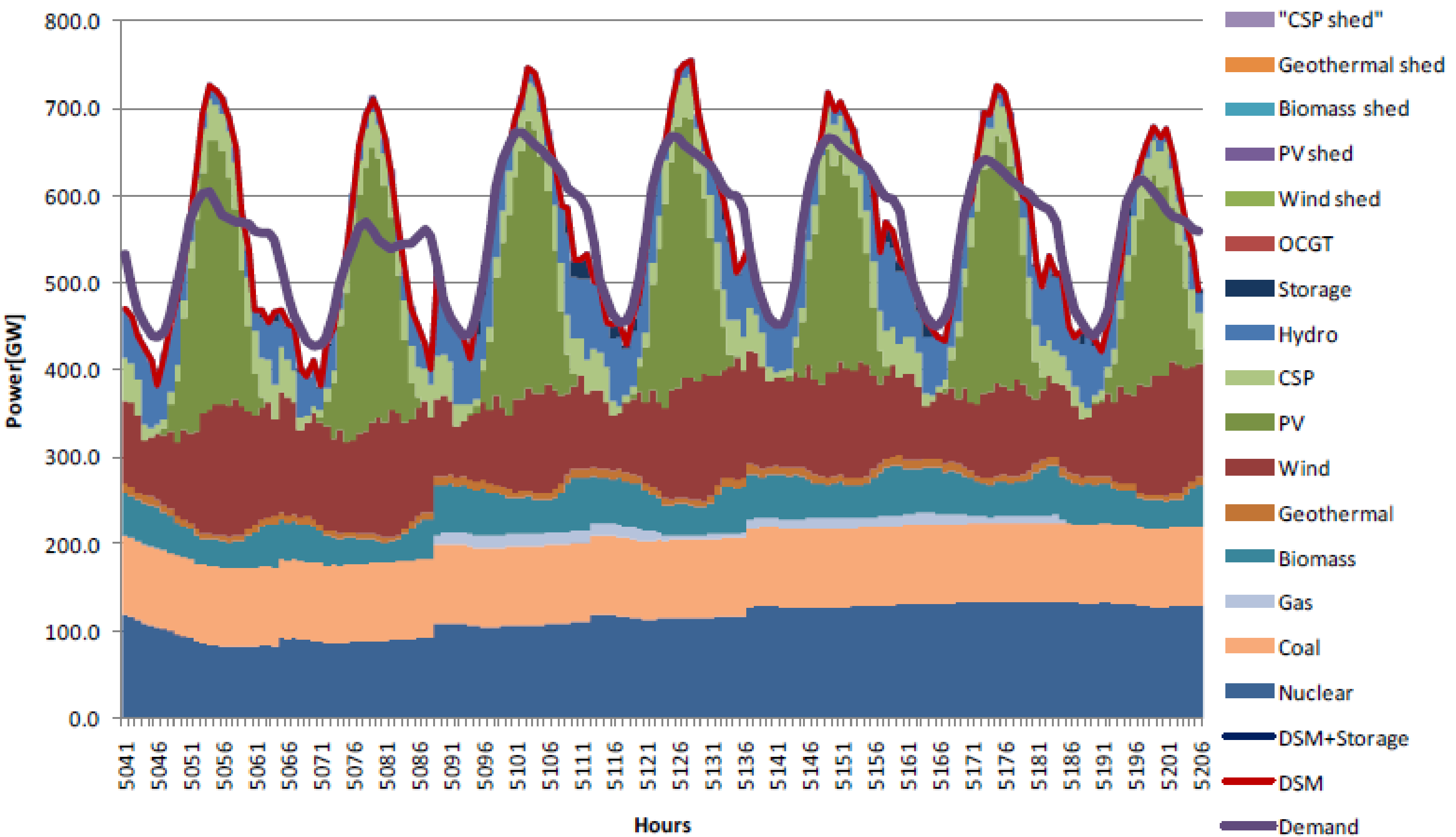

SOURCE: Team analysis

Both inter- and intra-regional transmission requirements are quantified

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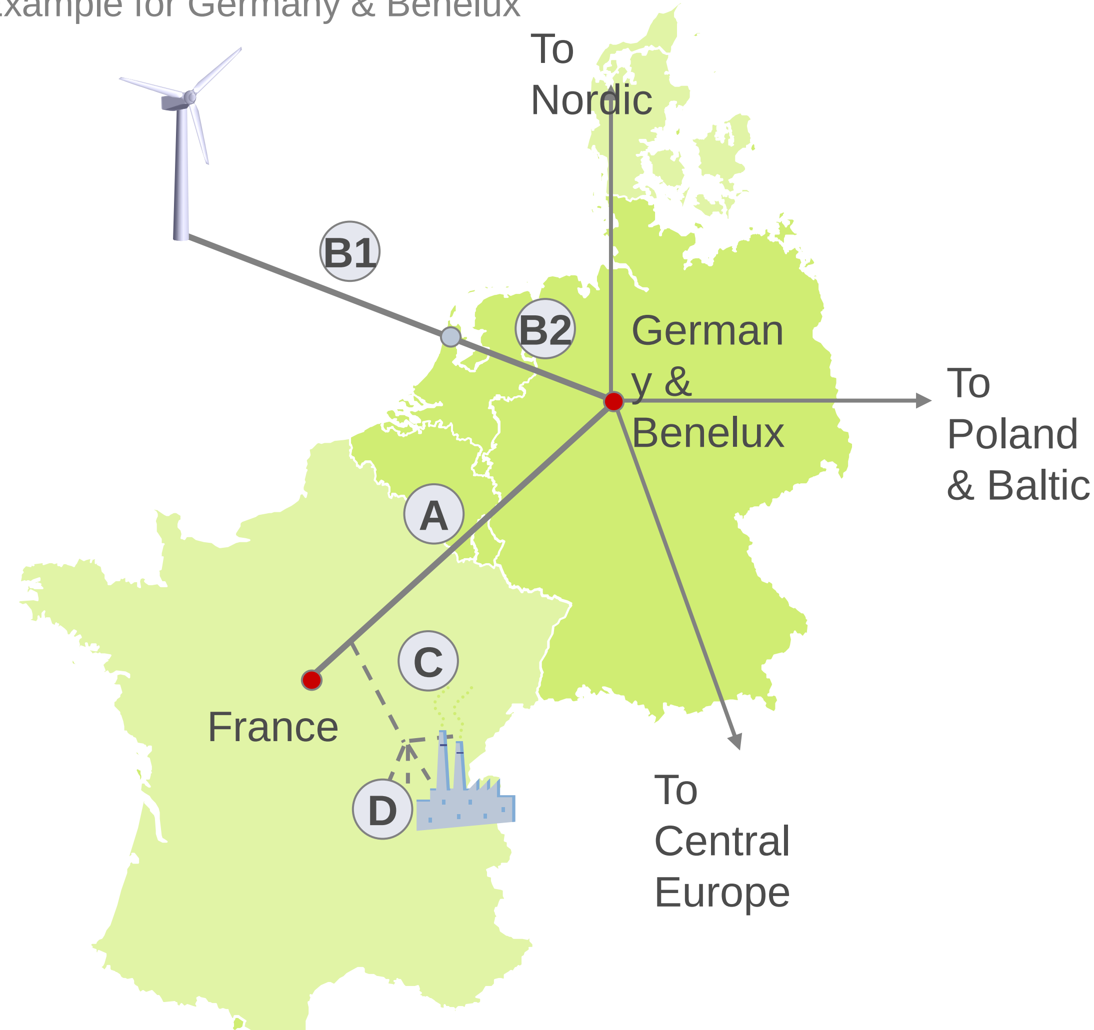
Example for Germany & Benelux



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

SOURCE: KEMA; team analysis

New inter-regional transfer capacity required (60% RES)

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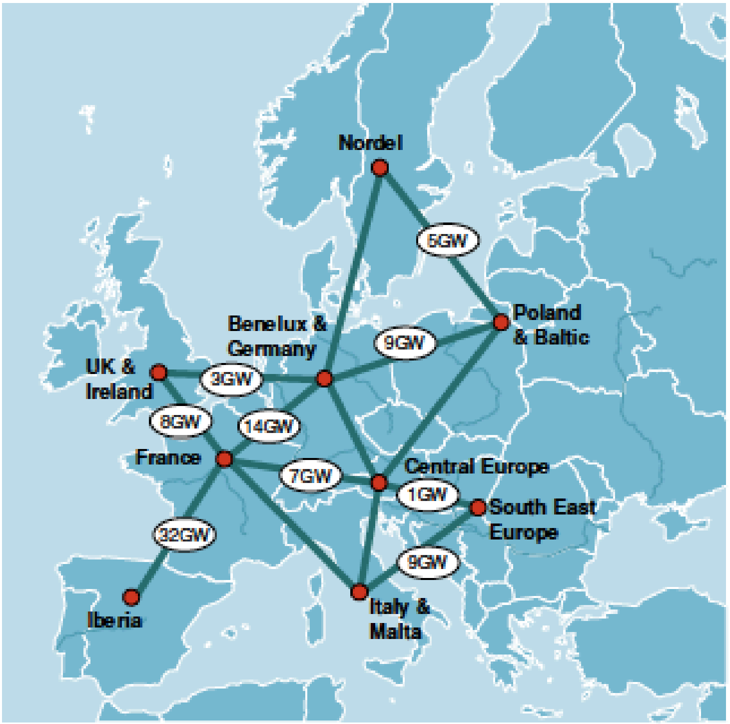

● Centre of gravity

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)**	

SOURCE: Team analysis

Reserve sharing between regions reduces total reserve requirements by ~40%

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Maximal reserve requirement[1], GW

Region	Baseline	80% RES	60% RES	40% RES
UK & Ireland	8	42	28	15
France	2	31	21	9
Iberia	7	40	27	10
Nordic	3	20	15	10
Benelux & Germany	13	44	28	10
Central-Europe	2	29	20	8
Poland & Baltic	2	18	12	5
South East Europe	2	18	12	4
Italy & Malta	2	40	27	10
Total EU27	42	281	191	80
Benefit of reserve sharing	20	98	66	32
Total with reserve sharing between regions	22	183	125	48
	-47%	-35%	-35%	-40%

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

SOURCE: Imperial College, KEMA, team analysis

All pathways can deliver power with roughly the same cost and reliability as the baseline with carbon price ≤ €50/tCO_2

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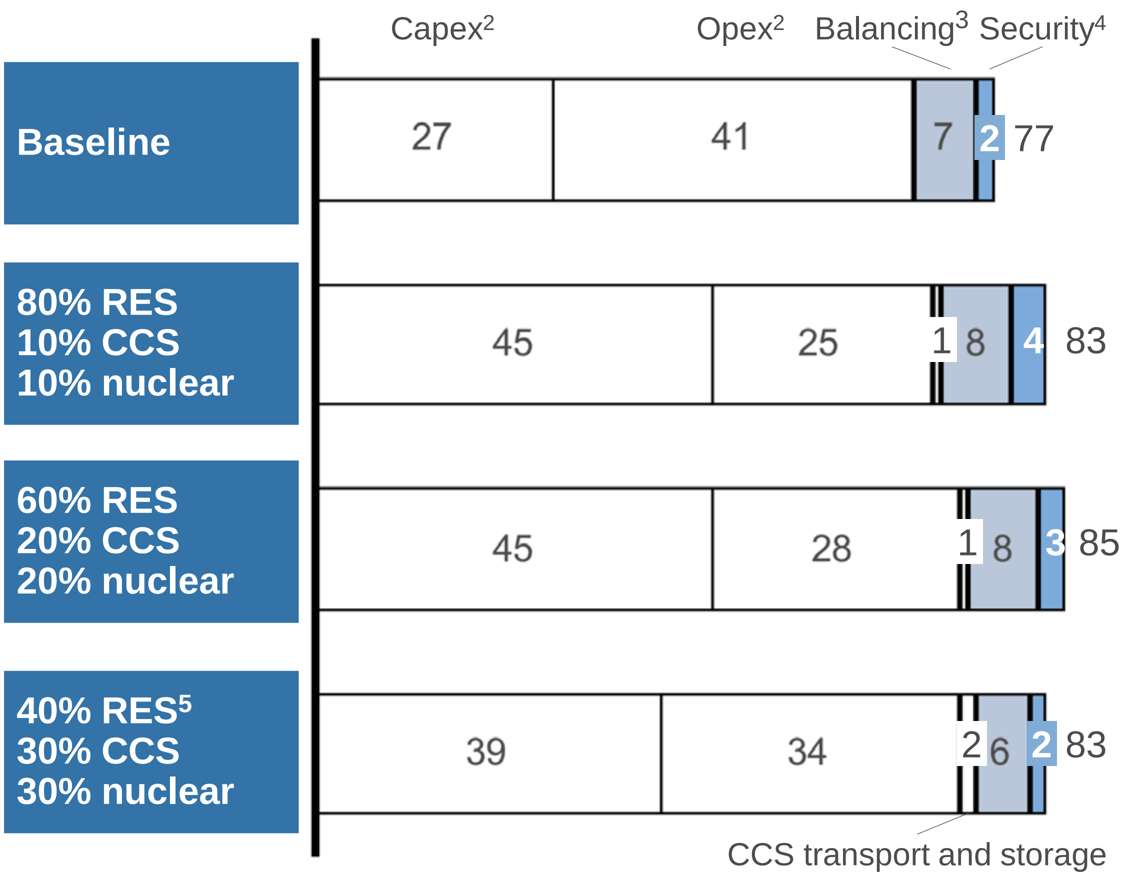
Average new built CoE from 2010 to 2050[1], EUR/MWh (real terms)



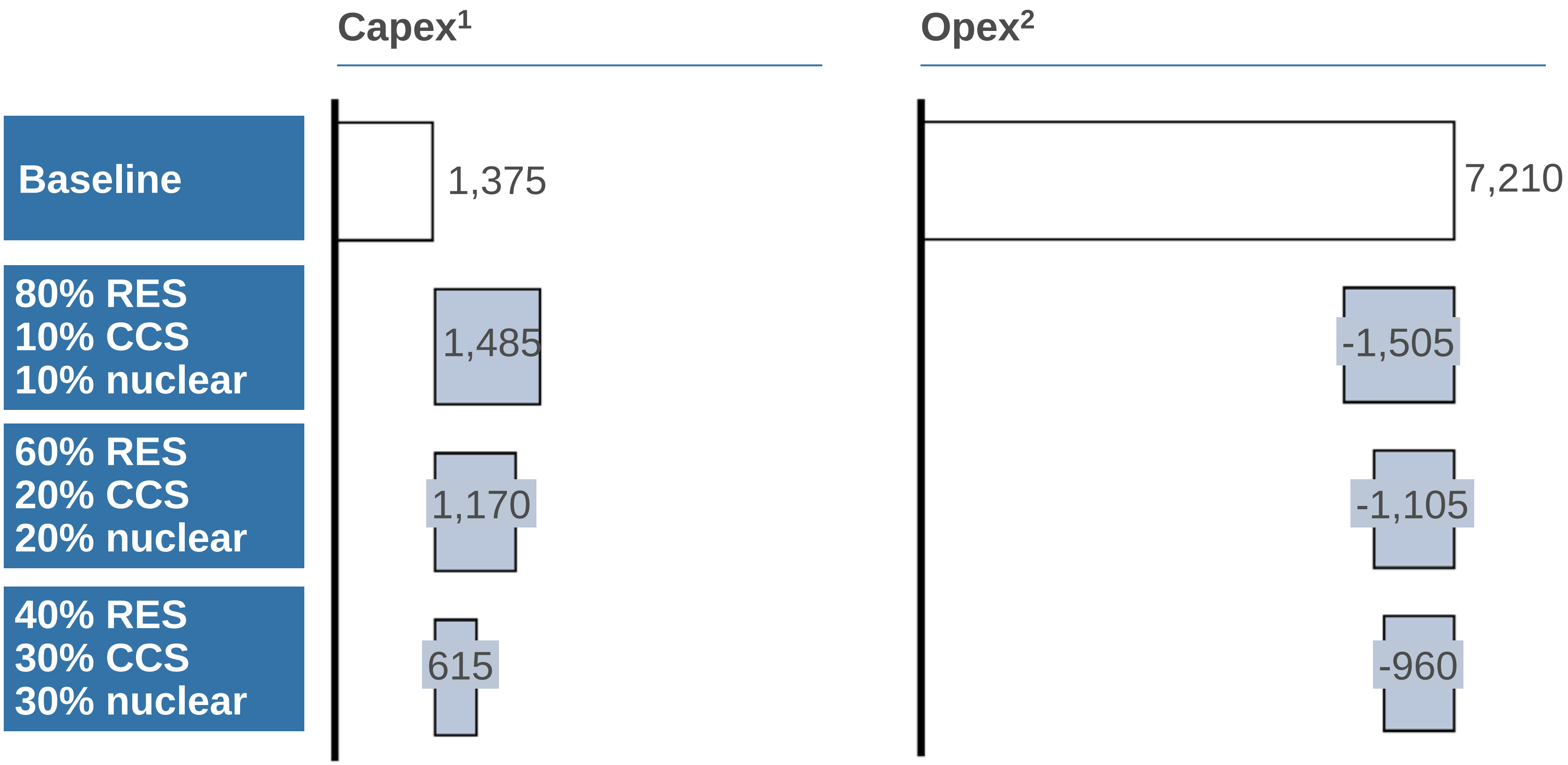
1 Weighted average based on the CoE in each 10-year time frame (2010, 2020, 2030, 2040, 2050)
2 Generation only
3 Cost related to non optimal plant use, system dispatch cost for secure operation, running backup plants, storage losses, reserve and response cost
4 Transmission and additional generation capex as well as fixed opex for transmission and backup
5 Grid not modeled by KEMA yet, impact estimated by interpolation from the other pathways

SOURCE: Team analysis

Decarbonized electricity requires more capex and less opex

Cumulative cost, 2011-2050, EUR billion, Real terms, no CO_2 costs included

INCLUDING GENERATION AND GRID



1 For new builds from 2011 to 2050, including additional grid capex

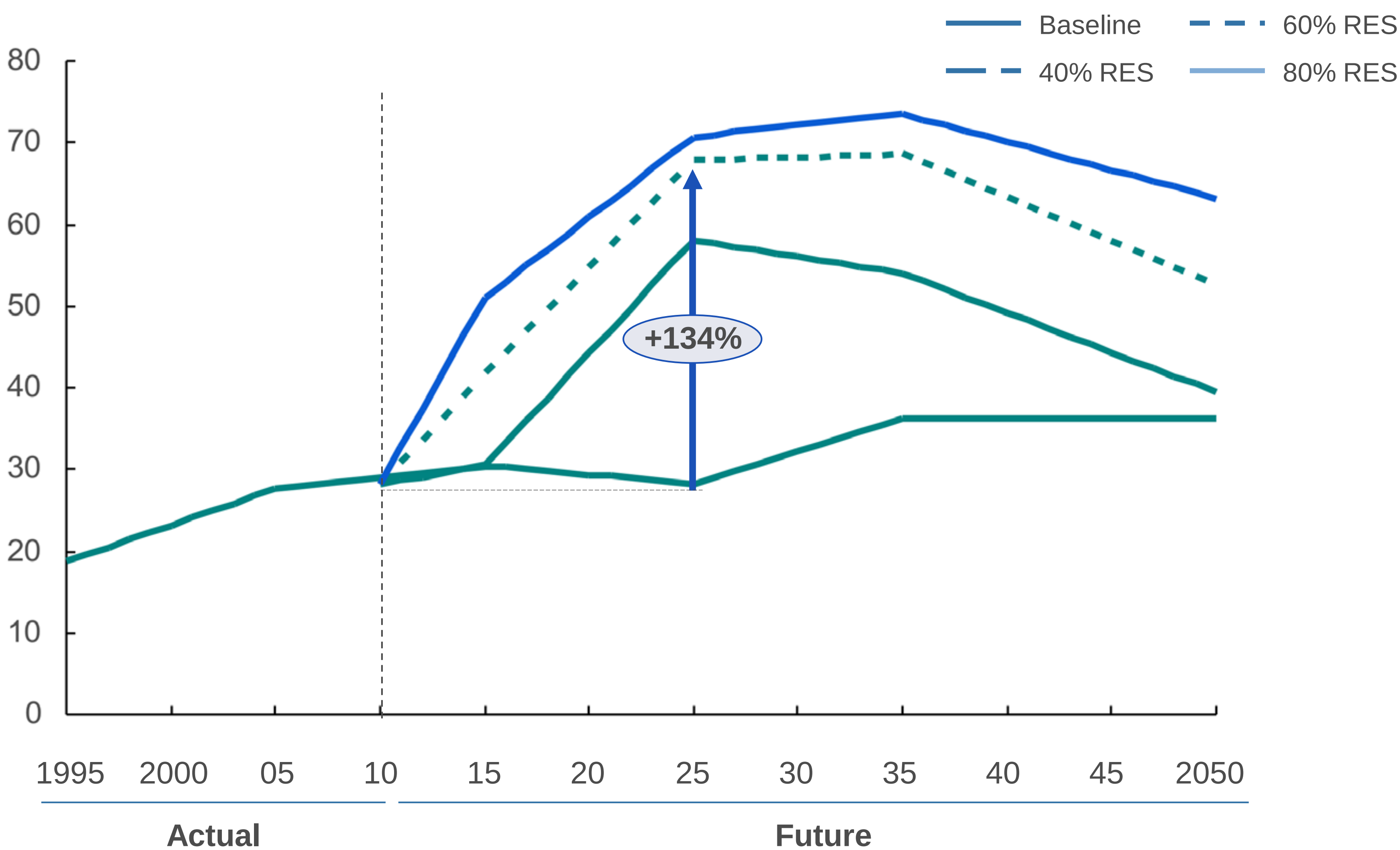
2 Opex for all new and operating plants includes variable, fixed, as well as fuel cost; also includes opex for additional backup plants and additional grid

SOURCE: Team analysis

A doubling of capex would be required over the next 15 years

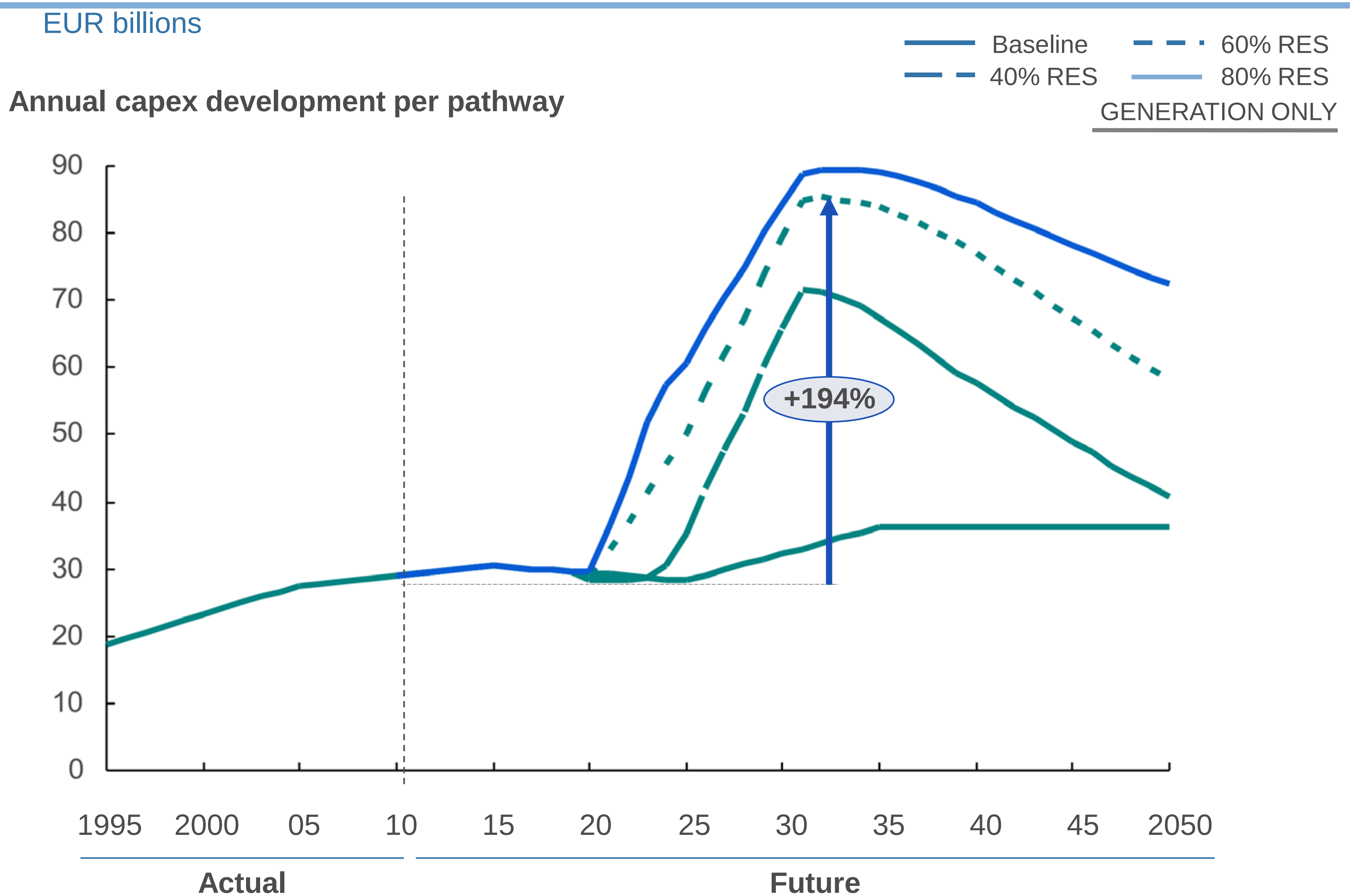
Annual capex development per pathway, € billions per year

GENERATION ONLY



SOURCE: Team analysis

Delayed by 10 years, the annual capex would be up by almost 200%



SOURCE: Team analysis

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Exhibit 20 Uncertainty on power prices and construction costs could hinder investments in nuclear power

Variable	Base case	Range	Impact on value of nuclear power plants (£m/GW), Base case: £332m/GW	
Most significant variables				
Gas price (p/th) Driver of power prices	50[1]	30/70	-1,005	1,004
CO_2 price (EUR/t) Driver of power prices	30[2]	10/50	-517	517
Construction costs (£/kW)	2,500	3,000/2,000	-393	392
Cost of capital (%)	7[3]	8/6	-362	469
Plant life (years)	40	30/50	-216	126
Capacity factor (%)	90	85/95	-154	153
Decommissioning costs (£/kW)	500	1,000/300	-62	25

Source: CBI analysis

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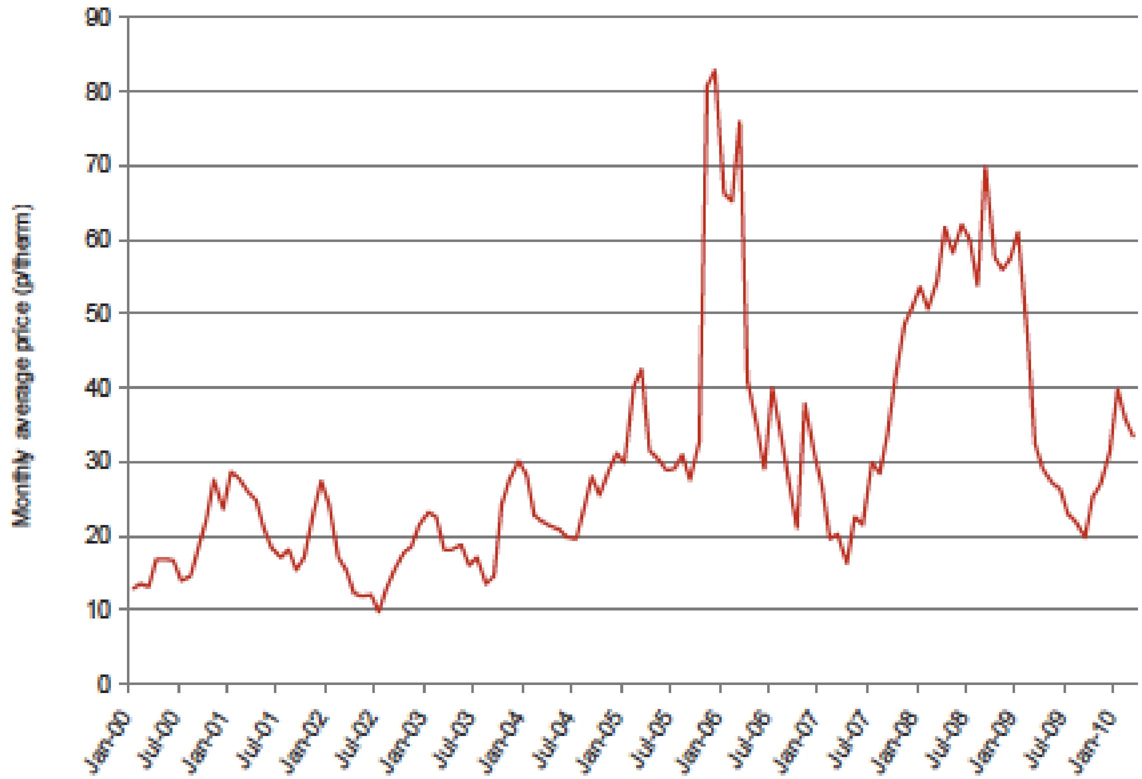
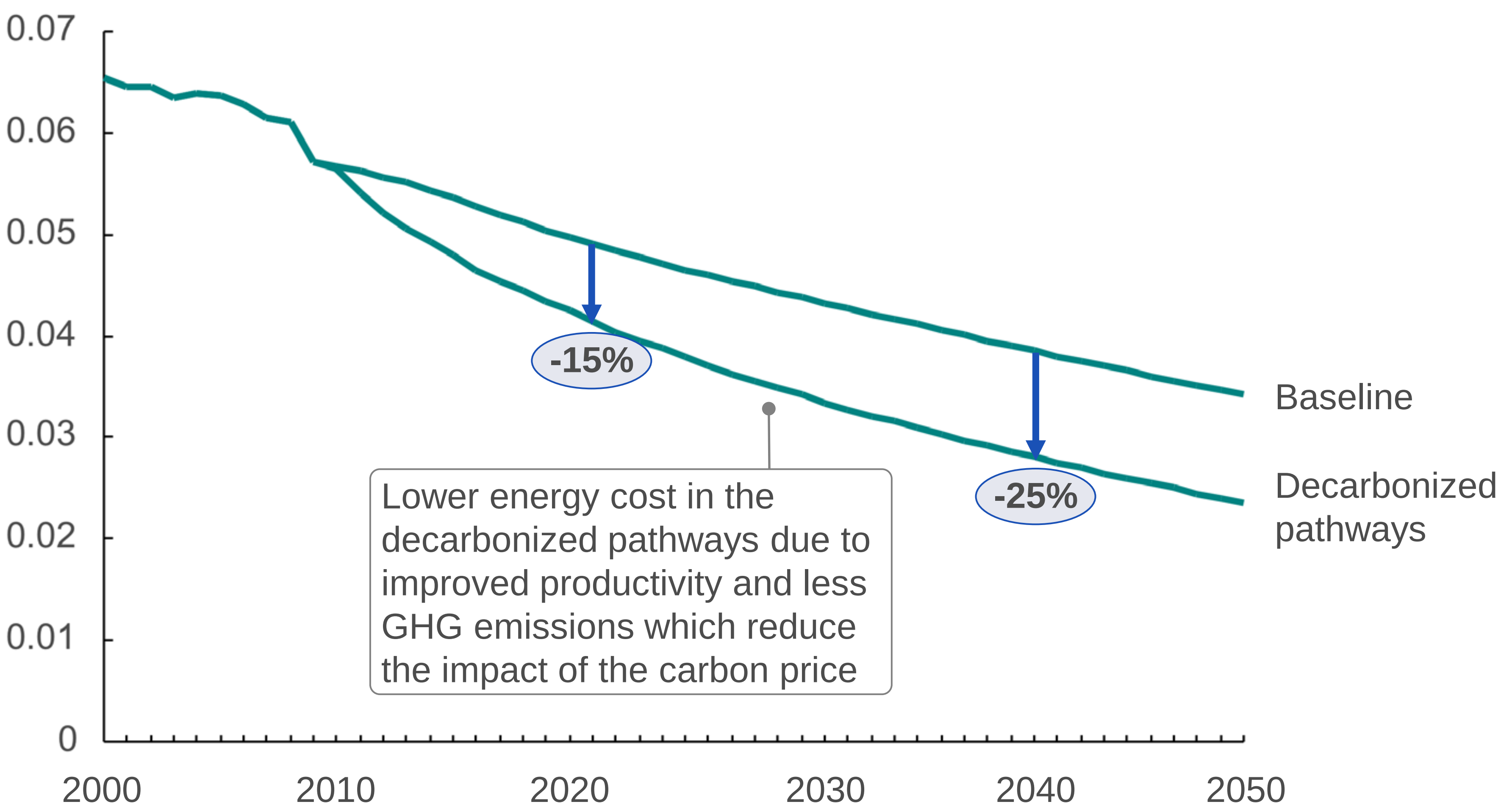
Chart 3.B: Gas price volatility Jan 2000 – March 2010



Source: ICIS Heren

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

The pathways require up to 70% more capex for all energy sectors: efficiency investments and a shift away from oil & gas

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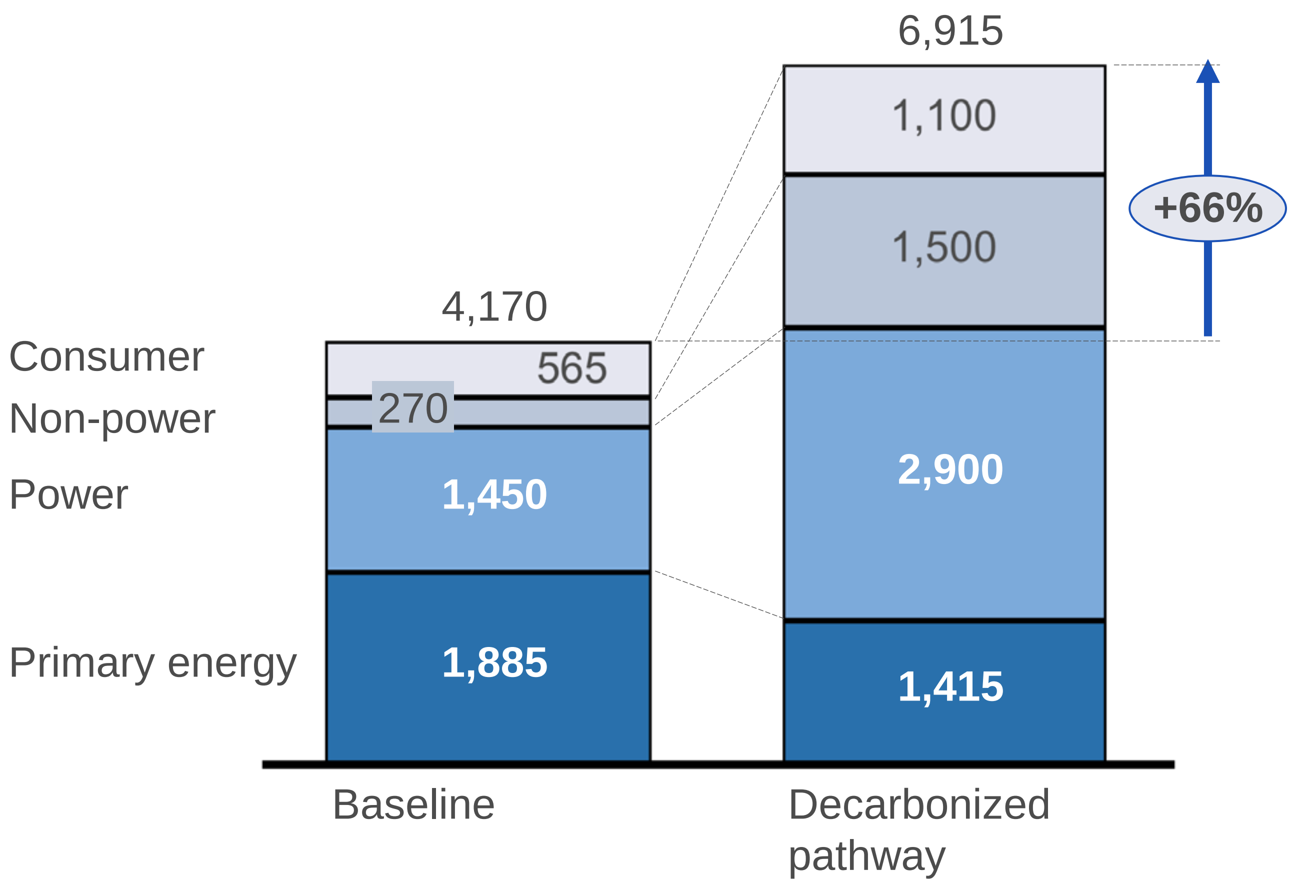
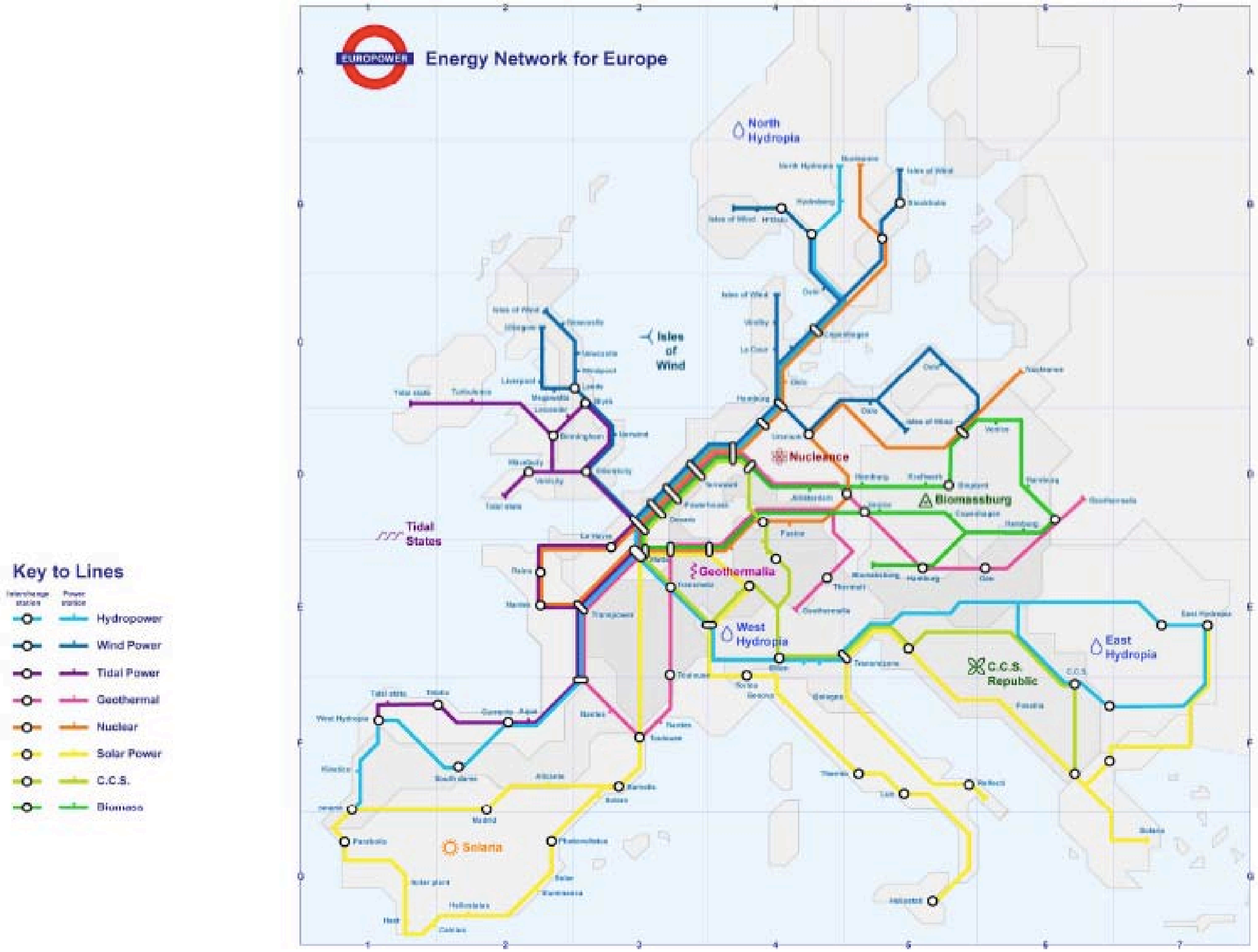
Cumulative capex 2010-50, EUR billions



NOTE Excludes additional capex for EV batteries and fuel cells for vehicles (in total approximately EUR 500 billion)

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

What REAL energy security looks like….



SOURCE: Team analysis

BACK-UP

Grid modeling methodology (more detail)

Despite slightly higher initial unit costs for power, impact on overall economic performance is neutral to positive

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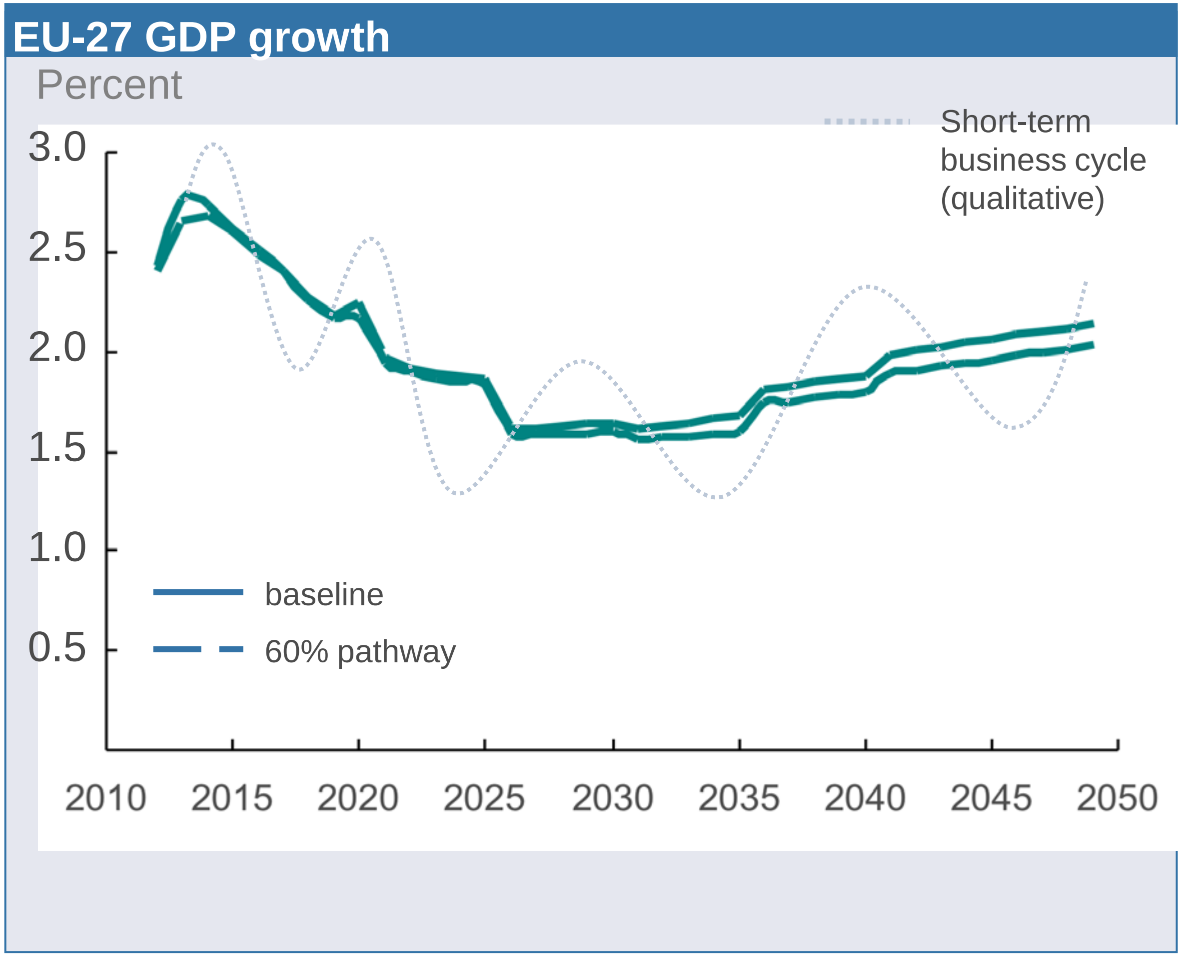

SOURCE: Team analysis

Learning rates are applied to estimate future capex

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

SOURCE: Stakeholder workshops; team analysis

Basic assumptions for generation technologies

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Type of generation		Generation technologies	Capex 2010 €/KW	OPEX fix €/KW	OPEX variable €/MWh	FUEL 2010 €/MWh
Fossil		Coal Conventional[1]	1,400-1,600	18-22	~1	20-25
Fossil		Gas Conventional	700-800	13-17	~1	45-50
Fossil		Coal CCS[2]	2,700-2,900[3]	60-80	~3	26-31
Fossil		Gas CCS[2]	1,500-1,600[3]	35-45	~2	55-60
Fossil		Coal CCS Retrofit[3]	1,250-1,450[3]	60-80	~3	26-31
Fossil		Gas CCS Retrofit[3]	750-950[3]	35-45	~2	55-60
Fossil		Oil	750-850	15-20	~1	100-150
Nuclear		Nuclear[4]	2,700-3,300	90-110	~0	7-9
RES	Intermittent	Wind Onshore	1,000-1,300	20-25	~0	~0
RES	Intermittent	Wind Offshore	3,000-3,600	80-100	~0	~0
RES	Intermittent	Solar PV	2,400-2,700	20-25	~0	~0
RES	Non-Intermittent	Solar CSP[5]	4,000-6,000	180-220	~0	~0
RES	Non-Intermittent	Biomass dedicated	2,300-2,600	13-15	8-10	45-55
RES	Non-Intermittent	Geothermal	2,700-3,300	90-110	~0	~0
RES	Non-Intermittent	Hydro	1,800-2,200	5-10	~0	~0

1 Taking an average between hard coal and lignite
2 Starting in 2020
3 starts in 2020, additional to conventional plants for retrofits
4 Lower assumption for France, higher for the rest of the countries
5 Including storage

SOURCE: Stakeholder workshops; team analysis

Basic assumptions for generation technologies

Type of generation		Generation technologies	Actual load factor input before grid modeling Percent	Construction time Years	Lifetime Years	Ramp up and down % of max output/h
Fossil		Coal Conventional	86	4	40	40
		Gas Conventional	60[1]	3	30	50
		Coal CSS	85	5	40	40
		Gas CCS	60[1]	4	30	50
		Coal CCS Retrofit	85	5	40	40
		Gas CCS Retrofit	60[1]	4	30	50
		Oil	21	3	30	60
Nuclear		Nuclear[4]	90	7	45	40
RES	Intermittent	Wind Onshore[2]	30	2	25	Based on available energy profile
		Wind Offshore[3]	37	2	25	
		Solar PV	10-17	1	25	
	Non-Intermittent	Solar CSP[4]	47	3	30	40
		Biomass dedicated	80	2	30	40
		Geothermal	91	4	30	40
		Hydro	~35	4	50	Fully flexible[5]

1 Maximum possible load factor is >90%
2 Load factor increases for new builds from 30% to 35% in 2050
3 Load factor increases from 37% to 45% for new builds in 2050
4 Including storage
5 Constrained by available energy & reservoir size limitations

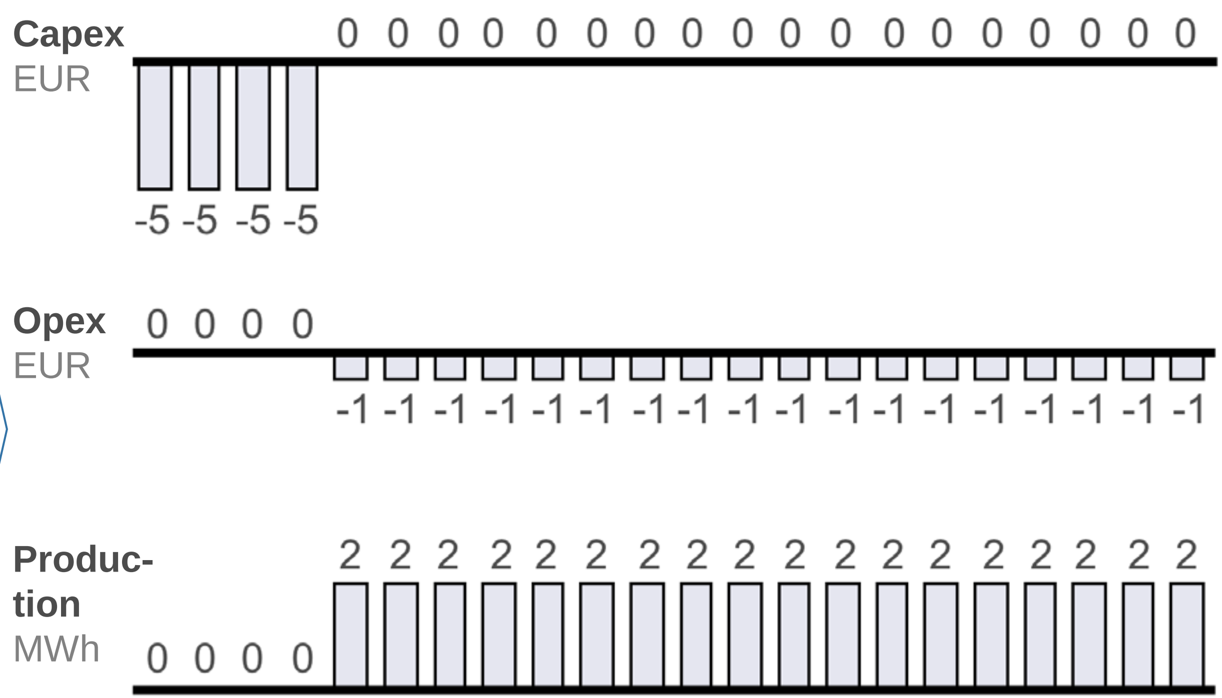
SOURCE: Stakeholder workshops; team analysis

The cost of electricity (CoE) is based on the present value of capex, opex and electricity production

Logic

- **Objective**: Assess levelized cost of electricity which are necessary to ensure an NPV of 0
- **Basic assumptions:**
  - WACC (real, after tax): 7%
  - 25% taxes, no subsidies

Illustrative example of the computation of the Cost of Electricity



CoE
EUR/MWh

$$= \frac{\text{PV (opex) + PV (capex)}}{\text{“PV” (production)}}$$

The grid system is designed by optimizing three elements, transmission investment, generation investment & operating costs

	Ensure adequate generation capacity	With the available transmission	To optimize the cost of operating the system	Overall optimization
Description	▪ Add back up and transmission capacity and optimize such that the system is able to meet peak every hour over the year	▪ Balance the investments in generation given the available transmission	▪ Schedule and dispatch generation ▪ Allocate reserves ▪ Includes stochastic wind and solar generation ▪ Add transmission to economically dispatch generation	▪ Iterate the simulations to seek optimal cost outcome – modifying investments in transmission and generation and operations costs

Outputs

- Generation investments for additional capacity to make system reliable "back-up generation"

- Transmission investments
- Transmission flows

- Cost of balancing
- Generation utilization
- Volumes of curtailment of renewables and others

SOURCE: Imperial College; KEMA; team analysis

Grid design approach

Input

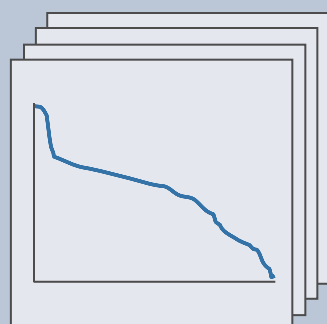
Power demand per region in 2050 by pathway

Installed capacity per technology per region in 2050 by pathway

McKinsey

Hourly demand and load curves based on historic data

Demand curves per region
Hourly demand patterns for a year



Supply curves per region
Hourly production patterns for a year for intermittent sources

KEMA

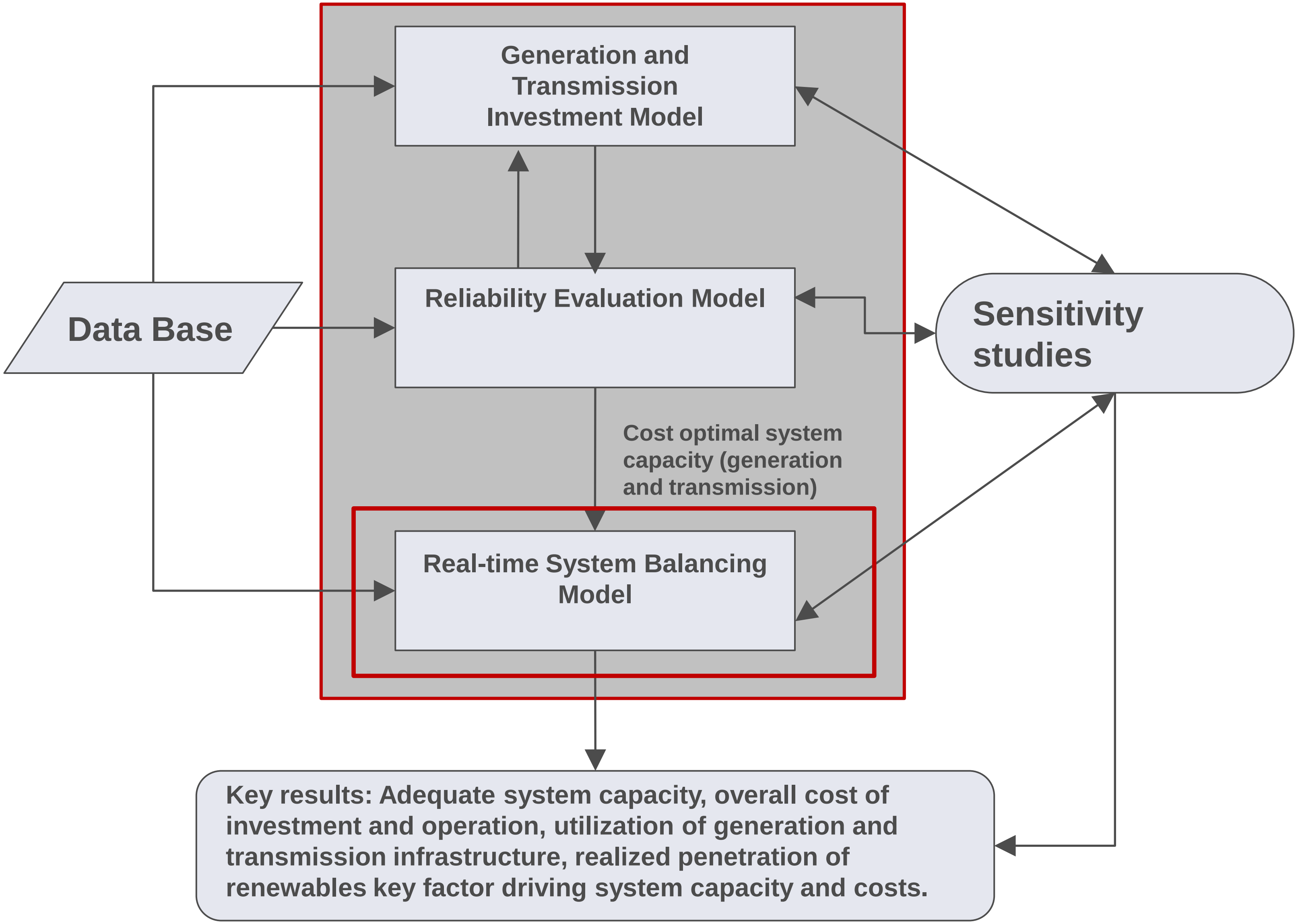
Output: Grid design

A grid and back-up capacity that matches demand at current quality levels

Imperial College

SOURCE: Imperial College; KEMA; team analysis

Model Structure



SOURCE: Imperial College; KEMA

Regional transmission has been calculated assuming ~27% DC and ~73% AC

European Climate Foundation

Transmission cost for element C

Transmission mix elements[1]	Share in cost mix	Share of cost
AC OHL long distance average terrain	56%	25%
AC OHL tough terrain (short distance)	6%	9%
AC underground (short distance) urban	10%	27%
AC subsea (medium distance)	1%	5%
TOTAL AC	**73%**	
DC subsea (long distance)	5%	20%
DC long distance underground cable	4%	6%
DC long distance OHL	18%	9%
TOTAL DC	**27%**	

1 Including substation cost

Average transmission cost between centers of gravity of

EUR 1,000 MW/km

based on:

- Current price levels
- A mix of AC and DC
- A mix of overhead lines and underground cables
- Substations are included, distribution is excluded

SOURCE: KEMA

Both energy efficiency and heating affect the load profile, top-down analysis suggests ~5% increase in peak over historic profile

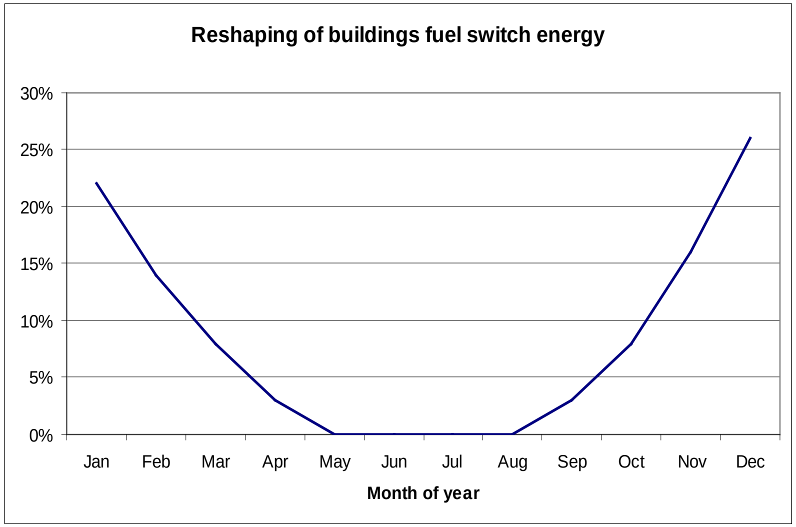
Review how fuel shifting and energy efficiency influences the 2050 demand profile

Baseline model used historic profile and assumed fuel shifting and energy efficiency effects were evenly distributed across the year

Challenge to review impact of energy efficiency and fuel shifting in different months of the year

Allocation of Buildings demand to the winter months and allocation of energy efficiency across summer for (AC) and winter (heat and light) reflecting energy usage

Additional energy associated with Building fuel shift allocated to winter months



Shape of the cumulative effect of energy efficiency across the year